ISSN 0042-8469
e-ISSN 2217-4753
УДК 623 + 355/359

Вол. 69, бр. 2
2021

ВТГ

НАУЧНИ ЧАСОПИС МИНИСТАРСТВА ОДБРАНЕ И ВОЈСКЕ СРБИЈЕ

ВОЈНОТЕХНИЧКИ ГЛАСНИК

2 2021 ВОЈНОТЕХНИЧКИ ГЛАСНИК

ВТГ.МО.УПР.СРБ

www.vtg.mod.gov.rs

ISSN 0042-8469
e-ISSN 2217-4753
УДК 623 + 355/359

Том 69, № 2
2021

НАУЧНЫЙ ЖУРНАЛ МИНИСТЕРСТВА ОБОРОНЫ
И ВООРУЖЕННЫХ СИЛ РЕСПУБЛИКИ СЕРБИЯ

ВОЕННО-ТЕХНИЧЕСКИЙ ВЕСТНИК

ВОЕННО-ТЕХНИЧЕСКИЙ ВЕСТНИК
2 2021

ВТГ.МО.УПР.СРБ
www.vtg.mod.gov.rs

ISSN 0042-8469
e-ISSN 2217-4753
UDC 623 + 355/359

Vol. 69, Issue 2
2021

MTC

SCIENTIFIC JOURNAL OF THE MINISTRY OF DEFENCE AND THE SERBIAN ARMED FORCES

MILITARY TECHNICAL COURIER

ВТГ.МО.УПР.СРБ

www.vtg.mod.gov.rs

MILITARY TECHNICAL COURIER
2 2021

ISSN 0042-8469
e-ISSN 2217-4753
UDC 623 + 355/359

НАУЧНИ ЧАСОПИС МИНИСТАРСТВА ОДБРАНЕ И ВОЈСКЕ СРБИЈЕ

ВОЈНОТЕХНИЧКИ ГЛАСНИК

ВОЛУМЕН 69 • БРОЈ 2 • АПРИЛ – ЈУН 2021.

NAUČNI ČASOPIS MINISTARSTVA ODBRANE I VOJSKE SRBIJE

VOJNOTEHNIČKI GLASNIK

VOLUMEN 69 • BROJ 2 • APRIL – JUN 2021.

втг.мо.упр.срб
www.vtg.mod.gov.rs
COBISS.SR-ID: 4423938
COBISS.SR-ID: 181287436
DOI: 10.5937/VojnotehnickiGlasnik

ISSN 0042-8469
e-ISSN 2217-4753
UDC 623 + 355/359

НАУЧНЫЙ ЖУРНАЛ МИНИСТЕРСТВА ОБОРОНЫ И ВООРУЖЁННЫХ СИЛ РЕСПУБЛИКИ СЕРБИЯ

ВОЕННО-ТЕХНИЧЕСКИЙ ВЕСТНИК

ТОМ 69 • НОМЕР ВЫПУСКА 2 • АПРЕЛЬ-ИЮНЬ 2021.

SCIENTIFIC JOURNAL OF THE MINISTRY OF DEFENCE AND SERBIAN ARMED FORCES

MILITARY TECHNICAL COURIER

VOLUME 69 • ISSUE 2 • APRIL-JUNE 2021

втг.мо.упр.срб
www.vtg.mod.gov.rs
COBISS.SR-ID: 4423938
COBISS.SR-ID: 181287436
DOI: 10.5937/VojnotehnickiGlasnik

Власници:
МИНИСТАРСТВО ОДБРАНЕ и ВОЈСКА СРБИЈЕ

Издавач:
УНИВЕРЗИТЕТ ОДБРАНЕ У БЕОГРАДУ, ВОЈНА АКАДЕМИЈА

Ректор
доц. др Горан Радовановић, генерал-потпуковник

Адреса редакције: ВОЈНОТЕХНИЧКИ ГЛАСНИК, Већка Лукића Курјака 33, 11042 Београд
http://www.vtg.mod.gov.rs
http://aseestant.ceon.rs/index.php/vtg/issue/current
http://scindeks.nb.rs/journaldetails.aspx?issn=0042-8469
http://elibrary.ru/title_about.asp?id=53280
https://doaj.org/toc/2217-4753
e-mail: vojnotehnicki.glasnik@mod.gov.rs

Претплата на штампано издање: e-mail: vojnotehnicki.glasnik@mod.gov.rs; тел. 066/87-00-123.

Часопис излази тромесечно.

Први штампани број *Војнотехничког гласника* објављен је 1. 1. 1953. године.

Прво електронско издање *Војнотехничког гласника* на Интернету објављено је 1. 1. 2011. године.

Војнотехнички гласник је лиценциран код EBSCO Publishing-а. Комплетан текст *Војнотехничког гласника* доступан је у базама података EBSCO Publishing-а.

Штампа: Војна штампарија – Београд, Ресавска 40б, e-mail: vojna.stamparija@mod.gov.rs

Собственники:
МИНИСТЕРСТВО ОБОРОНЫ и ВООРУЖЁННЫЕ СИЛЫ РЕСПУБЛИКИ СЕРБИЯ

Издательство:
УНИВЕРСИТЕТ ОБОРОНЫ В Г. БЕЛГРАД, ВОЕННАЯ АКАДЕМИЯ

РЕКТОР
Генерал-лейтенант доц. д-р Горан Радованович

ГЛАВНЫЙ И ОТВЕТСТВЕННЫЙ РЕДАКТОР ЖУРНАЛА «ВОЕННО-ТЕХНИЧЕСКИЙ ВЕСТНИК»
Кандидат технических наук Небойша Гачеша, подполковник
e-mail: nebojsa.gacesa@mod.gov.rs, тел.: +381 11 3603 260, +381 66 87 00 123, http://orcid.org/0000-0003-3217-6513

Адрес редакции: ВОЈНОТЕХНИЧКИ ГЛАСНИК, Ул. Велька Лукича Куряка 33, 11042 Белград, Республика Сербия
http://www.vtg.mod.gov.rs
http://aseestant.ceon.rs/index.php/vtg/issue/current
http://scindeks.nb.rs/journaldetails.aspx?issn=0042-8469
http://elibrary.ru/title_about.asp?id=53280
https://doaj.org/toc/2217-4753
e-mail: vojnotehnicki.glasnik@mod.gov.rs
Подписка на печатную версию журнала: e-mail: vojnotehnicki.glasnik@mod.gov.rs; тел. +381 66 87 00 123.
Журнал выпускается ежеквартально.
Первый номер журнала «Военно-технический вестник» выпущен 1.1.1953 года.
Первая электронная версия журнала размещена на интернет странице 1.1.2011 года.
«Военно-технический вестник» включен в систему EBSCO.
Типография: Војна штампарија – Белград, Ресавска 40б, e-mail: vojna.stamparija@mod.gov.rs

Owners:
MINISTRY OF DEFENCE and SERBIAN ARMED FORCES

Publisher:
UNIVERSITY OF DEFENCE IN BELGRADE, MILITARY ACADEMY

Rector
Lieutenant General Goran Radovanović, PhD, Assistant Professor

Address: VOJNOTEHNIČKI GLASNIK/MILITARY TECHNICAL COURIER, Veljka Lukića Kurjaka 33, 11042 Belgrade, Republic of Serbia
http://www.vtg.mod.gov.rs/index-e.html
http://aseestant.ceon.rs/index.php/vtg/issue/current
http://scindeks.nb.rs/journaldetails.aspx?issn=0042-8469

SCINDEKS Serbian Citation Index РОССИЙСКИЙ ИНДЕКС НАУЧНОГО ЦИТИРОВАНИЯ INDEXED IN DOAJ ROAD

http://elibrary.ru/title_about.asp?id=53280

https://doaj.org/toc/2217-4753

e-mail: vojnotehnicki.glasnik@mod.gov.rs

Subscription to print edition: e-mail: vojnotehnicki.glasnik@mod.gov.rs; Tel. +381 66 87 00 123.

The journal is published quarterly.

The first printed issue of the *Military Technical Courier* appeared on 1st January 1953.

The first electronic edition of the *Military Technical Courier* on the Internet appeared on 1st January 2011.

Military Technical Courier has entered into an electronic licensing relationship with EBSCO Publishing. The full text of *Military Technical Courier* can be found on EBSCO Publishing's databases.

Printed by Vojna štamparija – Belgrade, Resavska 40b, e-mail: vojna.stamparija@mod.gov.rs

С А Д Р Ж А Ј

ОРИГИНАЛНИ НАУЧНИ РАДОВИ

СТРУЧНИ РАДОВИ

С О Д Е Р Ж А Н И Е

C O N T E N T S

ОРИГИНАЛНИ НАУЧНИ РАДОВИ
ОРИГИНАЛЬНЫЕ НАУЧНЫЕ СТАТЬИ
ORIGINAL SCIENTIFIC PAPERS

EXISTENCE OF A SOLUTION FOR A GENERAL ORDER BOUNDARY VALUE PROBLEM USING THE LERAY–SCHAUDER FIXED POINT THEOREM

Nicola Fabiano[a], *Vahid* Parvaneh[b]

[a] Independent researcher, Rome, Italy,
e-mail: nicola.fabiano@gmail.com, **corresponding author,**
ORCID iD: https://orcid.org/0000-0003-1645-2071

[b] Islamic Azad University, Department of Mathematics,
Gilan-E-Gharb Branch, Gilan-E-Gharb, Islamic Republic of Iran,
e-mail: zam.dalahoo@gmail.com,
ORCID iD: https://orcid.org/0000-0002-3820-3351

DOI: 10.5937/vojtehg69-29703; https://doi.org/10.5937/vojtehg69-29703

FIELD: Mathematics

ARTICLE TYPE: Original scientific paper

Abstract:

Introduction/purpose: This paper illustrates the existence of a generic Green's function for a boundary value problem of arbitrary order that appears in many phenomena of heat convection, e.g. in the atmosphere, in the oceans, and on the Sun's surface.

Methods: A fixed point theorem in the Leray–Schauder form has been used to establish the existence of a fixed point in the problem.

Results: The existence of a solution has been shown for an arbitrary order of the problem. Some practical examples are proposed.

Conclusions: The boundary problem has a solution for an arbitrary order n.

Key words: fixed point, boundary value problem, Leray–Schauder fixed point theorem.

The problem

We consider the generic differential equation of order $2n, n \geq 1$, with the boundary conditions:

$$\begin{cases} y^{(2n)}(x) = \chi(x, y(x), y''(x)) \\ y^{(0)}(0) = y^{(1)}(0) = \ldots = y^{(n)}(0) = 0 \\ y^{(n+1)}(1) = y^{(n+2)}(1) = \ldots = y^{(2n-1)}(1) = 0. \end{cases} \tag{1}$$

This kind of equations occurs, for instance, when studying the problem of the beginning of thermal instability in horizontal layers of fluid heated from below. This kind of phenomena could be observed in convection patterns in several situations, for instance, in the atmosphere, in the oceans, when considering the coupling with a strong electromagnetic field, or on the Sun's surface (Chandrasekhar, 1961). This work will extend the results of (Fabiano et al, 2020), (Ahmad & Ntouyas, 2012) and (Ma, 2000) to an equation of a generic order $2n$.

Introduce the Green's functions $G_l(x, s, n)$ and $G_r(x, s, n)$ of problem (1) where $G_l(x, s, n)$ is defined for $0 \leq x < s \leq 1$ and $G_r(x, s, n)$ is defined for $0 \leq s < x \leq 1$, $(x, s) \mapsto G_{l,r}(x, s, n); (x, s) \in [0, 1] \times [0, 1], G_{l,r} \in C^{2n}$ over $\mathbb{R}$ such that solve the following equation:

$$\left(\frac{\partial}{\partial x}\right)^{2n} G_{l,r}(x, s, n) = \delta(s - x)\,. \tag{2}$$

The complete Green's function is thus obtained by the linear combination of the above two,

$$G(x, s, n) = \theta(s - x)G_l(x, s, n) + \theta(x - s)G_r(x, s, n)\ , \tag{3}$$

θ is the Heaviside step function. Given the inhomogeneous problem solved by $x \mapsto f(x), x \in [0, 1], f \in C$ over $\mathbb{R}$,

$$\begin{cases} y^{(2n)}(x) = f(x) \\ y^{(0)}(0) = y^{(1)}(0) = \ldots = y^{(n)}(0) = 0 \\ y^{(n+1)}(1) = y^{(n+2)}(1) = \ldots = y^{(2n-1)}(1) = 0\ , \end{cases} \tag{4}$$

the Green's function provides solution to (4) in the integral form

$$y(x) = \int_0^1 G(x, s, n) f(s) ds\ . \tag{5}$$

The functions $G_{l,r}(x,s,n)$ are multivariate polynomials in two variables x and s of the order $2n-1$ to be sought in the form

$$G_l(x,s,n) = \sum_{k=1}^{n} c(k,n) x^{k-1} s^{2n-k} \tag{6}$$

and

$$G_r(x,s,n) = \sum_{k=1}^{n} c(k,n) s^{k-1} x^{2n-k} \tag{7}$$

where the coefficient $c(k,n)$ is clearly given in combinatoric terms, $k \leq n$.

Imposing boundary conditions (4) to the Green's function, we obtain that

$$G_l(0,s,n) = \left(\frac{\partial}{\partial x}\right) G_l(x,s,n)\Big|_{x=0} = \ldots = \left(\frac{\partial}{\partial x}\right)^{n} G_l(x,s,n)\Big|_{x=0} = 0 \tag{8}$$

and

$$\left(\frac{\partial}{\partial x}\right)^{n+1} G_r(x,s,n)\Big|_{x=1} = \ldots = \left(\frac{\partial}{\partial x}\right)^{2n-1} G_r(x,s,n)\Big|_{x=1} = 0. \tag{9}$$

So, we could infer the following results.

For $G_l(x,s,n)$ the powers of x range from n to $2n-1$, while for the powers of s we have the range from 0 to $n-1$. For $G_r(x,s,n)$ we find the same situation when swapping s with x. Therefore, the coefficient $c(k,n)$ has to be symmetric under this exchange.

We conclude that the coefficient $c(k,n)$ of both functions $G_{l,r}(x,s,n)$ is given by:

$$c(k,n) = \frac{(-1)^k}{(2n-1)!}\binom{2n-1}{k-1} = \frac{(-1)^k}{(k-1)!(2n-k)!}\,. \tag{10}$$

Notice that $|c(k,n)| < 1$ for all k,n. This observation will be useful in the sequel.

The resulting Green's function $G(x,s,n)$ and its x derivatives are continuous up to order $2n-2$, and present the discontinuity in -1 at order $2n-1$, because of the Dirac's δ function.

The above discussion concludes the proof of the following lemma:

LEMMA 1. *Let $x \mapsto y(x), x \in [0,1]$ be a function of class C^{2n} in $\mathbb{R}$, let $(x,y,z) \mapsto \chi(x,y,z); x \in [0,1], (y,z) \in \mathbb{R}^2$ be a function of class C in $\mathbb{R}$ and*

let χ be a function of class C in $\mathbb{R}$. Then the Green's function of the problem (4) obeying to equation (2) is given by formulas (3), (6), (7), and (10).

Another property of these Green's functions is their homogeneity. In fact, under the scaling transformation $(x, s) \to (\alpha x, \alpha s)$ for $\alpha > 0$ one has

$$G_{l,r}(\alpha x, \alpha s, n) = \alpha^{2n-1} G_{l,r}(x, s, n),$$

that is, $G_{l,r}(x, s, n)$ is homogeneous of degree $2n - 1$.

Solution

In this section, we will provide the main result of this work: the solution of the problem in (1) for a generic n .

Define the integral operator Υ as follows:

$$\Upsilon y(x) := \int_0^x G_r(x, s, n) f(s) ds + \int_x^1 G_l(x, s, n) f(s) ds. \tag{11}$$

According to Lemma 1, this operator provides a solution of problem (4) for a generic order n provided that it has a fixed point.

We shall make use of the following theorem of (Bekri & Benaicha, 2018) and (Shanmugam et al, 2019), the Leray–Schauder form of the fixed point theorem appears in (Isac, 2006), (Deimling, 1985) and (Zvyagin & Baranovskii, 2010):

THEOREM 1. *Let $(E, ||\cdot||)$ be a Banach space, let $U \subset E$ be an open bounded subset for which $0 \in U$ and let $\Upsilon : \overline{U} \to E$ be a completely continuous operator. Then only one of the following possibilities is true:*

1. *Υ possesses a fixed point $\bar{x} \in \overline{U}$*
2. *there exist an element $x \in \partial\overline{U}$ and a real number $\lambda > 1$ such that $\Upsilon x = \lambda x$.*

Therefore, in order to establish the existence of a solution it is necessary to prove that our integral operator Υ possesses a fixed point. The following two theorems are devoted to this problem.

THEOREM 2. *Let $x \mapsto y(x), x \in [0, 1]$ be a function of class C^{2n} in $\mathbb{R}$, let $(x, y, z) \mapsto \chi(x, y, z); x \in [0, 1], (y, z) \in \mathbb{R}^2$ be a function of the class C in $\mathbb{R}$*

and $|\chi(x,0,0)| \neq 0$. *Suppose that there exist three nonnegative functions* $x \mapsto (u(x), v(x), w(x)) \in L^1[0,1]$ *such that*

$$|\chi(x,y,z)| \leq u(x)|y| + v(x)|z| + w(x).$$

Define the kernel

$$\mathcal{K}_n(s) := \sum_{k=1}^{2n-1} s^k$$

and suppose that

$$A := \int_0^1 \mathcal{K}_n(s)[u(s) + v(s)]ds < 1.$$

Then the problem (1) has at least one nontrivial solution $x \mapsto \xi(x), x \in [0,1]$ *of class* C^{2n} *in* $\mathbb{R}$.

Proof. Define the constant

$$B = \int_0^1 \mathcal{K}_n(s)w(s)ds.$$

From our hypothesis $A < 1$ and $w(s) \geq 0$. Observe that $\mathcal{K}_n(s) > 0$ for all $s \in [0,1]$. As $|\chi(x,y,z)| \leq u(x)|y| + v(x)|z| + w(x)$, for all $x \in [0,1]$ and $(y,z) \in \mathbb{R}^2$ and according to the fact that $\chi(x,0,0) \neq 0$ for all $x \in [0,1]$, there exist an interval $[a,b] \subset [0,1]$ such that $\max_{x\in[a,b]} |\chi(x,0,0)| > 0$. Therefore, $|\chi(x,0,0)| > 0$ and also $w(x) > 0$, for some $x \in [a,b] \subset [0,1]$. This implies the inequality $\int_0^1 \mathcal{K}_n(s)w(s)ds \geq \int_a^b \mathcal{K}_n(s)w(s)ds > 0$. We conclude that $A < 1$ and $B > 0$.

Define $L := B(1-A)^{-1}$ which is positive by construction, and the set $U = \{y \in E : ||y|| < L\}$. Assume that $y \in \partial U$ and $\lambda > 1$. As $\Upsilon y = \lambda y$, then $\lambda L = \lambda||y|| = ||\Upsilon y|| = \max_{x\in[0,1]} |(\Upsilon y)(x)|$. Adopting the simplified notation $d\mu = |\chi(s, y(s), y''(s)|ds$ we have:

$$\lambda L = \max_{x\in[0,1]} |(\Upsilon y)(x)| \leq \left\{ \int_0^x G_r(x,s,n)d\mu + \int_x^1 G_l(x,s,n)d\mu \right\} =$$
$$\sum_{k=1}^{n} c(k,n) \left\{ \int_0^x s^{k-1}x^{2n-k}d\mu + \int_x^1 x^{k-1}s^{2n-k}d\mu \right\} \leq$$

$$\sum_{k=1}^{n} c(k,n) \max_{x\in[0,1]} \left\{ \int_0^x s^{k-1} x^{2n-k} d\mu + \int_x^1 x^{k-1} s^{2n-k} d\mu \right\} =$$

$$\sum_{k=1}^{n} c(k,n) \left\{ \int_0^1 s^{k-1} d\mu + \int_0^1 s^{2n-k} d\mu \right\} =$$

$$\sum_{k=1}^{n} c(k,n) \left\{ \int_0^1 (s^{k-1} + s^{2n-k}) d\mu \right\} \leq$$

$$\sum_{k=1}^{n} \left\{ \int_0^1 (s^{k-1} + s^{2n-k}) d\mu \right\} = \sum_{k=1}^{2n-1} \int_0^1 s^k d\mu = \int_0^1 \mathcal{K}_n(s) d\mu \,. \quad (12)$$

from our hypothesis, $|\chi(x,0,0)|$ has an upper bound for all $x \in [0,1]$. So, one has

$$\int_0^1 \mathcal{K}_n(s) |\chi(s,0,0)| ds \leq \int_0^1 \mathcal{K}_n(s) \left[u(s)|y(s)| + v(s)|y''(s)| + w(s) \right] ds \leq$$

$$\int_0^1 \mathcal{K}_n(s) \left[u(s) \max_{s\in[0,1]} |y(s)| + v(s) \max_{s\in[0,1]} |y''(s)| + w(s) \right] ds \leq$$

$$\int_0^1 \mathcal{K}_n(s) \left[u(s)|y(s)|_\infty + v(s)|y''(s)|_\infty + w(s) \right] ds \leq$$

$$\int_0^1 \mathcal{K}_n(s) \left[u(s)||y|| + v(s)||y|| + w(s) \right] ds =$$

$$\int_0^1 \mathcal{K}_n(s) \left[u(s) + v(s) \right] ||y|| ds + \int_0^1 \mathcal{K}_n(s) w(s) ds =$$

$$A||y|| + B = AL + B \,. \quad (13)$$

Using equation (12), we obtain the bound $\lambda L \leq AL + B$ which implies that

$$\lambda \leq A + \frac{B}{L} = A + \frac{B}{B(1-A)^{-1}} = 1,$$

which contradicts the hypothesis for which $\lambda > 1$, that is point (2) of Theorem 2.1 is ruled out, while point (1) is fulfilled. Therefore, we conclude that there exists at least a nontrivial solution $\xi(x)$ of problem (1). □

Up to this point, we have established the existence of a solution for the boundary value problem. In the following theorem, we show some parameter dependent bounds that actually lead to the existence of a solution.

THEOREM 3. *Let* $(x,y,z) \mapsto \chi(x,y,z); x \in [0,1], (y,z) \in \mathbb{R}^2$, χ *is of class* C *in* $\mathbb{R}$ *and* $|\chi(x,0,0)| \neq 0$. *Suppose that there exist three nonnegative functions* $x \mapsto (u(x), v(x), w(x)) \in L^1[0,1]$ *such that*

$$|\chi(x,y,z)| \leq u(x)|y| + v(x)|z| + w(x).$$

Define

$$\mathcal{K}_n(s) := \sum_{k=1}^{2n-1} s^k$$

and suppose that either one of the following conditions holds:

1. *There exists a constant* $\ell > -2$ *such that*

$$u(s) + v(s) < \frac{s^\ell}{\psi(2n+\ell+1) - \psi(\ell+2)},\ 0 \leq s \leq 1\ ,$$

where

$$\psi(z) := \frac{d}{dz}\left[\log \Gamma(z)\right] \quad \textit{and} \quad \Gamma(z) := \int_0^\infty e^{-t} t^{z-1} dt.$$

2. *There exists a constant* $m > -1$ *such that*

$$u(s) + v(s) < \frac{m^2+m}{1-(m^2+m)\beta(m,2n+1)} \cdot (1-s)^m,\ 0 \leq s \leq 1\ ,$$

where

$$\beta(m,2n+1) = \frac{\Gamma(m)\Gamma(2n+1)}{\Gamma(2n+m+1)}.$$

3. *There exists a constant* $a > 1$ *such that*

$$\left[\int_0^1 (u(s)+v(s))^a ds\right]^{\frac{1}{a}} < \frac{1}{\sum_{k=1}^{2n-1}\left(\frac{1}{kb+1}\right)^{\frac{1}{b}}},\ \frac{1}{a} + \frac{1}{b} = 1$$

and

$$\int_0^1 \mathcal{K}_n(s)[u(s)+v(s)]ds < 1.$$

Then problem (1) has at least one nontrivial solution $x \mapsto \xi(x), x \in [0,1]$ *of class* C^{2n} *in* $\mathbb{R}$.

Proof. In order to prove this theorem, one has to show that the integral operator (11) has $A < 1$, A being defined in Theorem 2.

To prove point 1, we proceed as follows:

$$\int_0^1 \mathcal{K}_n(s)[u(s)+v(s)]ds < \frac{1}{\psi(2n+\ell+1)-\psi(\ell+2)} \int_0^1 \mathcal{K}_n(s)s^\ell ds = \frac{1}{\psi(2n+\ell+1)-\psi(\ell+2)} \sum_{k=1}^{2n-1} \int_0^1 s^{(k+\ell)} ds = \frac{1}{\psi(2n+\ell+1)-\psi(\ell+2)} \sum_{k=1}^{2n-1} \frac{1}{k+\ell+1} = [\psi(2n+\ell+1)-\psi(\ell+2)] \cdot \frac{1}{\psi(2n+\ell+1)-\psi(\ell+2)} = 1\,, \quad (14)$$

and when $\ell > -2$, one has

$$\frac{1}{\psi(2n+\ell+1)-\psi(\ell+2)} > 0.$$

For point 2, we have

$$\int_0^1 \mathcal{K}_n(s)[u(s)+v(s)]ds < \frac{m^2+m}{1-(m^2+m)\beta(m,2n+1)} \int_0^1 \mathcal{K}_n(s)(1-s)^m ds = \frac{m^2+m}{1-(m^2+m)\beta(m,2n+1)} \sum_{k=1}^{2n-1} \int_0^1 s^k(1-s)^m ds = \frac{m^2+m}{1-(m^2+m)\beta(m,2n+1)} \sum_{k=1}^{2n-1} \beta(k,m) = \left[\frac{m^2+m}{1-(m^2+m)\beta(m,2n+1)}\right] \cdot \left[\frac{1}{m^2+m} - \beta(m,2n+1)\right] = 1\,, \quad (15)$$

and when $m > -1$, one has

$$\frac{m^2+m}{1-(m^2+m)\beta(m,2n+1)} > 0.$$

In the case of point 3, we make use of Hölder inequality for which $\int_S |f(s)g(s)|ds \leq \left(\int_S |f(s)|^a ds\right)^{1/a} \left(\int_S |g(s)|^b ds\right)^{1/b}$, whenever f and g are measurable functions on the domain S and $1/a + 1/b = 1$. We have

$$\int_0^1 \mathcal{K}_n(s)[u(s)+v(s)]ds \leq \left[\int_0^1 (u(s)+v(s))^a ds\right]^{\frac{1}{a}} \cdot \sum_{k=1}^{2n-1} \left[\int_0^1 (s^k)^b ds\right]^{\frac{1}{b}} =$$

$$\left[\int_0^1 (u(s)+v(s))^a ds\right]^{\frac{1}{a}} \cdot \sum_{k=1}^{2n-1} \left(\frac{1}{kb+1}\right)^{\frac{1}{b}} <$$

$$\frac{1}{\sum_{k=1}^{2n-1}\left(\frac{1}{kb+1}\right)^{\frac{1}{b}}} \cdot \sum_{k=1}^{2n-1} \left(\frac{1}{kb+1}\right)^{\frac{1}{b}} = 1\,. \quad (16)$$

□

Examples

Example 1

Consider the problem for a generic $n \geq 1$

$$\begin{cases} y^{(2n)}(x) = \dfrac{x^\alpha}{2} y^2 e^{-y^2} + \dfrac{x^\alpha}{8} \dfrac{(y'')^4}{[(y'')^6+2]} \sin y'' + e^{-\frac{x^2}{2}} \\ y^{(0)}(0) = y^{(1)}(0) = \ldots y^{(n)}(0) = 0 \\ y^{(n+1)}(1) = y^{(n+2)}(1) = \ldots y^{(2n-1)}(1) = 0. \end{cases} \quad (17)$$

This problem satisfies all requirements of Theorem 2. In fact, one has

$$\chi(x,y,z) = \frac{x^\alpha}{2} y^2 e^{-y^2} + \frac{x^\alpha}{8} \frac{z^4}{z^6+2} \sin z + e^{-\frac{x^2}{2}}$$

together with

$$u(x) = \frac{x^\alpha}{2},\ v(x) = \frac{x^\alpha}{2},\ w(x) = e^{-\frac{x^2}{2}}\ .$$

For a generic $\alpha > 0$, following Theorem 3, hypothesis 1, we have that $(u(x), v(x), w(x)) \in L^1[0,1]$ are nonnegative functions. Moreover,

$$|\chi(x,y,z)| \leq u(x)|y| + v(x)|z| + w(x)$$

for all $x \in [0,1]$ and for all $(y,z) \in \mathbb{R}^2$.

Fabiano, N. et al, Existence of a solution for a gen. order bound. value problem using the Leray–Schauder fixed point theorem, pp.323–337

Setting $\alpha = \ell$ one has to consider the inequality

$$\left[\frac{1}{\psi(2n+\ell+1)-\psi(\ell+2)}-1\right]x^{\ell}>0 \tag{18}$$

for all $x \in [0,1]$. In the parameter space (α, ℓ, n), the above inequality is satisfied, for instance, for the case $\alpha = \ell = n$, whenever

$$1 \leq n \leq 12. \tag{19}$$

In this case, the existence of a nontrivial solution $\xi(x) \in C^{2n}[0,1]$ is guaranteed for problem (17).

Example 2

Consider the problem for a generic $n \geq 1$

$$\begin{cases} y^{(2n)}(x) = \frac{1}{4}(1-x)^{\alpha} y\cos y + \frac{1}{32}(1-x)^{\alpha} y''\tanh y'' + \cosh x \\ y^{(0)}(0) = y^{(1)}(0) = \ldots = y^{(n)}(0) = 0 \\ y^{(n+1)}(1) = y^{(n+2)}(1) = \ldots = y^{(2n-1)}(1) = 0. \end{cases} \tag{20}$$

This problem satisfies all requirements of Theorem 2. In fact, one has

$$\chi(x,y,z) = \frac{1}{4}(1-x)^{\alpha} y\cos y + \frac{1}{32}(1-x)^{\alpha} z\tanh z + \cosh x$$

together with

$$u(x) = \frac{(1-x)^{\alpha}}{2},\ v(x) = \frac{(1-x)^{\alpha}}{2},\ w(x) = \cosh x.$$

For a generic $\alpha > 0$, from hypothesis 2 of Theorem 3, we have that $(u(x), v(x), w(x)) \in L^1[0,1]$ are nonnegative functions. Moreover,

$$|\chi(x,y,z)| \leq u(x)|y| + v(x)|z| + w(x)$$

for all $x \in [0,1]$ and for all $(y,z) \in \mathbb{R}^2$.

Setting $\alpha = m$, one has to investigate the following inequality:

$$\left[\frac{m^2+m}{1-(m^2+m)\beta(m,2n+1)}-1\right]\cdot(1-x)^m > 0 \tag{21}$$

for all $x \in [0,1]$. In the parameter space (α, m, n), the above inequality is satisfied, for instance, for the case $\alpha = m = n$, whenever

$$n \geq 1. \tag{22}$$

In this case, the existence of a nontrivial solution $\xi(x) \in C^{2n}[0,1]$ is guaranteed for problem (20).

Example 3
Consider the problem for a generic $n \geq 1$

$$\begin{cases} y^{(2n)}(x) = \dfrac{x^\alpha}{2}\dfrac{y^3}{y^4+4}\tanh y + \dfrac{x^\alpha}{4}(y'')^2 e^{-(y'')^2} + e^x + 3 \\ y^{(0)}(0) = y^{(1)}(0) = \ldots y^{(n)}(0) = 0 \\ y^{(n+1)}(1) = y^{(n+2)}(1) = \ldots y^{(2n-1)}(1) = 0. \end{cases} \tag{23}$$

This problem satisfies all requirements of Theorem 2. In this example,

$$\chi(x,y,z) = \frac{x^\alpha}{2}\frac{y^3}{y^4+4}\tanh y + \frac{x^\alpha}{4}z^2 e^{-z^2} + e^x + 3$$

together with

$$u(x) = \frac{x^\alpha}{2},\ v(x) = \frac{x^\alpha}{2},\ w(x) = e^x + 3.$$

For a generic $\alpha > 0$, following assumption 3 of Theorem 3, we have that $(u(x), v(x), w(x)) \in L^1[0,1]$ are nonnegative functions. Moreover,

$$|\chi(x,y,z)| \leq u(x)|y| + v(x)|z| + w(x)$$

for all $x \in [0,1]$ and $(y,z) \in \mathbb{R}^2$.

We have

$$u(x)+v(x)=x^{\alpha},$$

that leads to the relation

$$\left(\frac{1}{\alpha a+1}\right)^{\frac{1}{a}} \leq \frac{1}{\sum_{k=1}^{2n-1}\left(\frac{1}{kb+1}\right)^{\frac{1}{b}}}. \tag{24}$$

Setting $a=b=2$, inequality (24) becomes:

$$\left(\frac{1}{2\alpha+1}\right)^{\frac{1}{2}} \leq \frac{1}{\sum_{k=1}^{2n-1}\left(\frac{1}{2k+1}\right)^{\frac{1}{2}}} = \frac{\sqrt{2}}{\zeta(\frac{1}{2},\frac{3}{2})-\zeta(\frac{1}{2},2n+\frac{1}{2})} \tag{25}$$

where

$$\zeta(s,q):=\sum_{k=0}^{\infty}\frac{1}{(k+q)^{s}}$$

is the Hurwitz zeta function, defined for $s\neq 1$ and $\Re(q)>0$. In our problem, it is always well defined since $q>0$ and $s=1/2$.

In the parameter space (α,n), setting $\alpha=n$, for instance one obtains that inequality (25) is satisfied whenever

$$1\leq n\leq 7. \tag{26}$$

Letting $\alpha=n^2$ we obtain that inequality (25) is satisfied whenever

$$n\geq 1. \tag{27}$$

For the above choice of parameters, the existence of a nontrivial solution $\xi(x)\in C^{2n}[0,1]$ is guaranteed for problem (23).

References

Ahmad B. & Ntouyas, S.K. 2012. A study of higher-order nonlinear ordinary differential equations with four-point nonlocal integral boundary conditions. *Journal of Applied Mathematics and Computing*, 39, pp.97-108. Available at: https://doi.org/10.1007/s12190-011-0513-0.

Bekri Z. & Benaicha, S. 2018. Nontrivial solution of a nonlinear sixth-order boundary value problem. *Waves, Wavelets and Fractals*, 4(1), pp.10-18. Available at: https://doi.org/10.1515/wwfaa-2018-0002.

Chandrasekhar, S. 1961. *Hydrodynamic and Hydromagnetic Stability*. New York, NY: Dover. Online ISBN: 9780486319209.

Deimling, K. 1985. *Nonlinear Functional Analysis*. Berlin, Heidelberg: Springer. Available at: https://doi.org/10.1007/978-3-662-00547-7. Online ISBN: 978-3-662-00547-7.

Fabiano, N., Nikolić, N., Shanmugam, T., Radenović, S. & Čitaković, N. 2020. Tenth order boundary value problem solution existence by fixed point theorem. *Journal of Inequalities and Applications*, art.number:166. Available at: https://doi.org/10.1186/s13660-020-02429-2.

Isac, G. 2006. *Leray–Schauder Type Alternatives, Complementarity Problems and Variational Inequalities*. Boston, MA: Springer. Available at: https://doi.org/10.1007/0-387-32900-5. Online ISBN: 978-0-387-32900-0.

Ma, R. 2000. Existence and uniqueness theorems for some fourth-order nonlinear boundary value problems. *International Journal of Applied Mathematics and Computer Science*, 23, art.ID:739631. Available at: https://doi.org/10.1155/S0161171200003057.

Shanmugam, T., Muthiah, M. & Radenović, S. 2019. Existence of Positive Solution for the Eighth-Order Boundary Value Problem Using Classical Version of Leray–Schauder Alternative Fixed Point Theorem. *Axioms*, 8(4), art.number:129. Available at: https://doi.org/10.3390/axioms8040129.

Zvyagin, V.G. & Baranovskii, E.S. 2010. Topological degree of condensing multi-valued perturbations of the $(S)_+$-class maps and its applications. *Journal of Mathematical Sciences*, 170, pp.405-422. Available at: https://doi.org/10.1007/s10958-010-0094-8.

СУЩЕСТВОВАНИЕ РЕШЕНИЯ КРАЕВОЙ ЗАДАЧИ ОБЩЕГО ПОРЯДКА С ИСПОЛЬЗОВАНИЕМ ТЕОРЕМЫ ЛЕРЕ-ШАУДЕРА О НЕПОДВИЖНОЙ ТОЧКЕ

Никола Фабиано[а], *Вахид* Парванех[б]

[а] независимый исследователь, г. Рим, Италия, **корреспондент**,

[б] Исламский университет Азад, факультет математики, филиал Гилан-э-Герб, г. Гилан-э-Герб, Исламская Республика Иран

РУБРИКА ГРНТИ: 27.00.00 МАТЕМАТИКА:
27.29.19 Краевые задачи и задачи на собственные значения для обыкновенных дифференциальных уравнений и систем уравнений,
27.29.21 Аналитическая теория обыкновенных дифференциальных уравнений и систем уравнений,
27.39.00 Функциональный анализ
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В данной статье приведено существование производящей функции Грина для решения краевой задачи произвольного порядка, которая встречается во многих явлениях тепловой конвекции как в атмосфере, в океанах, так и на поверхности Солнца.

Методы: В статье применена теорема неподвижной точки Лере - Шаудера, с целью подтверждения существования неподвижной точки в данной задаче.

Результаты: Доказано существование решения по произвольному порядку и предлагаются некоторые практические примеры.

Выводы: Краевая задача имеет решение по произвольному n-му порядку.

Ключевые слова: неподвижная точка, краевая задача, теорема Лере – Шаудера о неподвижной точке.

РЕШЕЊЕ ПРОБЛЕМА ГРАНИЧНЕ ВРЕДНОСТИ ОПШТЕГ РЕДА КОЈЕ КОРИСТИ ТЕОРЕМУ НЕПОКРЕТНЕ ТАЧКЕ ТИПА LERAY-SCHAUDER

Никола Фабиано[а], *Вахид* Парванех[б]

[а] независни истраживач, Рим, Италија, **аутор за преписку**,

[б] Исламски универзитет Азад, Одељење за математику, Огранак Гилан-Е-Гхарб, Гилан-Е-Гхарб, Исламска Република Иран

ОБЛАСТ: математика

ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: У раду се приказује постојање генеричке Гринове функције за проблем граничне вредности произвољног реда који се јавља код многих појава конвекције топлоте у, на пример, атмосфери, океанима и на површини Сунца.

Методе: Користи се теорема непокретне тачке типа Leray-Schauder како би се утврдило постојање непокретне тачке у наведеном проблему.

Резултати: Приказано је решење за произвољан ред проблема. Предложени су неки практични примери.

Закључак: Гранични проблем има решење за произвољни n-ти ред.

Кључне речи: непокретна тачка, проблем граничне вредности, теорема непокретне тачке типа Leray-Schauder.

Paper received on / Дата получения работы / Датум пријема чланка: 03.12.2020.
Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 01.03.2021.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 03.03.2021.

REVISITING AND REVAMPING SOME NOVEL RESULTS IN $\mathcal{F}$-METRIC SPACES

Zoran D. Mitrović[a], *Mudasir* Younis[b], *Miloje* D. Rajović[c]

[a] University of Banja Luka, Faculty of Electrical Engineering,
Banja Luka, Republic of Srpska, Bosnia and Herzegovina,
e-mail: zoran.mitrovic@etf.unibl.org, **corresponding author**,
ORCID iD: https://orcid.org/0000-0001-9993-9082

[b] University Institute of Technology-RGPV,
Department of Applied Mathematics, Bhopal, M.P, India,
e-mail: mudasiryouniscuk@gmail.com,
ORCID iD: https://orcid.org/0000-0001-5499-4272

[c] University of Kragujevac, Faculty of Mechanical Engineering,
Kraljevo, Republic of Serbia,
e-mail: rajovic.m@mfkv.kg.ac.rs,
ORCID iD: https://orcid.org/0000-0002-7574-3832

DOI: 10.5937/vojtehg69-29615; https://doi.org/10.5937/vojtehg69-29615

FIELD: Mathematics

ARTICLE TYPE: Original scientific paper

Abstract:

Introduction/purpose: This article establishes several new contractive conditions in the context of so-called $\mathcal{F}$-metric spaces. The main purpose was to generalize, extend, improve, complement, unify and enrich the already published results in the existing literature. We used only the property (F1) of Wardowski as well as one well–known lemma for the proof that Picard sequence is an $\mathcal{F}$-Cauchy in the framework of $\mathcal{F}$-metric space.

Methods: Fixed point metric theory methods were used.

Results: New results are enunciated concerning the F-contraction of two mappings S and T in the context of $\mathcal{F}-$complete $\mathcal{F}$-metric spaces.

Conclusions: The obtained results represent sharp and significant improvements of some recently published ones. At the end of the paper, an example is given, claiming that the results presented in this paper are proper generalizations of recent developments.

Key words: $\mathcal{F}$-metric space, F-contraction, fixed point.

Introduction and preliminaries

It is exactly one hundred years since S. Banach (Banach, 1922) proved the famous principle of contraction in his doctoral dissertation. Since then, many researchers have been trying to generalize that significant result in

many directions. In one direction, new classes of metric spaces were created and the renowned results were extended to these spaces. Among them, b-metric and $\mathcal{F}$-metric spaces stand out. The former ones were introduced by Bakhtin (Bakhtin, 1989) and Czerwik (Czerwik, 1993) and the latter were recently introduced by Jleli and Samet (Jleli & Samet, 2018). Not that these two cases of spaces are intangible. Namely, there is a b-metric space that is not $\mathcal{F}$-metric, and vie versa, there is an $\mathcal{F}$-metric that is not *b*-metric. Note that convergence, Cauchyness and completeness of both types of spaces are defined for ordinary metric spaces. Also, it is worth mentioning that *b*-metric and $\mathcal{F}$-metric do not have to be continuous functions with two variables as is the case with ordinary metric. In both types of spaces, a convergent sequence is a Cauchy and it has a unique limit. This is what they have in common with ordinary metric spaces. The continuity of mapping in both classes of spaces is sequential, i.e., the same as in ordinary metric spaces. Let us now list the definitions of each of the mentioned types of spaces. For more new details on $\mathcal{F}$-metric spaces and new developments in the metric fixed point theory, one can see some noteworthy papers (Asif et al, 2019), (Aydi et al, 2019), (Derouiche & Ramoul, 2020), (Jahangir et al, 2021), (Kirk & Shazad, 2014), (Mitrović et al, 2019), (Salem et al, 2020), (Som et al, 2020), (Vujaković et al, 2020), (Vujaković & Radenović, 2020), (Younis et al, 2019a), (Younis et al, 2019b).

Definition 1. *((Bakhtin, 1989), (Czerwik, 1993)) Let X be a nonempty set and $s \geq 1$ be a given real number. A function $d_b : X \times X \to [0, +\infty)$ is said to be a b-metric with the coefficient s if for all $x, y, z \in X$ the following conditions are satisfied:*

(d_b1) $d_b(x, y) = 0$ if and only if $x = y$

(d_b2) $d_b(x, y) = d_b(y, x)$

(d_b3) $d_b(x, y) \leq s[d_b(x, z) + d_b(z, y)]$.

Let $\mathcal{F}$ be the set of functions $f : (0, +\infty) \to (-\infty, +\infty)$ satisfying the following conditions:

$\mathcal{F}_1)$ f is non-decreasing,

$\mathcal{F}_2)$ For every sequence $\{t_n\} \subset (0, +\infty)$, we have

$$\lim_{n\to+\infty} t_n = 0 \text{ if and only if } \lim_{n\to+\infty} f(t_n) = -\infty.$$

Definition 2. *(Jleli & Samet, 2018) Let X be a (nonempty) set. A function $d_{\mathcal{F}} : X \times X \to [0, +\infty)$ is called a $\mathcal{F}$-metric on X if there exists $(f, \alpha) \in \mathcal{F} \times [0, +\infty)$ such that for all $x, y \in X$ the following conditions hold:*

$(d_{\mathcal{F}}1)$ $d_{\mathcal{F}}(x, y) = 0$ if and only if $x = y$.
$(d_{\mathcal{F}}2)$ $d_{\mathcal{F}}(x, y) = d_{\mathcal{F}}(y, x)$.
$(d_{\mathcal{F}}3)$ For every $N \in \mathbb{N}, N \geq 2$ and for every $\{u_i\}_{i=1}^{N} \subset X$ with $(u_1, u_N) = (x, y)$, we have

$$d_{\mathcal{F}}(x, y) > 0 \text{ yields } f(d_{\mathcal{F}}(x, y)) \leq f\left(\sum_{i=1}^{N-1} d_{\mathcal{F}}(u_i, u_{i+1})\right) + \alpha.$$

In this case, the pair $(X, d_{\mathcal{F}})$ is called a $\mathcal{F}-$metric space.

Wardowski (Wardowski, 2012) considered a nonlinear function $F : (0, +\infty) \to (-\infty, +\infty)$ with the following characteristics:
(F1) F is strictly increasing.
(F2) $\mathcal{F}_2)$ above.
(F3) There exists $l \in (0, 1)$ such that $\lim_{t \to 0^+} t^l F(t) = 0$.

Wardowski (Wardowski, 2012) called the mapping $T : X \to X$, defined on a metric space (X, d), an $F-$contraction if there exist $\tau > 0$ and F satisfying (F1)-(F3) such that

$$\tau + F(d(Tx, Ty)) \leq F(d(x, y)) \text{ whenever } d(Tx, Ty) > 0.$$

The authors in (Asif et al, 2019) take $\mathcal{B} = \{F : (0, +\infty) \to (-\infty, +\infty) : F \text{ satisfies } \mathcal{F}_1) \text{ and } \mathcal{F}_2)\}$.

In 2019, A. Asif et al., (Asif et al, 2019) formulated and proved the fixed-point and common fixed-point results for single-valued Reich-type and Kannan-type F-contractions in the setting of $\mathcal{F}$-metric spaces:

Theorem 1. *Suppose $(f, \alpha) \in \mathcal{B} \times [0, +\infty)$ and $(X, d_{\mathcal{F}})$ is an $\mathcal{F}-$complete $\mathcal{F}$-metric space. Let $S, T : X \to X$ be self-mappings. Suppose there exist $F \in \mathcal{F}$ and $\tau > 0$ such that*

$$\tau + F(d_{\mathcal{F}}(Sx, Ty)) \leq F(a \cdot d_{\mathcal{F}}(x, y) + b \cdot d_{\mathcal{F}}(x, Sx) + c \cdot d_{\mathcal{F}}(y, Ty)) \quad (1)$$

for $a, b, c \in [0, . + \infty)$ such that $a + b + c < 1$ with

$$\min\{d_{\mathcal{F}}(Sx, Ty), d_{\mathcal{F}}(x, y), d_{\mathcal{F}}(x, Sx), d_{\mathcal{F}}(y, Ty)\} > 0,$$

for all $(x, y) \in X \times X$. Then S and T have at most one common fixed point in X.

Corollary 1. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty)$ *and* $(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}$*-metric space Let* $S,T:X\to X$ *be self-mappings. Suppose that* $k\in[0,1)$*, there exist* $F\in\mathcal{F}$ *and* $\tau>0$ *such that*

$$\tau+F\left(d_{\mathcal{F}}\left(Sx,Ty\right)\right)\leq F\left(\frac{k}{2}\left(d_{\mathcal{F}}\left(x,Sx\right)+d_{\mathcal{F}}\left(y,Ty\right)\right)\right) \tag{2}$$

with $\min\left\{d_{\mathcal{F}}\left(Sx,Ty\right),d_{\mathcal{F}}\left(x,y\right),d_{\mathcal{F}}\left(x,Sx\right),d_{\mathcal{F}}\left(y,Ty\right)\right\}>0$*, for all* $(x,y)\in X\times X$*. Then* S *and* T *have at most one common fixed point in* X*.*

By replacing S with T, the authors obtained the following result for single mapping.

Corollary 2. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty)$ *and* $(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}$*-metric space Let* $T:X\to X$ *be self-mapping. Suppose that for* $k\in[0,1)$*, there exist* $F\in\mathcal{F}$ *and* $\tau>0$ *such that*

$$\tau+F\left(d_{\mathcal{F}}\left(Tx,Ty\right)\right)\leq F\left(\frac{k}{2}\left(d_{\mathcal{F}}\left(x,Tx\right)+d_{\mathcal{F}}\left(y,Ty\right)\right)\right) \tag{3}$$

with $\min\left\{d_{\mathcal{F}}\left(Tx,Ty\right),d_{\mathcal{F}}\left(x,Tx\right),d_{\mathcal{F}}\left(y,Ty\right)\right\}>0$*, for all* $(x,y)\in X\times X$*. Then* T *have at most one fixed point in* X*.*

Definition 3. *Let* $(X,d_{\mathcal{F}})$ *be an* $\mathcal{F}-$*complete* $\mathcal{F}$*-metric space and* $S,T:X\to X$ *be self-mappings. Suppose that* $a+b+c<1$ *for* $a,b,c\in[0,+\infty)$*. Then the mapping* T *is called a Reich-type F-contraction on* $B\left(x_0,r\right)\subseteq X$ *if there exist* $F\in\mathcal{F}$ *and* $\tau>0$ *such that for all* $x,y\in B\left(x_0,r\right)$

$$\tau+F\left(d_{\mathcal{F}}\left(Sx,Ty\right)\right)\leq F\left(a\cdot d_{\mathcal{F}}\left(x,y\right)+b\cdot d_{\mathcal{F}}\left(x,Sx\right)+c\cdot d_{\mathcal{F}}\left(y,Ty\right)\right). \tag{4}$$

Theorem 2. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty)$ *and* $(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}$*-metric space. Let* T *be a Reich-type F-contraction on* $B\left(x_0,r\right)\subseteq X$*. Suppose that for* $x_0\in X$ *and* $r>0$*, the following conditions are satisfied:*

(a) $B\left(x_0,r\right)$ is $\mathcal{F}-$closed,
(b) $d_{\mathcal{F}}\left(x_0,x_1\right)\leq(1-\lambda)\,r$, for $x_1\in X$ and $\lambda=\frac{a+b}{1-c}$,
(c) There exist $0<\varepsilon<r$ such that $f\left(\left(1-\lambda^{k+1}\right)r\right)\leq f\left(\varepsilon\right)-\alpha$, where $k\in\mathbb{N}$.
Then S and T have at most one common fixed point in $B\left(x_0,r\right)$.

Taking $S=T$ in Theorem 2, the authors in ((Asif et al, 2019), Corollary 3.) obtained the following result for single mappings.

Corollary 3. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty),(F,\tau)\in\mathcal{B}\times(0,+\infty),(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}$*-metric space and* $T:X\to X$ *is a self-mapping. Suppose that* $a+b+c<1$ *for* $a,b,c\in[0,+\infty)$. *Suppose that for* $x_0\in X$ *and* $r>0$, *the following conditions are satisfied:*

(a) $B(x_0,r)$ is $\mathcal{F}-$closed,

(b) $\tau+F(d_{\mathcal{F}}(Sx,Ty))\leq F(a\cdot d_{\mathcal{F}}(x,y)+b\cdot d_{\mathcal{F}}(x,Sx)+c\cdot d_{\mathcal{F}}(y,Ty))$for all $x,y\in B(x_0,r)$,

(c) $d_{\mathcal{F}}(x_0,x_1)\leq(1-\lambda)r$, for $x_1\in X$ and $\lambda=\frac{a+b}{1-c}$,

(c) There exist $0<\varepsilon<r$ such that $f\left(\left(1-\lambda^{k+1}\right)r\right)\leq f(\varepsilon)-\alpha$, where $k\in\mathbb{N}$.

Then T has at most one fixed point in $B(x_0,r)$.

Corollary 4. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty),(F,\tau)\in\mathcal{B}\times(0,+\infty),(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}$*-metric space. Let* $S,T:X\to X$ *be a self-mappings and* $k\in[0,1)$. *Suppose that for* $x_0\in X$ *and* $r>0$, *the following conditions are satisfied:*

(a) $B(x_0,r)$ is $\mathcal{F}-$closed,

(b) $\tau+F(d_{\mathcal{F}}(Sx,Ty))\leq F(a\cdot d_{\mathcal{F}}(x,y)+b\cdot d_{\mathcal{F}}(x,Sx)+c\cdot d_{\mathcal{F}}(y,Ty))$for all $x,y\in B(x_0,r)$,

(c) $d_{\mathcal{F}}(x_0,x_1)\leq(1-\lambda)r$, for $x_1\in X$ and $\lambda=\frac{k}{2-k}$,

(c) There exist $0<\varepsilon<r$ such that $f\left(\left(1-\lambda^{k+1}\right)r\right)\leq f(\varepsilon)-\alpha$, where $k\in\mathbb{N}$.

Then S and T have at most one common fixed point in $B(x_0,r)$.

Further in the same paper ((Asif et al, 2019), Definitions 6, 8, Theorem 5, Corollary 5.), the authors gave the following:

Definition 4. *Let* $(X,d_{\mathcal{F}})$ *be a metric space. Let* $CB(X)$ *be the family of all non-empty closed and bounded subsets of* X. *Let* $H:CB(X)\times CB(X)\to[0,+\infty)$ *be a function defined by*

$$H(A,B)=\max\left\{\sup_{x\in A}D(x,B),\sup_{y\in B}D(y,A)\right\},\tag{5}$$

where $D(x,B)=\inf\{d_{\mathcal{F}}(x,y):y\in B\}$. *Then* H *defines a metric on* $CB(X)$ *called the Hausdorff-Pompeiu metric induced by* $d_{\mathcal{F}}$.

Definition 5. *Let $(X, d_{\mathcal{F}})$ be an $\mathcal{F}$-metric space. Suppose $F \in \mathcal{B}$ and $H : CB(X) \times CB(X) \to [0, +\infty)$ be the Hausdorff-Pompeiu metric function defined in Definition 2. A mapping $T : X \to CB(X)$ is known as a set-valued Reich-type contraction if there is some $\tau > 0$ such that*

$$2\tau + F(H(Tx, Ty)) \leq F(a \cdot d_{\mathcal{F}}(x, y) + b \cdot d_{\mathcal{F}}(x, Sx) + c \cdot d_{\mathcal{F}}(y, Ty)) \quad (6)$$

for $(x, y) \in X \times X$ and $a, b, c \in [0, +\infty)$ such that $a + b + c < 1$.

Theorem 3. *Let $(X, d_{\mathcal{F}})$ be an $\mathcal{F}-$complete $\mathcal{F}$-metric space and $(f, \alpha) \in \mathcal{B} \times [0, +\infty)$. If the mapping $T : X \to CB(X)$ is a set-valued Reich-type F-contraction such that F is right continuous, then T has a fixed point in X.*

Corollary 5. *Suppose $(f, \alpha) \in \mathcal{B} \times [0, +\infty)$ and $(X, d_{\mathcal{F}})$ is an $\mathcal{F}-$complete $\mathcal{F}$-metric space. Let $T : X \to CB(X)$ be a Reich-type $F-$contraction such that F is right continuous. Suppose that for $k \in [0, 1)$, there exist $F \in \mathcal{B}$ and $\tau > 0$ such that*

$$\tau + F(H(Tx, Ty)) \leq F\left(\frac{k}{2}(d_{\mathcal{F}}(x, Tx) + d_{\mathcal{F}}(y, Ty))\right) \quad (7)$$

with $\min\{H(Tx, Ty), d_{\mathcal{F}}(x, Tx), d_{\mathcal{F}}(y, Ty)\} > 0$ for all $(x, y) \in X \times X$. Then T has a fixed point in X.

In the sequel, we will use the following two results:

Lemma 1. *((Mitrović et al, 2019), Lemma 1.) Let (X, d_b) (resp. $(X, d_{\mathcal{F}})$ be a b-metric (resp. $\mathcal{F}-$metric) space and $\{x_n\}_{n=1}^{+\infty}$ the sequence in it such that*

$$d_b(x_n, x_{n+1}) \leq \lambda \cdot d_b(x_{n-1}, x_n) \quad (\text{resp. } d_{\mathcal{F}}(x_n, x_{n+1}) \leq \lambda \cdot d_{\mathcal{F}}(x_{n-1}, x_n)), \quad (8)$$

for all $n \in \mathbb{N}$, where $\lambda \in [0, 1)$. Then $\{x_n\}_{n=1}^{+\infty}$ is a d_b-Cauchy sequence in (X, d_b) (resp.$d_{\mathcal{F}}-$Cauchy sequence in $(X, d_{\mathcal{F}})$).

Lemma 2. *Let $\{x_{n+1}\}_{n \in \mathbb{N} \cup \{0\}} = \{Tx_n\}_{n \in \mathbb{N} \cup \{0\}} = \{T^n x_0\}_{n \in \mathbb{N} \cup \{0\}}, T^0 x_0 = x_0$ be a Picard sequence in $\mathcal{F}$-metric space inducing by mapping $T : X \to X$ and initial point $x_0 \in X$. If $d_{\mathcal{F}}(x_n, x_{n+1}) < d_{\mathcal{F}}(x_{n-1}, x_n))$ for all $n \in \mathbb{N}$ then $x_n \neq x_m$ whenever $n \neq m$.*

Proof. Let $x_n = x_m$ for some $n, m \in \mathbb{N}$ with $n < m$. Then $x_{n+1} = Tx_n = Tx_m = x_{m+1}$. Further, we get

$$d_{\mathcal{F}}(x_n, x_{n+1}) = d_{\mathcal{F}}(x_m, x_{m+1}) < d_{\mathcal{F}}(x_{m-1}, x_m) < ... < d_{\mathcal{F}}(x_n, x_{n+1}),$$

which is a contradiction. □

Some improved results

Firstly, since $F : (0, +\infty) \to (-\infty, +\infty)$ it follows that (1) is possible only if $d_{\mathcal{F}}(Sx, Ty) > 0$ where $x, y \in X$. Also, the condition (F1) yields that $a \cdot d_{\mathcal{F}}(x, y) + b \cdot d_{\mathcal{F}}(x, Sx) + c \cdot d_{\mathcal{F}}(y, Ty) > 0$ for all $x, y \in X$ for which $d_{\mathcal{F}}(Sx, Ty) > 0$. This means that at least of $a, b, c \in [0, +\infty)$ must be distinct of 0. Now we can improve the formulation of Theorem 1 and all its corollaries from (Asif et al, 2019) and give new proofs as the following.

Theorem 4. *Suppose* $(f, \alpha) \in \mathcal{B} \times [0, +\infty)$ *and* $(X, d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}-$*metric space. Let* $S, T : X \to X$ *be self mappings. Suppose there exist a strictly increasing function* $F : (0, +\infty) \to (-\infty, +\infty)$ *and* $\tau > 0$ *such that* $d_{\mathcal{F}}(Sx, Ty) > 0$ *yields*

$$\tau + F(d_{\mathcal{F}}(Sx, Ty)) \leq F(a \cdot d_{\mathcal{F}}(x, y) + b \cdot d_{\mathcal{F}}(x, Sx) + c \cdot d_{\mathcal{F}}(y, Ty)), \quad (9)$$

for $a, b, c \in [0, +\infty)$ *such that* $a^2 + b^2 + c^2 > 0$ *and* $a + b + c < 1$.
Then S *and* T *have at most one common fixed point in* X, *if at least one of the mappings* S *or* T *is continuous.*

Proof. Already, we first eliminate the function F. Indeed, from (9) if $d_{\mathcal{F}}(Sx, Ty) > 0$ follows

$$d_{\mathcal{F}}(Sx, Ty) < a \cdot d_{\mathcal{F}}(x, y) + b \cdot d_{\mathcal{F}}(x, Sx) + c \cdot d_{\mathcal{F}}(y, Ty), \quad (10)$$

where $a, b, c \in [0, +\infty)$, $a^2 + b^2 + c^2 > 0$ and $a + b + c < 1$. Further, we give the proof in several steps:

The step 1.

The point $\overline{x}$ is a fixed of S if and only if it is a fixed point of T. Let $S\overline{x} = \overline{x}$ and $T\overline{x} \neq \overline{x}$. Putting $x = y = \overline{x}$ in (10) we get

$$d_{\mathcal{F}}(\overline{x}, T\overline{x}) = d_{\mathcal{F}}(S\overline{x}, T\overline{x}) < a \cdot d_{\mathcal{F}}(\overline{x}, \overline{x}) + b \cdot d_{\mathcal{F}}(\overline{x}, S\overline{x}) + c \cdot d_{\mathcal{F}}(\overline{x}, T\overline{x})$$
$$= a \cdot 0 + b \cdot 0 + c \cdot d_{\mathcal{F}}(\overline{x}, T\overline{x}),$$

i.e., $(1 - c)\, d_{\mathcal{F}}(\overline{x}, T\overline{x}) < 0$. Since, $c \in [0, 1)$ we obtain the contradiction. Therefore, $T\overline{x} = \overline{x}$.

Conversely, let $\overline{x} = T\overline{x}$ and $S\overline{x} \neq \overline{x}$. In this case, we get

$$d_{\mathcal{F}}\left(\overline{Sx}, \overline{x}\right) = d_{\mathcal{F}}\left(\overline{Sx}, T\overline{x}\right) < a \cdot d_{\mathcal{F}}\left(\overline{x}, \overline{x}\right) + b \cdot d_{\mathcal{F}}\left(\overline{x}, S\overline{x}\right) + c \cdot d_{\mathcal{F}}\left(\overline{x}, \overline{x}\right)$$

$$= a \cdot 0 + b \cdot d_{\mathcal{F}}\left(\overline{x}, S\overline{x}\right) + c \cdot 0,$$

i.e., $(1-b)\, d_{\mathcal{F}}\left(\overline{Sx}, \overline{x}\right) < 0$ which is a contradiction, because $b \in [0, 1)$. Hence, it follows that $S\overline{x} = \overline{x}$.

The step 2.

The uniqueness of a possible common fixed point for S and T.

Let $\overline{x} \neq \overline{y}$ be two common fixed points for S and T. Then putting in (10) $x = \overline{x}$ and $y = \overline{y}$ we get:

$$d_{\mathcal{F}}\left(S\overline{x}, T\overline{y}\right) < a \cdot d_{\mathcal{F}}\left(\overline{x}, \overline{y}\right) + b \cdot d_{\mathcal{F}}\left(\overline{x}, S\overline{x}\right) + c \cdot d_{\mathcal{F}}\left(\overline{y}, T\overline{y}\right),$$

i.e., $(1-a) \cdot d_{\mathcal{F}}\left(\overline{x}, \overline{y}\right) < 0$. Which is a contradiction with $\overline{x} \neq \overline{y}$. This means that a possible common fixed point for S and T is unique.

The step 3.

In this step, we shall prove the existence of at least one common fixed point of S and T.

Therefore, suppose that x_0 is an arbitrary point and define a sequence $\{x_n\}$ by

$$x_{2n+1} = Sx_{2n} \text{ and } x_{2n+2} = Tx_{2n+1},$$

for $n \in \mathbb{N} \cup \{0\}$. It is clear that $d_{\mathcal{F}}\left(x_{2n+1}, x_{2n+2}\right) > 0$ and $d_{\mathcal{F}}\left(x_{2n+3}, x_{2n+2}\right) > 0$ for all $n \in \mathbb{N} \cup \{0\}$. Now, by (10) we further get ($x = x_{2n}, y = x_{2n+1}$)

$$d_{\mathcal{F}}\left(x_{2n+1}, x_{2n+2}\right) < a \cdot d_{\mathcal{F}}\left(x_{2n}, x_{2n+1}\right) + b \cdot d_{\mathcal{F}}\left(x_{2n}, x_{2n+1}\right) + c \cdot d_{\mathcal{F}}\left(x_{2n+1}, x_{2n+2}\right),$$

i.e., $d_{\mathcal{F}}\left(x_{2n+1}, x_{2n+2}\right) < k \cdot d_{\mathcal{F}}\left(x_{2n}, x_{2n+1}\right)$ where $k = \frac{a+b}{1-c} \in [0, 1)$. And similar $d_{\mathcal{F}}\left(x_{2n+3}, x_{2n+2}\right) < k \cdot d_{\mathcal{F}}\left(x_{2n+2}, x_{2n+1}\right)$. Hence, for all $n \in \mathbb{N}$ we have

$$d_{\mathcal{F}}\left(x_n, x_{n+1}\right) < k \cdot d_{\mathcal{F}}\left(x_{n-1}, x_n\right) < d_{\mathcal{F}}\left(x_{n-1}, x_n\right).$$

According to Lemmas 9 and 10, we have that the sequence $\{x_n\}$ is a $d_{\mathcal{F}}-$Cauchy in an $\mathcal{F}-$complete $\mathcal{F}$-metric space $(X, d_{\mathcal{F}})$ and $x_n \neq x_m$ whenever $n \neq m$. This further means that there is (unique) $x^* \in X$ such that $x_n \to x^*$ as $n \to +\infty$.

Firstly, let S be continuous. Then $x_{2n+1} = Sx_{2n} \to Sx^* = x^*$ since in each $\mathcal{F}-$metric space the subsequence of each convergent sequence

converges to the unique limit. Now, we will prove that also $Tx^* = x^*$. Indeed, if $Tx^* \neq x^*$ then by using (10) with $x = y = x^*$ we get

$$d_{\mathcal{F}}(x^*, Tx^*) = d_{\mathcal{F}}(Sx^*, Tx^*) < a \cdot d_{\mathcal{F}}(x^*, x^*) + b \cdot d_{\mathcal{F}}(x^*, Sx^*) + c \cdot d_{\mathcal{F}}(x^*, Tx^*)$$

$$= a \cdot d_{\mathcal{F}}(x^*, x^*) + b \cdot d_{\mathcal{F}}(x^*, Sx^*) + c \cdot d_{\mathcal{F}}(x^*, Tx^*) = a \cdot 0 + b \cdot 0 + c \cdot d_{\mathcal{F}}(x^*, Tx^*).$$

Finally, we obtain that $(1 - c) \cdot d_{\mathcal{F}}(x^*, Tx^*) < 0$ which is a contradiction because we suppose $d_{\mathcal{F}}(x^*, Tx^*) \neq 0$.

If the mapping T is continuous, the proof is similar.

The theorem is completely proved. □

Remark 1. Our Theorem 11 generalizes, improves, complements and unifies the corresponding Theorem 3 from (Asif et al, 2019) in several directions. First of all, it is worth to notice that some parts of the proof for Theorem 3 are doubtful. Namely, the authors in their proof use that $\mathcal{F}$-metric $d_{\mathcal{F}}$ is a continuous function with two variables ($d_{\mathcal{F}}(x_n, y_n) \to d_{\mathcal{F}}(x, y)$ if $d_{\mathcal{F}}(x_n, x) \to 0$ and $d_{\mathcal{F}}(y_n, y) \to 0$), which is not case. Also, it is clear that the function F in their Theorem 3 and in both Corollaries 1 and 2 is superfluous.

The next two corollaries follows from our Theorem 11.

Corollary 6. *Suppose* $(f, \alpha) \in \mathcal{B} \times [0, +\infty)$ *and* $(X, d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}-$*metric space. Let* $S, T : X \to X$ *be self mappings. Suppose there exist strictly increasing function* $F : (0, +\infty) \to (-\infty, +\infty)$ *and* $\tau > 0$ *such that* $d_{\mathcal{F}}(Sx, Ty) > 0$ *yields*

$$\tau + F(d_{\mathcal{F}}(Sx, Ty)) \leq F\left(\frac{k}{2}(d_{\mathcal{F}}(x, Sx) + c d_{\mathcal{F}}(y, Ty))\right), \qquad (11)$$

for $k \in [0, 1)$.
By replacing S *with* T*, we get the following result for single mapping:*

Corollary 7. *Suppose* $(f, \alpha) \in \mathcal{B} \times [0, +\infty)$ *and* $(X, d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}-$*metric space. Let* $T : X \to X$ *be self mapping. Suppose there exist strictly increasing function* $F : (0, +\infty) \to (-\infty, +\infty)$ *and* $\tau > 0$ *such that*

$d_{\mathcal{F}}(Tx,Ty)>0$ *yields*

$$\tau+F\left(d_{\mathcal{F}}(Tx,Ty)\right)\leq F\left(\frac{k}{2}\left(d_{\mathcal{F}}(x,Tx)+cd_{\mathcal{F}}(y,Ty)\right)\right), \tag{12}$$

for $k\in[0,1)$.
Then T *has at most one fixed point in* X, *if it is continuous.*

Remark 2. Now we give the following **Important Notice:**

It is useful to note that the other results from (Asif et al, 2019) can be repaired and supplemented in the same or similar way. It should also be said that the results on Hausdorff-Pompeiu metric given in (Asif et al, 2019) are dubious. This will be discussed in another of our papers.

The immediate consequences of our Theorem 11 are the following new contractive conditions that complement the ones given in (Collaco & Silva, 1997), (Rhoades, 1977) for usual metric spaces. For more contractive conditions in the framework of metric spaces see (Ćirić, 2003), (Consentino & Vetro, 2014), (Dey et al, 2019), (Karapınar, et al), (Piri & Kumam, 2014), (Salem et al, 2020), (Wardowski & Dung, 2014). In the sequel we will obtain several new contractive conditions in the framework of $\mathcal{F}-$metric spaces.

Corollary 8. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty)$ *and* $(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}-$*metric space. Let* $S,T:X\to X$ *be self mappings. Suppose there exist* $\tau_1>0$ *such that* $d_{\mathcal{F}}(Sx,Ty)>0$ *yields*

$$\tau_1+d_{\mathcal{F}}(Sx,Ty)\leq a\cdot d_{\mathcal{F}}(x,y)+b\cdot d_{\mathcal{F}}(x,Sx)+c\cdot d_{\mathcal{F}}(y,Ty), \tag{13}$$

for $a,b,c\in[0,+\infty)$ *such that* $a^2+b^2+c^2>0$ *and* $a+b+c<1$.
Then S *and* T *have at most one common fixed point in* X, *if one of the mappings* S *or* T *is continuous.*

Corollary 9. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty)$ *and* $(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}-$*metric space. Let* $S,T:X\to X$ *be self mappings. Suppose there exist* $\tau_2>0$ *such that* $d_{\mathcal{F}}(Sx,Ty)>0$ *yields*

$$\tau_2+d_{\mathcal{F}}(Sx,Ty)\leq a\cdot d_{\mathcal{F}}(x,y), \tag{14}$$

for $a\in[0,1)$.
Then S *and* T *have at most one common fixed point in* X, *if one of the mappings* S *or* T *is continuous.*

Corollary 10. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty)$ *and* $(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}-$*metric space. Let* $S,T:X\to X$ *be self mappings. Suppose there exist* $\tau_3>0$ *such that* $d_{\mathcal{F}}(Sx,Ty)>0$ *yields*

$$\tau_3+d_{\mathcal{F}}(Sx,Ty)\leq b\cdot d_{\mathcal{F}}(x,Sx)+c\cdot d_{\mathcal{F}}(y,Ty), \tag{15}$$

for $b,c\in[0,+\infty)$ *such that* $b^2+c^2>0$ *and* $b+c<1$.
Then S *and* T *have at most one common fixed point in* X, *if one of the mappings* S *or* T *is continuous.*

Corollary 11. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty)$ *and* $(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}-$*metric space. Let* $S,T:X\to X$ *be self mappings. Suppose there exist* $\tau_4>0$ *such that* $d_{\mathcal{F}}(Sx,Ty)>0$ *yields*

$$\tau_4-\frac{1}{d_{\mathcal{F}}(Sx,Ty)}\leq-\frac{1}{b\cdot d_{\mathcal{F}}(x,Sx)+c\cdot d_{\mathcal{F}}(y,Ty)}, \tag{16}$$

for $b,c\in[0,+\infty)$ *such that* $b^2+c^2>0$ *and* $b+c<1$.
Then S *and* T *have at most one common fixed point in* X, *if one of the mappings* S *or* T *is continuous.*

Corollary 12. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty)$ *and* $(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}-$*metric space. Let* $S,T:X\to X$ *be self mappings. Suppose there exist* $\tau_5>0$ *such that* $d_{\mathcal{F}}(Sx,Ty)>0$ *yields*

$$\begin{aligned}\tau_5-\frac{1}{d_{\mathcal{F}}(Sx,Ty)}+d_{\mathcal{F}}(Sx,Ty)\leq&-\frac{1}{b\cdot d_{\mathcal{F}}(x,Sx)+c\cdot d_{\mathcal{F}}(y,Ty)}\\&+b\cdot d_{\mathcal{F}}(x,Sx)+c\cdot d_{\mathcal{F}}(y,Ty),\end{aligned} \tag{17}$$

for $b,c\in[0,+\infty)$ *such that* $b^2+c^2>0$ *and* $b+c<1$.
Then S *and* T *have at most one common fixed point in* X, *if at least one of the mappings* S *or* T *is continuous.*

Corollary 13. *Suppose* $(f,\alpha)\in\mathcal{B}\times[0,+\infty)$ *and* $(X,d_{\mathcal{F}})$ *is an* $\mathcal{F}-$*complete* $\mathcal{F}-$*metric space. Let* $S,T:X\to X$ *be self mappings. Suppose there exist* $\tau_6>0$ *such that* $d_{\mathcal{F}}(Sx,Ty)>0$ *yields*

$$\tau_6+\frac{1}{1-\exp\left(d_{\mathcal{F}}(Sx,Ty)\right)}\leq-\frac{1}{1-\exp\left(b\cdot d_{\mathcal{F}}(x,Sx)+c\cdot d_{\mathcal{F}}(y,Ty)\right)}, \tag{18}$$

for $b, c \in [0, +\infty)$ *such that* $b^2 + c^2 > 0$ *and* $b + c < 1$.
Then S *and* T *have at most one common fixed point in* X, *if one of the mappings* S *or* T *is continuous.*

Proof. As each of the functions $F_i(r) = r$, $i = \overline{1,3}$, $F_4(r) = -\frac{1}{r}$, $F_5(r) = -\frac{1}{r} + r$, $F_6(r) = \frac{1}{1-\exp(r)}$ is strictly increasing on $(0, +\infty)$, the proof immediately follows by our Theorem 11 and their corollaries. □

Example 1. Finally, we give the following simple example that support our Theorem 11 with $S = T$. Suppose that $X = \{2n + 1 : n \in \mathbb{N}\}$. Define the $d_{\mathcal{F}}-$metric given by the following

$$d_{\mathcal{F}}(x, y) = \begin{cases} 0 \text{ if } x = y \\ e^{|x-y|} \text{ if } x \neq y. \end{cases}$$

Let $F(r) = -e^{-r}$ and $T : X \to X$ is defined by

$$T(2n + 1) = \begin{cases} 3 \text{ if } n \in \{1, 2\} \\ 2n - 1 \text{ if } n \geq 3. \end{cases}.$$

It is clear that $d_{\mathcal{F}}$ is a $\mathcal{F}-$metric and F is strictly increasing on $(0, +\infty)$. All the conditions of Theorem 11 are satisfied. Indeed, putting in equation (9) $b = c = 0$, we get for $x \neq y$:

$$\tau - e^{-|Tx-Ty|} \leq -a \cdot e^{-|x-y|},$$

i.e., $e^{-|Tx-Ty|} > a \cdot e^{-|x-y|}$. Taking $x = 2n + 1, y = 2m + 1, n \neq m$ we further obtain $e^{-|2n-2m|} > a \cdot e^{-|2n-2m|}$. Since $n \neq m$ this means that there exists $a \in [0, 1)$ such that (9) holds true, i.e., T has a unique fixed point in $X = \{2n + 1 : n \in \mathbb{N}\}$, which is $x = 3$. Note that $\lim_{r \to +0} F(r) = -1$, then Theorem 3 from (Asif et al, 2019) is not applicable here. This shows that our results are proper generalizations of the ones from (Asif et al, 2019).

Conclusion

In this article, we obtained several new contractive conditions in the framework of $\mathcal{F}-$metric spaces. Our results improve, extend, complement, generalize, and unify various recent developments in the context of $\mathcal{F}-$metric spaces. An example shows that the main results of (Asif et al, 2019) are not applicable in our case. We think that this is a useful contribution in the framework of F-contraction introduced by D. Wardowski.

References

Asif, A., Nazam, M., Arshad, M. & Kim, S.O. 2019. F-Metric, F-contraction and Common Fixed-Point Theorems with Applications. *Mathematics*, 7(7), 586. Available at: https://doi.org/10.3390/math7070586.

Aydi, H., Karapinar, E., Mitrović, Z.D. & Rashid, T. 2019. A remark on "Existence and uniqueness for a neutral differential problem with unbounded delay via fixed point results F-metric spaces". *Revista de la Real Academia de Ciencias Exactas, Fisicas y Naturales. Serie A. Matemáticas (RACSAM)*, 113, pp.3197-3206. Available at: https://doi.org/10.1007/s13398-019-00690-9.

Bakhtin, I.A. 1989. The contraction mapping principle in quasimetric spaces. *Func. An., Gos. Ped. Inst. Unianowsk*, 30, pp.26-37.

Banach, S. 1922. Sur les opérations dans les ensembles abstraits et leur applications aux équations intégrales. *Fundamenta Mathematicae*, 3, pp.133-181 (in French). Available at: https://doi.org/10.4064/fm-3-1-133-181.

Collaco, P. & Silva, J.C.E. 1997. A complete comparison of 25 contraction conditions. *Nonlinear Analysis: Theory, Methods & Applications*, 30(1), pp.471-476. Available at: https://doi.org/10.1016/S0362-546X(97)00353-2.

Consentino, M. & Vetro, P. 2014. Fixed point result for F-contractive mappings of Hardy-Rogers-Type. *Filomat*, 28(4), pp.715-722. Available at: https://doi.org/10.2298/FIL1404715C.

Czerwik, S. 1993. Contraction mappings in b-metric spaces. *Acta Mathematica et Informatica Universitatis Ostraviensis*, 1, pp.5-11 [online]. Available at: https://dml.cz/handle/10338.dmlcz/120469 [Accessed: 20 November 2020].

Ćirić, Lj. 2003. *Some Recent Results in Metrical Fixed Point Theory*. Belgrade: University of Belgrade.

Derouiche, D. & Ramoul, H. 2020. New fixed point results for F-contractions of Hardy-Rogers type in b-metric spaces with applications. *Journal of Fixed Point Theory and Applications*, 22(art.number:86). Available at: https://doi.org/10.1007/s11784-020-00822-4.

Dey, L.K., Kumam, P. & Senapati, T. 2019. Fixed point results concerning $\alpha - F-$ contraction mappings in metric spaces. *Applied General Topology*, 20(1), pp.81-95. Available at: https://doi.org/10.4995/agt.2019.9949.

Jahangir, F., Haghmaram, P. & Nourouzi, K. 2021. A note on $\mathcal{F}$-metric spaces. *Journal of Fixed Point Theory and Applications*, 23(art.number:2). Available at: https://doi.org/10.1007/s11784-020-00836-y.

Jleli, M. & Samet, B. 2018. On a new generalization of metric spaces. *Journal of Fixed Point Theory and Applications*, 20(art.number:128). Available at: https://doi.org/10.1007/s11784-018-0606-6.

Karapınar, E., Fulga, A. & Agarwal, R. 2020. A survey: F-contractions with related fixed point results. *Journal of Fixed Point Theory and Applications*, 22(art.number:69). Available at: https://doi.org/10.1007/s11784-020-00803-7.

Kirk, W.A. & Shahzad, N. 2014. *Fixed Point Theory in Distance Spaces*. Springer International Publishing Switzerland.

Mitrović, Z.D., Aydi, H., Hussain, H. & Mukheimer, A. 2019. Reich, Jumgck, and Berinde comon fixed point results on $\mathcal{F}$-metric spaces and an application. *Mathematics*, 7(5), 387. Available at: https://doi.org/10.3390/math7050387.

Piri, H. & Kumam, P. 2014. Some fixed point theorems concerning F-contraction in complete metric spaces. *Fixed Point Theory and Applications*, art.number:210. Available at: https://doi.org/10.1186/1687-1812-2014-210.

Rhoades, B.E. 1977. A comparison of various definitions of contractive mappings. *Trans. Amer. Math. Soc.*, 226, pp.257-290. Available at: https://doi.org/10.1090/S0002-9947-1977-0433430-4.

Saleem, N., Iqbal, I., Iqbal, B. & Radenović, S. 2020. Coincidence and fixed points of multivalued F-contractions in generalized metric space with applications. *Journal of Fixed Point Theory and Applications*, 22(art.number:81). Available at: https://doi.org/10.1007/s11784-020-00815-3.

Som, S., Bera, A. & Dey, L.K. 2020. Some remarks on the metrizability of $\mathcal{F}$-metric spaces. *Journal of Fixed Point Theory and Applications*, 22(art.number:17). Available at: https://doi.org/10.1007/s11784-019-0753-4.

Vujaković, J., Mitrović, S., Pavlović, M. & Radenović, S. 2020. On recent results concerning F-contraction in generalized metric spaces. *Mathematics*, 8(5), 767. Available at: https://doi.org/10.3390/math8050767.

Vujaković, J. & Radenović, S. 2020. On some F-contraction of Piri-Kumam-Dung type mappings in metric spaces. *Vojnotehnički glasnik/Military Technical Courier*, 68(4), pp.697-714. Available at: https://doi.org/10.5937/vojtehg68-27385.

Wardowski, D. 2012. Fixed points of a new type of contractive mappings in complete metric spaces. *Fixed Point Theory and Applications*, art.number:94. Available at: https://doi.org/10.1186/1687-1812-2012-94.

Wardowski, D. & Van Dung, N. 2014. Fixed points of F-weak contractions on complete metric spaces. *Demonstratio Mathematica*, 47(1), pp.146-155. Available at: https://doi.org/10.2478/dema-2014-0012.

Younis, M., Singh, D. & Goyal, A. 2019a. A novel approach of graphical rectangular b-metric spaces with an application to the vibrations of a vertical heavy hanging cable. *Journal of Fixed Point Theory and Applications*, 21(art.number:33). Available at: https://doi.org/10.1007/s11784-019-0673-3.

Younis, M., Singh, D. & Petrusel, A. 2019b. Applications of Graph Kannan Mappings to the Damped Spring-Mass System and Deformation of an Elastic Beam. *Discrete Dynamics in Nature and Society*, art.ID:1315387. Available at: https://doi.org/10.1155/2019/1315387.

ПЕРЕСМОТР И УЛУЧШЕНИЕ НЕКОТОРЫХ НОВЫХ РЕЗУЛЬТАТОВ В F-МЕТРИЧЕСКИХ ПРОСТРАНСТВАХ

Зоран Д. Митрович[а], *Мудасир* Йоунис[б], *Милое* Д. Раович[в]

[а] Университет в г. Баня-Лука, электротехнический факультет, г. Баня-Лука, Республика Сербская, Босния и Герцеговина, **корреспондент**

[б] Университетский технологический институт РГПВ, кафедра прикладной математики, г. Бхопал, М.П, Индия

[в] Крагуевацкий университет, машиностроительный факультет, г. Кралево, Республика Сербия

РУБРИКА ГРНТИ: 27.00.00 МАТЕМАТИКА:
27.25.17 Метрическая теория функций,
27.33.00 Интегральные уравнения,
27.39.29 Приближенные методы функционального анализа

ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В данной статье устанавливается несколько новых сжимающих условий в контексте так называемых F-метрических пространств. Основная цель статьи заключается в обобщении, расширении, улучшении, дополнении, объединении ранее опубликованных результатов в существующей литературе. Мы использовали только свойство (F1) Вардовского, а также одну хорошо известную лемму для доказательства того, что последовательность Пикара тождественна F-Коши в рамках F-метрического пространства.

Методы: В статье применены методы метрической теории неподвижной точки.

Результаты: Сформулированы новые результаты о F-сжатии двух отображений S и T в контексте F-полных F-метрических пространств.

Выводы: Полученные результаты значительно улучшены по сравнению с некоторыми недавно опубликованными результатами. В заключении приводится пример, доказывающий, что результаты, представленные в данной статье, являются соответствующим обобщением недавних результатов.

Ключевые слова: F-метрическое пространство, F-сжатие, неподвижная точка.

РЕВИЗИЈА И ПОБОЉШАЊЕ НЕКИХ НОВИХ РЕЗУЛТАТА У $\mathcal{F}$-МЕТРИЧКИМ ПРОСТОРИМА

Зоран Д. Митровић[а], *Мудасир* Јоунис[б], *Милоје* Д. Рајовић[в]

[а] Универзитет у Бањој Луци, Електротехнички факултет, Бања Лука, Република Српска, Босна и Херцеговина, **аутор за преписку**

[б] Универзитетски институт за технологију - РГПВ, Одељење за примењену математику, Бопал, М. П, Индија

[в] Универзитет у Крагујевцу, Машински факултет, Краљево, Република Србија

ОБЛАСТ: математика

ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Овај рад успоставља неколико нових контрактивних услова у контексту такозваних $\mathcal{F}$-метричких простора. Главни циљ је генерализација, проширење, побољшање, допуна и обједињење већ добијених резултата у постојећој литератури. Коришћено је само својство (F_1) Вардовског, као и једна добро позната лема за доказ да је Пикаров низ $\mathcal{F}$-Кошијев у оквиру $\mathcal{F}$-метричког простора.

Методе: Коришћене су методе метричке теорије фиксне тачке.

Резултати: Објављени су нови резултати у вези са $\mathcal{F}$-контракцијама за два пресликавања у оквиру $\mathcal{F}$-комплетних $\mathcal{F}$-метричких простора.

Закључак: Добијени резултати представљају значајна побољшања, као и праву генерализацију неких недавно објављених резултата, што показује пример наведен на крају рада.

Кључне речи: $\mathcal{F}$-метрички простор, F-контракција, фиксна тачка.

Paper received on / Дата получения работы / Датум пријема чланка: 28.11.2020. Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 01.03.2021.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 03.03.2021.

Mitrović, Z. et al, Revisiting and revamping some novel results in $\mathcal{F}$-metric spaces, pp.338–354

MODEL FOR SELECTING A ROUTE FOR THE TRANSPORT OF HAZARDOUS MATERIALS USING A FUZZY LOGIC SYSTEM

Teodora D. Milošević[a], *Dragan* S. Pamučar[b], *Prasenjit* Chatterjee[c]

[a] University of Defence in Belgrade, Military Academy, Department of Logistics, Belgrade, Republic of Serbia, e-mail: tmilosevic9@gmail.com, ORCID iD: https://orcid.org/0000-0002-9200-832X

[b] University of Defence in Belgrade, Military Academy, Department of Logistics, Belgrade, Republic of Serbia, e-mail: dragan.pamucar@va.mod.gov.rs, **corresponding author,** ORCID iD: https://orcid.org/0000-0001-8522-1942

[c] MCKV Institute of Engineering, Department of Mechanical Engineering, Howrah, West Bengal, Republic of India, e-mail: dr.prasenjitchatterjee6@gmail.com, ORCID iD: https://orcid.org/0000-0002-7994-4252

DOI: 10.5937/vojtehg69-29629; https://doi.org/10.5937/vojtehg69-29629

FIELD: Mathematics, Transport, Logistics
ARTICLE TYPE: Original scientific paper

Abstract:

Introduction/purpose: The paper presents a model for the selection of a route for the transport of hazardous materials using fuzzy logic systems, as a type of artificial intelligence systems. The system presented in the paper is a system for assistance in the decision-making process of the traffic service authorities when choosing one of several possible routes on a particular path when transporting hazardous materials.

Methods: The route evaluation is performed on the basis of five criteria. Each input variable is represented by three membership functions, and the output variable is defined by five membership functions. All rules in a fuzzy logic system are determined by applying the method of weight premise aggregation (ATPP), which allows the formation of a database based on experience and intuition. Based on the number of input variables and the number of their membership functions, the basic base of 243 rules is defined. Three experts from the Ministry of Defense were interviewed to determine the weighting coefficients of the membership functions, and the values of the coefficients were determined using the Full Consistency Method (FUCOM).

Results: A user program which enables the practical application of this model has been created for the developed fuzzy logic system.

Conclusion: The user platform was developed in the Matlab 2008b software package.

Key words: Fuzzy logic, Fuzzy set, ATPP, FUCOM, hazardous materials, Matlab.

Introduction

When managing the transport of hazardous materials (hazmat), special attention is paid to mitigate the negative consequences of transport, especially those that affect the safety of the population and the environment. One of the main problems of transport management is the selection of a route for the transport of hazmat, due to the harmfulness and possible consequences of accidental situations. With the development of technology, there is an increasing application of modern software systems based on artificial intelligence in solving the problem of transporting hazmat. Artificial intelligence offers possibilities for the development of automatic control systems, route optimization systems, as well as decision support systems. Although this technology has been present for some time, the possibility of its application in the transport of hazmat has not been fully researched.

The Ministry of Defense and the Serbian Armed Forces have not yet developed a model based on artificial intelligence that solves the problems of hazmat routing. The paper presents a model for the selection of a route for the transport of hazardous materials using fuzzy logic systems, as a type of artificial intelligence systems. The system presented in the paper is a system for assistance in the decision-making process of the traffic service authorities when choosing one of several possible routes on a particular path when transporting hazmat. The evaluation of the route is performed on the basis of five criteria, which are: the length of the route, the exposure of the population, the impact on the environment, the reaction speed of rescue services, and the probability of a traffic accident. These criteria were defined after a literature analysis and the interviews with experts from the Ministry of Defense. After entering the value of the input criteria in the user form, calculation and evaluation are performed. A preference to the entered route is given as an output from the fuzzy system.

The presented model was tested during the selection of a route for the transport of motor fuel. Three routes were considered for a given distance. After the calculation and evaluation of individual routes, the

values of the output variables of the fuzzy system were obtained in the user form and the preference for a route was obtained in the form of a numerical value and a linguistic descriptor (Kayapinar Kaya, 2020). Based on the system output values for each route, the ranking and selection of the route with the highest preference value was performed. A user program has been created for the developed fuzzy logic system, which enables the practical application of this model. The user platform was developed in the Matlab 2008b software package.

The rest of the paper is structured throughout several other sections. In the second section, there is a review of the literature related to the problems of hazmat transport and routing. The third section presents the development of a new fuzzy logic system for hazmat routing. The fourth section is a case study presenting the problem in detail and the fuzzy logic system to solve it. Finally, there are concluding considerations with further research suggestions moving in several different directions.

Literature review

A large number of authors deal with the problems of transport and routing of hazmat. Solutions to these problems are widely used in civilian structures, using modern software and information systems as decision-making support. Despite a good basis, due to more frequent transport of hazmat, explosives, propellants, etc., they have not found a wider application in the military system. The most common methods and criteria used in solving such problems are described below.

According to Starčević and Gošić (2014), the first step in managing the transport of hazmat is to determine the dangerous substance being transported and the consequences it has on the population and the environment. Then, it is important to determine the amount of dangerous goods transported, as well as the flows of dangerous goods between its source and destination, based on which the load of dangerous goods can be carried out and restrictions that may affect the choice of transport route (physical restrictions, ecological zones, restrictions within the framework of legal regulations, etc.). In the next phase, alternatives and criteria for route selection are defined, on the basis of which those that meet all previously set requirements are selected from the set of roads that serve sources and destinations. After defining the potential route and sections within it for the transport of oil and oil derivatives, the risk assessment process is carried out for each of the sections separately. The parameters for the analysis were divided into two groups. The first group includes: road category, geometric characteristics of the road,

access control, existence of level crossings, condition of the road, size of the traffic flow, participation of trucks in the traffic flow, congestion in the traffic flow, and traffic accidents. The second group of parameters consists of: population density, land use, population response to the incident situation, environmental impact, road drainage system, response time of rescue services (ambulance, fire and police), speed limit, and climatic influences (weather conditions). Depending on the probability of occurrence and the consequences of incident situations, risk assessment is performed by forming a risk matrix for each section and comparing the risk with the allowed values. If the risk degree on all sections is satisfying, the transport can be performed by the chosen route.

In order to establish a more precise method for determining possible risks on certain sections, various dispersive models are used. The concentration level can be calculated as a function of distance and the measured weather (climate change) parameters can be used in the GPM (Gausian plume model) and the GIS (Geographic Information System). In their paper, Zhang et al. (2000) applied an approach from the aspect of expected consequences. Risk is defined as a consequence of possible side effects (injuries, diseases, death) and effects on the population. As the risk factor for each section on the network must be calculated for the transport of hazmat, the use of the GPM (instead of the length of the section) as a factor is used to determine the point and degree of pollution spreading. In order to simplify the method, rasterization is performed using a GIS system where a certain space is transformed into a mosaic network of rectangles, or pixels. The network is organized in the form of layers (maps), where each of them represents a certain characteristic so that each pixel on each layer represents the same location. Each pixel has its own number of rows and columns, transferred to the Cartesian coordinate system, x = column × cell size (pixels) and y = row × cell size. Using the coordinate system, the distance and the direction are calculated.

According to Milovanović et al. (2012), the method for determining the optimal route for the transport of hazmat consists of eleven steps and can be applied to all groups of hazardous substances except for the substances from the seventh group (radioactive substances). The first step involves defining the type of hazardous substance, the characteristics of the hazard, and the zone of influence of hazardous substances. Then, the total amount of hazardous material being transported is defined as well as the amount at the source. The third step includes determining the source and the destination, followed by the formation of the initial-final matrix of vehicle movement and then

determining the load of roads with hazmat. The next step includes the analysis of the established restrictions, both legal and ecological (ecological zones, sensitive natural areas), after which alternatives, acceptable routes, continuity of routes, alternative routes and slowdowns that may occur on the selected routes are defined. The seventh step of the method is to define the criteria for choosing the optimal route. The basic criteria used was the existing source and destination locations, the roads most commonly used to transport hazmat, the use of roads reserved for the movement of trucks, the minimization of the transport route between the source and the destination, and the reduction of potentially endangered areas. The next step is to define the parameters for the risk analysis which include the parameters of the impact of the possibility of the occurrence of an incident situation and the parameters of the impact of the extent of the consequences of the incident situation. The last three steps are to define the impact of each parameter on the basis of expert monitoring, to implement a method for determining the optimal route as well as to identify, correct, and approve the route.

Frank et al. (2000) presented risk mitigation by selecting specific routes and elimination by using the SDSS (Spatial Decision Support System). The cycling system is the coverage of real roads on the territories of the target countries, as well as a multitude of loading and unloading points (laid and civilian points). The system is designed for route selection over long distances. In order to minimize costs and travel time, long-distance transportation should be done by highways, which means passing through populated areas and high exposure of the population to risk. Settlements can be avoided by using slower and bypass roads. Using the SDSS, several alternative transport routes are generated based on one optimizing criterion. The most commonly used approach is a combination of several criteria and their transformation into one criterion. This criterion is usually a linear function of the risk to the population, distance, travel time and the probability of an incident situation. Another approach is the choice of routes with multiple goals, where by minimizing travel time and exposing the population to risk, a larger number of routes are obtained, which include a large number of bypass routes suitable for practical application. Nevertheless, this approach is considered impractical. Another approach is to minimize one cost attribute while limiting the sum of other cost attributes. For example, travel time, as a direct cause of final costs, is minimized while other attributes - population exposure, distance, possibility, and consequences of the incident - are constant.

In their paper, Barilla et al. (2009) discussed the problem of integration of different sources of risk, different hazards and different elements exposed to risk and their sensitivity. The method is based on the application of a multi-criteria and multi-attribute analysis. Factors related to the economic problems of hazmat transport are considered to ensure the economic sustainability of transport, while human factors and natural hazards are taken as risk factors, and the population and facilities will be considered as elements exposed to risk. The applied model determines a possible risk on each route and, based on the set criteria, it selects a route with minimal risk. The criteria considered in this method are: minimization of travel time, transport route, risk to the population, risk to the urban environment, and risks related to natural hazards. As a product of this methodology, various solutions are obtained, representing a specific tool for decision-making support.

Using MOMR (Multiple Objective Mathematical Programming), Castillo (2004) estimated different and conflicting goals in order to calculate the optimal route for the transport of hazmat regarding the optimizing criterion. The optimizing criterion is flexible and depends on who participates in the decision making and its requirements. The objectives used as route optimization criteria are to minimize travel time, transport route, population risk, urban risk, and natural hazards.

Pamučar et al. (2016) combine adaptive neural networks (ANFIS - Adaptive Neuro Fuzzy Inference System) and the Dijkstra's algorithm as a method for calculating the optimal route for the transport of hazmat through urban areas. In the first phase of the ANFIS-D method, a transport network is formed in the urban area and the input criteria are defined on the basis of which the values of branches in the network are determined. The criteria taken to define the value of branches in the network are: speed of response of emergency services, risk associated with environmental impact, risk of traffic accidents, consequences of traffic accidents, risk associated with infrastructure facilities, and risk of terrorist attacks. To define the values of the branches in the network, an adaptive neural network is formed where the input data are the previously listed criteria. In the second phase, the initial fuzzy logic system is constructed and the adaptive neural network is trained using the Artificial Bee Colony (ABC), where the value of a specific branch in the network is obtained as an output. The algorithm is repeated until each branch in the network is assigned a value. After determining the value of the branches using the Dijkstra algorithm, the optimal route for the transport of dangerous goods is determined.

In his paper, Milovanović (2012) considers the problems in the selection of routes for the transport of hazmat from the aspect of the analysis of individual and social risk, as well as the levels of absolute and specific risks. A specific risk is derived quantity that estimates the percentage of damage of a certain element exposed to risk that can be expected in an incident situation, while an absolute risk is a quantification of a specific risk expressed as the product of the specific risk value and the element exposed to risk. The individual risk degree means the rate of suffering of an individual, as a member of the social community, who is constantly exposed to hazmat on an annual basis. Social risk is defined as the cumulative value of the probability of an accident with several casualties in the zone of hazmat influence. Based on the research and the methods applied in Italy, the USA and the Netherlands, the author improves these methods through 11 steps. The first five steps include the first phase of risk management, hazard identification, and consequence analysis. They include determining the hazmat type, determining the hazmat quantity, determining the source and the destination points, and forming a matrix of original target movements of vehicles, determining the load on the road network restrictions. The sixth and seventh steps include defining alternatives for the analysis (which are acceptable routes, continuity of the route, alternative routes, possible delays during transport) and defining the criteria for route selection. After these two steps, routes are obtained that meet all the requirements and needs for the transport of hazmat. However, the obtained routes must be checked from the aspect of the allowed degree of risk. Risk assessment is performed by defining the parameters for risk analysis (the parameters that affect the probability of an incident situation and the parameters related to the size of the consequences) and then it is necessary to connect each parameter with the size of the risk and determine its weighting factor.The size of weight factors was determined by surveying experts in the field of transport of hazmat, who stated the degree of the influence of the parameters on the choice of a route for transport of dangerous goods on a scale from 0 to 4, where 0 represents a value where a parameter has no influence on route selection and 4 represents a parameter that has a critical impact. After the above, a risk assessment is performed for each of the sections of the selected routes, where by comparing the obtained values with the allowed level of risk, a decision is made whether the observed section is suitable for transport of hazmat or not. This comparison of values for each section on a particular route leaves the possibility of defining alternative sections that would connect the previous and the next section between which there was a section that is not acceptable in terms of risk

level or mitigate the consequences or reduce the posibility of incident in order to reduce risk. Thus, the section will re-enter the process of considering eligibility for the transport of hazmat. Based on the previous review of the literature that considers different methods for selection and optimization of the route for transport of hazmat, it was determined that the authors used different criteria. Based on that, the criteria used in this research were defined. The most commonly used criteria in selecting the optimal route for the transport of dangerous goods are shown in Table 1.

Table 1 – The most commonly used criteria for selecting a route for the transport of hazardous materials
Таблица 1 – Наиболее часто используемые критерии выбора маршрута перевозки опасных грузов
Табела 1 – Најчешће коришћени критеријуми за одабир оптималне руте за транспорт опасног терета

References	Criteria						Problem/ Method
	Time of travel	Transportation route	Inpact on the population	Environmental inpact	Speed of response of rescue services	The probability of an accident	
(Starčević & Gošić, 2014)			+	+		+	Risk Analysis
(Pamučar et al, 2016)	+	+		+	+	+	Adaptive Neural Networks and Dykstra's Algorithm
(Frank et al, 2000)	+	+	+				Spatial Decision Support System
(Zografus & Adroutsopoulos, 2008)	+	+	+	+			Decision Support System
(Zografus & Adroutsopoulos, 2008)	+		+				Bicriteria Method
(Pradhanaga et al, 2010)	+		+	+			Ant Colony Method

References	Criteria						Problem/ Method
	Time of travel	Transportation route	Inpact on the population	Environmental inpact	Speed of response of rescue services	The probability of an accident	
(Xie et al, 2012)			+	+			Routing and Multimodal Locating Methods
(Leonelli et al, 2000)	+	+	+	+	+		Risk Analysis
(Zhang et al, 2000)			+	+			Use of GIS Risk Assessment Systems
(Milovanović et al, 2012)			+	+	+		Risk Analysis
(Milovanović, 2012)	+	+		+			Rick Menagment
(Jovanović & Živković, 2010)		+	+	+			Routing Problem
(Leonardi, 2008)			+	+			Planning the rout for the transport of hazardous materials
(Barilla et al, 2009)	+	+	+	+			Rick analysis
(Castillo, 2004)	+	+	+	+			Optimization of the rout for the transport of hazardous materials

References	Criteria						Problem/ Method
	Time of travel	Transportation route	Inpact on the population	Environmental inpact	Speed of response of rescue services	The probability of an accident	
(Ristić, 2018)		+			+		Multicriteria Decision Making Method
(Biočanin & Stefanov, 2011)		+			+		Environmental Safety of Hazardous Materials

In this research, a fuzzy logic system was used to create a model for the selection of a route for the transport of hazmat in the Ministry of Defense and the Serbian Armed Forces (SAF), as one of the models of artificial intelligence, because it is the basis for decision making in a dynamic environment. The analysis of the literature showed that there is no software based on artificial intelligence that is used to select a route for the transport of dangerous goods in the Ministry of Defense and the SAF. Based on the analysis of the literature and the interviewing of experts from the Ministry of Defense, the criteria that represent the input variables in the software based on artificial intelligence are defined. The criteria and their descriptions are presented in Table 2.

Table 2 – Defined criteria for the selection of a route for the transport of hazardous materials in the Ministry of Defence and Serbian Armed Forces
Таблица 2 – Утвержденные критерии выбора маршрута для перевозки опасных грузов в Министерстве обороны и вооруженных силах Сербии.
Табела 2 – Дефинисани критеријуми за избор руте за транспорт опасног терета у Министарству одбране и Војсци Србије

	Criterion	Description
1	Route length	The distance (expressed in km) that the vehicle travels when transporting hazardous materials
2	Impact/Exposure of the population	Degree of the impact of the consequences of incident situations on the population.

	Criterion	Description
3	Environmental impact	Degree of the impact of the consequences of incident situations on the environment.
4	Speed of response of rescue services (ambulance, firefighters, police)	The time during which city services (fire services, emergency services and police) react in case of incidents. The average response time is taken as the input parameter.
5	Probability of a traffic accident	The impact of road sections on which due to the characteristics of the section (terrain configuration, traffic density, railway crossings, traffic quality, enemy action, etc.) exists an increased risk of a traffic accident.

Fuzzy logic system

Fuzzy logic is used to model complex systems in which it is difficult to determine the interdependence between individual elements of the system by applying other methods. The creator of fuzzy logic is considered to be Lotfi Zadeh (Zadeh, 1975a, 1975b, 1975c), who in 1973 first spoke about the use of mathematical tools to represent spoken language and human knowledge by introducing the terms fuzzy rule and linguistic variable into the theory of automatic control. Fuzzy logic itself is based on the theory of fuzzy sets that were introduced with the basic goal of representing and modeling uncertainty in linguistics in a mathematically formalized way. Unlike classical sets where an element either belongs or does not belong to a defined set, a fuzzy set is a set of elements with similar characteristics, where the membership of an element can be any real number in the interval [0.1]. The main difference between these two types of sets is that classical sets always have a unique membership function, while for a fuzzy set there are infinitely many different membership functions by which it can be described.

Fuzzy relations are used to represent the conection between elements that are valid to some degree. In the case of binary relations, e.g. "<" (Less), two elements can either satisfy or not satisfy the relation (Precup et al, 2020). In relations that are not binary (which is often the case), for example: there is a weak connection, there is a middle connection, there is a close connection, the strength of the relation is expressed by expressions that show gradualness. The fuzzy relation between the elements is satisfied to a certain extent, which is expressed as a number from the interval [0.1].

One of the basic rules of fuzzy logic is fuzzy composition, where the composition of two fuzzy relations gives a new relation. The composition must satisfy transitivity, associativity, and symmetry. A fuzzy statement contains linguistic values, and the truth of the statement is a number from the interval [0.1] (Vesković et al, 2020).

Fuzzy reasoning does not contradict the rules of logical reasoning, but it cannot use them in their original form, because the result of logical reasoning is only a part of possible conclusions when using fuzzy sets and fuzzy variables. The complex rule of reasoning was proposed by Zadeh (Zadeh, 1965) and it symbolically reads:

Premise: x is A
Condition: x R y
Conclusion: y is B

x R y means that x and y are connected by a fuzzy relation R (x, y). If we denote "x is A" by the fuzzy set A, then the meaning of "y is B" can be calculated as (Kushwaha et al, 2020):

$$B = A \circ R \tag{1}$$

which represents the composition of the fuzzy set and a fuzzy relation.

The rules used in the fuzzy system, obtained on the basis of expert knowledge, can be expressed using a certain number of linguistic rules in spoken or artificial language words and serve as a link between the inputs and outputs of the fuzzy system. All rules consist of two parts: the IF part which represents the input state and the fuzzy proposition represents the premise, and the THEN part which represents the output state and the fuzzy proposition represents the conclusion. The if-then rules are interrelated with the expression *else*. In addition to this conjunction, they also can be connected by the conjunction *and*. There are two ways to define the rules that differ in that part. The first way is the classic rule format proposed by Zadeh, and the second rule format was proposed by Takagi and Sugeno.

The classic rule format:

Rule: IF<fuzzy statement>THEN<fuzzy statement

where the fuzzy statement may be an atomic statement or a complex statement, e.g.

If *x* is *A*, ***then*** *z* is *C*
If *x* is *A* and *y* is *B* ***then*** *z* is *C*
If *x* ***is not*** *A* ***then*** *z* is *C* and *v* is *D*

The Tagaki-Sugeno rule format:

Unlike the classic format, the Takagi-Sugeno format contains a fuzzy statement only in the IF part of the rule, and the THEN part is defined by a function whose arguments are input fuzzy variables. A special case is when a constant is used instead of a function, e.g.

If *x* is *A* ***then*** *z* is $f_1(x)$

If *x* is *A* else *y* is *B* ***then*** *z* is $f_2(x,y)$

If *x* is **not** *A* ***then*** *z* is $f_1(x)$ and *v* is *12*

More than one rule needs to be defined to describe a particular fuzzy system. These rules are executed in parallel, connected by an operator else (union), so the execution of *n* parallel rules can be expressed using the fuzzy relation:

$$R = \bigcup_{k=1}^{n} R_k \qquad (2)$$

where R_k refers to the k-th rule.

When the classical implication fuzzy system is used, only true variables are considered, while untruths are not considered. In the case of using the Takagi-Sugeno format, the implication is already defined in the THEN part (function or constant).

A number of rules for defining a fuzzy system in which words describe the solution to a problem is called a rule base or expert rules. In reality, the input variables are usually represented by a number, and the output value is obtained in the numerical form. Since the given system is described verbally (qualitatively) through production rules, first, numerical values are converted (fuzzyfied) by applying a fuzzy logical operation. After that, they are processed by the mechanism of approximate reasoning in the fuzzy system through the phases of aggregation, activation, and accumulation, and the numerical output value is obtained by the process of defuzzyfication.

Aggregation is a phase in which certain values of the membership function are added to the measured numerical value, i.e. it is a process by which it is determined with which degree of confidence (truth level) an input numerical value belongs to a given fuzzy set. In the case where there is only one input, aggregation is equivalent to fuzzyfication.

Activation is the conclusion drawn in the THEN part of the rule. There are two methods of activation, MIN (minimum) and PROD (product) methods. The MIN method performs truncation, while the PROD method performs scaling, proportional reduction of the conclusion.

In the process of accumulation, all activated conclusions are accumulated. Accumulation is usually realized through two methods:

MAX and SUM. By applying the MAX method, the final shape is obtained as the union of two fuzzy sets, while by applying the SUM method the final contours are obtained as the algebraic sum of the contours obtained by the activation process. If the obtained sum is greater than one, then it is normalized to the value of one. When the type of approximate reasoning mechanism is specified, then it is the MIN-MAX or PROD-SUM method.

Defuzzyfication is the operation of converting the resulting fuzzy set into a real number. Just as fuzzy systems can be divided into two groups, so can defuzzyfication methods be divided into Mamdani and Sugeno (or Takagi-Sugeno). Since mathematical defuzzyfication is represented as mapping a vector (value of a linguistic variable) into a real number, there is a reduction of information. Information reduction occurs because different values of a linguistic variable can be mapped to the same converted real number. Therefore, it is necessary to be very careful when choosing a method for defuzzyfication, because there is no method that is optimal for all cases.

The analysis of input-output mappings is performed in order to notice the influence of the choice of membership functions and their arrangement on the shape of the output, the set of possible solutions (Badi et al, 2019). The dependence of one output on another one can be shown by a graph of the function, and its analysis helps in selecting the membership function and forming rules. The shape of the curve on the graph can be controlled to some extent by manipulating the membership functions.

Modeling a fuzzy logic system for route selection for transport of dangerous goods

Based on the described concept, the basis is created to model the system of interdependence of input criteria as a complex fuzzy system for the selection of a route for the transport of hazardous materials. It goes through several phases in order to reach the final solution, which in general modeling represents system design, optimization and application. In the fuzzy model, the stages gone through to reach a final solution can be defined as:

- Problem analysis,
- Defining linguistic variables,
- Selection of membership functions,
- Forming a database of rules,
- Selection of inference and defasing methods, and
- Application of a fuzzy model.

Problem analysis

A detailed analysis of the problem, when modeling a fuzzy logic system, is performed to determine the number of variables and their interdependence. In case the problem is complex, the system can be divided into several smaller subsystems, the goal and purpose of each subsystem is determined, after which the way of connecting these subsystems and the priorities between them are determined.

Defining liguistic variables

As previously explained, linguistic variables take values from spoken language or are artificially synthesized and represented by fuzzy sets. It is pointed out that the designed fuzzy system contains five linguistic variables, as follows:

- Route length,
- Exposure of the population,
- Environmental impact,
- Response speed of rescue services, and
- Probability of a traffic accident,

including the output linguistic variable *Route preference*.

The values of the input variables include the intervals listed in the table.

Table 3 – Intervals of input and uotput linguistic varialbes
Таблица 3 – Интервалы ввода и вывода лингвистических переменных
Табела 3 – Интервали улазних и излазне лингвистичке променљиве

Input linguistic variables	Interval	
	from	to
Route length	0	300
Exposure of the population	1	10
Environmental impact	1	10
Response speed of rescue services	1	10
Probability of a traffic accident	1	10
Output linguistic variable	Interval	
	from	to
Route preference	0	100

Once the linguistic variables have been defined, the number and type of membership functions need to be determined for all input and output variables. The higher the number of membership functions, the higher is the number of rules, which can make it difficult to set up the system, so it is advisable to start with the smallest number of functions, in accordance with the nature of the variable. Reducing the number of functions must not be done to the harm of the quality of the description of the variable. Based on that, it was decided that in the model each input variable (route length, population exposure, environmental impact, speed of response of rescue services and probability of an accident) has three membership functions, and the output variable (route preference) five membership functions. The linguistic values of all input variables are *Small, Medium* and *Large*, while the values of the output linguistic variable are *Very Small, Small, Medium, Large,* and *Very Large.*

A larger number of linguistic values were not needed since it is a decision support system, so it does not require enormous precision. With three linguistic values, a satisfactory gradual change in output values was achieved, which limits the number of rules to 243 and enters the domain that the expert can control.

Selection of a membership functions

An important phase in modeling a fuzzy logic system is the choice of membership functions and their arrangement on the membership interval. In the initial phase of system design, triangular functions were chosen as membership functions. However, their adjustment does not provide sufficient system sensitivity. Therefore, Gaussian bells functions were used in the system as they well describe the input and output variables and allow for satisfactory system sensitivity. Figures 1 and 2 show the membership functions of the input and output variables.

The values of the membership functions of the input variables are shown in Table 4, where the first number in the interval represents the left and right distributions of the Gaussian curve along the abscissa, and the second number represents the value at which the Gaussian curve reaches the maximum.

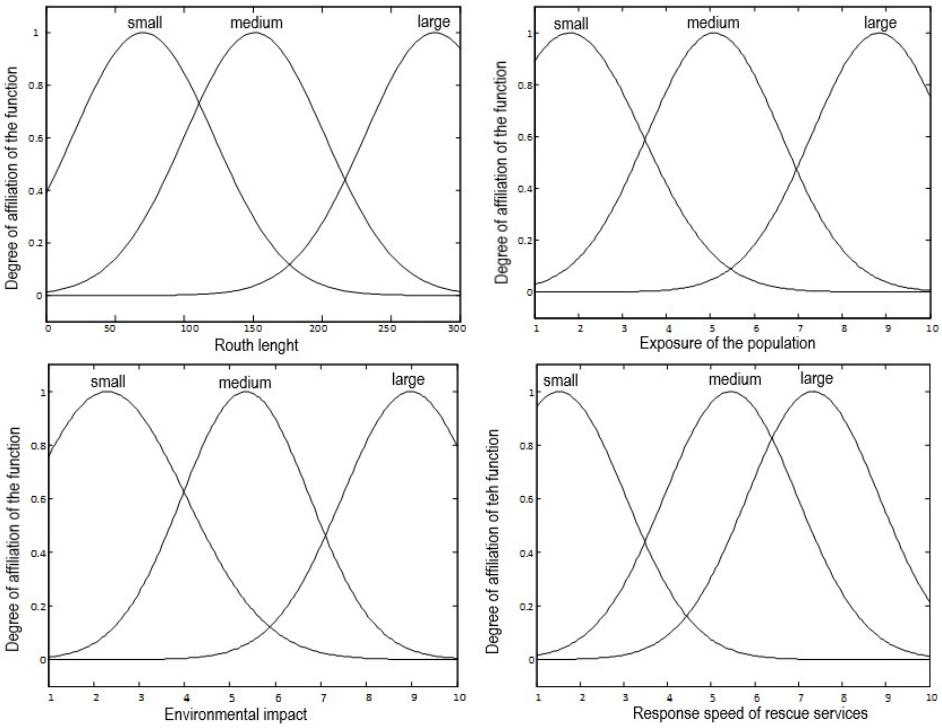


Figure 1 – Membership functions of the input variables
Рис. 1 – Функции принадлежности входных переменных
Слика 1 – Функције припадности улазних променљивих

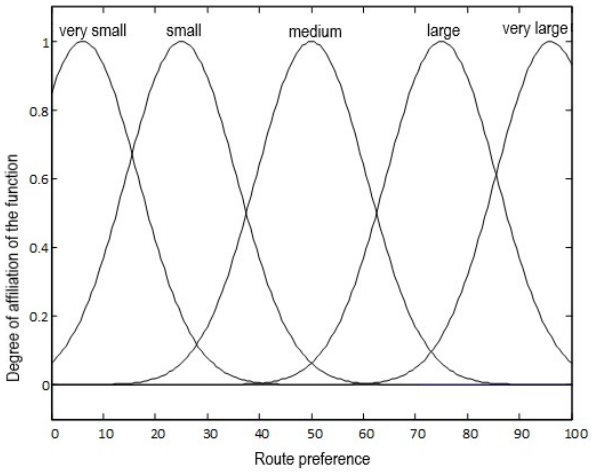


Figure 2 – Membership functions of the output variable
Рис. 2 – Функции принадлежности выходной переменной

Слика 2 – Функције припадности излазне променљиве
Table 4 – Values of the mambership functions of the input varables
Таблица 4 – Значения функций принадлежности входных переменных
Табела 4 – Вредности функција припадности улазних променљивих

Membership function/ input value	Small	Medium	Large
Route length	(51.2 , 70.35)	(51 , 151.2)	(51 , 281.8)
Exposure of the population	(1.66 , 1.803)	(1.53 , 5.09)	(1.54 , 8.844)
Environmental impact	(1.74 , 2.301)	(1.41 , 5.348)	(1.51 , 8.977)
Reaction speed of rescue services	(1.53 , 1.52)	(1.53 , 5.447)	(1.52 , 7.335)
Probability of a traffic accident	(1.53 , 2.335)	(1.53 , 4.977)	(1.53 , 9.135)

Forming a database of rules

Linguistic rules are constructed as a link between inputs and outputs. In complex systems, one of the major problems is the lack of a standard and systematic method for transforming expert knowledge or experience into fuzzy rules (Pamučar & Ćirović, 2013), (Jovanović et al, 2014). Another problem is the lack of a universal method for determining the optimal number of rules, given that many factors influence such a decision, and this is important for the speed of the system.

The expert domain is primarily entered through production rules. Initially, it is important that for each combination of input values of linguistic variables, the expert suggests an appropriate output value (Ćirović et al, 2014). As the system has five input linguistic variables (n=5) with three linguistic values each (M=3), they can be combined in the database with a total of $M^n = 3^5 = 243$ rules.

All rules for the fuzzy logic system are determined by applying the aggregation weight premise rules method (ATPP), Božanić and Pamučar (2014). There are many methods for constructing a rule base of a fuzzy logic system from a known set of numerical values, but the ATPP method allows the creation of a rule base based on experience and intuition. The steps of the ATPP methods are as folows:

Step 1: Determination of the weight coefficients of the membership functions of the input variables.

For the weight coefficients of the membership functions, the condition applies:

$$\sum_{j=1}^{m} w_{x_i}^{(j)} = g_{X_i} \quad (3)$$

where:
$w_{(xi)}^{(j)}$ - weight coefficient of the membership function, j = 1, ..., m, (m total number of membership functions),

g_{xi}- weight coefficient of the input variable i = 1, ..., n.

Most often, $w_{(xi)}^{(j)}$ is determined based on the subjective assessment of the expert modeling a fuzzy logic system. However, in addition to subjective assessment, the weight coefficient of the membership function can be determined by group decision-making and the aggregation of experts. The distribution of the weight coefficients of the membership functions should reflect reality as much as possible. In this particular case, $w_{(xi)}^{(j)}$ was determined by interviewing experts and applying the FUCOM (Full Consistency Method) method (Pamučar et al, 2018), (Bozanic et al, 2019), (Fazlollahtabar et al, 2019), (Puška et al, 2019), (Erceg & Mularifović, 2019), (Durmić, 2019), (Nenadić, 2019), (Žižović & Pamucar, 2019), (Bozanic et al, 2020), (Durmić et al, 2020). Three experts were interviewed, and the results of the calculation of the weight coefficients are shown in Table 5. Lingo software was used to solve this problem and for the calculation.

Expert 1- *min* ε

$$\begin{cases} \left|\frac{w_2}{w_4} - 2\right| \le \varepsilon, \left|\frac{w_4}{w_5} - 1.5\right| \le \varepsilon, \left|\frac{w_5}{w_3} - 1.33\right| \le \varepsilon \\ \left|\frac{w_3}{w_1} - 1.25\right| \le \varepsilon, \left|\frac{w_2}{w_5} - 3\right| \le \varepsilon, \left|\frac{w_4}{w_3} - 2\right| \le \varepsilon \\ \left|\frac{w_5}{w_1} - 1.67\right| \le \varepsilon \\ \sum_{j=1}^{5} w_j = 1, w_j \ge 0, \forall j \end{cases}$$

Expert 2- *min* ε

$$\begin{cases} \left|\frac{w_5}{w_1}-1.3\right|\le\varepsilon, \left|\frac{w_1}{w_2}-1\right|\le\varepsilon, \left|\frac{w_2}{w_3}-1\right|\le\varepsilon \\ \left|\frac{w_3}{w_4}-1.6\right|\le\varepsilon, \left|\frac{w_5}{w_2}-1.3\right|\le\varepsilon, \left|\frac{w_1}{w_3}-1\right|\le\varepsilon \\ \left|\frac{w_2}{w_4}-1.6\right|\le\varepsilon \\ \sum_{j=1}^{5} w_j = 1, w_j \ge 0, \forall j \end{cases}$$

Expert 3- *min* ε

$$\begin{cases} \left|\frac{w_5}{w_1}-2\right|\le\varepsilon, \left|\frac{w_1}{w_4}-1.5\right|\le\varepsilon, \left|\frac{w_4}{w_2}-1.67\right|\le\varepsilon \\ \left|\frac{w_2}{w_3}-1.4\right|\le\varepsilon, \left|\frac{w_5}{w_4}-3\right|\le\varepsilon, \left|\frac{w_1}{w_2}-2.5\right|\le\varepsilon \\ \left|\frac{w_4}{w_3}-2.33\right|\le\varepsilon \\ \sum_{j=1}^{5} w_j = 1, w_j \ge 0, \forall j \end{cases}$$

Table 5 – Weight coefficients of the input variables
Таблица 5 – Весовые коэффициенты входных переменных
Табела 5 – Тежински коефицијенти улазних променљивих

Criteria	Weight coefficient	$w_{x_i}^{(1)}$	$w_{x_i}^{(2)}$	$w_{x_i}^{(3)}$
K_1 (route length)	0.1734	0.173	0.1	0.05
K_2 (exposure of the population)	0.2442	0.244	0.17	0.08
K_3 (environmental impact)	0.1261	0.126	0.085	0.03

Criteria	Weight coefficient	$w_{x_i}^{(1)}$	$w_{x_i}^{(2)}$	$w_{x_i}^{(3)}$
K_4 (reaction speed of rescue services)	0.1664	0.08	0.11	0.166
K_5 (probability of a traffic accident)	0.2898	0.289	0.18	0.05

Step 2: Generate an initial "incomplete" rule base with the maximum number of combinations

N input (X_i) variables and the output variable (*Y*) are described with different numbers of the membership functions. Starting from that, it is necessary to determine the maximum number of rules, i.e. the maximum number of combinations (*c*) by which the membership functions can be combined. The initial rule base contains only the premises (the IF part of the rule) or the combinations of all membership functions of the input variables of the fuzzy logical system ($x_i^{(j)}$). The initial "incomplete" base of the *R* rule is displayed in the form of a matrix as:

$$R = \begin{array}{c} \\ R_1 \\ R_2 \\ \vdots \\ R_c \end{array} \begin{array}{c} \begin{array}{cccc} X_1 & X_2 & \dots & X_n \end{array} \\ \begin{pmatrix} x_1^{(1)} & x_2^{(1)} & \dots & x_n^{(1)} \\ x_1^{(2)} & x_2^{(1)} & \dots & x_n^{(2)} \\ \vdots & \vdots & \dots & \vdots \\ x_1^{(m)} & x_2^{(m)} & \dots & x_n^{(m)} \end{pmatrix} \end{array} \tag{4}$$

Step 3: Generating a "complete" rule base by assigning appropriate conclusions ($y_i^{(r)}$) to premises ($x_i^{(j)}$). Generating a complete rule base begins with the formation of a matrix R 'in which combinations of input pairs are replaced by weighting coefficients ($w_{(xi)}^{(j)}$).

$$R' = \begin{pmatrix} w_{x_1}^{(1)} & w_{x_2}^{(1)} & w_{x_3}^{(1)} & \dots & w_{x_n}^{(1)} \\ w_{x_1}^{(2)} & w_{x_1}^{(2)} & w_{x_3}^{(2)} & \dots & w_{x_n}^{(2)} \\ w_{x_1}^{(3)} & w_{x_2}^{(3)} & w_{x_3}^{(3)} & \dots & w_{x_n}^{(3)} \\ \dots & \dots & \dots & \dots & \dots \\ w_{x_1}^{(m)} & w_{x_2}^{(m)} & w_{x_3}^{(m)} & \dots & w_{x_n}^{(m)} \end{pmatrix} \tag{5}$$

After forming the matrix R ', the elements of the matrix are summed in rows:

$$w_j = \sum_{j=1}^{n} w_{x_i}^{(j)}\, y^+, y^+ \in [y^-, y^+] \quad (6)$$

where y^+ represents the upper limit of the confidence interval $[y^-, y^+]$ of the output variable *Y*. After this, it is necessary to determine the degree of belonging of the real number w_j to the membership function $y^{(r)}$ of the output variable *Y.*

$$y^{(r)} = \max(w_y \cap \mu_{y^{(r)}}) \quad (7)$$

Step 4: Optimization of the number of rules, elimination of redundant rules.

When generating the rule base, each pair of the membership functions ($x_i^{(j)}$) of the input variables (X_i) is associated with the corresponding membership function ($y^{(r)}$) of the output variable (*Y*). After defining the rule base, redundant rules that unnecessarily burden the system are eliminated. Elimination is performed when there are two or more rules that have similar or the same combination of the membership functions of the input / output variables. In this case, what is left is a rule whose sum of weight coefficients of the membership functions, contained in the rule, is higher.

$$R = \max \sum w_{x_R}^{(i)}\ , i = 1,2, \dots, n \quad (8)$$

where $w_{xR}^{(i)}$ represents the weight coefficient of the membership functions contained in the rule R.

If we mark:

A – route length,
B – exsposure of the population,
C – environmental inpact,
D – response speed of rescue services,
E – probability of a traffic accident, and
F – route preference,

then the role example is:

IF (A is Large) **AND** (B is Small) **AND** (C is Medium) **AND** (D is Medium) **AND** (E is Small) **THEN** (F is Large).

Selection of inference and defasing methods

The most commonly used methods for direct inference are MIN-MAX and PROD-SUM (Mamdani method). In the initial phase of system development, the MIN-MAX method was used. This method is a common choice when it is not important to manage the entire confidence interval of the output variable. However, a large number of system simulations have shown that the MIN-MAX method is unsuitable. One of the basic requirements was to achieve a satisfactory level of system sensitivity, which means that with certain small changes in the input, the output from the fuzzy system must also have small changes, which could not be achieved by applying the MIN-MAX method. Figures 3 and 4 show the graphical representations of the solution according to the MIN-MAX method in the form of the interdependence of the solution and two input variables.

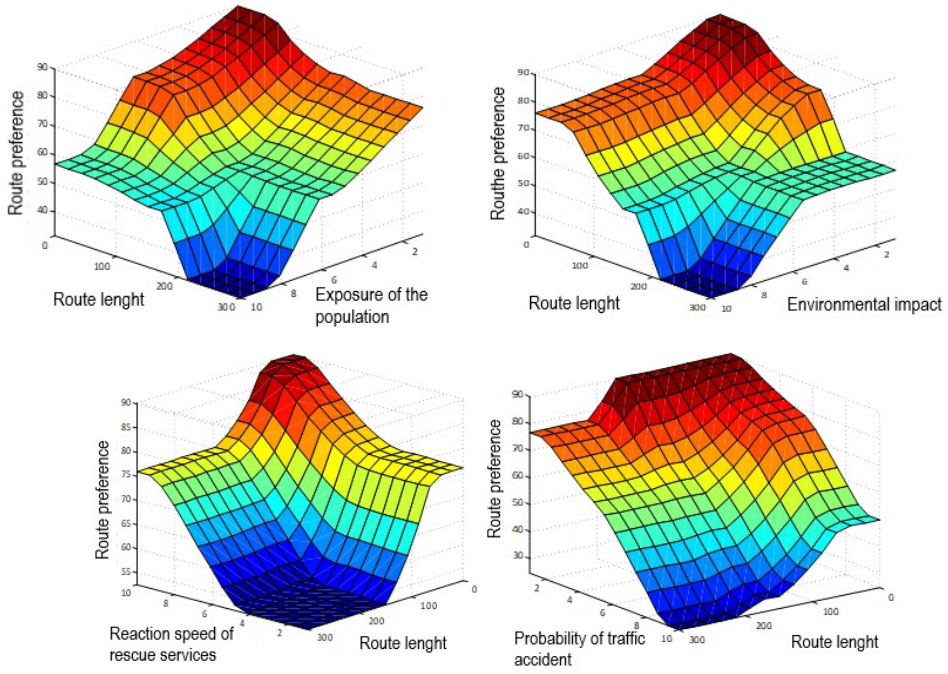


Figure 3 – Interdependence of the solution and two input variables by the MIN-MAX method
Рис. 3 – Взаимозависимость решения и двух входных переменных с использованием метода MIN-MAX
Слика 3 – Међузависност решења и две улазне променљиве применом методе MIN-MAX

The Matlab 2008b software package was used to construct the fuzzy logic system.

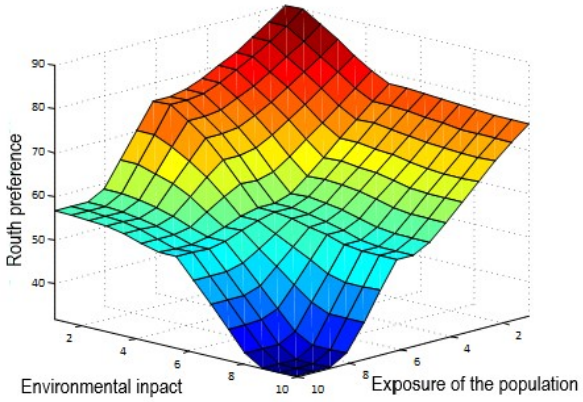


Figure 4 – Interdependence of the solution and two input variables by the MIN-MAX method
Рис. 4 – Взаимозависимость решения и двух входных переменных с использованием метода MIN-MAX
Слика 4 – Међузависност решења и две улазне променљиве применом методе MIN-MAX

It can be seen from the figure that the system obtained using the MIN-MAX method is very insensitive. The insensitivity of the system is represented by the plateaus on the figures.

The settings could not achieve the desired shape, and even if the desired shape was obtained, it would be valid only for certain values of the input variables.

By changing the parameters, the surface would look even less acceptable, and thus the system would be even less sensitive. In order to increase the sensitivity of the system, the PROD-SUM method of direct inference was used, as the best offered by the Matlab software package.

Figures 5 and 6 graphically show a set of possible solutions of the input variables using the PROD-SUM method.

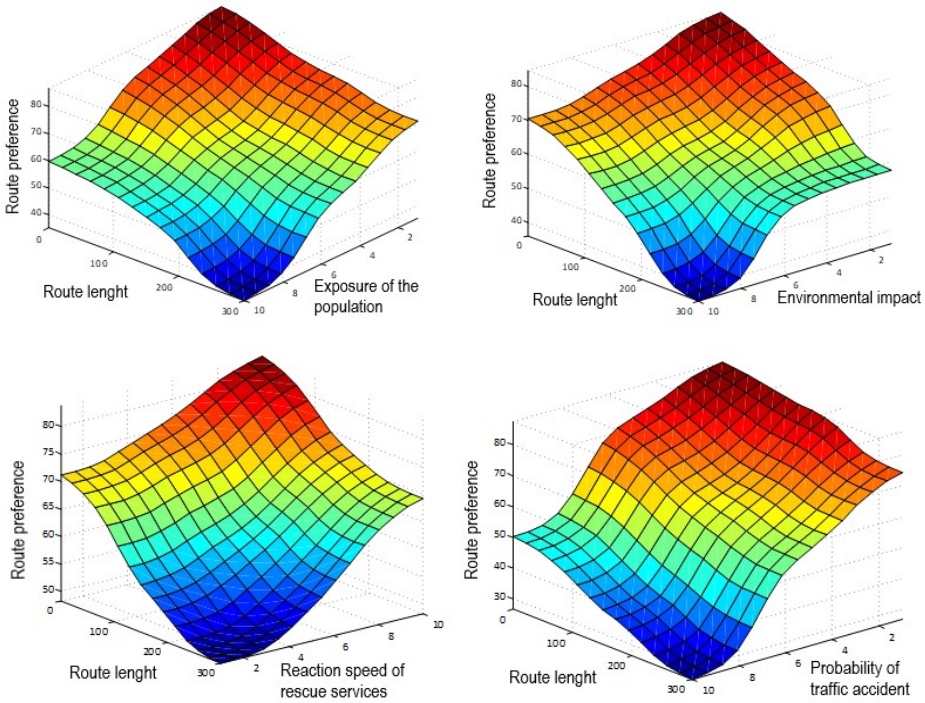


Figure 5 – Interdependence of the solution and two input variables by the PROD-SUM method
Рис. 5 – Взаимозависимость решения и двух входных переменных с использованием метода PROD-SUM
Слика 5 – Међузависност решења и две улазне променљиве применом методе PROD-SUM

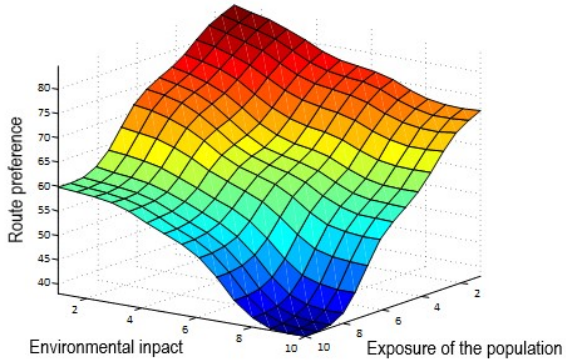


Figure 6 – Interdependence of the solution and two input variables by the PROD-SUM method
Рис. 6 – Взаимозависимость решения и двух входных переменных с использованием метода PROD-SUM
Слика 6 – Међузависност решења и две улазне променљиве применом методе PROD-SUM

The reasoning process in a fuzzy logic system takes place by the fuzzyfication of the values of the input variables at the very beginning. In the fuzzyfication process, the membership functions defined for the input variables are applied to the actual value of the input variable to determine the degree of affiliation for the premise of each of the rules in the database. For example, if the Route Length is described by the linguistic descriptor Low, Exposure of the Population described as Medium, Environmental Impact as Medium, Response Speed of Rescue Services as Medium, and Probability of a Traffic Accident described as High. After obtaining these values, the expert system performs the analysis in accordance with the previously defined limits, which represent the membership functions of individual variables. Each variable consists of several fuzzy sets and the purpose of fazzyfication is to determine which fuzzy set "belongs" to each input variable and to represent this affiliation with numerical values in the interval [0,1].

After the fuzzyfication of the input values, the analysis of these values is performed as well as their comparison with the sets of values of the premise of the rule from the rule base. In the case of this system, all rules were activated when entering values. By activating the rules, intermediate solutions are obtained. The union of fuzzy sets is applied to the obtained intermediate results, and on that occasion the resulting fuzzy set is obtained.

The method of the center of gravity (COG) was chosen for the method of defuzzyfication. In the case of a discrete confidence interval, defuzzyfication is calculated according to:

$$u = \frac{\sum_{i=1}^{n} \mu(x_i) x_i}{\sum_{i=1}^{n} \mu(x_i)} \tag{9}$$

where

μ_i -fuzzy set obtained after the accumulation phase;

n - the number of discretization levels of the specified fuzzy set per x;

x_i - i-th discrete value; and

$\mu(x_i)$- fuzzyfied value of x_i.

Application of the fuzzy system

The application of the system is one of the components in the system life cycle. The model should be applied and, if necessary, certain corrections, changes and improvements should be made again, which is relatively easy in a fuzzy system.

A user program has been created for the developed fuzzy logic system, which enables the practical application of this model. The user platform was developed in the Matlab 2008b software package. Entering "PP" in the command line of the Matlab software package starts the program for selecting the route for the transport of hazardous materials. The user form is shown in Figure 7.

Figure 7 – User form of the developed program for the selection of a route for transport of hazmat
Рис. 7 – Пользовательская форма программы для выбора оптимального маршрута перевозки опасных грузов
Слика 7 – Корисничка форма програма за избор оптималне руте за транспорт опасног терета

Pressing the "Pokreni program" (run program) button opens a fuzzy logic model in which the user enters the desired values of the input variables. The value of the criterion "Route length" has an interval [0,300], while the values of other criteria can be selected from the interval [1,10]. The values can be entered by typing or moving the slider keys. By pressing the “Pokreni” (Run) button, the calculation is performed. The output from the fuzzy system is shown in the lower part as a numerical and linguistic value of the preference according to the entered route.

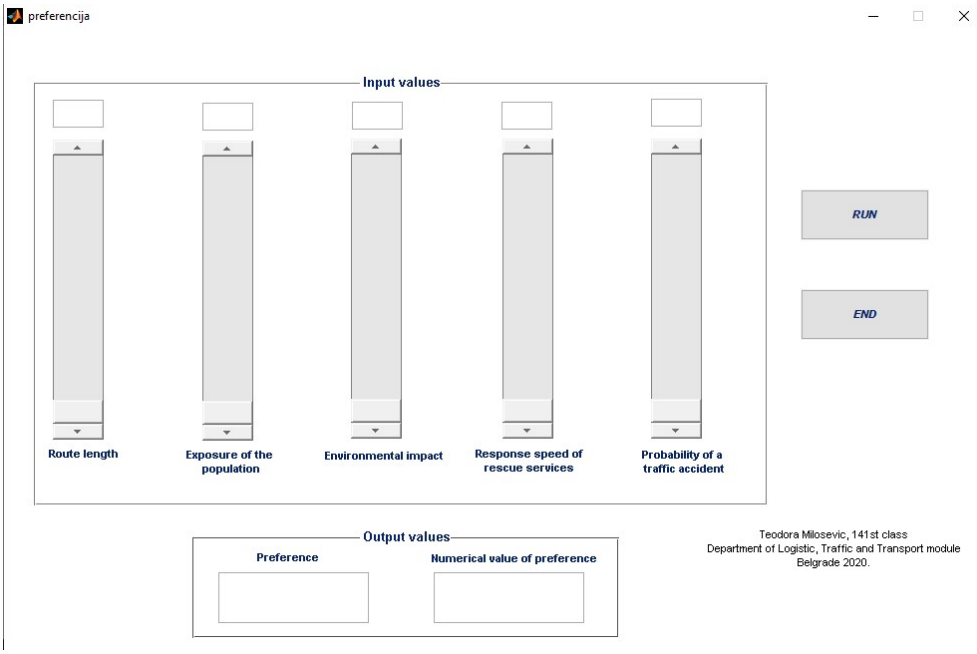


Figure 8 – Fuzzy logic model for enetering the input values and displaying the output value
Рис. 8 – Модель для ввода входных значений в систему и отображения выходных значений из системы нечеткой логики.
Слика 8 – Модел за уношење улазних вредности у систем и приказ излазних вредности из fuzzy логичког система.

The designed model was tested during the selection of a route for the transport of fuel. Three transport routes were considered and they represent alternatives.

Tabel 6 shows the values of the input variables in the fuzzy logic system for each route. The values were determined based on a subjective assessment of the model designer.

After entering the input parameters into the fuzzy logic system, the calculation and evaluation of the mentioned alternatives is performed. The results of the calculation, i.e. the output values of the fuzzy logic system are shown in Table 7.

Table 6 – Input values of the selected routes
Таблица 6 – Входные значения выбранных маршрутов
Табела 6 – Улазне вредности разматраних рута

	Route length (km)	Exposure of the population	Environmental impact	Reaction speed of rescue services	Probability of a traffic accident
A1	255	8	7	8	7
A2	181	5.5	5	6	6
A3	181	6.4	6	5	3.6

Table 7 – Numerical and linguistic values of the selected routes after the calculation
Таблица 7 – Числовые и лингвистические значения рассматриваемых маршрутов после расчета
Табела 7 – Нумеричке и лингвистичке вредности разматраних рута након прорачуна

Alternatives	Route preference	
	Numerical value	Linguistic value
A1	31.25	Very small
A2	60.75	Medium
A3	65.36	Large

After evaluating the alternatives, it was found that the highest preference was given to alternative 3. The ranking of the alternatives can be displayed as A3> A2> A1.

This model expands the theoretical framework of knowledge in the field of choosing the route for the transport of hazmat. The existing problem is considered with a new methodology, which creates a basis for further theoretical and practical upgrades.

Conclusion

The paper presents a new model for the selection of a route for the transport of hazardous materials using fuzzy logic systems. Fuzzy logic systems belong to a group of models based on artificial intelligence which can be applied as a decision support in the decision-making process of the traffic service authorities in the Ministry of Defense and the Serbian Armed Forces. In the research listed in the literature, there are various models for the selection and optimization of the route for the transport of dangerous goods, which aim to reduce the risk of occurrence and reduction of the consequences of accident situations.

After analyzing the literature and interviewing experts from the Ministry of Defense, the authors defined five criteria which represented the input values of the fuzzy system. The selected criteria are: (1) The

length of the route, which represents the distance the vehicle travels carrying hazmat; (2) Exposure of the population, i.e. the degree of impact of the consequences of the incident situation on the population; (3) Impact on the environment, which represents the degree of impact of the consequences of the incident situation on the environment; (4) Speed of response of rescue services, i.e. average time for which city services (fire service, ambulance service, and police) react in case of an incident, and (5) Probability of a traffic accident, i.e. the impact of road sections where due to the characteristics and conditions on the road there is a probability of a traffic accident. In addition to the mentioned criteria that represent the input variables, the output variable of the fuzzy system is defined and presented as the Route Preference.

Each input variable is represented by three membership functions, and the output variable is defined by five membership functions. Since one of the basic requirements when modeling the system was the existence of a certain degree of sensitivity of the system, Gaussian bell functions were used as functions for the input and output variables. All rules in a fuzzy logic system are determined by applying the method of weight premise aggregation (ATPP), which allows the formation of a database based on experience and intuition. Based on the number of input variables and the number of their membership functions, the basic base of 243 rules is defined. Three experts from the Ministry of Defense were interviewed to determine the weighting coefficients of the membership functions, and the values of the coefficients were determined using the FUCOM method. In order to increase the sensitivity of the system, the PROD-SUM method of direct inference was used. The system itself was tested on the choice of route for the transport of motor fuel. One of the advantages of using this system is that the system is adaptive, which is reflected in the ability to configure the base of fuzzy rules. Fuzzy inference rules are essential for managing the transport of hazmat, due to the descriptive approach and the heuristic solution of the problem. Due to the application of the fuzzy logic model, the limitations of conventional evaluation methods are overcome. The solution obtained by applying the fuzzy logic model is obtained on the basis of simple aggregation of criteria values. Also, this system is implemented as a user program within the Matlab software package. As such, it is suitable for application in a dynamic environment and real-time decision making. The described system leaves room for further research that should move in the direction of identifying additional parameters that may affect the choice of a route for the transport of dangerous goods and the implementation of additional decision criteria in the presented model.

References

Badi, I., Shetwan, A. & Hemeda, A. 2019. A grey-based assessment model to evaluate health-care waste treatment alternatives in Libya. *Operational Research in Engineering Sciences: Theory and Applications*, 2(3), pp.92-106 [online]. Available at: https://oresta.rabek.org/index.php/oresta/article/view/40/31 [Accessed: 20 November 2020].

Barilla, D., Leonardi, G. & Puglisi, A. 2009. Risk assessment for hazardous materials transportation. *Applied Mathematical Sciences*, 3(46), pp.2295-2309 [online]. Available at: http://m-hikari.com/ams/ams-password-2009/ams-password45-48-2009/puglisiAMS45-48-2009-1.pdf [Accessed: 20 November 2020].

Biočanin, R., & Stefanov, S. 2011. Ecological safety of transport of hazardous materials. In: *38. nacionalna konferencija o kvalitetu*, Kragujevac (Serbia), pp.A283-A288, May 19-21 [online]. Available at: http://www.cqm.rs/2011/FQ2011/pdf/38/45.pdf (in Serbian) [Accessed: 20 November 2020].

Božanić, D. & Pamučar, D. 2014. Izrada baze pravila fuzzy logičkog sistema za podršku u odlučivanju agregacijom težina premisa pravila. *Tehnika*, 69(1), pp.129-138 (in Serbian). Available at: https://doi.org/10.5937/tehnika1401129B.

Bozanic, D., Tešić, D. & Kočić, J. 2019. Multi-criteria FUCOM – Fuzzy MABAC model for the selection of location for construction of single-span bailey bridge. *Decision Making: Applications in Management and Engineering*, 2(1), pp.132-146 [online]. Available at: https://dmame.rabek.org/index.php/dmame/article/view/32 [Accessed: 20 November 2020].

Bozanic, D., Tešić, D. & Milić, A. 2020. Multicriteria decision making model with Z-numbers based on FUCOM and MABAC model. *Decision Making: Applications in Management and Engineering*, 3(2), pp.19-36 [online]. Available at: https://dmame.rabek.org/index.php/dmame/article/view/72 [Accessed: 20 November 2020].

Castillo, J.E.A. 2004. *Rout Optimization For Hazardous Mateials Transport*. Enshede, the Netherlands: International Institute for Geo-Information Science and Earth Observation [online]. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.58.7226&rep=rep1&type=pdf [Accessed: 20 November 2020].

Ćirović, G. & Pamučar, D. 2013. Decision support model for prioritizing railway level crossings for safety improvements: Application of the adaptive neuro-fuzzy system. *Expert Systems with Applications*, 40(6), pp.2208-2223. Available at: https://doi.org/10.1016/j.eswa.2012.10.041.

Ćirović, G., Pamučar, D. & Božanić, D. 2014. Green logistic vehicle routing problem: Routing light delivery vehicles in urban areas using a neuro-fuzzy model. *Expert Systems with Applications*, 41(9), pp.4245-4258. Available at: https://doi.org/10.1016/j.eswa.2014.01.005.

Durmić, E. 2019. Evaluation of criteria for sustainable supplier selection using FUCOM method. *Operational Research in Engineering Sciences: Theory and Applications*, 2(1), pp.91-107 [online]. Available at: https://oresta.rabek.org/index.php/oresta/article/view/18 [Accessed: 20 November 2020].

Durmić, E., Stević, Ž., Chatterjee, P., Vasiljević, M. & Tomašević, M. 2020. Sustainable supplier selection using combined FUCOM – Rough SAW model. *Reports in Mechanical Engineering*, 1(1), pp.34-43 [online]. Available at: https://frontpres.rabek.org/index.php/asd/article/view/4 [Accessed: 20 November 2020].

Erceg, Ž. & Mularifović, F. 2019. Integrated MCDM model for processes optimization in supply chain management in wood company. *Operational Research in Engineering Sciences: Theory and Applications*, 2(1), pp.37-50 [online]. Available at: https://oresta.rabek.org/index.php/oresta/article/view/17 [Accessed: 20 November 2020].

Fazlollahtabar, H., Smailbašić, A. & Stević, Ž. 2019. FUCOM method in group decision-making: Selection of forklift in a warehouse. *Decision Making: Applications in Management and Engineering*, 2(1), pp.49-65 [online]. Available at: https://dmame.rabek.org/index.php/dmame/article/view/26 [Accessed: 20 November 2020].

Frank, W.C., Thill, J-C. & Batta, R. 2000. Spatial decision support system for hazardous material truck routing. *Transportation Research Part C: Emerging Technologies*, 8(1-6), pp.337-359. Available at: https://doi.org/10.1016/S0968-090X(00)00007-3.

Jovanović, A., Pamučar, D. & Pejčić-Tarle, S. 2014. Green vehicle routing in urban zones – A neuro-fuzzy approach. *Expert systems with Applications*, 41(7), pp.3189-3203. Available at: https://doi.org/10.1016/j.eswa.2013.11.015.

Jovanović, D. & Živković, N. 2010. Routing problems in transportation of hazardous materials. *Facta universitatis - series: Working and Living Environmental Protection*, 7(1), pp.43-51 [online]. Available at: http://facta.junis.ni.ac.rs/walep/walep2010/walep2010-05.html [Accessed: 20 November 2020].

Kayapinar Kaya, S. 2020. Evaluation of the Effect of COVID-19 on Countries' Sustainable Development Level: A comparative MCDM framework. *Operational Research in Engineering Sciences: Theory and Applications*, 3(3), pp.101-122 [online]. Available at: https://oresta.rabek.org/index.php/oresta/article/view/76 [Accessed: 20 November 2020].

Kushwaha, D.K., Panchal, D. & Sachdeva, A. 2020. Risk analysis of cutting system under intuitionistic fuzzy environment. *Reports in Mechanical Engineering*, 1(1), pp.162-173 [online]. Available at: https://www.frontpres.rabek.org/index.php/asd/article/view/21 [Accessed: 20 November 2020].

Leonelli, P., Bonvicini, S. & Spadoni, G. 2000. Hazardous materials transportation: a risk-analysis-based routing methodology. *Journal of Hazardous Materials,* 71(1-3), pp.283-300. Available at: https://doi.org/10.1016/S0304-3894(99)00084-9.

Milovanović, B. 2012. *Development of methodology for the selection of routes for transporting dangerous goods in terms od risc managemet*. Ph.D. thesis. Belgrade: University of Belgrade - Faculty of Transport and Traffic Engeeniring.

Milovanović, B., Jovanović, V.D., Živanović, P. & Žeželj, S. 2012. Metodology for establishing the routes for transportation of dangerous goods on the basis of risk level-Case study: City of Belgrade. *Scientific Research and Essays,* 7(1), pp.38-50. Available at: https://doi.org/10.5897/SRE11.655.

Nenadić, D. 2019. Ranking dangerous sections of the road using MCDM model. *Decision Making: Applications in Management and Engineering*, 2(1), pp.115-131 [online]. Available at: https://dmame.rabek.org/index.php/dmame/article/view/31 [Accessed: 20 November 2020].

Pamučar, D., Ljubojević, S., Kostadinović, D. & Đorović, B. 2016. Cost and Risk aggregation in multi-objective route planning for hazardous materials transportation - A neuro-fuzzy and artificial bee colony approach. *Expert Systems with Applications*, 65, pp.1-15. Available at: https://doi.org/10.1016/j.eswa.2016.08.024.

Pamučar, D, Stević, Ž. & Sremac, S. 2018. A New Model for Determining Weight Coefficients of Criteria in MCDM Models: Full Consistency Method (FUCOM). *Symmetry*, 10(9), art.number:393. Available at: https://doi.org/10.3390/sym10090393.

Precup, R-E., Preitl , S., Petriu, E., Bojan-Dragos , C-A., Szedlak-Stinean, A-I., Roman, R-C. & Hedrea, E-L. 2020. Model-Based Fuzzy Control Results for Networked Control Systems. *Reports in Mechanical Engineering*, 1(1), pp.10-25 [online]. Available at: https://www.frontpres.rabek.org/index.php/asd/article/view/2 [Accessed: 20 November 2020].

Puška, A., Stojanović, I. & Maksimović, A. 2019. Evaluation of sustainable rural tourism potential in Brcko district of Bosnia and Herzegovina using multi-criteria analysis. *Operational Research in Engineering Sciences: Theory and Applications*, 2(2), pp.40-54 [online]. Available at: https://oresta.rabek.org/index.php/oresta/article/view/26 [Accessed: 20 November 2020].

Starčević, S. & Gošić, A. 2014. Methodology for choosing a route for transport of dangerous goods: Case study. *Vojnotehnički glasnik/Military Technical Courier*, 63(3), pp.165-184 (in Serbian). Available at: https://doi.org/10.5937/vojtehg62-4970.

Vesković, S., Milinković, S., Abramović, B. & Ljubaj, I. 2020. Determining criteria significance in selecting reach stackers by applying the fuzzy PIPRECIA method. *Operational Research in Engineering Sciences: Theory and Applications*, 3(1), pp.72-88 [online]. Available at: https://oresta.rabek.org/index.php/oresta/article/view/48 [Accessed: 20 November 2020].

Xie, Y., Lu, W., Wang, W. & Quadrifoglio, L. 2012. A multimodal location and routing model for hazardous materials transportation. *Journal of Hazardous Materials,* 227-228, pp.135-141. Available at: https://doi.org/10.1016/j.jhazmat.2012.05.028.

Zadeh, L.A. 1965. Fuzzy sets. *Information and Control*, 8(3), pp.338-353. Available at: https://doi.org/10.1016/S0019-9958(65)90241-X.

Zadeh, L A. 1975a. The concept of a linguistic variable and its application to approximate reasoning I. *Information Sciences*, 8(3), pp.199-249. Available at: https://doi.org/10.1016/0020-0255(75)90036-5.

Zadeh, L.A. 1975b. The concept of a linguistic variable and its application to approximate reasoning II. *Information Sciences*, 8(4), pp.301-357. Available at: https://doi.org/10.1016/0020-0255(75)90046-8.

Zadeh, L.A. 1975c. The concept of a linguistic variable and its application to approximate reasoning III. *Information Sciences*, 9(1), pp.43-80. Available at: https://doi.org/10.1016/0020-0255(75)90017-1.

Zhang, J., Hodgson, J. & Erkut, E. 2000. Using GIS to assess the risks of hazardous materials transport in networks. *Europian Jurnal of Operational Research*, 121(2), pp.316-329. Available at: https://doi.org/10.1016/S0377-2217(99)00220-9.

Zografus, K. & Androutsopoulus, K. 2008. A decision support system for integrated hazardous materials routing and emergency response decisions. *Transportation Research Part C: Emerging Technologies,* 16(6), pp.684-703. Available at: https://doi.org/10.1016/j.trc.2008.01.004.

Žižović, M. & Pamucar, D. 2019. New model for determining criteria weights: Level Based Weight Assessment (LBWA) model. *Decision Making: Applications in Management and Engineering*, 2(2), pp.126-137 [online]. Available at: https://dmame.rabek.org/index.php/dmame/article/view/48 [Accessed: 20 November 2020].

МОДЕЛЬ ВЫБОРА МАРШРУТА ПЕРЕВОЗКИ ОПАСНЫХ ГРУЗОВ С ИСПОЛЬЗОВАНИЕМ СИСТЕМЫ НЕЧЕТКОЙ ЛОГИКИ

Теодора Д. Милошевич[а], *Драган* С. Памучар[а], **корреспондент**, *Прасенджит* Чаттерджи[б]

[а] Университет обороны в г. Белград, Военная академия, Департамент логистики, г. Белград, Республика Сербия

[б] Институт инженерии MCKV, Департамент машиностроения, г. Ховрах, Западная Бенгалия, Республика Индия

РУБРИКА ГРНТИ: 27.00.00 МАТЕМАТИКА:
27.47.00 Математическая кибернетика;
27.47.19 Исследование операций
73.00.00 ТРАНСПОРТ:
73.01.00 Общие вопросы транспорта;
73.01.77 Методы исследования и моделирования. Математические и кибернетические методы
80.00.00 ПРОЧИЕ ОТРАСЛИ ЭКОНОМИКИ:
81.88.00 Материально-техническое снабжение. Логистика

ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В данной статье представлена модель выбора маршрута перевозки опасных грузов с использованием систем нечеткой логики, как разновидности систем искусственного интеллекта. Представленная в статье система представляет собой систему поддержки транспортно-логистическим организациям в процессе принятия решений при выборе одного из нескольких возможных маршрутов при перевозке опасных грузов.

Методы: Оценка маршрута выполняется по пяти критериям. Каждая входная переменная представлена тремя функциями принадлежности, а выходная переменная определяется пятью функциями принадлежности. Все правила в системе нечеткой логики определяются путем применения метода агрегирования весового товара (ATPP), который позволяет создать базу данных на основе опыта и интуиции. Основываясь на количестве входных переменных и количестве их функций принадлежности, определяется основная база, включающая 243 правила. Для определения весовых коэффициентов функций принадлежности было опрошено три эксперта из Министерства обороны, а значения коэффициентов были определены с помощью метода полной согласованности (FUCOM).

Результаты: Для разработанной системы нечеткой логики создана пользовательская программа, позволяющая практическое применение этой модели.

Выводы: Пользовательская платформа разработана в рамках программного пакета Matlab 2008b.

Ключевые слова: нечеткая логика, нечеткое множество, ATPP, FUCOM, опасные грузы, Matlab.

МОДЕЛ ЗА ИЗБОР РУТЕ ЗА ТРАНСПОРТ ОПАСНОГ ТЕРЕТА ПРИМЕНОМ FUZZY ЛОГИЧКОГ СИСТЕМА

Теодора Д. Милошевић[а], *Драган* С. Памучар[а], **аутор за преписку**, *Прасенџит* Чатерџи[б]

[а] Универзитет одбране у Београду, Војна академија, Катедра логистике, Београд, Република Србија

[б] Институт за инжењерство MCKV, Одељење за машинство, Ховрах, Западни Бенгал, Република Индија

ОБЛАСТ: математика, саобраћај, логистика
ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Представљен је модел за избор руте за транспорт опасног терета применом fuzzy логичких система, као врсте система вештачке интелигенције. Систем представљен у раду помаже органу саобраћајне службе при избору једне од неколико могућих рута за транспорт опасног терета.

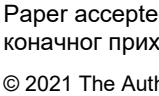
Методе: Процена руте врши се на основу пет критеријума. Свака улазна променљива представљена је са три функције припадности, а излазна променљива дефинисана је са пет тих функција. Сва правила у fuzzy логичком систему одређују се применом методе агрегације тежина премиса правила (АТПП), која омогућава формирање базе правила засноване на искуству и интуицији. На основу броја улазних променљивих и броја њихових функција припадности дефинисана је основна база од 243 правила. Интервјуисана су три експерта из Министарства одбране како би се утврдили пондерисани коефицијенти функција припадности, а њихове вредности одређене су методом потпуне конзистентности (FUCOM).

Резултати: За развијени fuzzy логички систем створен је кориснички програм који омогућава практичну примену овог модела.

Закључак: Корисничка платформа развијена је у програмском пакету Matlab 2008b.

Кључне речи: fuzzy логика, fuzzy скуп, АТПП, FUCOM, опасне материје, Matlab.

Paper received on / Дата получения работы / Датум пријема чланка: 29.11.2020.
Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 10.03.2021.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 12.03.2021.



PHYSICAL NATURE OF “ANOMALOUS” ELECTRONS IN HIGH-CURRENT VACUUM DIODES

Vasily Y. Kozhevnikov[a], *Andrey* V. Kozyrev[b]
Institute of High Current Electronics, Department of Theoretical Physics, Tomsk, Russian Federation
[a] e-mail: Vasily.Y.Kozhevnikov@ieee.org, **corresponding author**, ORCID iD: https://orcid.org/0000-0001-7499-0578
[b] e-mail: kozyrev@to.hcei.tsc.ru, ORCID iD: https://orcid.org/0000-0002-7078-7991

DOI: 10.5937/vojtehg69-30116; https://doi.org/10.5937/vojtehg69-30116

FIELD: High-current vacuum electronics
ARTICLE TYPE: Original scientific paper

Abstract:

Introduction/purpose: A fundamental theoretical explanation is given for the fact that in subnanosecond vacuum diodes there exists a group of electrons with kinetic energies much higher than the applied voltage (multiplied by the value of the elementary charge) qU_{max}.

Methods: A mathematical method is used based on the numerical solution of the Vlasov-Poisson differential equations system for one-dimensional vacuum diodes of various designs.

Results: It is shown in detail that the so-called "anomalous" electrons appear in the transient time domain characterizing the processes of establishing current flow in vacuum diodes.

Conclusion: It has been convincingly shown that the presence of “anomalous” electrons is not associated with either the diode design or the presence of additional current carriers. In vacuum diodes with a subnanosecond leading edge of the voltage pulse, the excess of energy over qU_{max} can be over 20%.

Key words: numerical simulation, vacuum electronics, vacuum breakdown.

Introduction

The electrodynamic effects of space-charge limited flows are associated with many interesting phenomena appearing in various fields of applied electrodynamics and electronics. Generally, the space-charge limits (SCL) can be observed in a fairly generalized two-electrode system (diode) to which a certain voltage is applied. By increasing the charges

injection into the diode, we neglect the electric potential near the emission region bringing the electric field near the zero value. This tendency limits the maximum current that can be carried through the diode.

In the beginning, the SCL effect was studied for the simplest case of a planar one-dimensional vacuum diode (Child, 1911), (Langmuir, 1913). It is known as Child's law

$$j_{C.L.} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m}}\frac{U^{3/2}}{D^2}\ , \qquad (1)$$

where U – the applied voltage, D – the interelectrode distance, q and m – the electron charge and mass, respectively, and ε_0 – the vacuum dielectric permittivity.

Although Child's law involves many rough assumptions, it gives a good theoretical framework for understanding the SCL phenomenon and its operating limits. Regarding Child's law, in order to obtain the SCL current value (1), it was assumed that in a planar diode there are only electrons with zero initial velocities. Another important peculiarity of Child's law is that the system was assumed to be in a steady state.

To extend the applicability of Child's law, many theoretical and experimental research studies have been done. The problem of oversimplification was connected to zero initial by accurately taking into the account thermal electron velocities (Langmuir, 1923), (Jaffé, 1944). The extension of a single-species consideration to Child's law showed that adding positive ions weakens the SCL effects (Lin, 2005). Various investigations have been also carried out in order to relax the assumption of one-dimensionality. In this direction, even nontrivial two- and three-dimensional cases were treated by using both analytical and numerical computational approaches (Rokhlenko & Lebowitz, 2007), (Koh et al, 2005).

Overcoming the steady-state assumption is much more difficult from the theoretical point of view. This takes place because the study of diode transient processes requires non-stationary theoretical models or Particle in cell simulations (PIC). In the beginning of the computational physics era, the PIC method allowed studying a large number of transient processes (Birdsall & Langdon, 1991), including SCL-associated problems for vacuum electronics (Ragan-Kelley et al, 2009), (Griswold et al, 2012). Later, some serious disadvantages of the PIC approach were discovered (Kozhevnikov et al, 2016), (Kozhevnikov et al, 2017), imposing certain restrictions to the solutions of fundamental problems.

A classical planar vacuum diode and Child's law are nowadays connected with the investigations of high-voltage nanosecond and subnanosecond electronics. As a result, new effects have been discovered experimentally in nanosecond high-current pulsed vacuum electronic diodes. One of them is the effect of fast electron appearance with kinetic energies $\varepsilon > qU_{max}$ greater than the maximum voltage value U_{max} being applied to the vacuum diode (multiplied by an elementary charge q). Such electrons are called electrons having “anomalously high” energies (“anomalous” electrons).

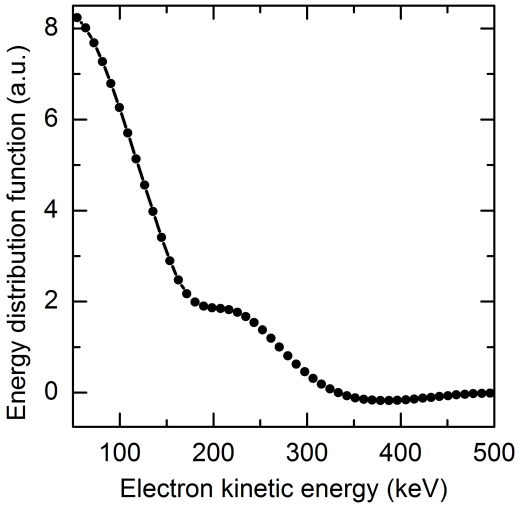


Figure 1 – Experimentally reconstructed fast electron spectrum in the vacuum diode
Рис. 1 – Восстановленный экспериментальный спектр быстрых электронов вакуумного диода
Слика 1 – Експериментално реконструисани спектар брзих електрона у вакуумској диоди

Let us consider one of striking experimental examples in which this effect of the appearance of electrons with anomalous energies is observed (Kozyrev et al, 2010). In this experimental paper, a RADAN-220 nanosecond high-voltage generator was attached to an IMAZ-150E vacuum diode in a simple circuit with 20 Ω ballast impedance. The voltage pulse waveform was a trapezium having an amplitude of 250 kV with a total pulse duration equal to 2 ns and the 0.5 ns risetime. We reconstructed an energy spectrum by using the Tikhonov regularization routine (Kozyrev et al, 2010) thus obtaining two spectral groups of electrons. This could be seen in Figure 1. The main group represents the

majority of low-energy electrons with the mean energy values continuously decreasing to ~ 200 keV. The second group is an ensemble of high-energy ("anomalous") electrons with the mean energy maximum around 220 keV and with a long "distribution tail" stretching to ~320 keV. Such "anomalous" distributions arise in multiple experiments considering vacuum diodes of different configurations where ultra-short pulses have been applied to them.

Explaining the physical nature of this phenomenon within the framework of the simplified SCL theories is impossible due to their stationarity – "anomalous" electrons do not appear in steady-state current flow regimes. Some theoretical aspects of unsteady current flows in planar vacuum diodes have been studied early (Kadish et al, 1985). Namely, simplified transient models show the existence of relaxation oscillations during the current establishing in the diode. The amplitude of the first oscillation period can be ~ 2.75 times greater than the steady-state current value(1). Nevertheless, simplified unsteady current flow theories do not provide the spectral composition of an electron beam reaching the anode.

Here we propose an accurate simulation performed by using the fundamental principles of physical kinetics based on a direct (numerical) solution of the kinetic Vlasov-Poisson system of equations. We show that, in vacuum diodes, the "anomalous" electrons appearance is provoked by the restricted duration of the voltage pulse front. Electrons with "anomalously" high energies are neither a consequence of the cathode plasma existence nor connected to the geometrical peculiarities of diode construction.

Kinetic theoretical model

As already mentioned above, the theoretical consideration of transient processes in a vacuum diode is based on the solution of a nonstationary kinetic equation, more precisely, the Vlasov-Poisson system of equations for a one-dimensional gap

$$\begin{cases} \dfrac{\partial f}{\partial t} + \dfrac{p_x}{m\gamma\left(p_x\right)}\dfrac{\partial f}{\partial x} - qE_x\dfrac{\partial f}{\partial p_x} = 0 \\ \dfrac{\partial^2 \varphi}{\partial x^2} = -\dfrac{q}{\varepsilon_0}\displaystyle\int_{-\infty}^{\infty} f dp_x, \quad E_x = -\dfrac{\partial \varphi}{\partial x} \end{cases}, \tag{2}$$

where f – the electron distribution function, x – the coordinate, t – time , φ - the electrostatic potential, E_x – a component of the electrostatic field,

and γ – the relativistic factor. It should be mentioned that a planar one-dimensional vacuum diode is considered here. That is done intentionally in order to get rid of probable geometrical pecularities affecting the current flow in the Child's vacuum diode.

One-dimensionality significantly simplifies the problem because Poisson's equation in (2) can be solved in quadratures, so the exact solution is represented as follows

$$E_x(x,t) = -\frac{q}{\varepsilon_0}\int_0^x\int_{-\infty}^{\infty} f(x,p_x,t)\,dp_x dx - \\ -\frac{U(t)}{D} + \frac{q}{\varepsilon_0 D}\int_0^D\int_0^{x'}\int_{-\infty}^{\infty} f(x,p_x,t)\,dp_x dx' dx. \quad (3)$$

where *U(t)* – the anode potential.

The boundary and initial conditions for the Vlasov equation have been chosen according to those in previous papers (Kozhevnikov et al, 2016, Kozhevnikov et al, 2017). The numerical simulation starts with an empty gap (i.e. *f* = 0). In the cathode, we maintain the electron emission where the electron distribution function is assumed to be Maxwellian.

The solution of the Vlasov equation has been obtained using the numerical so-called semi-Lagrangian methods. In order to perform the numerical solution accurately, the cubic spline interpolation scheme (Cheng & Knorr, 1976) was used. To validate the numerical solution, the PIC4 high-precision numerical scheme was also used (Umeda et al, 2012). Both numerical schemes were implemented on the uniform 5,000 by 10,000 elements phase space grid to provide a high accuracy of numerical computations. On the basis of the result of the joint numerical solution procedure for the Vlasov-Poisson system of equations (2), we obtain the electron distribution function $f(x, p_x, t)$ and compute the collector (anode) current density for each simulation time-step

$$j(t) = -\frac{q}{m}\int_{-p_{\max}}^{p_{\max}} \frac{p_x}{\gamma(p_x)} f(x=D,p_x,t)\,dp, \quad (4)$$

where p_{max} is the largest available momentum in the computational scheme. All numerical integrals, e.g. (4), have been computed using the Simpson integration rule. Also, the seven-point Savitzky-Golay filtering (Savitzky & Golay, 1964) was used to perform smoothing of the anode

voltage waveform front edge. The numerical algorithm was implemented in the Mathworks MATLAB system using the computation functionality of the Nvidia CUDA GPU graphics subsystem.

Results of the numerical simulation

Let us consider a planar vacuum diode having the following parameters: D = 1 cm and U_{max} = 2 kV. It turns to be nonrelativistic, so one can assume the relativistic factor to be $\gamma \sim 1$. At the cathode, we take an average electron density to be around ~$1.5 \cdot 10^{18}$ m^{-3} and thermal spread ~1 eV. For these values, the emission current value is much higher than Child's value (1), so the cathode can be assumed to have unrestricted emission capability.

In the following plot (Figure 2), we compare three diode current density time profiles given for different values of risetime. For the same Umax, we take the quasi-stationary risetime value ~1 ns, i.e. compared to the simulation end time (5 ns), as well as subnanosecond risetime value ~0.1 ns and the intermediate value ~0.5 ns. We can easily notice that the current density profiles significantly differ. Long (quasi-stationary) risetime leads to a slow growth of a collector current to the value equal to Child's law (1). We get a completely contrasting situation if the risetime is much less than one nanosecond. In this case, the emergence of relaxation oscillations can be seen in the transition region. The maximum amplitude of relaxation oscillations significantly exceeds the Child's value (1). In all three cases of the calculation presented in Figure 2, the diode (collector) current finally reaches the values equal to (1). Also, there is a time delay between t = 0 and the time point of non-zero collector current. This time delay determines an instant from which the electron beam reaches the anode (collector).

After reaching the anode, relaxation oscillations of the current begin. It can be noted that the higher their amplitude is, the faster the anode potential changes, i.e. risetime. The increased nonstationarity in the transition region leads to the fact that in the gap there are space charge oscillations. They are associated with a sharp decrease in the charge in the gap when the beam reaches the anode and with a subsequent increase in the current extraction from the cathode. Further on, the process goes in waves up to the moment of a steady current flow.

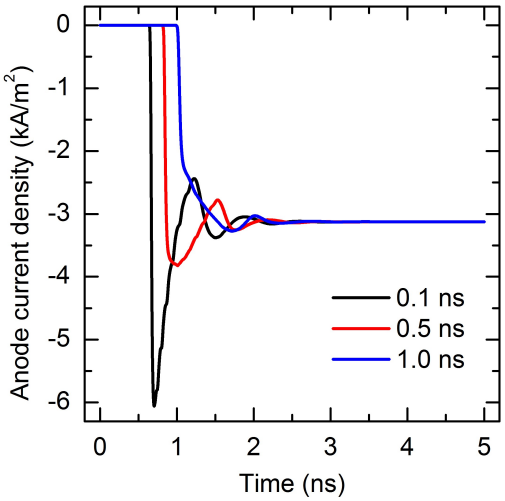


Figure 2 – Time profiles of the diode current density given at various risetimes
Рис. 2 – Временные профили плотности тока диода при различных временах нарастания
Слика 2 – Временски профили густине струје диоде у различитим временима раста

A more particular case of the formation of a sharp surge in the collector current in a planar vacuum diode with an "instantaneous" supply of the anode potential has already been considered in the literature (Kadish et al, 1985). However, due to the use of the simplified transition region theory, the authors of early works did not clarify the velocity distribution of electrons, which "deliver" the maximum amplitude of relaxation oscillations of the collector current density to the anode. Our theoretical model is based on the use of the evolution of the electron distribution function; therefore, it allows one to fix instantaneous velocity distributions at any spatial point.

Figures 3, 4 and 5 show the density plots of the electron distribution function at times that approximately correspond to those time points at which (for risetime ~0.1 ns) the maxima of collector current density relaxation oscillations are formed. The highest collector current is achieved at t = 0.7 ns (Figure 3), the next point of the oscillation period corresponds to t = 1.5 ns (Figure 4). In Figure 5, the phase portrait of the distribution function is shown, corresponding to the diode current steady state at t = 4 ns, where the relaxation oscillations are completely damped.

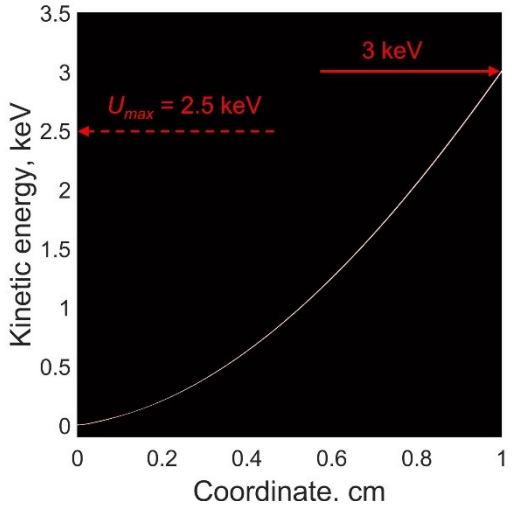


Figure 3 – Electron distribution function density plot at 0.7 ns
Рис. 3 – График плотности функции распределения электронов при 0.7 нс
Слика 3 – Графикон густине функције расподеле електрона на 0,7 нс

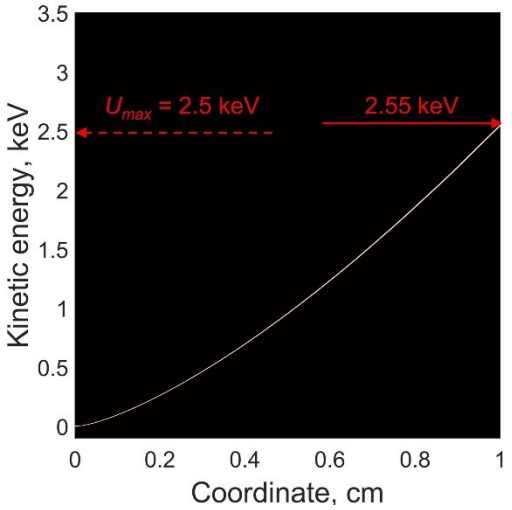


Figure 4 – Electron distribution function density plot at 1.5 ns
Рис. 4 – График плотности функции распределения электронов при 1.5 нс
Слика 4 – Графикон густине функције расподеле електрона на 1,5 нс

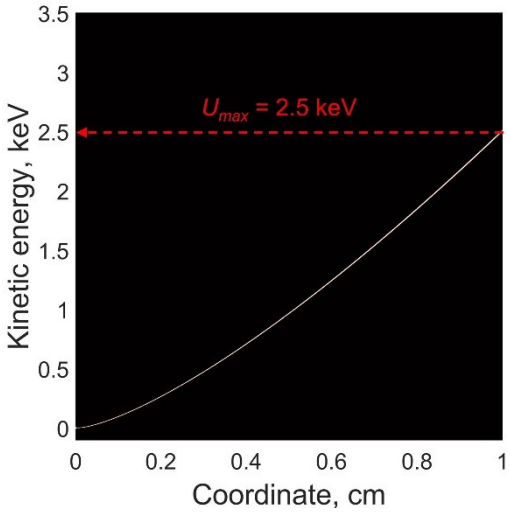


Figure 5 – Electron distribution function density plot at 4 ns (steady-state current flow regime)
Рис. 5 – График плотности функции распределения электронов при 4 нс (режим установившегося токопротекания)
Слика 5 – Графикон густине функције расподеле електрона на 4 нс (стационарни ток струје)

Three figures above demonstrate the essence of the physical effect discovered by various researchers in series of experimental studies. In a nonstationary rapidly changing electromagnetic field, the transport of charged particle beams (for example, an electron beam in a planar vacuum diode) is always affected by space charge oscillations. This effect is interrelated with the acceleration of charges to kinetic energies exceeding the value of the instantaneously "applied voltage" (multiplied by elementary charge). Such phenomena are typical for physical situations where charged particles interact with an electric field of the "traveling wave" type (Kozyrev et al, 2018).

In Figure 3, the average value of the energy of the electron beam arriving at the anode is 3 keV with the maximum amplitude of the anode potential equal to 2.5 kV. This excess of the anode potential is about 20 %. The theory convincingly indicates that it is the "anomalous" electrons that form the peak of the collector current's relaxation oscillations in the diode operating in the subnanosecond mode. For a diode with a prolonged (over 1 ns) risetime, the phase portrait of the distribution function does not contain an "anomalous" energy component and is similar to a stationary current flow (in Figure 5). The integral

spectrum of the beam, i.e. of the electrons falling on the collector will be mainly represented by the 2.5 keV maximum, since the relative fraction of "anomalous" electrons for a diode operating in a steady-state current flow mode is negligible.

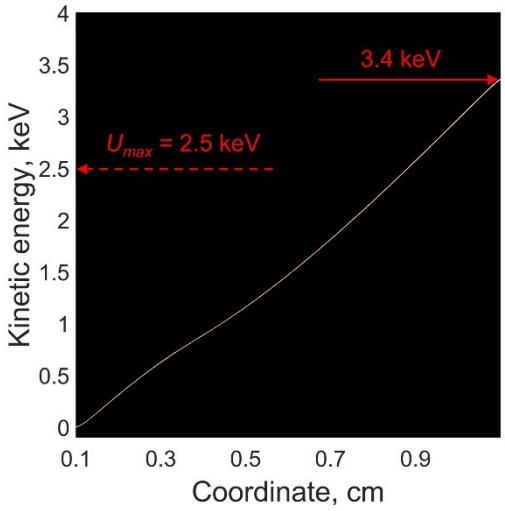


Figure 6 – Electron distribution function density plot at 0.5 ns for the axially-symmetric vacuum diode
Рис. 6 – График плотности функции распределения электронов в осесимметричном вакуумном диоде при 0.5 нс
Слика 6 – Графикон густине функције расподеле електрона у осносиметричној вакуумској диоди на 0,5 нс

The planar diode was deliberately taken in order to demonstrate that the appearance of "anomalous" electrons is not related to the peculiarities of the diode geometry. Most often, experimental diodes are a cathode with a small radius of curvature and a relatively "flat" anode. Because of this fact, the existence of "anomalous" electrons was mistakenly associated with the fact that the electric field strength near the cathode is much stronger than the near-anode one.

In fact, the presence of spatial non-uniformities leads to an increase in the relative fraction of electrons with "anomalous" energies. In order to demonstrate this effect, a simulation of an axisymmetric vacuum diode was performed. The design of the electrodes consisted of two coaxial cylinders (the cathode is inside). The interelectrode gap was 1 cm, the cathode radius was 1 mm, and the anode was 11 mm. The amplitude of the anode voltage was chosen to be similar - 2.5 kV. The voltage rise time was 0.1 ns. With these parameters, as in the previous case,

relaxation oscillations of the collector current were observed. The maximum amplitude of the oscillations occurred at a time instant of 0.5 ns. At a given time, the electron distribution function density plot is given in Figure 6. It can be seen that, at this time point, the average energy of the electron beam is 3.4 keV, which is 36 % higher than the voltage across the diode.

Conclusions

In this paper, we have convincingly shown that "anomalous" electrons (with kinetic energies $\varepsilon > qU_{max}$) always arise in the transient mode of a vacuum diode. Modeling convincingly shows that the source of these "anomalous" electrons in vacuum diodes is not connected with any specific diode design, alternative cathode emission mechanism, or the presence of other charge carriers in the gap (for example, positive ions). The reason for the appearance of "anomalous" electrons is directly related to the process of buildup of relaxation oscillations of the space charge; the more intense it is, the shorter risetime the anode voltage pulse has.

Special acknowledgment

This paper is dedicated to the blessed memory of the choir conductor, head of the Department of Choral Conducting, the honored professor of Tomsk State University - Vitaly Sotnikov (1939-2020). The authors express their sincere gratitude to doctors and nurses around the world, the people who found the strength to fight COVID-19, not sparing their health and lives for the sake of defeating the pandemic for the benefit of all mankind.

References

Birdsall, C.K. & Langdon, A.B. 1991. *Plasma Physics via Computer Simulation*. Boca Raton: CRC Press. Available at: https://doi.org/10.1201/9781315275048. ISBN: 9781315275048.

Cheng, C.Z. & Knorr, G. 1976. The integration of the vlasov equation in configuration space. *Journal of Computational Physics*, 22(3), pp.330–351. Available at: https://doi.org/10.1016/0021-9991(76)90053-X.

Child, C.D. 1911. Discharge From Hot CaO. *Physical Review (Series I)*, 32(5), pp.492-511. Available at: https://doi.org/10.1103/PhysRevSeriesI.32.492.

Griswold, M.E., Fisch, N.J. & Wurtele, J.S. 2012. Amended conjecture on an upper bound to time-dependent space-charge limited current. *Physics of Plasmas*, 19(2), art.number:024502. Available at: https://doi.org/10.1063/1.3671961.

Jaffé, G., 1944. On the Currents Carried by Electrons of Uniform Initial Velocity. *Physical Review*, 65(3-4), pp.91-98. Available at: https://doi.org/10.1103/PhysRev.65.91.

Kadish, A., Peter, W. & Jones, M.E. 1985. A Generalization of the Child-Langmuir Relation for One-Dimensional Time-Dependent Diodes. *IEEE Transactions on Nuclear Science*, 32(5), pp.2576-2578. Available at: https://doi.org/10.1109/TNS.1985.4333985.

Koh, W.S., Ang, L.K. & Kwan, T.J.T. 2005. Three-dimensional Child–Langmuir law for uniform hot electron emission. *Physics of Plasmas*, 12(5), art.number:053107. Available at: https://doi.org/10.1063/1.1913612.

Kozhevnikov, V.Y., Kozyrev, A.V. & Semeniuk, N.S. 2016. Kinetic modelling of the one-dimensional planar virtual cathode oscillator. In: *24th Telecommunications Forum (TELFOR),* Belgrade, pp.1-4, November 22-23. Available at: https://doi.org/10.1109/telfor.2016.7818844.

Kozhevnikov, V.Y., Kozyrev, A.V. & Semeniuk, N.S. 2017. Modeling of Space Charge Effects in Intense Electron Beams: Kinetic Equation Method Versus PIC Method. *IEEE Transactions on Plasma Science*, 45(10), pp.2762-2766. Available at: https://doi.org/10.1109/tps.2017.2726501.

Kozyrev, A.V., Kozhevnikov, V.Yu., Baksht, E.Kh., Buranchenko, A.G. & Tarasenko, V.F. 2010. Spectrum reconstruction of a nanosecond electron beam from the data on its extinction in thin foils. *Russian Physics Journal*, 53(4), pp.361-368. Available at: https://doi.org/10.1007/s11182-010-9430-1.

Kozyrev, A., Kozhevnikov, V. & Semeniuk, N. 2018. Why do Electrons with “Anomalous Energies” appear in High-Pressure Gas Discharges? In: Torrisi, L. & Cutroneo, M. (Eds.) *EPJ Web of Conferences*, 167, art.number:01005. Available at: https://doi.org/10.1051/epjconf/201816701005.

Langmuir, I. 1913. The Effect of Space Charge and Residual Gases on Thermionic Currents in High Vacuum. *Physical Review*, 2(6), pp.450-486. Available at: https://doi.org/10.1103/physrev.2.450.

Langmuir, I. 1923. The Effect of Space Charge and Initial Velocities on the Potential Distribution and Thermionic Current between Parallel Plane Electrodes. *Physical Review*, 21(4), pp.419-435. Available at: https://doi.org/10.1103/physrev.21.419.

Lin, M-C. 2005. Space-charge effects of electrons and ions on the steady states of field-emission-limited diodes. *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, 23(2), art.number:636. Available at: https://doi.org/10.1116/1.1875352.

Ragan-Kelley, B., Verboncoeur, J. & Feng, Y. 2009. Two-dimensional axisymmetric Child–Langmuir scaling law. *Physics of Plasmas*, 16(10), art.number:103102. Available at: https://doi.org/10.1063/1.3243474.

Rokhlenko, A. & Lebowitz, J.L. 2007. Space-charge-limited, two-dimensional unmagnetized flow in a wedge geometry. *Journal of Applied Physics*, 102(12), art.number:123307. Available at: https://doi.org/10.1063/1.2822471.

Savitzky, A. & Golay, M.J.E. 1964. Smoothing and Differentiation of Data by Simplified Least Squares Procedures. *Analytical Chemistry*, 36(8), pp.1627-1639. Available at: https://doi.org/10.1021/ac60214a047.

Umeda, T., Nariyuki, Y. & Kariya, D. 2012. A non-oscillatory and conservative semi-Lagrangian scheme with fourth-degree polynomial interpolation for solving the Vlasov equation. *Computer Physics Communications*, 183(5), pp.1094-1100. Available at: https://doi.org//10.1016/j.cpc.2012.01.011.

ФИЗИЧЕСКАЯ ПРИРОДА «АНОМАЛЬНЫХ» ЭЛЕКТРОНОВ В СИЛЬНОТОЧНЫХ ВАКУУМНЫХ ДИОДАХ

Василий Ю. Кожевников, **корреспондент**, *Андрей В.* Козырев

Институт сильноточной электроники, Лаборатория теоретической физики, г. Томск, Российская Федерация

РУБРИКА ГРНТИ: 29.00.00 ФИЗИКА:
29.27.00 Физика плазмы;
29.27.47 Численные методы в физике плазмы
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Дается фундаментальное теоретическое объяснение тому факту, что в субнаносекундных вакуумных диодах существует группа электронов с кинетической энергией, намного превышающей приложенное напряжение (умноженное на величину элементарного заряда) qU_{max}.

Методы: Используется математический метод, основанный на численном решении системы дифференциальных уравнений Власова-Пуассона для одномерных вакуумных диодов различной конструкции.

Результаты: Подробно показано, что так называемые «аномальные» электроны появляются в переходной временной области, характеризующей процессы установления протекания тока в вакуумном диоде.

Выводы: Убедительно показано, что наличие «аномальных» электронов не связано ни с конструкцией диода, ни с наличием дополнительных носителей тока. В вакуумных диодах с субнаносекундным передним фронтом импульса напряжения превышение энергии над qU_{max} может составлять более 20%.

Ключевые слова: численное моделирование, вакуумная электроника, вакуумный пробой.

ФИЗИЧКА ПРИРОДА „АНОМАЛНИХ" ЕЛЕКТРОНА У ВИСОКО-ВАКУУМСКИМ ДИОДАМА

Василиј J. Кожевников*,* **аутор за преписку**, *Андреј* В. Козирев

Институт високе струје, Лабораторија за теоријску физику,
Томск, Руска Федерација

ОБЛАСТ: физика плазме
ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Рад даје основно теоријско објашњење чињенице да у субнаносекундним вакуумским диодама постоји група електрона са кинетичком енергијом много већом од примењеног напона (помноженог са елементарним наелектрисањем) qU_{max}.

Методе: Примењена је математичка метода заснована на нумеричком решењу система диференцијалних једначина Власов-Поисон за једнодимензионалне вакуумске диоде различитог дизајна.

Резултати: Детаљно је приказано да се у прелазном временском домену појављују такозвани „аномални" електрони, што карактерише процесе успостављања струјног тока у вакуумској диоди.

Закључак: Доказано је да присуство „аномалних" електрона није повезано ни са дизајном диоде, ни са присуством додатних носача струје. У вакуумским диодама са субнаносекундном предњом ивицом импулса напона вишак енергије преко qU_{max} може бити већи од 20%.

Кључне речи: нумеричка симулација, вакуумска електроника, вакуумски пробој.

Paper received on / Дата получения работы / Датум пријема чланка: 30.12.2021.
Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 25.01.2021.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 27.01.2021.

BIDIRECTIONAL STACK DECODING OF POLAR CODES

Aleksandar Đ. Minja[a], *Dušan* P. Dobromirov[b], *Vojin* I. Šenk[c]

[a] University of Novi Sad, Faculty of Technical Sciences,
IEM Department, Novi Sad, Republic of Serbia,
e-mail: aminja@uns.ac.rs,
ORCID iD: https://orcid.org/0000-0001-6701-2258

[b] University of Novi Sad, Faculty of Technical Sciences,
IEM Department, Novi Sad, Republic of Serbia,
e-mail: ddobromirov@uns.ac.rs, **corresponding author**,
ORCID iD: https://orcid.org/0000-0003-0553-7993

[c] University of Novi Sad, Faculty of Technical Sciences,
IEM Department, Novi Sad, Republic of Serbia,
e-mail: vojin_senk@uns.ac.rs,
ORCID iD: https://orcid.org/0000-0003-3029-0486

DOI: 10.5937/vojtehg69-29858; https://doi.org/10.5937/vojtehg69-29858

FIELD: Telecommunications, Computer sciences

ARTICLE TYPE: Original scientific paper

Abstract:

Introduction/purpose: The paper introduces a reduced latency stack decoding algorithm of polar codes, inspired by the bidirectional stack decoding of convolutional codes and based on the folding technique.

Methods: The stack decoding algorithm (also known as stack search) that is useful for decoding tree codes, the list decoding technique introduced by Peter Elias and the folding technique for polar codes which is used to reduce the latency of the decoding algorithm. The simulation was done using the Monte Carlo procedure.

Results: A new polar code decoding algorithm, suitable for parallel implementation, is developed and the simulation results are presented.

Conclusions: Polar codes are a class of capacity achieving codes that have been adopted as the main coding scheme for control channels in 5G New Radio. The main decoding algorithm for polar codes is the successive cancellation decoder. This algorithm performs well at large blocklengths with a low complexity, but has very low reliability at short and medium blocklengths. Several decoding algorithms have been proposed in order to improve the error correcting performance of polar codes. The successive cancellation list decoder, in conjunction with a cyclic redundancy check, provides very

ACKNOWLEDGMENT: The research described in this paper has been supported by the Serbian Ministry of Education, Science and Technological Development through Project no. 451□03-68/2020-14/200156 titled ”Innovative scientific and artistic research from the Faculty of Technical Sciences activity domain”.

good error-correction performance, but at the cost of a high implementation complexity. The successive cancellation stack decoder provides similar error-correction performance at a lower complexity. Future machine-type and ultra reliable low latency communication applications require high-speed low latency decoding algorithms with good error correcting performance. In this paper, we propose a novel decoding algorithm, inspired by the bidirectional stack decoding of classical convolutional codes, with reduced latency that achieves similar performance as the classical successive cancellation list and successive cancellation stack decoding algorithms. The results are presented analytically and verified by simulation.

Key words: polar codes, successive cancellation, stack and list decoding, folding.

Introduction

Context and motivation. Polar codes, introduced in (Arikan, 2009), are the first class of codes with an explicit construction and a low complexity encoding and decoding that provably achieve the symmetric capacity of a binary input discrete memoryless channel (bi-DMC). The standard decoding algorithm for polar codes is the successive cancellation decoding (SCD). Although the SCD has good error correcting performance for large blocklengths and is an important procedure for proving the capacity achieving property of polar codes, it underperforms for short and medium blocklengths. Several new decoding algorithms are developed to correct this. The most important algorithms in this category are definitely the successive cancellation list decoding (SCLD), introduced in (Tal & Vardy, 2015) and improved in (Balatsoukas-Stimming et al., 2015) and (Hashemi et al., 2016), the successive cancellation stack decoding (SCSD) introduced in (Niu, K. & Chen, K., 2012a) and improved in (Xiang et al., 2019), (Aurora et al., 2018), (Xiang et al., 2020) and the belief propagation decoding (BPD) (Arikan, 2008), (Arikan, 2010). Cyclic redundancy check (CRC) aided polar codes, coupled with the SCLD or the SCSD (Niu & Chen, 2012b), (Li et al., 2012) have been proposed to further improve the error correcting performance of polar codes for practical applications. Other research direction deals with reducing the latency of the decoding algorithm. The simplified successive cancellation algorithm (SSCD) was proposed in (Alamdar-Yazdi & Kschischang, 2011) and further improved in (Sarkis et al., 2014), (Hanif & Ardakani, 2017). The main idea of the SSCD is to identify small constituent codes that can efficiently be decoded. The

four common constituent codes usually considered are the rate-0 code, the repetition code, the rate-1 code, and the single parity check code. The reduced latency SCLD was presented in (Li et al., 2013) and an efficient implementation of the SCSD was proposed in (Aurora et al., 2018). One way of reducing latency is to exploit the recursive nature of polar codes. This approach known as folding, was introduced in (Kahraman et al., 2013). Several decoding algorithms based on the folding technique were proposed in (Kahraman et al., 2014a), (Kahraman et al., 2014b), (Vangala et al., 2014a), (Vangala et al., 2014b), (Huang et al., 2018). A reduced latency implementation of the SCSD was given in (Xiang et al., 2020).

Polar codes have been adopted as the main coding scheme for control and physical broadcast channels in the enhanced mobile broadband (eMBB) and the ultra reliable low latency communications (URLLC) service categories, defined in the fifth generation (5G) wireless communications standard (-3rd Generation Partnership Project., 2016), (Won & Ahn, 2020), (Hashemi et al., 2020). It is well known that the CRC aided $(2048, 1024)$ polar codes with list decoding can outperform LDPC and Turbo codes of the same length (Li et al., 2012). Although polar codes have good error correcting performance, the decoding latency still remains an important research topic (Hashemi et al., 2020). In this work, we focus on improving the decoding latency of the SCSD algorithm.

Contribution. In this paper, we present a novel low latency decoding algorithm that is constructed by applying the folding technique to the SCSD algorithm. The new decoding algorithm is in part inspired by the bidirectional decoding of convolutional codes (Senk & Radivojac, 1997) where the channel output is divided into two parts and each part is processed in parallel, while an inner component code is used to combine the results. We name this new decoding algorithm the bidirectional stack decoding (BSD). To the best of our knowledge, no such algorithms has ever been presented. We also show that the reduced latency decoding algorithm presented in (Xiang et al., 2020) can also be constructed by applying the folding technique to the classical SCSD algorithm. This reduced latency SCSD can be used as a component decoder of our algorithm, presented here.

Paper organization. The remainder of the paper is composed of four sections. The section System model introduces the polar codes and

gives a brief overview of the SCD, the SCLD and the SCSD algorithms. The section Bidirectional stack decoding algorithm describes the new decoding algorithm introduced in this paper. The next section presents the Simulation results. The section Conclusion gives an overview of the future work and concludes the paper.

Notation. Throughout the paper, uppercase letters represent random variables, lowercase letters represent realizations of the corresponding random variables, uppercase bold letters represent random vectors, and lowercase bold letters represent their realization. The i-th component of a vector $\boldsymbol{x}$ is denoted x_i. $P[\cdot]$ represents the probability of an event, $E[\cdot]$ represents the mean of a random variable and Var$[\cdot]$ represents the variance of a random variable. Cursive uppercase letters represent sets, and $\mathcal{A}^N$ represents the set of all N-tuples of a set $\mathcal{A}$. The cardinality of $\mathcal{A}$ is denoted $|\mathcal{A}|$. Sometimes a set will be defined only by its elements, i.e $\{a_1, a_2, \dots a_N\}$. Given a set $\mathcal{A} = \{a_1, a_2, \dots, a_K\}$ and an N-dimensional vector $\boldsymbol{x}$, such that $N \geq K$, we define a new vector $\boldsymbol{x}_{\mathcal{A}} = [x_{a_1}, x_{a_2}, \dots, x_{a_K}]$. Other notation is introduced as it is used.

System model

In this paper, we consider only binary polar codes constructed by the Arikan kernel (Arikan, 2009)

$$F_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}, \tag{1}$$

as they are most often used in practical applications. Given a vector $\boldsymbol{u} = [u_0, u_1]$, we define $\boldsymbol{u} \cdot F_2 = \boldsymbol{x} = [x_0, x_1]$. A useful graphical representation of this multiplication is given in Fig. 1. Note that $\boldsymbol{u} = \boldsymbol{x}F_2^{-1} = \boldsymbol{x}F_2$ can be represented by the same logical circuit in Fig. 1, by treating values x_0 and x_1 as the input, and u_0 and u_1 as the output. The Kronecker product of the matrix F_2 with itself is defined as

$$F_2 \otimes F_2 = \begin{bmatrix} 1 \cdot F_2 & 0 \cdot F_2 \\ 1 \cdot F_2 & 1 \cdot F_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix}. \tag{2}$$

Given $N = 2^m$, we define an N-dimensional polar transform as $F_N = F_2^{\otimes m} = F_2^{\otimes m-1} \otimes F_2$. A logical circuit representation of a higher-order matrix

can be recursively constructed from smaller order circuits as shown in Fig. 2 for the case of the matrix in eq. (2).

The polar code $\mathcal{C} : (N, K, \mathcal{A})$ is a linear block code of length N and dimension K defined by a set of indices $\mathcal{A} \subset \{0, 1 \ldots, N-1\}$, such that $|\mathcal{A}| = K$. The generator matrix of the code $\mathcal{C}$ is given by $G = F_{N\mathcal{A}}$, which consists only of the rows of F_N specified by the values in $\mathcal{A}$. Encoding can be defined as

$$\boldsymbol{i} \cdot G = \boldsymbol{x}. \tag{3}$$

Alternatively, we can define an N-dimensional vector $\boldsymbol{u}$, such that $\boldsymbol{u}_{\mathcal{A}} = \boldsymbol{i}$, and $\boldsymbol{u}_{\mathcal{A}^c}$ bits are said to be frozen and set to some predefined value (usually all zeros) which is known both by the encoder and the decoder. This is useful as we can now use a logical circuit (as the one given in Fig. 1 and Fig. 2) to define the encoding and decoding. There are many methods for constructing the set $\mathcal{A}$ (Vangala et al., 2015). In this paper, we used the method based on Bhattacharyya bound approximation proposed in (Arikan, 2009).

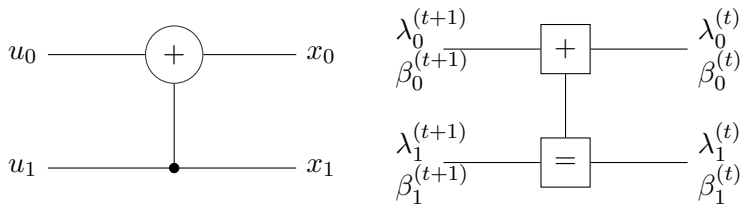


Figure 1 – Polar code unit circuit.
Encoding circuit (left) and decoding circuit (right).
Рис 1 − Схема блока полярного кода.
Схема кодирования (слева) и схема декодирования (справа).
Слика 1 – Основно коло поларног кода.
Коло за кодовање (лево) и коло за декодовање (десно).

Successive cancellation decoding

Let $\boldsymbol{X}$ be a random codeword, and $\boldsymbol{C} = \phi(\boldsymbol{X})$, where $\phi(\cdot)$ represents the BPSK mapping, defined as $\phi(x) = 1 - 2x$. $\boldsymbol{C}$ is transmitted over an additive white Gaussian channel (AWGN), and the channel output $\boldsymbol{Y} = \boldsymbol{C} + \boldsymbol{W}$ is received. $\boldsymbol{W}$ represents the AWGN noise vector with mean 0 and variance σ^2. Let $\boldsymbol{y}$ be a specific channel output, then $\boldsymbol{\lambda} = \frac{2\boldsymbol{y}}{\sigma^2}$ represents the log-likelihood ratio (LLR) vector.

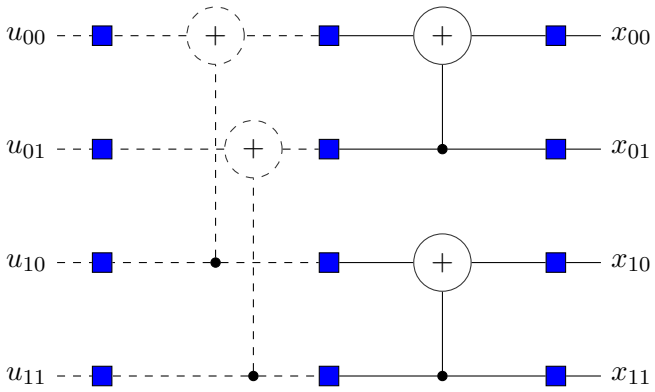


Figure 2 – Recursive construction of a 4-dimentional polar transform from two unit circuits
Рис 2 − Рекурсивное построение 4-мерного полярного преобразования из двух единичных схем
Слика 2 – Рекурзивна конструкција 4-димензионалне поларне трансформације спајањем два основна кола

The decoding factor graph can be constructed from the encoding circuit by replacing all summation blocks with check nodes and all junctions with variable nodes (Fig. 1) (Forney, 2001).

The SCD decoding algorithm works by passing the LLR values along such a defined factor graph from right to left, and hard decisions (β values) from left to right. When an updated LLR value reaches the end of the decoding circuit, a hard decision is made and propagated in the other direction. The SCD decoding procedure for the case of $N = 2$ is shown in Fig. 1. The update rules in Fig. 1 are given by:

$$\begin{aligned}
\lambda_0^{(t+1)} &= f(\lambda_0^{(t)}, \lambda_1^{(t)}),\\
\beta_0^{(t+1)} &= h(\lambda_0^{(t+1)}),\\
\lambda_1^{(t+1)} &= g(\lambda_0^{(t)}, \lambda_1^{(t)}, \beta_0^{(t)}),\\
\beta_1^{(t+1)} &= h(\lambda_1^{(t+1)}),\\
\beta_0^{(t)} &= \beta_0^{(t+1)} + \beta_1^{(t+1)},\\
\beta_1^{(t)} &= \beta_1^{(t+1)},
\end{aligned} \tag{4}$$

where the functions $f(\cdot)$, $g(\cdot)$ and $h(\cdot)$ are defined as

$$\begin{aligned} f(\lambda_0, \lambda_1) &\approx \operatorname{sign}(\lambda_0)\operatorname{sign}(\lambda_1)\min(|\lambda_0|, |\lambda_1|), \\ g(\lambda_0, \lambda_1, \beta) &= (-1)^{\beta} \cdot \lambda_0 + \lambda_1, \\ h(\lambda) &= \begin{cases} 0 & \lambda \geq 0 \\ 1 & \lambda < 0 \end{cases}. \end{aligned} \tag{5}$$

The high-level description of the SCD algorithm for $N = 2^m$, $m \geq 1$ is given in Alg. 1 (Vangala et al., 2015). Let $\Lambda \in \mathbb{R}^{N \times m+1}$ and $B \in \mathbb{F}_2^{N \times m+1}$, be two matrices for storing the calculated LLR and hard estimate values, respectively. Each column of the matrix Λ (B) corresponds to a given level (numerated from left to right) in the decoding factor graph. At the beginning of the algorithm, the first column of the matrix Λ is set to the channel LLRs ($\boldsymbol{\lambda}$). Furthermore, let $\zeta(\cdot)$ represent the standard bit reversal function. For an efficient implementation of the SCD algorithm, see (Aurora & Gross, 2018).

Algorithm 1: SCD algorithm

Input : $\boldsymbol{\lambda}, N, \mathcal{A}^c$
Output: $\boldsymbol{\beta}$
Initialize Λ and B;
$\Lambda_{i,0} = \lambda_i \; i = 0, \ldots N-1$;
for $i = 0, \ldots N-1$ **do**
  $b = \zeta(i)$;
  recursively calculate $\Lambda_{b,m}$;
  if $b \in \mathcal{A}^c$ **then**
    $B_{b,m} = 0$;
  else
    $B_{b,m} = h(\Lambda_{b,m})$;
  end
  recursively propagate $B_{b,m}$;
end
$\beta_i = B_{i,m} \; i = 0, \ldots N-1$;

Successive cancellation list and stack decoding

The main drawback of the SCD algorithm is the fact that once the algorithm makes a hard decision, that decision is never again revisited, and an error can easily propagate. The list and stack algorithms were proposed to fix this problem. Let $s_l = (\Lambda, B, PM^i, i)$ represent the current state of the decoder. The matrices Λ and B are the same as before and i represents the index of the last decoded bit. PM^i represents the path metric at the time i and it is calculated as (Balatsoukas-Stimming et al., 2015)

$$PM^i = \begin{cases} PM^{i-1}, & B_{\zeta(i),m} = h(\Lambda_{\zeta(i),m}) \\ PM^{i-1} + |\Lambda_{\zeta(i),m}|, & B_{\zeta(i),m} \neq h(\Lambda_{\zeta(i),m}) \end{cases} \tag{6}$$
$$PM^{-1} = 0$$

The SCLD algorithm works by keeping a list of states. At each time step, all states in the list are expanded. Every time a decision is made, the other decision is also considered and a new element is added to the list. If the list size is greater than some predefined size L, the list is sorted according to the path metric and only the best L are kept. The SCSD algorithm works in a similar manner, but instead of a list of states, a stack of states is kept and at each step only the best (top) state is considered. As the SCSD is an important component of the BSD, the high level description of the SCSD algorithm is given in Alg. 2. For a description of the SCLD, see (Balatsoukas-Stimming et al., 2015). In Alg. 2 the function top$(\cdot)$ returns the top of the stack. The matrix $\overline{B}$ is calculated by flipping a single bit in B, while the $\overline{PM}$ is the path metric of this changed state. We assume the stack is sorted in the descending order of the path metric, so that the best path is at the top of the stack. If the stack size is greater than some predefined size L, then the worst path is discarded. For an efficient implementation of the SCSD, see (Aurora & Gross, 2018), (Xiang et al., 2020).

Bidirectional stack decoding algorithm

Let $\mathcal{I} = \{0, 1, \ldots N/2 - 1\}$ and $\mathcal{J} = \{N/2, \ldots N - 1\}$ be two non-overlapping index sets. Furthermore, let $\mathcal{E} \subset \{0, 1, \ldots N - 1\}$ be the set of all even numbers lower than N, and $\mathcal{O} \subset \{0, 1, \ldots N - 1\}$ be the set of all odd numbers lower than N. Using the recursive structure of polar codes, we can write (Kahraman et al., 2013)

Algorithm 2: SCSD algorithm

Input : $\boldsymbol{\lambda}, N, \mathcal{A}^c$
Output: $\boldsymbol{\beta}$
Initialize Λ and B and create an empty stack $\boldsymbol{s}$;
Add the state $(\Lambda, B, 0, -1)$ to the stack $\boldsymbol{s}$;
$(\Lambda, B, i, PM) = \boldsymbol{s}$.top();
while $i < N$ **do**
  $b = \zeta(i+1)$;
  recursively calculate $\Lambda_{b,m}$;
  if $b \in \mathcal{A}^c$ **then**
    $B_{b,m} = 0$;
    $i = i + 1$ and update PM using eq. (6);
    recursively propagate $B_{b,m}$;
  else
    $B_{b,m} = h(\Lambda_{b,m})$;
    $\overline{B}_{b,m} = B_{b,m} \oplus 1$;
    $i = i + 1$ and update PM and $\overline{PM}$ using eq. (6);
    recursively propagate $B_{b,m}$ and $\overline{B}_{b,m}$;
    Add the state $(\Lambda, \overline{B}, i, \overline{PM})$ to the stack $\boldsymbol{s}$;
  end
  recursively propagate $B_{b,m}$;
  sort and prune $\boldsymbol{s}$;
  $(\Lambda, B, i, PM) = \boldsymbol{s}$.top();
end
$\beta_i = B_{i,m}\ i = 0, \dots N-1$;

$$\boldsymbol{x} = \boldsymbol{u} \cdot F_N = [\boldsymbol{u}_{\mathcal{I}}, \boldsymbol{u}_{\mathcal{J}}] \cdot \begin{bmatrix} F_{\frac{N}{2}} & \mathbf{0} \\ F_{\frac{N}{2}} & F_{\frac{N}{2}} \end{bmatrix}. \tag{7}$$

It follows that

$$\begin{aligned} \boldsymbol{x}_{\mathcal{I}} &= (\boldsymbol{u}_{\mathcal{I}} \oplus \boldsymbol{u}_{\mathcal{J}}) \cdot F_{\frac{N}{2}} \\ \boldsymbol{x}_{\mathcal{J}} &= \boldsymbol{u}_{\mathcal{J}} \cdot F_{\frac{N}{2}} \end{aligned} \tag{8}$$

This operation is called the basic folding and it splits the original code into two polar codes of the length $\frac{N}{2}$. A folded decoding factor graph corresponding to a polar code of the length $N = 8$ is shown in Fig. 3. This

decoder consists of two polar codes of the length $N = 4$ that can work in parallel, and a combination phase that is used to reconcile the upper and lower decoder. The upper and lower decoders are usually implemented as a SCD, while the choice of the combination decoder may vary. If the combination decoder is also a SCD, then the error performance would be equal to that of a classical SCD algorithm. Usually, the combination phase is implemented as a maximum likelihood (ML) decoder (Vangala et al., 2014b), (Li et al., 2014), a list decoder (Li et al., 2014) or a stack decoder (Xiang et al., 2020). The upper and lower decoders can be folded again in order to further reduce latency (Xiang et al., 2020). The multiple folding technique consists of applying the same operation several times (Kahraman et al., 2013), (Kahraman et al., 2014b).

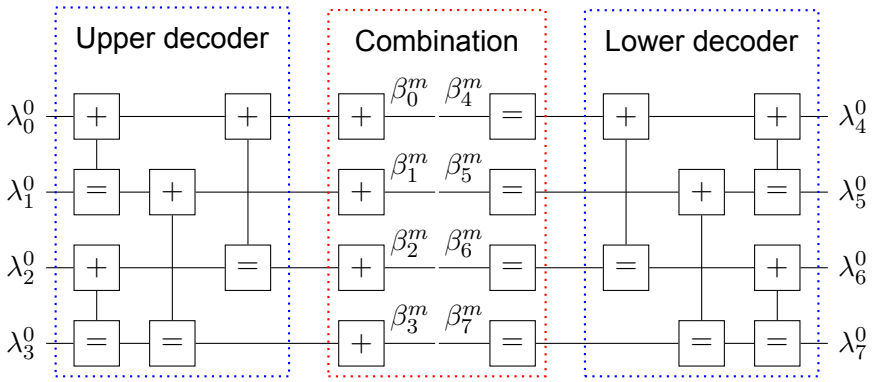


Figure 3 – Folded decoding factor graph for the polar codes of the length $N = 8$.
Рис 3 − Граф сверточного кода для декодирования полярных кодов длиной $N = 8$.
Слика 3 – Граф савијеног фактора за декодовање поларних кодова дужине $N = 8$.

Note that a similar folding operation can be obtained by splitting the even and odd code bits into two parts and applying the polar transform in the opposite direction.

$$\begin{aligned} \boldsymbol{w}_{\mathcal{E}} &= \boldsymbol{x}_{\mathcal{E}} \oplus \boldsymbol{x}_{\mathcal{O}} \\ \boldsymbol{w}_{\mathcal{O}} &= \boldsymbol{x}_{\mathcal{O}} \end{aligned} \tag{9}$$

This operation splits the code into two polar codes of half the length, similarly as before. An example of this operation is shown in Fig. 4 for

the case of a polar code of the length $N = 8$.

$$\begin{aligned} \boldsymbol{w}_{\mathcal{E}} &= \boldsymbol{u}_{\mathcal{E}} \cdot F_{\frac{N}{2}} \\ \boldsymbol{w}_{\mathcal{O}} &= \boldsymbol{u}_{\mathcal{O}} \cdot F_{\frac{N}{2}} \end{aligned} \tag{10}$$

By combining equations (9) and (10), we get

$$\begin{aligned} \boldsymbol{x}_{\mathcal{E}} &= \boldsymbol{u}_{\mathcal{E}} \cdot F_{\frac{N}{2}} \oplus \boldsymbol{u}_{\mathcal{O}} \cdot F_{\frac{N}{2}} \\ \boldsymbol{x}_{\mathcal{O}} &= \boldsymbol{u}_{\mathcal{O}} \cdot F_{\frac{N}{2}} \end{aligned} \tag{11}$$

The same procedure can be applied to $\boldsymbol{w}_{\mathcal{E}}$ and $\boldsymbol{w}_{\mathcal{O}}$ to construct multiple folds.

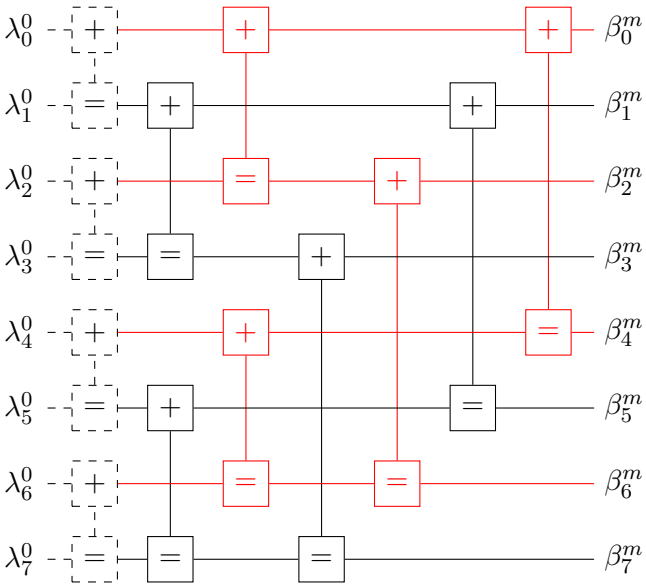


Figure 4 – Folded operation splits a polar code of the length $N = 8$ into two overlapping polar codes of the length $N = 4$.
Рис 4 − Операция свертки делит полярный код длиной $N = 8$ на два перекрывающихся полярных кода длиной $N = 4$.
Слика 4 – Савијање дели поларни код дужине $N = 8$ на два учешљана поларна кода дужине $N = 4$.

The new SCSD algorithm based on the odd-even folding is presented in Alg. 3. Let $\text{SCSD}_{\mathcal{E}}$ and $\text{SCSD}_{\mathcal{O}}$ represent the SCSD decoder of the even polar code and the odd polar code, respectively. Note that the reduced

latency SCSD decoder, presented in (Xiang et al., 2020), can be used as a component decoder in our algorithm. Let ENCO$_{\mathcal{E}}$ represents the encoder of the even polar code. The described decoding algorithm performs slightly worse than the classical SCSD algorithm. The reason for this is the fact that we keep only the best surviving state of the SCSD$_{\mathcal{E}}$ decoder and discard all the rest. In order to improve performance, we modify the component SCSD algorithm to return a list of D best candidate states. This can easily be implemented by popping the best state and rerunning the SCSD with a modified stack. The decoder output is selected amongst all D^2 paths based on the combined path metric or by checking the CRC. As D does not need to be very large, an ML decision can also be applied.

Algorithm 3: Bidirectional stack decoding algorithm

Input : $\boldsymbol{\lambda}, N$
Output: $\boldsymbol{\beta}$
Initialize $\boldsymbol{\alpha}$ as
for $i = 0, 2, 4, \ldots N-1$ **do**
  $\alpha_{i/2} = f(\lambda_i, \lambda_{i+1})$;
end
$\boldsymbol{\beta}_{\mathcal{E}} =$ SCSD$_{\mathcal{E}}(\boldsymbol{\alpha})$;
$\boldsymbol{w} =$ ENCO$_{\mathcal{E}}(\boldsymbol{\beta}_{\mathcal{E}})$;
for $i = 0, 2, 4, \ldots N-1$ **do**
  $\alpha_{i/2} = g(\lambda_i, \lambda_{i+1}, w_{i/2})$;
end
$\boldsymbol{\beta}_{\mathcal{O}} =$ SCSD$_{\mathcal{O}}(\boldsymbol{\alpha})$;

Simulation results

As we are primarily interested in URLLC applications, we consider the polar codes of rate 0.5 and block lengths 128 and 256. Although we present results only for short blocklengths, the proposed algorithm can be applied to polar codes of any length. The codes were constructed using the Bhattacharyya bound approximation method, and the simulation was done using the Monte Carlo method for different values of E_b/N_0 ranging from $-1.6dB$ to $3.9dB$ with a step of $0.5dB$. All simulations were run until a relative precision of $\delta = 0.05$ was reached.

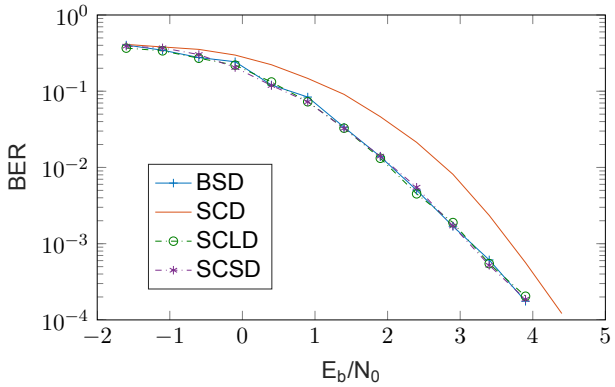


Figure 5 – BER of the $(128, 64)$ polar code using the BSD, SCD, SCLD and SCSD algorithms.
Рис 5 − BER кривая полярного кода $(128, 64)$ с использованием алгоритмов BSD, SCD, SCLD и SCSD.
Слика 5 – BER крива $(128, 64)$ поларног кода применом BSD, SCD, SCLD и SCSD алгоритма.

The SCLD algorithm was run with a list size of $L = 32$, while the SCSD algorithm was run with a stack of size $L = 100$. In the case of the bidirectional stack algorithm, the component SCSD algorithms were run with a stack of size $L = 32$, and they both returned a list of $D = 4$ candidate states. Out of $D^2 = 16$ possible candidates, we select the ML one. Fig. 5 shows the bit error rate (BER) as a function of E_b/N_0 for different decoders in the case of the $(128, 64)$ polar code.

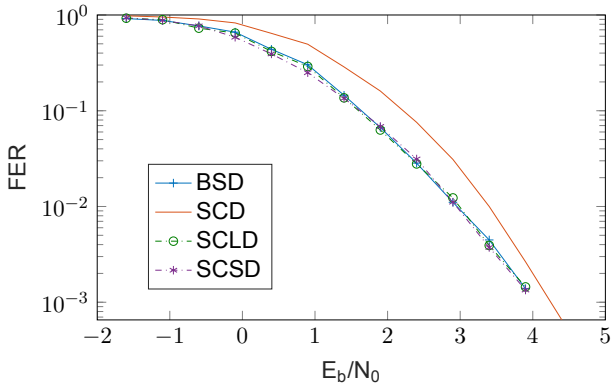


Figure 6 – FER of the $(128, 64)$ *polar code using the BSD, SCD, SCLD and SCSD algorithms.*
Рис 6 − FER кривая полярного кода $(128, 64)$ *с использованием алгоритмов BSD, SCD, SCLD и SCSD.*
Слика 6 – FER крива $(128, 64)$ *поларног кода применом BSD, SCD, SCLD и SCSD алгоритма.*

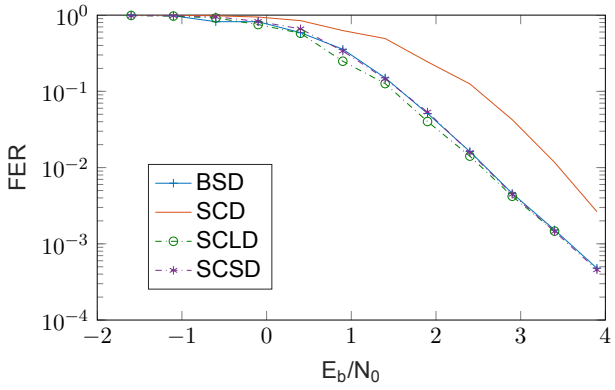


Figure 7 – FER of the $(256, 128)$ *polar code using the BSD, SCD, SCLD and SCSD algorithms.*
Рис 7 − FER кривая полярного кода $(256, 128)$ *с использованием алгоритмов BSD, SCD, SCLD и SCSD.*
Слика 7 – FER крива $(256, 128)$ *поларног кода применом BSD, SCD, SCLD и SCSD алгоритма.*

Fig. 6 shows the frame error rate (FER) as a function of E_b/N_0 for different decoders in the case of the $(128, 64)$ polar code. The FER of the $(256, 128)$ polar code is shown in Fig. 7.

Based on these results, we see that the new BSD algorithm has the same error rate as the original SCSD algorithm. The speed of the proposed algorithm is higher than that of the original SCSD algorithm because of the smaller stack size and the fact that the algorithm is split into two parts, where each one is a SCSD of half the length of the original code.

Conclusion

In this paper, we presented a novel bidirectional stack decoding algorithm based on the folding technique. It was shown that the proposed algorithm has the same error performance as the existing algorithms. Future research will deal with further improving the bidirectional algorithm. The folding procedure is a powerful technique that can be used to construct a wide range of hybrid decoders. Different combinations of decoders could give better results - which is something that needs to be investigated. It is possible to further improve the proposed algorithm by applying the folding operation multiple times. The use of multiple CRC codes can also improve the performance of the decoder. An efficient hardware implementation of the proposed algorithm will also be developed.

References

-3rd Generation Partnership Project. 2016. *Final report of 3GPP TSG RAN WG1 #87 v1.0.0.* [online]. Available at: https://www.3gpp.org/DynaReport/TDocExMtg--R1-87--31665.htm [Accessed: 1 February 2021].

Alamdar-Yazdi, A. & Kschischang, F.R. 2011. A Simplified Successive-Cancellation Decoder for Polar Codes. *IEEE Communications Letters*, 15(12), pp. 1378–1380. Available at: https://doi.org/10.1109/LCOMM.2011.101811.111480.

Arikan, E. 2008. A performance comparison of polar codes and Reed-Muller codes. *IEEE Communications Letters*, 12(6), pp. 447–449. Available at: https://doi.org/10.1109/LCOMM.2008.080017.

Arikan, E. 2009. Channel Polarization: A Method for Constructing Capacity-Achieving Codes for Symmetric Binary-Input Memoryless Channels. *IEEE Transactions on Information Theory*, 55(7), pp. 3051–3073. Available at: https://doi.org/10.1109/TIT.2009.2021379.

Arikan, E. 2010. Polar codes: A pipelined implementation. In: *Proc. 4th Int. Symp. on Broad. Commun. ISBC 2010*. pp. 11–14.

Aurora, H., Condo, C. & Gross, W.J. 2018. Low-Complexity Software Stack Decoding of Polar Codes. In: *2018 IEEE International Symposium on Circuits and Systems (ISCAS)*. pp. 1–5. Available at: https://doi.org/10.1109/ISCAS.2018.8351832.

Aurora, H. & Gross, W.J. 2018. *Towards Practical Software Stack Decoding of Polar Codes*. [online]. Available at: https://arxiv.org/abs/1809.03606 [Accessed: 1 February 2021].

Balatsoukas-Stimming, A., Parizi, M.B. & Burg, A. 2015. LLR-Based Successive Cancellation List Decoding of Polar Codes. *IEEE Transactions on Signal Processing*, 63(19), pp. 5165–5179. Available at: https://doi.org/10.1109/TSP.2015.2439211.

Forney, G.D. 2001. Codes on graphs: normal realizations. *IEEE Transactions on Information Theory*, 47(2), pp. 520–548. Available at: https://doi.org/10.1109/18.910573.

Hanif, M. & Ardakani, M. 2017. Fast Successive-Cancellation Decoding of Polar Codes: Identification and Decoding of New Nodes. *IEEE Communications Letters*, 21(11), pp. 2360–2363. Available at: https://doi.org/10.1109/LCOMM.2017.2740305.

Hashemi, S.A., Condo, C. & Gross, W.J. 2016. Simplified Successive-Cancellation List decoding of polar codes. In: *2016 IEEE International Symposium on Information Theory (ISIT)*. pp. 815–819. Available at: https://doi.org/10.1109/ISIT.2016.7541412.

Hashemi, S.A., Mondelli, M., Fazeli, A., Vardy, A., Cioffi, J. & Goldsmith, A. 2020. *Parallelism versus Latency in Simplified Successive-Cancellation Decoding of Polar Codes*. [online]. Available at: https://arxiv.org/abs/2012.13378 [Accessed: 1 February 2021].

Huang, Y., Zhang, Z., You, X. & Zhang, C. 2018. Efficient Folded SC Polar Line Decoder. In: *2018 IEEE 23rd International Conference on Digital Signal Processing (DSP)*. pp. 1–5. Available at: https://doi.org/10.1109/ICDSP.2018.8631807.

Kahraman, S., Viterbo, E. & Çelebi, M.E. 2013. Folded tree maximum-likelihood decoder for Kronecker product-based codes. In: *2013 51st Annual Allerton Conference on Communication, Control, and Computing (Allerton)*. pp. 629–636. Available at: https://doi.org/10.1109/Allerton.2013.6736584.

Kahraman, S., Viterbo, E. & Çelebi, M.E. 2014a. Folded successive cancelation decoding of polar codes. In: *2014 Australian Communications Theory Workshop (AusCTW)*. pp. 57–61. Available at: https://doi.org/10.1109/AusCTW.2014.6766428.

Kahraman, S., Viterbo, E. & Çelebi, M.E. 2014b. Multiple Folding for Successive Cancelation Decoding of Polar Codes. *IEEE Wireless Communications Letters*, 3(5), pp. 545–548. Available at: https://doi.org/10.1109/LWC.2014.2343970.

Li, B., Shen, H. & Tse, D. 2012. An Adaptive Successive Cancellation List Decoder for Polar Codes with Cyclic Redundancy Check. *IEEE Communications Letters*, 16(12), pp. 2044–2047. Available at: https://doi.org/10.1109/LCOMM.2012.111612.121898.

Li, B., Shen, H. & Tse, D. 2013. *Parallel Decoders of Polar Codes*. [online]. Available at: https://arxiv.org/abs/1309.1026v1 [Accessed: 1 February 2021].

Li, B., Shen, H., Tse, D. & Tong, W. 2014. Low-latency polar codes via hybrid decoding. In: *2014 8th International Symposium on Turbo Codes and Iterative Information Processing (ISTC)*. pp. 223–227. Available at: https://doi.org/10.1109/ISTC.2014.6955118.

Niu, K. & Chen, K. 2012b. CRC-Aided Decoding of Polar Codes. *IEEE Communications Letters*, 16(10), pp. 1668–1671. Available at: https://doi.org/10.1109/LCOMM.2012.090312.121501.

Niu, K. & Chen, K. 2012a. Stack decoding of polar codes. *Electronics Letters*, 48, pp. 695–697(2). Available at: https://doi.org/10.1049/el.2012.1459.

Sarkis, G., Giard, P., Vardy, A., Thibeault, C. & Gross, W.J. 2014. Fast Polar Decoders: Algorithm and Implementation. *IEEE Journal on Selected Areas in Communications*, 32(5), pp. 946–957. Available at: https://doi.org/10.1109/JSAC.2014.140514.

Senk, V. & Radivojac, P. 1997. The bidirectional stack algorithm. In: *Proceedings of IEEE International Symposium on Information Theory*. pp. 500–. Available at: https://doi.org/10.1109/ISIT.1997.613437.

Tal, I. & Vardy, A. 2015. List Decoding of Polar Codes. *IEEE Transactions on Information Theory*, 61(5), pp. 2213–2226. Available at: https://doi.org/10.1109/TIT.2015.2410251.

Vangala, H., Viterbo, E. & Hong, Y. 2014a. Improved multiple folded successive cancellation decoder for polar codes. In: *2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)*. pp. 1–4. Available at: https://doi.org/10.1109/URSIGASS.2014.6929238.

Vangala, H., Viterbo, E. & Hong, Y. 2014b. A new multiple folded successive cancellation decoder for polar codes. In: *2014 IEEE Information Theory Workshop (ITW 2014)*. pp. 381–385. Available at: https://doi.org/10.1109/ITW.2014.6970858.

Vangala, H., Viterbo, E. & Hong, Y. 2015. *A Comparative Study of Polar Code Constructions for the AWGN Channel*. [online]. Available at: https://arxiv.org/abs/1501.02473 [Accessed: 1 February 2021].

Won, J.W. & Ahn, J.M. 2020. 3GPP URLLC patent analysis. *ICT Express*. Available at: https://doi.org/10.1016/j.icte.2020.09.001.

Xiang, L., Kaykac Egilmez, Z.B., Maunder, R.G. & Hanzo, L. 2019. CRC-Aided Logarithmic Stack Decoding of Polar Codes for Ultra Reliable Low Latency Communication in 3GPP New Radio. *IEEE Access*, 7, pp. 28559–28573. Available at: https://doi.org/10.1109/ACCESS.2019.2901596.

Xiang, L., Zhong, S., Maunder, R.G. & Hanzo, L. 2020. Reduced-Complexity Low-Latency Logarithmic Successive Cancellation Stack Polar Decoding for 5G New Radio and Its Software Implementation. *IEEE Transactions on Vehicular Technology*, 69(11), pp. 12449–12458. Available at: https://doi.org/10.1109/TVT.2020.3026915.

ДВУНАПРАВЛЕННОЕ СТЕКОВОЕ ДЕКОДИРОВАНИЕ ПОЛЯРНЫХ КОДОВ

Александр Дж. Миня, *Душан* П. Добромиров, **корреспондент**, *Войин* И. Шенк

Нови-Садский университет, факультет технических наук, кафедра телекоммуникаций и обработки сигналов, г. Нови-Сад, Республика Сербия

РУБРИКА ГРНТИ: 28.00.00 КИБЕРНЕТИКА:
28.21.00 Теория информации;
28.21.19 Теория кодирования,
27.00.00 МАТЕМАТИКА:
27.03.00 Основания математики и математическая логика;
27.03.17 Алгоритмы и вычислимые функции

ВИД СТАТЬИ: оригинальная научная статья

russian

Резюме:

Введение/цель: В данной статье представлен новый алгоритм декодирования полярных кодов с уменьшенной задержкой, вдохновленный двунаправленным стековым декодированием сверточных кодов, разработанный с помощью метода свертки.

Методы: Алгоритм стекового декодирования (также известный как стековый поиск), применяется при декодировании древовидных кодов, декодировании списка, разработанного Питером Элиасом, методе свертки, применяемой для минимизации задержки алгоритмов

декодирования. Моделирование проводилось методом Монте-Карло.

Результаты: Разработан новый алгоритм декодирования полярных кодов, подходящий для параллельного внедрения. В статье представлены сравнительный анализ нового алгоритма с существующими и результаты моделирования.

Выводы: Полярные коды − это класс кодов, который достигает пропускной способности каналов, используемый в качестве основной схемы кодирования для каналов управления в 5G New Radio. Основным алгоритмом декодирования полярных кодов является последовательное декодирование списка отмен (англ. Successive cancellation decoding - SCD). Данный алгоритм отличается простотой и отличными характеристиками относительно длинных кодов, но он ненадежен относительно коротких и средних кодов. В данной связи предлагаются несколько алгоритмов декодирования, с целью улучшения характеристик полярных кодов. Последовательное декодирование списка отмен в сочетании с циклическим избыточным кодом обеспечивает точное исправление ошибок, но за счет высокой сложности внедрения. Стековое декодирование отмен обеспечивает аналогичную точность при исправлении ошибок, но при меньшей сложности внедрения. Помимо высокой надежности, новые приложения в критических ситуациях требуют небольших задержек, поэтому необходимо минимизировать время работы декодера. В данной статье предлагается новый алгоритм двунаправленного декодирования, который обеспечивает значительно меньшую задержку и аналогичную надежность, как у наилучших существующих алгоритмов. В статье представлен сравнительный анализ нового алгоритма с существующими, а также результаты моделирования.

Ключевые слова: полярные коды, последовательное декодирование, стековое декодирование, декодирование списка отмен, свертка.

БИДИРЕКЦИОНО СТЕК ДЕКОДОВАЊЕ ПОЛАРНИХ КОДОВА

Александар Ђ. Миња, *Душан* П. Добромиров, **аутор за преписку**, *Војин* И. Шенк
Универзитет у Новом Саду, Факултет техничких наука, Катедра за телекомуникације и обраду сигнала, Нови Сад, Република Србија

ОБЛАСТ: телекомуникације, рачунарске науке

ВРСТА ЧЛАНКА: оригинални научни рад

serbian

Сажетак:

Увод/циљ: Рад уводи нови алгоритам за декодовање поларних кодова са смањеним кашњењем који је инспирисан бидирекционим стек декодовањем класичних конволуционих кодова, а заснован је на техници савијања (енг. folding).

Методе: Стек алгоритма (познат и као стек претрага) погодан је за декодовање кодова са структуром стабла, декодер са листом. Ова техника савијања, коју је увео Петар Елиас, користи се за смањивање кашњења алгоритама за декодовање. Симулације су рађене применом поступка Монте Карло.

Резултати: Развијен је нови алгоритам за декодовање поларних кодова који је погодан за паралелну имплементацију. Нови алгоритам упоређен је са постојећим, а резултати симулације су приказани.

Закључак: Поларни кодови су класа кодова која достиже капацитет канала, и усвојена је за кодовање контролних канала у 5G новом радију. Главни алгоритам декодовања за поларне кодове јесте секвенцијални алгоритам - тзв. декодер са сукцесивним поништавањем (енг. Successive cancellation decoding - SCD). Овај алгоритам има ниску комплексност и одличне перформансе у случају кодова са великом дужином, али и врло малу поузданост на кратким и средњим дужинама. Предложено је неколико алгоритама за декодовање како би се побољшале перформансе поларних кодова. Декодер са листом и сукцесивним поништавањем (енг. Successive cancellation list decoding - SCLD), заједно са цикличким кодом за проверу грешака

(енг. Cyclic redundancy check - CRC), пружа веома добре перформансе при исправљању грешака, али по цену велике комплексности имплементације. Стек декодер са сукцесивним поништавањем (енг. Successive cancellation stack decoding - SCSD) пружа сличне перформансе по питању вероватноће грешке при нижој комплексности. Поред ниске вероватноће грешке, нове апликације за рад у критичним ситуацијама захтевају и мало кашњење, па је потребно смањити време рада декодера. У раду је предложен нови бидирекциони алгоритам за декодовање, који постиже знатно мање кашњење уз приближно исту поузданост као и најбољи постојећи алгоритми. Нови алгоритам је упоређен са постојећим алгоритмима, а резултати симулације су приказани.

Кључне речи: поларни кодови, секвенцијални декодер, стак декодовање и декодер са листом, савијање.

Paper received on / Дата получения работы / Датум пријема чланка: 08.02.2021.
Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 10.03.2021.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 12.03.2021.

25 YEARS OF THE TETRA STANDARD AND TECHNOLOGY FOR CONTEMPORARY DIGITAL TRUNKING SYSTEMS OF PROFESSIONAL MOBILE RADIO COMMUNICATIONS

Slađan M. Svrzić

Tesla Systems Ltd, Belgrade, Republic of Serbia,
e-mail: milosavljevic_svrzic@hotmail.com,
ORCID iD: https://orcid.org/0000-0003-4525-9844

DOI: 10.5937/vojtehg69-29340; https://doi.org/10.5937/vojtehg69-29340

FIELD: Telecommunications
ARTICLE TYPE: Original scientific paper

Abstract:

Introduction/purpose: For the construction of functional mobile radio communication systems today, the trunking systems of digital mobile radio communications are almost exclusively used, the main representative of which is the system with the application of TETRA standards. This article describes the beginnings and historical development of this standard, with the activities of ETSI and TETRA MoU in the fight for the availability and harmonization of the frequency spectrum.

Methods: A description of relevant issues of the origin and development of the TETRA 1 standard is given as well as the analysis of the characteristic moments of the innovated TETRA 2 standard.

Results: This article describes the beginnings and historical development of this standard, with the activities of ETSI and TETRA MoU in the fight for the availability and harmonization of the frequency spectrum. It also systematize the use of the key TETRA systems in the world and shows its share in the world market by sectors, emphasizing the dilemma of its further development at the crossroads after 25 years of existence. Also, a basic overview of the TETRA 1 standard is given while the basic elements and the principle of its application are described. The innovated TETRA 2 standard and the improvements achieved in the way of data transmission are described in more detail; the process of interoperability certification and, in connection with that, the entry of TETRA into the North American market is emphasized. The parameters selected for advanced data transfer according to the TETRA 2-TEDS standard are presented and analyzed, together with an overview of some limitations during practical application.

Conclusion: In the conclusion, the current moment of TETRA is analyzed with a focus on its future after 25 years of development, emohasizing a possibility of modernizing and improving the TETRA network of the Ministry of the Interior of Serbia for the needs of the MoD and the Serbian Armed Forces.

Key words: mobile radio communications-MR, public mobile radio communication system-PAMR, professional mobile radio communication system-PMR, area-interface-AI, digital trunking system of mobile radio communications-TETRA, TETRA enhanced data service-TEDS, European telecommunications standardization institute-ETSI.

Introduction

The earliest beginnings of TETRA (*Terrestrial Trunked Radio*) date back to 1989, when four leading European companies for the production of mobile radio equipment: *Ericsson*, *Motorola Solutions*, *Nokia* and *Philips*, began work on the development of *digital trunking systems for mobile radio communications*, called MDTRS (*Mobile Digital Trunked Radio System*). During the same year, work began in North America on the development of a new, accompanying *Standard for Interoperable Digital Mobile Radio Communications for Voice Transmission*, now known as P25 (*Project 25*). While the development of the *P25 standard* was the responsibility of the *North American public-safety community* (NAPsC), TETRA was developed under the auspices of the *European Telecommunications Standards Institute* (ETSI), supported by many manufacturers and equipment vendors, system users and, of course, regulatory bodies. (Ovčinnikov et al, 2000), (Svrzić & Ćosović, 2002a), (Swan, 2015)

From the very beginning, the development of TETRA was a cornerstone for establishing a new standard for UHF (*Ultra High Frequency*) mobile radio communication MR (*Mobile Radio*), with unique recommendations. Thus, during 1993, the support of the manufacturers of equipment for *Functional Mobile Radio Communications Systems*-PMR (*Professional Mobile Radio*) significantly improved and the way was paved for the emergence of a strong and solidary association of sellers of this type of equipment. This enabled the TETRA MoU (*TETRA Memorandum of Understanding*) to be formed and put into operation in December 1994, uniting the then most important manufacturers and sellers of PMR equipment. As a united organization of producers and sellers, the TETRA MoU association played a very important role not only for the permanent development of TETRA but also for maintaining

interoperability, for creating new market opportunities, as well as for fight against fierce competition which, uderstandably, advocated other standards and technologies. (Svrzić & Ćosović, 2002a), (Swan, 2015)

The MDTRS standard grew into a standard called TETRA (*Trans-European Trunked RAdio*) in 1991, which was only an approximate interpretation of the current name of the *TETRA standard*. Namely, as ambitions on a global level were immediately tied to the standard, the acronym "TETRA" is today interpreted as a natural abbreviation derived from the word *TErrestrial Trunked Radio*. An important date in the emergence of TETRA is December 1995, when ETSI adopted and approved the new TETRA V + D radio interface-TAI (*TETRA Voice plus Data Air interface*), as a complete *European Telecommunications Standard*-ETS for integrated transmission speech and signal data, ETSI EN 300 392-2, although TETRA even then showed its undisguised ambitions for application in the entire world market (ETSI, 2001). In contrast, it is believed that TETRA was not a standard associated with the then existing *Public Access Mobile Radio System* (PAMR) from the beginning, nor was PAMR part of TETRA. Namely, TETRA V + D has proven to be a flexible standard for *digital mobile radio communication systems* whose infrastructure is formed by switching elements, a number of base and many mobile radio stations as a highly redundant and flexible system for all requirements, making it ideal for regular business and functional mobile radio communications, as well as for mobile radio communications in conditions of critical situations for public safety. The standard includes the necessary recommendations-specifications (type: ETSI EN 300 xxx) for group, broadband and emergency calls, then for quick access to the system (which is usually shorter than 300 ms), for *Trunking Mode Operation*-TMO and *Direct Mode Operation*-DMO type of work, for different levels of application of information encryption, for telephony with participants from functional networks with PABX and from public networks-PSTN (including full duplex) and support for smooth operation of checkpoints (*Control -management and dispatch centers*) (Swan, 2015).

At the time of the *TETRA V + D standard*, the data transfer rate in it was relatively low and comparable to the data transfer rate of other technologies, which is no longer valid today, but it should be noted that the *TETRA standard* already offered a powerful system of *Status Messages*-StM and *Short Written Messages*-SDM, as well as a special data package related to the execution of special tasks in the field in critical situations. The entire industry which surrounded TETRA was already determined at that time not to allow the new standard to be

undermined and its strengthening to be hindered. Therefore, the *European Regulatory Organization for Safety and Protection of People at Work* formed a special working group of experts, with the task of clarifying to potential clients at the (very) beginning of the existing (and turned out to be false) beliefs about the alleged danger to OSH work by pulsed radiation of mobile *TETRA terminals*. Namely, the entire world industry of mobile radio communications today is very serious and comprehensive in approaching the solution of issues in the field of OSH, so it invests significant funds for that. In that respect, everything about TETRA, in relation to them, does not differ at all. Therefore, the RF (*Radio Frequency*) sensitive work environment was protected from the very beginning by a novelty, which is characterized by *TETRA terminals*, and which is called *Transmit Inhibit Mode* (TMI). It enables users of the *TETRA terminal* to perform their duty unhindered in environments where sensitive medical equipment is present (in healthcare centres and hospitals) or electronic measuring equipment in laboratories and in the field (instruments, speedometers, breathalyzers, etc.), all without interfering with the operation of the equipment or compromising the accuracy of the obtained measurement results (Swan, 2015).

Frequency spectrum allocation for TETRA

The availability and harmonization of the *frequency spectrum*, that is, the spectral efficiency, was one of the key moments for the worldwide success of the *TETRA standard*. Namely, an open MR standard, which implies that equipment from different manufacturers, can be used in a single radio network, must offer the system owner, on the one hand, sufficient spectral efficiency, with the possibility of choosing equipment from different manufacturers, and at the same time, on the other hand, enable the achievement of reasonable economy on the existing scale in order to maintain a broadly competitive world market of sellers. Therefore, immediately, i.e. in the early 1990s, work began on defining the adjusted bandwidth for MDTRS, which was managed by the *European Radiocommunications Office*-ERO from the *Community of European Conference of Postal and Telecommunications Administrations*-CEPT. In addition, in the middle of the same year, primarily thanks to consultations with NATO and their cooperation, as well as the cooperation of some other radio spectrum users in Europe, within the frequency range 380 to 400MHz, which is strictly intended for users in security public services for the needs of TETRA in Europe, two new subbands of frequencies of 5MHz (380-385 / 390-395MHz) were

defined, which is 200 *communication radio channels* with a width of 25kHz.

The mentioned work within CEPT also gave positive results, as for the needs of using TETRA in various commercial services in Europe, four more subbands of frequencies in parts of the spectrum 410-430 / 450-470MHz were defined (which is another 800 *radio channels* 25kHz wide) and 870-876 / 915-921MHz (which is an additional 240 *radio channels* 25kHz wide). In addition, the mentioned parts of the spectrum, 380-395 MHz and 410-430 MHz, which are designated as the *basic band*, together with the newly allocated auxiliary band 870-876MHz, have also become widely available for use by TETRA in other regions of the world (meaning those outside Europe). Despite initial concerns, whether such a specific radio spectrum width will be sufficient for the frequency plan, and whether it will allow the required density of *TETRA network* elements, necessary for good *radio coverage* and *adjusted capacity of communication channels*, to be implemented in the field, improved technical the RF characteristics of the third generation *TETRA terminals* have allowed mobile participants to operate successfully on the combined broadband configuration of both parts of the basic band, i.e. from 380 to 430MHz. This means that since then, by combining the *basic spectral bands* 380-400MHz and 410-430MHz, it has been possible to provide additional *radio coverage* and increase the capacity of communication channels, wherever necessary (of course, if spectrum is available).

It should be noted that TETRA has already unequivocally proven its pronounced *spectral efficiency* in this area, as it has enabled, from the very beginning, a large number of national networks operating today to function simultaneously and successfully, using only the *basic part* of the spectrum (380 up to 400MHz) that is, without the use of assigned TETRA *supplementary radio spectrum bands.* (Svrzić & Ćosović, 2002a, 2002b), (Swan, 2015)

The most famous realized TETRA systems in the world and an overview of the world TETRA market

The Autonomous Island of Jersey, located in the English Channel, was the country where, in June 1996, the world's first *TETRA network* was activated, and then several test systems were set up across Europe over the next few years. At the same time, after the approval for the use of TETRA in large national networks had been obtained, the planning and procurement of *TETRA systems* for the support of functional mobile

radio communications in the public security sector began. Based on that, by the end of 2000, in 21 different countries of the world, the construction of 32 *TETRA networks* of different levels had already been completed or was being completed. The first major European achievements in the application of TETRA for the construction of mobile radio communications include the following realized projects:

• the national network “PSRCP / AIRWARE” in Great Britain, for the construction of which a contract was signed in 1977, but the works were completed and the system was put into operation in 2001,

• the national network “VIRVE” in Finland, whose planning began in 1995, construction work began in 1998, and operational use at the national level began in 2002,

• the national network "ASTRID" in Belgium, whose planning and construction lasted from 1995 to 2002, when it was introduced into operational use at the national level,

• the national network “C2000” in the Netherlands, whose construction works started in 1999, and the complete infrastructure was completed and the system established at the national level in 2004, and

• the national network “BD-BOS” in Germany, for the construction of which an extensive research was started in 2007 and which was supposed to be intended for the police exclusively. This network was completed only a few years ago and today is the largest TETRA network in the world.

From today's point of view in the modern world, *TETRA serves* almost every segment of the global PMR market and is present on all continents. The global percentage of TETRA users by social and economic sectors is shown in the diagram in Figure 1. The diagram shows that the largest part of the global TETRA market of 33% is intended for *Public Security Sector*, in which TETRA began to be used initially. Across Europe and the Middle East, there are significant national *TETRA networks* for the needs of *Security Services*, which regularly operate in emergency and critical situations, as well as for the needs of *Rapid Response Organizations*. In that sense, the key aspect of TETRA is that it allows the system owner in regular radio communications full autonomy of work, and that when acting in emergency and crisis situations, it provides full interoperability between different services and agencies. The second largest world TETRA market share, with a 24% share, covers the owners of PMR from *the Transport Sector*. This part of the TETRA market is growing fastest today, especially in systems for fast and mass transport of people and goods, as well as in large ports and

airports, which account for an additional 5% share. It should be noted that the pioneering projects for the implementation of TETRA in the USA were located within this sector, which started only after the long-awaited (until September 2012) approval of the FCC (*Federal Communications Commission*) for its smooth implementation on the North American continent. (Swan, 2015)

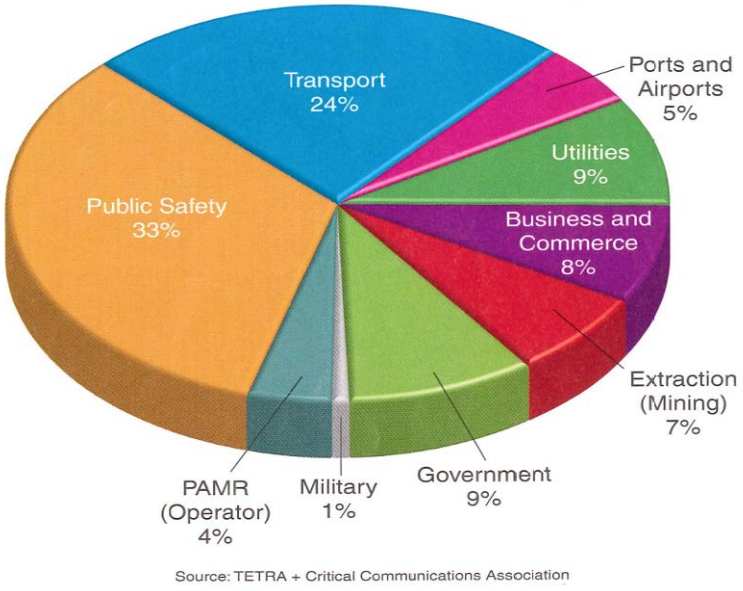


Figure 1 – Overview of the percentage share of TETRA users in the world PMR market (Swan, 2015)
Рис. 1 – Обзор процентной доли пользователей TETRA на мировом рынке PMR (Swan, 2015)
Слика 1 – Приказ процентуалног удела корисника TETRA на светском тржишту PMR (Swan, 2015)

The great success of TETRA, as well as its high percentage share in the world PMR market, has attracted a large number of equipment manufacturers, followed by application developers, as well as suppliers of peripherals and services. For these reasons, the TETRA market continues to grow permanently. For example, in 2013, IHS announced that a total of 600,000 sets of new *TETRA terminals* were being delivered to the global market, which is a significant number for a part of almost 3.2 million *TETRA terminals* already in operation in the world. A GSMA source stated that this number of approximately 4 million mobile

terminals in various *TETRA networks* in 2015 realized a colossal 6.5 billion active connections. The analysis of the existing TETRA market over time shows that, from year to year, there has been a steady increase in the number of activated *TETRA terminals* in the world of 8%, which today results in approximately 6 million terminals worldwide (Swan, 2015). In addition, the results of the analysis of the global distribution of implemented *TETRA 1 systems* up to the first half of the 2000s are impressive, primarily for the needs of functional users, but (in some cases) for public system operators as well, as shown in Figure 2 (ETSI, 2004).

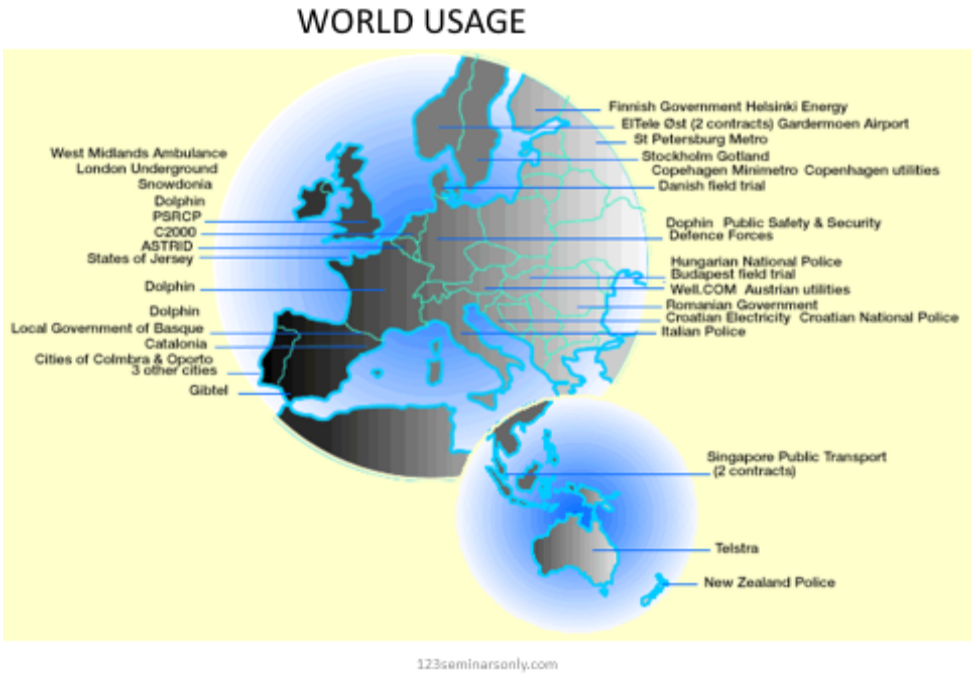


Figure 2 – Overview of the implemented TETRA Systems in the world up to the first half of the 2000s (ETSI, 2004)
Рис. 2 – Обзор внедренных систем TETRA в мире до первой половины 2000-х годов (ETSI, 2004)
Слика 2 – Преглед реализованих система TETRA у свету до прве половине 2000-тих (ETSI, 2004)

It can be seen from the figure that, in Serbia's neighboring countries, significant capacities of the *TETRA 1 system* were already built at that time, as follows:

Svrzić. S., 25 years of TETRA technology and standards for contemporary digital trunking systems of professional mobile radio communications, pp.426-460

- for the Hungarian National Police,
- for the Government of Romania,
- for the national police and the Croatian power industry,
- for the Italian National Police, and
- for a set of utility companies (electricity, gas, water) in Austria.

At that time, Serbia was also considering the construction of modern mobile radio connections based on the principle of digital trunking according to the *TETRA 1 standard*. This primarily referred to the *Oil Industry of Serbia* (NIS), which already in the mid-1990s wanted to replace its outdated and insufficiently functional, *analog and conventional system of mobile radio communications*. In that sense, in order to build a completely new functional system of digital telecommunications, during 2001 and early 2002, NIS conducted a comprehensive market research of *Analog Trangig Systems Standard MPT-1327* (Svrzić & Ćosović, 2000) and *Digital Trangig Systems Standard TETRA 1*. Based on the comparative analyses and the obtained results as well as on the a priori determined positions of the NIS management on the need to favor digital connections, in March 2002, within the "*Study of NIS Radio Connection M-21* (part-V)" the "*Preliminary design for construction NIS mobile radio communication system in digital trunking technology* " was prepared with the Technical Solution, which favoured Rohde & Schwarz "*ACCESSNET-T*" TETRA V + D network (Rohde & Schwarz, 1999b) for the coverage of the territory of the Republic of Serbia (primarily in the areas where business activities of NIS were performed). (Jorgić & Svrzić, 2002)

As for the *Serbian Armed Foces* (SAF), the then decision-makers of the General Staff-*Directorate for Telecommunications* took the position that such a system was too comfortable and expensive for independent construction in the army, since it is primarily intended for public security and safety services, and created to operate in crises. Therefore, the *Ministry of the Interior of Serbia* (their expert telecommunications service) was entrusted to conduct a market research program and procurement of equipment, on the basis of which (in the second half of the 2000s) works began on the construction of the *National TETRA network* type "*DIMETRA/System Release 6.2*" Motorola (Motorola Solutions, 2008). Of course, today the MoD and the SAF are regular participants in that network, with a large number of handheld and car mobile radios, and with the contribution to its infrastructure of 2 built fixed base radio stations (in constant use) and a couple of mobile base radio stations (for temporary use), but with little authority for its own, i.e. autonomous operational modeling or control (Krstić & Marjanović Jakovljević, 2018).

A crossroads for TETRA after 25 years of experience

In November 2011, the existing *TETRA MoU Association* changed its name to *TETRA + Critical Communications Association*-TCCA to demonstrate its focus on broadband digital mobile radio communications for professional users. In fact, the *Critical Communications Broadband Group* (CCBG) then paved the way for the development and adoption of a global common standard for mobile broadband, as well as a solution for all those users who operate on a daily basis performing dangerous tasks, or regular activities in critical environments. The CCBG is a group that brings together users from a wide range of technologies, markets and territories, working together to further develop a global and unique standard for broadband mobile radio communications. At the same time, the group that develops TETRA within ETSI changed the previously existing name *Technical Committee*-TC to the new name TETRA and Developed Mobile Radio Communications for Crisis Situations-TCCE (*TETRA and Critical Communications Evolution*), which is still today valid. It turned out that that moment was actually a crossroads both for the *TETRA standard* itself and for TCCA. Figure 3 shows the course of the complete development of TETRA, from the initial agreement of the manufacturers in 1989 for the development and production of MDTRS to the mentioned moment of the creation of TCCA in November 2011.

However, nowadays there are still such PMR holders for whom, due to the narrow frequency spectrum assigned to them, broadband transmission of radio information is simply uneconomical or completely unacceptable. In this regard, regardless of the fact that TETRA is, realistically speaking, the first and most sought-after technology of today for such purposes, there is no doubt that it, as such, will meet strong opposition and competition in the future. That is why the *TETRA standard* still needs a strong and focused association which will successfully defend the interests of *suppliers of network infrastructure equipment*, *mobile radio terminals*, *peripherals, and software applications* in the market. On the other hand, it has been proven many times that TETRA works very successfully and reliably with other mobile radio communications networks (which operate according to different standards and technologies), and especially with the networks of public mobile radio communications operators. The possibility, that is, the permission for the modern *4G LTE network* (*Long Term Evolution*), which is primarily intended for *very fast packet data transmission* (Gospić et al, 2010), in terms of complementarity, to coincide with TETRA was obtained ten years ago, and this was done much earlier for the *North American standard P25*.

Figure 3 – Overview of the TETRA development line (Swan, 2015)
Рис. 3 – Обзор линии развития TETRA (Swan, 2015)
Слика 3 – Приказ линије развоја TETRA (Swan, 2015)

Now the only question is whether, at some point, the mentioned modern *4G LTE network* (or the most modern and "controversial" *5G Global System Mobile-GSM network*), which normally supports *simultaneous voice transmission and very fast data transmission* for public mobile radio communications (in critical situations as well), will become a direct competitor to TETRA in terms of functional user support? What this chapter will look like in the book of TETRA's historical development cannot yet be predicted with certainty, but it seems to be already anticipated that, with certain limitations, TETRA will successfully cope with such an opportunity and competition of this kind. (Swan, 2015)

The basis of TETRA technology

Today, TETRA is the most modern open standard for *Functional digital trunking systems of mobile radio communications* which consists of a series of specifications developed by the *European Institute of Telecommunications Standards*-ETSI (Svrzić & Ćosović, 2002b). Basically, TETRA is intended as a standard for owners and users of *Functional digital mobile trunking radio communication systems* in the field of national and public security (police, gendarmerie, army, fire service, ambulance service), large companies engaged in energy distribution (electricity, oil and gas industry), transport companies (airports, railways, ports, road transport), service providers and, finally, public mobile telephony operators with integrated data transmission. As a complete digital system of mobile trunking radio connections, *modern TETRA systems* are characterized not only by exceptional efficiency in using available *frequency spectrum* but also by high quality processing, transmission and switching *of speech and data signals*, pronounced security of system access and information transmission with crypto protection services and modes of operation, and a wide range of basic and ancillary services (ETSI, 2009). All this contributes to the fact that these mobile radio communication systems are highly professional, efficient and flexible for different applications, enabling solid coexistence with still existing *analog trunking* and *conventional functional* and *public mobile radio communication systems*, and that today they are, as such, the most promising and most interesting for owners and users of functional communication systems, and even (in some circumstances) for network operators and providers of public mobile telephony services (Ovchinnikov et al, 2000), (Svrzić & Ćosović, 2002a, 2002b).

Mobile radio communication trunking systems, *analogue* and *digital*, are in fact *UHF mobile radio systems* that perform automatic switching of

available *Communication Radio Channels* (CCh) of *Base Radio Stations* (BS), for interconnection of mobile participants, as well as for connection of mobile participants with other participants. One of these CCs must be used as a *Management Channel* (MCh). Through this channel, calls are registered by mobile and other participants, status messages are transmitted and the order of connection requests is assigned. Namely, as soon as the request for establishing a connection arrives, one of the free CCh (channels from the capacity of the respective BS, in whose service zone the participant who sent the request for establishing a connection is) is assigned to participants in connection with exclusive use, for mutual communication. In cases when, during the established connection, new calls for establishing connections via the same BS arrive on the system, they are assigned the remaining, not occupied, CCh for the connection, until the full utilization of the Communication Channels capacity on the respective BS. If all channels are busy, new connection requests are queued (these requests are queued), and as soon as one of the busy channels is released, the system assigns it to the first participant on the queue. This means that in the trunking system of mobile-radio connections, the call for connection is sent only once because, in case of impossibility for current connection, that call will be placed on the waiting list and will be processed later in the order and priority that the participant has (Ovchinnikov et al, 2000), (Svrzić & Ćosović, 2002a). Figure 4 block diagram shows the general principle of the organization of digital trunking system of mobile radio communications with the TETRA 1 standard (Rohde & Schwartz, 1999a), (ETSI, 2019).

Trunking mobile radio communication systems belong to the class of mobile radio communication systems which are, above all, oriented to the formation of *various functional* and *corporate radio networks*, which provide for the active application of mobile users in *separate speech groups*, formed for some permanent or temporary assignment. It is clear that such systems are mainly used by the police, specialized social security and protection services, companies engaged in land and air transport, large producers and distributors of all types of energy (oil, gas, electricity, etc.) in different countries, as well as the military, in order to provide functional connections between mobile radio participants, mobile radio participants and fixed radio participants, as well as mobile radio participants with participants of public telephone-PSTN and ISDN and functional telephone networks-PABX (Ovchinnikov et al, 2000), (Svrzić & Ćosović, 2002a), (ETSI, 2004). In connection with the above, Figure 5 shows different possibilities for connecting to a *TETRA network*.

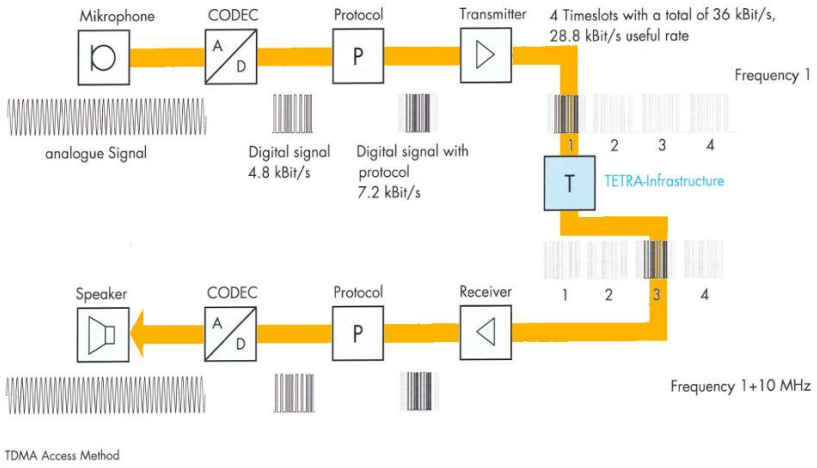


Figure 4 – Block diagram and the general principle of organizing the digital trunking system of mobile radio links TETRA 1 (Rohde & Schwartz, 1999a)
Рис. 4 – Блок-схема и общий принцип организации цифровой транкинговой системы мобильной радиосвязи TETRA 1 (Rohde & Schwartz, 1999a)
Слика 4 – Блок-шема и општи принцип организовања дигиталног транкинг система мобилних радио-веза TETRA 1 (Rohde & Schwartz, 1999a)

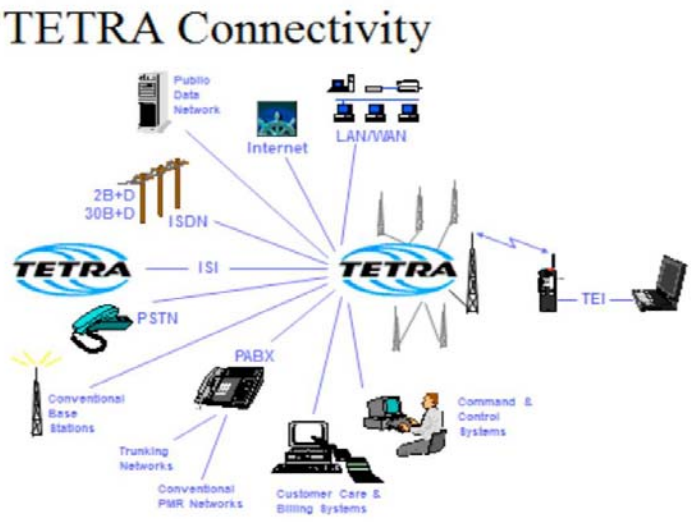


Figure 5 – Overview of different connectivity options in TETRA networks (ETSI, 2004)
Рис. 5 – Обзор различных вариантов подключения к сети TETRA (ETSI, 2004)
Слика 5 – Приказ различитих могућности за повезивање у TETRA мреже (ETSI, 2004)

Second generation of TETRA, data transmission development, improved interoperability and penetration on the North American market

Improving standards

Fewer than five years passed since its inception, and back in 1999, the members of the ETSI TETRA project, which included both users and manufacturers within the then *TETRA Technical Committee* (TC) and the *TETRA Association* (TA), recognized the need for the necessary generational advancement of the existing standard, tentatively called *TETRA 1*, in several areas. Although the number of these areas was initially wide, significant developments in the telecommunications industry, combined with changes in market needs, led to ETSI deciding in September 2000 to start activities to improve the existing standard towards the *second-generation TETRA*. As a result of these activities, a document was published at the end of 2005 defining the areas, services and characteristics of the *TETRA 1 standard* envisaged for treatment and improvements through the new *TETRA 2 standard* (Swan, 2015). Thus, according to the new *TETRA 2 standard*, special attention is paid to achieving improvements in the following areas:

- *increase connection range in TMO mode*,
- *use of AMR* (*Adaptive Multiple Rate*) *voice CODEC*,
- *use of mixed excitation, with line prediction, excited voice CODEC MELPe* (*Mix Exitation Line Prediction*), and
- *introduction of an advanced part of the High-Speed Data standard, called TETRA Enhanced Data Service-TEDS.* (Nouri, 2016)

Increasing the connection range in TMO mode was the need for the innovated TETRA to be able to operate outside the existing 58 km range limits, which was a limitation imposed by the *TDMA network infrastructure*, related to synchronization transmission. This was primarily a requirement of the user organization (system owner) to enable efficient *air-ground-air* (A-G-A) communications, while working on TMO in the relevant network infrastructure. Therefore, the necessary modifications of the "*burst*" on both links ("*up-link*" and "*down-link*") were defined, as well as the shortening of the time for their realization, thus making the *TMO connection range* for AGA communications applications in network increase to 83 km. Of course, since the *DMO mode* in the *TETRA network* has no connection range limitation (in terms of *TDMA infrastructure*), because the synchronization in this mode is realized at

the beginning of each of transmission sessions, it was not a topic in this case when innovating the standard.

The use of AMR's multi-purpose adaptive voice CODEC, which only works with an *A/D conversion* rate of 4.75 kb/s, was stopped by TC at the very beginning because the completion of innovations for the *AI radio interface* was delayed, and to which AMR actually needs to adapt. The explanation was to wait until a real market need for its implementation is clearly established.

The use of mixed excitation, with linear prediction, of the induced voice CODEC MELPe, which is standardized by NATO (*called STANAG 4591*) for use in their *military communications*, was introduced to improve the *TETRA standard* primarily due to the low bit rate for *A/D conversion* of only 2,400 b/s, followed by high resistance to high levels background noise and due to acceptable voice encoding / decoding performance. Since it was clear from the very beginning that there is a great suitability for the use of TETRA in *military communications*, TC made a study of the technical feasibility of applying *voice CODEC MELPe* to TETRA, from the framework that resulted in:

• possibility of working with government systems and other state institutions (without working in tandem),

• possibility of suppressing high levels of noise and noise from the environment,

• possibility of enhanced RF coverage using spare bits available for direct error correction of FEC (forward correction) in transmitted information, and

• possibility of integrated (V + D) use of spare bits available for Data.

However, when emphasizing all the above benefits, it should be noted that the very technique of implementing *voice CODEC MELPe* in TETRA contributes to increasing the delay in voice transmission in "*end to end*" communications, which is understandably a disadvantage. Therefore, the completion of the *TETRA 2 standard* with *voice CODEC MELPe* depended on the outcome of the relationship between these benefits and on the increase of the cost of its implementation, compared to the costs that existed until then using the current *ACELP voice CODEC.* (Nouri, 2016)

The introduction of an advanced standard for High-Speed Data transmission-TEDS had its prehistory, since at the beginning, in fact, two different ways of developing data transmission according to the *TETRA 2 standard* were planned (and took place):

1. *TETRA Advancet Packet Service* - TAPS, which is based on the evolution of *GRPS/EDGE standards*, and thus was focused mainly on the PAMR market (*for public communications*), and

2. *TETRA Enhanced Data Service* - TEDS, which implied a slightly different appearance of the standard, in terms of data transfer speed, and was aimed at the entire TETRA market (*across all sectors*). In addition, it envisaged full compatibility with TETRA V + D (*TETRA 1*) and easy migration of equipment from TETRA V + D to TEDS, as well as flexible use of the existing frequency spectrum allocated for use in PMR of different holders.

The decision on that issue was postponed for some time, but it was finally made, after the consensus on the *WG4 EPT working group* reached on July 4, 2002. The concept of TEDS won, as a route preferred by the world's six largest manufacturers of *TETRA equipment* (with five different technologies) and by most of the functional users of PMR. However, the new standard was not reached easily, but through painstaking debates over the choice of one of these initially offered-proposed options of 5 technologies (6 different manufacturers). Therefore, there were many failed attempts to reach a consensus on this issue, so that the development of the standard lasted for the next 4 years, so the amended *TETRA 2 standard* was not officially published until 2006 (Swan, 2015), (Nouri, 2016), (Dewaele, 2016).

Since then, until today, several significant improvements have been made within the new *TETRA 2 standard*, including: *High Speed Data* (HSD) and the selection and standardization of additional *CODECs* for *speech digitization*. In addition, the following were realized: the evolution of the *TETRA SIM card*, achieving interoperability, and even roaming, between TETRA 2 and public GSM, as well as the transition from *2.5G / 3G network*, while maintaining broad compatibility with the *first generation* of all types of *TETRA 1 devices* and the full integration of their features into the *new generation of TETRA 2 devices* (Swan, 2015), (Nouri, 2016).

In this regard, it should be noted that all these improvements did not immediately and simultaneously come to life in practice, but it was crucial to recognize in time the need for the standard to evolve, especially in terms of increasing data rates (over 10 times). Of course, such an evolution could not go hand in hand with other PAMRs, from GSM to GPRS, EDGE, UMTS / 3G, all the way to the state-of-the-art super-fast LTE data transmission system. For example, some well-versed in this technology claim that the emergence of a new model for HSD, i.e. TEDS,

in the historical development of the TETRA standard, was actually its new, second beginning. Indeed, for such a (until then) successful standard, the speed with which potential users-owners of the PMR system recognized all the qualities of TEDS was initially disappointing. This is confirmed by the fact that immediately after its appearance, at the beginning of December 2006, TEDS was accepted and implemented only in the national network of mobile radio communications in Norway, called "NODNET", and for the needs of public security of that country. Only a little later, during 2010, the innovated TEDS standard began to be applied in other national TETRA networks. Specifically, it was within the Finnish TETRA network of operators "VIRVE", in which it was first tested in the same year, and then the operational implementation of TETRA TEDS began. (Swan, 2015)

Development of data transmission applications

When it comes to the domain of data transmission application, the recent history of the standard shows that TETRA is primarily a successful standard in the domain of data transmission for *Short Message* and *Status Messaging Systems*. Namely, it is known that there is a whole special "industry" that writes software applications intended for user radio terminals and the operator of the *TETRA terminal*. These applications enable efficient machine-machine transfer of various important information and Data from the field to the control centers in real time In particular, the sector of companies engaged in the transport of people and goods has realized that TETRA is, in this respect, very efficient and highly efficient, for example, in the subways of large, densely populated world capitals such as Hong Kong, Singapore and London. This was also understood by large bus transport systems, such as the one in Barcelona. Finally, this was realized very early on by companies operating a number of large airports around the world.

Wih the evolution of the displays of the participating *mobile radio terminals*, with more and more options, as well as with the evolution of the processing power of terminals themselves, the developers are constantly making better and more complex software applications for them. In addition, for certain interest groups of users, the use of the *Peripheral Equipment Interface*-PEI has been introduced into the common standard, enabling the functioning of a wide range of supported peripherals, as well as the monitoring and control of SCADA *process management data* reception where there is no requirement for special information protection and where a relatively low data rate is sufficient. This occurs, for example, in mining, in oil and gas pipelines, or in the

distribution of electricity and water. The location information, where the terminal user is located, is by far the most used *TETRA application*, directly related to Data transmission, which is why most *TETRA terminals* are equipped with the GPS (*Global Position System*). Of course, the transmission of the mentioned location information is one of the main features of TETRA, whether it is a systematic monitoring or updating of MS locations in the "*Home Register*", precise determination of the location of the operator in a critical situation, or determination of the terminal location where the alarm is activated for some reason. Finally, GPS data also enables local distribution of accurate time, as well as accurate time stamping of status and short text messages, thus supporting one of the newer features of TETRA on the market: the production of high-resolution photographs with accurate time stamping. This capability makes the *TETRA terminal* more than a communication device. The photographs taken in this way are stored and stored at the terminal itself, in safe and isolated conditions, and can be switched from the built-in memory card to another medium if needed (Swan, 2015).

However, the first years of TETRA's existence showed why in the beginning it was necessary to very carefully advertise the possibilities of the standard in the field of application of data transmission. Namely, although the claims that *TETRA 1* can successfully support a data transfer rate of 28.8kb/s - at a time when public GSM could support a transfer rate of only 9.6 kb/s - were incorporated into many business offers, it turned out that in practice it was still unsustainable for some time. Indeed, the first packet data transmissions with a base speed of 7.2 kb/s, which used one "*time slot*", i.e. one *Communication Channel*, from the *basic TETRA 1 TDM frame*, were not operational until 2000.

Higher-speed packet transmissions (14.4 - 28.8 kbit / sec), i.e. those that use multiple time slots (2.3 or all 4), became operational only in 2005 (Swan, 2015). Of course, with the improvement of standards with the advent of *TEDS*, user data rates have *increased many times*, so they vary from 30 kb/s (for 25 kHz wide *RF radio channel*) to a maximum of 500 kb/s (for 150 kHz wide *RF radio channel*). (Nouri, 2016)

Improving interoperability

Interoperability and its positive certification tests are the essence of any open standard. In the *TETRA standard*, this is obtained through the interoperability certification regime, which is a strictly controlled process performed by an independent certification body. This process was defined by the *TETRA MoU Association*, and the first certificates were obtained in 1999 for *TETRA products* of four large manufacturing

companies, which are still key in the market of *TETRA technology*: Marconi (now SELEX), Motorola (now Motorola Solutions), Nokia (now Airbus Defence and Space) and SIMOCO (former Philips Telecom). Since then, more than *750 interoperability certificates* have been issued, but each has a different combination of *TETRA radio network infrastructure* and *radio terminals* themselves. (Swan, 2015)

TETRA in North America as well

How the new *TETRA 2 standard* managed to enter the North American PMR market is an interesting story. With much drama, the *Federal Communications Commission*-FCC allowed TETRA to be implemented in the United States no sooner than April 2011, except for some PMR users in the public security sector, whose assigned spectrum was then under reconfiguration. When the FCC completed the final change in the *frequency spectrum* in September 2012, it issued licenses for the unrestricted use of *TETRA technology* and for *public safety mobile radio communications in critical situations* for the parts of the spectrum 450-470 MHz and 809-824/854-869 MHz. After that, the following situation prevailed in the North American PMR market: "*TETRA has clearly become a valuable option for all those owners of functional mobile radio systems (licensees for the use of frequencies), whose basic requirements are that such systems must have high spectral efficiency. In addition, it has become clear that TETRA offers much more effective protection from of neighboring radio channels, compared to all other PMR systems currently operating in LRM bands*."

In many ways, the opportune moment for *TETRA standards* to enter the North American market proved to be a very good opportunity for the already existing set of finished products (*mobile terminals* and *infrastructure devices*), together with their accompanying and peripheral equipment, as well as for a large number of already proven applications which, as such, could all together be immediately offered to the market. This further proved to be quite true, because some large *TETRA systems* have been implemented throughout the United States today, primarily in the segment of transport and services, and it can be said with certainty that there will be many more of them in other organizational and government structures in the future. (Swan, 2015)

Data transmission according to the TETRA 2 standard

When it was decided within ETSI to improve the *TETRA 1 standard*, especially in the framework of the *TETRA data transmission part*, the following reasons were primarily specified and taken into account:

• due to very rapid changes in the world of telecommunications, it was necessary to provide assistance to the entire *TETRA community* in the development of *broadband* and *multimedia services*;

• the introduction of an innovated-more modern standard actually *extends the life cycle* of *TETRA technology* as a whole;

• by introducing an innovated standard, the existing users - owners of *TETRA V + D networks* (*TETRA 1*) are supported for the smooth implementation of "*up-grade*" on these networks;

• the introduction of the innovated standard enables uninterrupted operation of TETRA with *new public mobile telephony networks* (2.5G/3G);

• the new standard actually ensures the future of the existing and security of *new investments* to *TETRA system holders*; and

• by applying this standard, which includes HSD, many benefits of new technologies are realized.

After that, the *Commission No. 28 of EPT TETRA* adopted a revised terms of reference for the innovated *TETRA 2 standard*, which included the implementation of the already partially mentioned requirements:

- support for packet data transmission at higher speeds, which are *up to 10 times higher* than that allowed by the *TETRA 1 standard* (*TETRA V + D* and *TETRA PDO*);

- selection and standardization of additional-new CODECs, for even more effective realization of digitalization of speech signals;

- new improvements in the part of the standard related to the *TETRA radio interface*;

- improving interoperability and enabling roaming with GSM and *2.5G/3G networks* of public mobile radio links;

- development of the *TETRA SIM card* into a new, *TETRA U-SIM card*;

- spatial expansion of operational operability (connection range) in *TETRA networks*, with minimum requirements for the introduction of new BS or for a new expansion of the spectrum; and

- enabling full compatibility and integration of technologies between the *innovated TETRA 2* and the existing *TETRA 1 standard* and the necessary migration. (Nouri, 2016)

For the realization of the thus defined *TETRA 2 standard*, as stated earlier, out of the two proposed different paths of development (two different concepts called *TAPS* and *TEDS*), the concept of TEDS prevailed, which was based on the initial solutions of 5 different technologies of six manufacturing companies. According to the adopted concept, in practice, *new-heterogeneous TETRA structures* were created, whose integration into the system of public radio networks of mobile telephony 3G was realized in the way shown in Figure 6.

Shortly after the release of the innovated *TETRA 2 standard*, several different user requirements were reconciled, which slowly led to better adaptation to changing market conditions, as well as to resolving some of the problems that had led to "conflicts" in the earlier standard. Therefore, the *TETRA 2 User Workshop* (together with the *WG1 EPT*) was able to achieve the following practical results:

• most data transmission applications in previously built *TETRA 1 systems* could now be raised to *the level of speeds of 50-80 kb/s*;

• at the edges of the *BS coverage zones*, a data transfer rate of at *least 50 kb/s* was now provided;

• it is possible to develop adaptive technologies and technologies for high data transmission speeds in order to ensure the investments of the system owner in the long run;

• integrated high-speed voice and data transmission is achieved, where (if required) *speech transmission must be given priority*;

• it was agreed that mobile *handheld terminals* will be made with a *power of 1W* while *mobile transport devices* will have a *power of 3W*; and

• it was agreed that all technological processes be revised in accordance with the above practical results. (Nouri, 2016)

In addition to the above compromise reached between 6 global equipment manufacturers, WG4 EPT has raised some other unresolved issues from the standard, namely:

• resolving all remaining unresolved issues in the domain of the physical layer of the protocol;

• resolving the issue of the highest network layer protocol; and

• resolving the issue of adaptive use of resource systems.

Of course, care was taken to use, as much as possible, the existing quality solutions from the TETRA V + D specification, in order to ensure the necessary compatibility between the earlier TETRA 1 and the modernized version of the TETRA 2 standard (for example: within TEDS, a solution is adopted for the use of the Common Management Channel,

which is identical to the solution of the Management Channel at TETRA V + D). (Nouri, 2016)

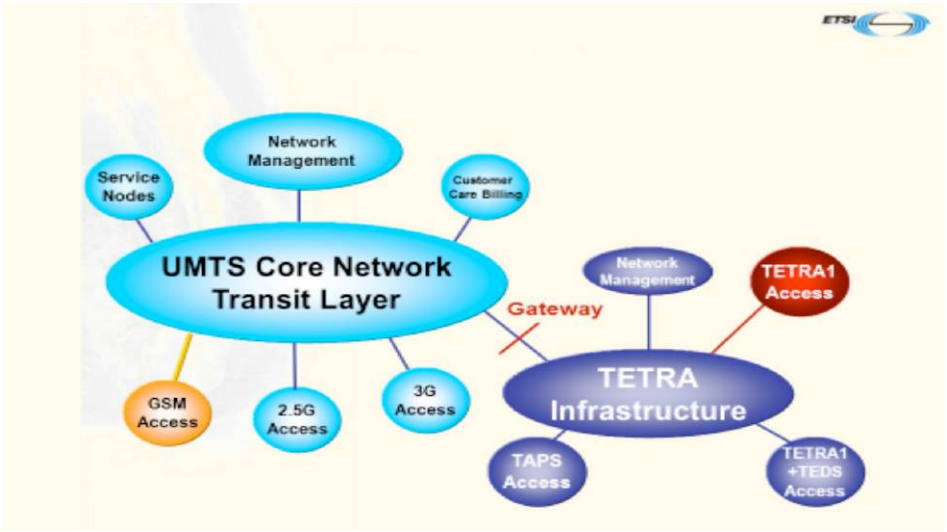


Figure 6 – Presentation of the formation of heterogeneous TETRA structure in the era of 3G network (Nouri, 2016)
Рис. 6 – Презентация формирования гетерогенной структуры TETRA в эпоху сетей 3G (Nouri, 2016)
Слика 6 – Приказ настанка хетерогене TETRA структуре у ери 3G мреже (Nouri, 2016)

Selected parameters from the framework of TEDS technology

TEDS is part of the *new TETRA 2 high-speed packet data standard*, which uses different *RF radio channel* widths for different data rates, with flexible use of the assigned frequency spectrum in the PMR of different system holders. This *TETRA 2 standard* is fully compatible with *TETRA 1*, and provides the ability to easily migrate from *TETRA V + D* to *TEDS*. It is optimized for efficient use of the part of the *radio frequency spectrum* assigned for use to the holders of *functional mobile radio communication systems* and is designed for all applications from the TETRA market segment. TEDS uses a platform with *several radio frequency carriers* on which *TDMA is organized*. In doing so, an *adaptive selection* of several *offered types* and *types* of *modulation* and *coding* was adopted, all in accordance with the current conditions for propagation prevailing in the air and (of course) in accordance with the possible desired *data signal transmission rate*. (Nouri, 2016)

Regarding data *signal modulation*, within TEDS, *5 types were selected from the framework* of *2 types of digital modulations* (QAM and DPSK), as follows:

• 4QAM, to achieve stable and efficient links, even on the edges of BS zones, where radio coverage is not of the highest quality;

• 16QAM, for medium data transfer;

• 64QAM, for high speed data transmission;

• π/4 DQPSK, for the *Official Control Channel* for *TETRA V + D* and *TEDS*; and

• π/8 D8PSK, at the beginning of the migration of previously built *TETRA 1 systems* into new systems (or parts of systems) with TEDS, and when a modest increase in data transfer speed is achieved.

Regarding channel coding, it should be said that within TEDS, optimized coding in the channel is applied, which is in accordance with the *recommendation of STF 179* (*Specialist Task Forces*). In addition, TEDS defines *4 different frequency range widths* around the *radio carrier* (*RF radio channels*), which is directly related to the required data rate, namely:

• 25 kHz,

• 50 kHz,

• 100 kHz, and

• 150 kHz. (Nouri, 2016).

Table 1 shows the ratio of *possible-estimated packet data rates* in (kb/s), depending on the *selected width of the RF radio channel*, and with a strictly defined application of the type and *type of signal modulation*, on the connecting path at the improved "*down-link* ". From the presented Table, it follows that user data signal flow rates *in the range of 10-500 kb/s can be expected* by applying adaptive selection of type and type of modulation, adjusted *RF channel* width and realization of coding according to currently existing conditions for radio wave propagation.

These *estimates of numerical values of flow rates* are valid for the moments when the permission for synchronization and transmission of "*pilot symbol*" (according to the system protocol) has been given, and after the *realized channel coding*, and *transmission of headers* and *functions of lower* (*channel*) *system protocol level*. (Nouri, 2016)

Table 1 – Ratio of possible-estimated packet data rates (in kb/s), depending on the selected width of the RF radio channel and the type of signal modulation
Таблица 1 – Соотношение возможных расчетных скоростей передачи пакета данных (в кБ / с), в зависимости от выбранной ширины РЧ радиоканала и применяемого вида модуляции сигнала
Табела 1 – Однос могућих-процењених брзина пакетског преноса података (у kb/s), у зависности од одабране ширине РФ радио-канала и примењеног типа модулације сигнала

TYPE OF MODULATION	Type of channel (frequency spectrum width)			
	25kHz	50kHz	100kHz	150kHz
π/4-DQPSK	15.6 kb/s			
π/4-D8PSK	24.3 kb/s			
4-QAM	11 kb/s	27 kb/s	58 kb/s	90 kb/s
16-QAM	22 kb/s	54 kb/s	116 kb/s	179 kb/s
64-QAM (r=1/2)	33 kb/s	80 kb/s	175 kb/s	269 kb/s
64-QAM (r=2/3)	44 kb/s	107 kb/s	233 kb/s	359 kb/s
64-QAM (r=1)	66 kb/s	160 kb/s	249 kb/s	538 kb/s

NOTE: All channels use 4 slots

The *flow rate estimation*, in the enhanced link, is actually based on the use of the *MAC-U-BLCK PDU sub-levels* of *the system protocol*, for "*up-link*", and the *MAC-D-BLCK PDU*, for "*down-link*", without permission *for merging multiple* "*slots*". *The PILOT SYMBOL method,* within *TEDS,* is used to assess the quality of data transmission according to the displayed flow rates, through some of the thus formed *Communication channels* with permission to use all 4 "*time slots* "on *one radio carrier*. Such estimates of flow rates and transmission quality enable TEDS to transmit up to *8 multimedia applications* with defined QoS for *real-time transmission* class applications, such as *voice*, *image and video transmission*, *telemetry signal transmission* and others, and all with prescribed characteristics for the selection of flow rate, delay, priority and reliability.

Due to the fact that the new standard maximizes the possibility of reusing the stacks of the *TETRA 1 protocol* and its *TDMA infrastructure*, in practice the processes of evolution and migration from *TETRA 1* to *TETRA 2* have been greatly facilitated, i.e. to the *TEDS standard*. In this way, support is given for the smooth operation of "*isolated radio cells*" within the *heterogeneous network infrastructure*, which will occur when certain parts based on TEDS are implemented in the network. In addition, it also means that within the resulting *heterogeneous infrastructure* "*TETRA 1-TEDS-TERA1*" *networks* normally continue to use existing *TETRA 1 BS*, as there is no systemic conditionality for the

procurement of new ones. As for the essential principle of operation, as mentioned, the *concept of TDMA* has been retained, but now the duration of the "*time slot*" in the *basic TEDS TDM frame* is different, depending on the selected bandwidth (i.e. the selected baud rate data). Thus, the duration of the basic time slot (i.e. the Communication chennel) is now:

• 14.167 ms, when using 25 kHz (or possibly 50 kHz) *radio channel width* on the selected radio frequency carrier, where a *low level of digital signal modulation speed* is realized; and

• 7.08 ms, when using 100 kHz (or possibly 150 kHz*) radio channel width* on the selected radio frequency carrier, achieving a *high level of digital signal modulation speed*. (Nouri, 2016)

Within the innovated standard, it has also been adopted that in *adaptively* selected *quaternary digital signal amplitude modulation* (i.e., xQAM type), each *QAM carrier* consists of *several QAM subcarriers*, around which the basic frequency bands of the 3.125 kHz speech signal are formed. Thus, for example, in a *radio channel* with *a width of 25 kHz*, a total of *8 QAM subcarriers* are realized, each with its basic frequency band of 3.125 kHz. In *radio channels with a width of 50, 100 and 150 kHz*, a relatively *larger number of QAM subcarriers* is realized, so data transfer speeds from 30 to 350 kb/s can be realized in reality. Finally, in this standard it is adopted and realized that *the higher levels of the system protocol from the framework of TETRA V + D* are fully compatible with the *system protocol TEDS*.

As for the support provided by the STF, part of ETSI, for the implementation of the TEDS standard, it consists of the following contributions:

• optimized coding in the radio channel is defined and carrier repetition is enabled;

• an adapted TETRA 2-TEDS protocol has been defined, which refers to higher levels of the protocol - without a physical layer;

• the adaptive TEDS (Link Control) Control Channel has been defined; and

• the use of multimedia services is defined.

In this way, the innovated TETRA standard with TEDS created the conditions which enabled its implementation in the field (in practical mobile radio trunking systems) to achieve fully completed results of providing quality advanced services for the integration of voice

transmission and fast data transmission ("voice" and "data" services), as follows:

• within the mobile radio transmission (group, individual, priority calls and emergency call according to TMO, as well as realization of DMO),

• within mobile telephony (full duplex voice transmission), and

• within high-speed mobile data transmission (transmission of SM and SDTS messages, packet-switched data transmission, circuit-switched data transmission). (Nouri, 2016)

Of course, it would be correct to present the existing limitations of TEDS application in practice, especially in the part of the dependence of the desired data rate on the selected width of the Communication Radio Channel and the distance of the mobile radio terminal from BS, which is systematized in the (Dewaele, 2016).

Conclusion

Due to a very pronounced quality of service it offers, the introduction of a single frequency plan, the possibility of organizing a large number of *Communication-Traffic and Management channels*, as well as the introduction of high-level communications protection, and thus its great prospects, the standard for *Digital Tranning Mobile Radio Communications* has gained high references in just a few years of its existence. After 25 years of its existence, it is safe to say that the *TETRA standard* has become the most accepted in the world, not only *for functional*, but partly *for public mobile radio communication systems* (Svrzić & Ćosović, 2002b). In the development and implementation of this standard so far in a large number of small and large *digital trunking networks of mobile radio communications*, it turned out that, compared to other systems of *digital trunking mobile radio communications*, it is the most suitable and very much needed for application in the Sector of public safety and security, the Transport Sector, the Commercial Services Sector, the Industry, Electricity and Mining Sector, the Government Organizations Sector and local governments and, finally, the military (Svrzić & Ćosović, 2002a, 2002b). Therefore, the total number of *TETRA terminals* operated to date has exceeded the number of 6 million sets, expressing their permanent annual growth of 8% (Swan, 2015).

In this regard, it is important to remember that (based on the *Memorandum of Cooperation and Understanding* of the MoU from 1994) TETRA as an open standard was first accepted, and to this day continuously supported, by most of the world's leading manufacturers of *Analog trunking systems mobile radio communication*. Since then, the

number of manufacturers-supporters of TETRA has been constantly increasing from year to year, so that the list of manufacturers of equipment for mobile radio communication systems according to the *TETRA standard* is very long today.

In fact, the real expansion of the *TETRA standard* occurred in early 1999, when Europe's largest public mobile radio operator Dolphin Telecom Plc decided to start building a *National public TETRA mobile radio system* in the UK and France, and then very soon afterwards in Germany and Belgium. At the *First World Annual TETRA Congress* held in Berlin in 1998, the marketing director of that operator, *Mr. Mark Riley*, stated that the infrastructure of an impressive number of 655 *Base Radio Stations* had been planned for the *National TETRA system of public mobile radio communications* in Great Britain. According to the project, they were supposed to provide coverage of 95% of the total population in Great Britain by the end of 2001. A total of about *200,000 terminal devices* (*10,000 mobile radios for installation in vehicles* and *190,000 portable radio devices*) had been ordered for work in the networks of that system. Unfortunately, due to business failures in general (not related to *TETRA networks*) this large *European public mobile operator of radio communications* had to go bankrupt, so all its built *TETRA networks* were excluded from operational work by the end of 2002 (Swan, 2015).

At that time, many owners of functional systems also took steps to replace their existing systems of *Analog trunking of mobile radio connections*, that is, to build new modern systems of *Digital mobile radio communications* according to the *TETRA standard*. Today, the following realized projects are considered to be the main achievements of *TETRA application* in *Functional systems of mobile radio communications*: *National Network* "*PSRCP/AIRWARE*" in Great Britain, which was put into operation in 2001, then *National Network* "*VIRVE*" in Finland, whose operational use began in 2002, followed by the *National Network* "*ASTRID*" in Belgium, put into operation by 2002, the *National Network* "*C2000*" in the Netherlands, established in 2004 and, most recently, the *National Network* "*BD -BOS* "in Germany, which was completed only a few years ago and which today represents the largest *TETRA network* in the world.

In terms of the future of *mobile radio communications* in general, it should be noted once again that the application of digital technology has enabled integration between *UHF mobile radio communications systems* of the *second generation*, primarily their services, which was the basic direction of further development to *new mobile radio third generation systems*, such as:

1) UMTS (*Universal Mobile Telecommunications Services*), which is a *universal mobile telecommunications system*, within which satellite communications are supported, all with a set of diverse and flexible services, and

2) DAWS (*Digital Advanced Wireless Services*), which is a supplement to UMTS for the transition to *the fourth generation of mobile systems* (developed on the basis of *TETRA PDO*) in order to provide data transmission speeds above 2 Mb/s, that is, up to ATM speeds of 155 Mb/s (*Asynchronous Transfer Mode*), i.e. transfer speeds above those provided by UMTS.

Note that the second generation systems include: *TETRA systems*, Global System Mobile Communications-GSM, then DECT (*Digital Enhanced Cordeless Telecommunications*), and ERMES (*European Radio MEssaging System*).

In this way, *TETRA systems* were provided with a prominent role through the *third generation of mobile radio communication systems*. The permission was obtained that the most modern *4G LTE network* (for now), optimized for *packet data transmission of high speeds* and *low delays*, in terms of complementarity, coincides with TETRA, which speaks of the remarkable perspective of TETRA and its bright future (Swan, 2015).

Finally, it should be noted that the construction of large systems according to the *TETRA standard* is an extremely expensive investment which can only be made by government and state organizations, the richest companies or large operators. Namely, previous experiences and calculations show that the value per connection of the *TETRA system* generally ranges between 1,000 and 1,300 US $. Therefore, smaller owners of the *System of Functional Mobile Radio Communications in Serbia* are about to look for a solution for the construction of such a system for their needs in a joint investment with large economic entities (EPS, NIS, ŽS, JKP and others), with which they will form *virtual TETRA radio networks* for their needs within the already built integrated *TETRA system*. In that sense, in *their virtual TETRA network*, they can then realize a special, closed numbering, and even a special application of cryptosecurity and other ways to protect the confidentiality of information (Svrzić & Ćosović, 2002a), (ETSI, 2009).

When it comes to the part of the *TETRA V + D network "DIMETRA/System Release 6.2"*, which works for the needs of the *MoD and the Serbian Armed Forces* within the *National TETRA network of the Ministry of Interior*, the solution should also be sought in joint activities

with the *Ministry of Interior* on software modernization of the network as a whole, say, in version "*DIMETRA/System Release 8.1*", gradually raising the hardware level of the infrastructure according to the *TEDS specification* (Motorola Solutions, 2013). Reaching that level and the purchase of necessary licenses will create a possibility for the *MoD and the SAF*, within the territorially and infrastructurally unique *TETRA network* with the *Ministry of Interior*, to form its own *virtual functional network*, with its numbering, its cryptographic protection by type "End to end ", with its connecting path capacities and IP connection to the *Military Internet* (*Intranet VS*) and, most importantly, its *Center for Autonomous Administration*, *Management and Supervision* (Motorola Solutions, 2016), (ETSI, 2019), (Motorola Solutions, 2020). In addition to contributing to the infrastructure of the single network, by introducing several new BSs (where in practice it has been shown that there is no quality radio coverage for the SAF), by expanding the capacity of traffic channels by adapting BS MTS-2 to MTS-4 (where practice has shown that existing capacity is unsatisfactory), and with additional successive procurement of modern *TETRA radio terminals* of all types (*manual*, *transport*, *fixed*), coupled with various *peripherals and line terminals for high-speed data transmission* (HSD) and *multi media*, it could then be an *operational and functional high-efficiency UHF mobile radio network*. Such a *TETRA network* could (of course) in peacetime, both in regular and critical and emergency situations, provide exceptional comfort to members of the *MoD and the Serbian Armed Forces* for the implementation of the most complex tasks in the field, training grounds, airports, barracks, command facilities and operational centers, on the move, on the march, and even in the city center itself.

References

Dewaele, J. 2016. *TETRA TEDS Colloquium: "User Requirements", slides 16-25* [online]. Available at: https://cupdf.com/document/tetra-enhanced-data-service-teds-5689e2a49ebfe.html [Accessed: 10 November 2020].

-ETSI-European Telecommunications Standards Institute. 2004. *TETRA PRESENTATION-13121110014-phpappp01*.

-ETSI-European Telecommunications Standards Institute. 2009. *EN 300 392-1 v1.4.1 TETRA Voice plus Data (V+D), Part 1: General network desing* [online]. Available at: https://www.etsi.org/deliver/etsi_en/300300_300399/30039201/01.04.01_60/en_30039201v010401p.pdf [Accessed: 10 November 2020].

-ETSI-European Telecommunications Standards Institute, 2001. *EN 300 392-2 v2.3.2 TETRA Voice plus Data (V+D), Part 2: Air Interface (AI)* [online]. Available at: https://www.etsi.org/deliver/etsi_en/300300_300399/30039202/02.03.02_60/en_30039202v020302p.pdf [Accessed: 10 November 2020].

-ETSI-European Telecommunications Standards Institute. 2019. *ETSI TS 100 392-2 V3.9.1 (2019-01). Technical specification. Terrestrial Trunked Radio (TETRA); Voice plus Data (V+D); Part 2: Air Interface (AI)* [online]. Available at: https://www.etsi.org/deliver/etsi_ts/100300_100399/10039202/03.09.01_60/ts_10039202v030901p.pdf [Accessed: 10 November 2020].

Gospić, N., Tomić, I., Popović, D. & Bogojević, D. 2010. *Razvoj mobilnih komunikacija - od GSM do LTE*. Belgrade: University of Belgrade - Faculty of Transport and Traffic Engineering (in Serbian). ISBN: 978-86-7395-268-0.

Jorgić, D. & Svrzić, S. 2002. *Sistem radio-veze NIS-a "M-21" (deo-V): Koncepcija za izgradnju mobilnih radio-veza NIS-a u tehnologiji digitalnog trankinga (studija).* Novi Sad: Oil Industry of Serbia (in Serbian).

Krstić, M. & Marjanović Jakovljević, M. 2018. Primena TETRA sistema u Vojsci Srbije. In: *Sinteza 2018 - International Scientific Conference on Information Technology and Data Related Research,* Belgrade, pp.210-216, April 20 (in Serbian). Available at: https://doi.org/10.15308/Sinteza-2018-210-216.

-Motorola Solutions. 2008. *DIMETRA™ System Documentation-Dimetra IP D6.2SR: Dimetra IP System Overview.* October, 6866600D54-B.

-Motorola Solutions. 2013. *System Release 8.1, DIMETRA™, DIMETRA IP Compact (DIPC)/Scalable DIMETRA IP (SDIP), System Overview* [online]. Available at: https://kupdf.net/download/motorola-tetra-infrastructure-technical-documentation-library-dimetra-ipcompact81-system-overview-dipc_599e4563dc0d60977053a1f8_pdf [Accessed: 10 November 2020].

-Motorola Solutions. 2016. *MOTOROLA DIMETRA, Applications Cataloogue, Word class solutions handpicked by a world leader in critical communications* [online]. Available at: https://www.motorolasolutions.com/content/dam/msi/docs/business/product_lines/dimetra_tetra/applications/motorola_solutions/documents/static_files/dimetra_applications_catalogue.pdf [Accessed: 10 November 2020].

-Motorola Solutions. 2020. *DIMETRA TETRA infrastructure software features* [online]. Available at: https://www.motorolasolutions.com/content/dam/msi/docs/business/products/scada_products/_documents/static_files/dimetra_tetra_infrastructure_software_features_catalog.pdf [Accessed: 10 November 2020].

Nouri, M. 2016. *TEDS Colloquium: TETRA Enhanced Data Service (TEDS), slides 1-15* [online]. Available at: https://cupdf.com/document/tetra-enhanced-data-service-teds-5689e2a49ebfe.html [Accessed: 10 November 2020].

Ovchinnikov, A.M., Vorobev, S.V. & Sergeev, S.I. 2000. *Otkrytye standarty cifrovoj trankingovoj radiosvjazi*. Moscow: MCNTI, OOO Mobilnye kommunikacii (Ser. izd. Svjaz i biznes). ISBN: 5-93184-008-7. (In the original: Овчинников, А.М., Воробьев, С.В., Сергеев, С.И. 2000. *Открытые стандарты цифровой транкинговой радиосвязи*. Москва: МЦНТИ, ООО "Мобильные коммуникации" (Сер. изд."Связь и бизнес"). ISBN 5-93184-008-7).

-Rohde & Schwartz. 1999a. *TETRA Trans European Trunked Radio for Professional Cellular Systems* [online]. Available at: https://cdn.rohde-schwarz.com/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/Tetra_e.pdf [Accessed: 10 November 2020].

-Rohde & Schwarz. 1999b. *ACCESSNET-T Digital Trunked Radio Network from Rohde & Schwarz* [online]. Available at: https://cdn.rohde-schwarz.com/pws/dl_downloads/dl_common_library/dl_news_from_rs/178/n178_accessnet.pdf [Accessed: 10 November 2020].

Swan, D. 2015. 20 years of TETRA Technology. *RadioResource International*, quarter 2 [online]. Available at: https://radioamador.files.wordpress.com/2012/04/revista.pdf [Accessed: 10 November 2020].

Svrzić, S. & Ćosović, D. 2000. Analogni tranking sistem mobilnih radio-veza (special report - separat). *Novi glasnik*, 1, pp.3-18 (in Serbian).

Svrzić, S. & Ćosović, D. 2002a. TETRA novi standard za digitalne tranking sisteme mobilnih radio-veza (special report - separat). *Novi glasnik*, 2-3, pp.3-36 (in Serbian).

Svrzić, S. & Ćosović, D. 2002b. Comparative analysis of the standards for digital trunked mobile radio systems. *Vojnotehnički glasnik/Military Technical Courie*r, 50(6), pp.567-588 (in Serbian). Available at: https://doi.org/10.5937/vojtehg0206567S.

25 ЛЕТ ТЕХНОЛОГИИ TETRA И СТАНДАРТА СОВРЕМЕННЫХ ЦИФРОВЫХ ТРАНКИНГОВЫХ СИСТЕМ ПРОФЕССИОНАЛЬНОЙ МОБИЛЬНОЙ РАДИОСВЯЗИ

Сладжан М. Сврзич

ООО “Тесла системи“, г. Белград, Республика Сербия

РУБРИКА ГРНТИ: 49.00.00 СВЯЗЬ:
49.33.00 Сети и узлы связи;
49.33.29 Сети связи
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Сегодня для построения функциональных систем мобильной радиосвязи практически исключительно используются транкинговые системы цифровой мобильной радиосвязи, основными представителями которых являются

системы с применением стандартов TETRA. В данной статье описываются истоки и историческое развитие этого стандарта, а также деятельность ETSI и TETRA MoU в борьбе за доступность и гармонизацию радиочастотного спектра.

Методы: В статье освещены важные вопросы о происхождении и развитии стандарта TETRA 1, а также анализ характерных моментов обновленного стандарта TETRA 2.

Результаты: В данной статье описываются истоки и историческое развитие этого стандарта, а также деятельность ETSI и TETRA MoU в борьбе за доступность и гармонизацию радиочастотного спектра. В статье приведено систематизированное использование ключевых систем TETRA в мире с обзором его доли на мировом рынке по секторам, а также освещается дилемма в связи с его дальнейшим развитием, находящемся на перекрестке после 25 лет своего существования. В статье также приведен базовый обзор стандарта TETRA 1 и описаны основные элементы и принципы его применения. Более подробно описываются обновленный стандарт TETRA 2 и улучшения, касающиеся способа передачи данных; особое внимание уделяется процессу сертификации функциональной совместимости и выходу TETRA на рынок Северной Америки. Параметры, выбранные для расширенной передачи данных в соответствии со стандартом TETRA 2-TEDS, представлены и проанализированы наряду с обзором некоторых ограничений при практическом применении.

Выводы: В заключении комментируется настоящее положение современной системы TETRA и анализируется ее будущее после 25-летних разработок, подчеркивая возможность модернизации и улучшения сети TETRA для нужд Министерства внутренних дел Республики Сербия, а также Министерства обороны и Вооруженных сил Республики Сербия.

Ключевые слова: мобильная радиосвязь-MR, система мобильной радиосвязи общего пользования-PAMR, профессиональная система мобильной радиосвязи-PMR, радио-интерфейс-AI, цифровая транкинговая система мобильной радиосвязи TETRA, TETRA расширенная служба передачи данных-TEDS, Европейский институт по стандартизации в области телекоммуникаций-ETSI.

25 ГОДИНА ТЕТРА ТЕХНОЛОГИЈЕ И СТАНДАРДА ЗА САВРЕМЕНЕ ТРАНКИНГ СИСТЕМЕ ФУНКЦИОНАЛНИХ ДИГИТАЛНИХ МОБИЛНИХ РАДИО-КОМУНИКАЦИЈА

Слађан М. Сврзић

Тесла системи д.о.о., Београд, Република Србија

ОБЛАСТ: телекомуникације
ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: За изградњу функционалних система мобилних радио-комуникација данас се готово искључиво користе дигитални системи транкинг мобилних радио-комуникација, чији је главни представник систем са применом TETRA стандарда. У раду се наводе околности настанка и историјски развој тог стандарда, са активностима ETSI и TETRA MoU у борби за доступност и хармонизацију фреквенцијског спектра.

Методе: Описује се развој TETRA 1 стандарда и анализирају карактеристични моменти иновираног TETRA 2 стандарда.

Резултати: Наводе се околности настанка и историјски развој стандарда (са активностима ETSI и TETRA MoU у борби за доступност и хармонизацију фреквенцијског спектра). Систематизована је употреба кључних TETRA система у свету, приказан је њихов удео на светском тржишту по ресорима, а наводи се и дилема у вези с њиховим даљим развојем након 25 година постојања. Такође, представљен је основни стандард TETRA 1, описују се његови основни елементи и принципи примене. Иновирани стандард TETRA 2 и побољшања постигнута у начину преноса података детаљније су описана, наглашен је поступак сертификације интероперабилности и, с тим у вези, улазак TETRA на северноамеричко тржиште. Анализирани су параметри одабрани за напредни пренос података према TETRA 2-TEDS стандарду, а наведена су и нека ограничења током практичне примене.

Закључак: Анализиран је савремени тренутак TETRA и приказана перспектива овог стандарда. Истакнута је могућност модернизације и унапређења TETRA мреже МУП-а Србије за потребе МО и Војске Србије.

Кључне речи: мобилне радио-комуникације-MR, систем јавних мобилних радио-комуникација-PAMR, sistem funkcionalnih mobilnih radio-komunikacija-PMR, радио-интерфејс-AI, digitalni tranking sistem mobilnih radio-komunikacija-TETRA, унапређени TETRA стандард-TEDS, Европски институт за стандардизацију у телекомуникацијама-ETSI.

Svrzić. S., 25 years of TETRA technology and standards for contemporary digital trunking systems of professional mobile radio communications, pp.426-460

Paper received on / Дата получения работы / Датум пријема чланка: 12.11.2020.
Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 11.03.2021.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 12.03.2021.

SPOOFING IN AVIATION: SECURITY THREATS ON GPS AND ADS-B SYSTEMS

Dejan V. Kožović[a], *Dragan* Ž. Đurđević[b]

[a] BEN AIR, Belgrade, Republic of Serbia,
e-mail: dejankozovic@gmail.com, **corresponding author**,
ORCID iD: https://orcid.org/0000-0002-7816-1248

[b] Megatrend University, Faculty of Civil Aviation,
Belgrade, Republic of Serbia,
e-mail: djurdjevic.dragan@gmail.com,
ORCID iD: https://orcid.org/0000-0002-3551-7662

DOI: 10.5937/vojtehg69-30119; https://doi.org/10.5937/vojtehg69-30119

FIELD: Information-comunication technology, Air traffic, Air traffic control
ARTICLE TYPE: Original scientific paper

Abstract:

Introduction/purpose: The paper provides a review of recent research in the field of GPS and ADS-B spoofing. Systems that rely on satellite positioning technology can be targeted by spoofing in order to generate incorrect positioning/timing, which is accomplished by inserting false signals into the "victim's" receiver. Attackers try to insert false positioning information into systems that, for example, provide navigation of airplanes or drones for the purpose of hijacking or distracting security/safety in airspace surveillance. New concepts of navigation and ATC will thus be necessary.

Methods: Using a scientific approach, the paper gives an evaluation of GPS and ADS-B spoofing/antispoofing and how spoofing affects the cyber security of aviation systems.

Results: Based on the methodological analysis used, the importance of studying spoofing/anti-spoofing in aviation is shown.

Conclusion: Although spoofing in aviation is only a potential threat, its technical feasibility is realistic and its potential is considerable; it becomes more flexible and cheaper due to very rapid advancement of SDR technologies. The real risk, in the time to come, are potential spoofing attacks that could occur from the air, using drones. However, aircraft systems are not exposed to spoofing without any defense; receivers can detect it by applying various anti-spufing techniques. Also, pilots are able to detect and solve problems at every stage of the flight. However, due to a possibility of more sophisticated spoofing attacks, international organizations such as ICAO are proactively working to increase GPS and ADS-B systems robustness on spoofing.

Key words: ADS-B, aviation, GPS, radio-frequency interference, spoofing, antispoofing.

Introduction

The modern aerospace system relies heavily on the use of a number of wireless technologies necessary for the safe and secure operation of this very complex system. Thus, communication between air traffic controllers (ATC) and pilots is realized *via* VHF (30-300 MHz) radio frequency (RF) channels. The use of the ADS-B (Automatic Dependent Surveillance-Broadcast) wireless communication protocol or the GNSS (Global Navigation Satellite System), as an integral part of the ADS-B, allows the broadcasting of status data (aircraft position, speed, call sign, etc.), while Primary Surveillance Radar and Secondary Surveillance Radar allow locating aircraft and provide relevant information to air traffic controllers. The TCAS (Traffic Alert and Collision Avoidance System), independent of the air traffic control system, enables the detection and warning of potential collisions of aircraft with other aircraft in the air. In addition to the possibility of verbal communication, aircraft usually have the ACARS system (Aircraft Communications, Addressing and Reporting System) which uses RF communication channels, enabling the sending of automated messages in both directions, by aircraft as well as aircraft and other aircraft entities. Also, many radio navigation systems, such as the GPS (Global Position System), the VOR (VHF Omnidirectional Radio Range), the DME (Distance Measuring Equipment) and the ILS (Instrument Landing System), play key roles in different phases of aircraft flight.

Systems based on satellite positioning techniques, such as the GPS and the ADS-B, can be the target of various attacks, including the so-called spoofing attacks – a sophisticated form of RF interference (RFI) which makes the receiver believe it is at a false location. During a spoofing attack, a radio transmitter, a SDR (Software Defined Radio) for example, located nearby, sends fake GPS signals (which mimic authentic satellite signals, but with higher power and different time delay compared to authentic signals) into the target receiver. Thus, ″a cheap SDR can make a smartphone believe it's on Mount Everest″ (Simsky, 2019).

Regarded as a ″hoax″, ″trick″, or ″deceive″ in the IT world, the term, spoof/spoofing has also been used in the aviation field, in recent studies. Related to the structure of the GPS signal (it is public and unlike military GPS signal, this is not encrypted/authenticated), it would not be difficult/expensive for an adversary to build a system that creates signals that would appear to a receiver to be from GPS satellites. Transmitting these false signals to receivers may cause them to lock onto the false signals instead of the authentic satellite signals. Thus, in 2001, the U.S.

Department of Transportation assessed the U.S. transportation infrastructure's vulnerability to civil GPS disruption (John A. Volpe National Transportation Systems Center, 2001). Their report known as the Volpe report, considers civil GPS spoofing, a dangerous type of intentional interference whereby a GPS receiver is fooled into tracking counterfeit GPS signals. Spoofing is more sinister than intentional jamming because the targeted receiver cannot detect a spoofing attack and therefore cannot warn users that its navigation solution is untrustworthy. Moreover, even if not fully successful, spoofing usually will inject hazardously misleading information and create significant PVT (Position, Velocity, Time) errors. Ever since, civil GPS receivers remain as vulnerable as ever to this threat.

Recent efforts to modernize ATC have mandated the gradual replacement of the existing analogue radar system with a next-generation (NextGen) digital one. Part of this NextGen system is the ADS-B standard. The ADS-B aims at improving aviation safety by enabling aircraft to broadcast navigation information. However, the current ADS-B standard does not provide mechanisms for verifying the integrity of navigation broadcasts. Consequently, the ADS-B system is extremely vulnerable to various spoofing attacks (Schäfer et al, 2013). Therefore, concerns about its safety will continue to increase with the development of ATC and the further popularization and application of the ADS-B.

It should be emphasized that, unlike spoofing attacks from the ground, potential attacks that could be carried out from the air (the attacker is in the air) are still insufficiently investigated (Costin & Francillon, 2012), but they represent a real threat. These attacks can be realized with the use of drones, i.e. UAV (Unmanned Aerial Vehicle), and special attention must be paid to this type of potential attacks. Because of all this, the OpenSky Network research project collects ADS-B reports and makes them available for security/safety analysis and development of spoofing attack detection concepts, as well as locating spoofing devices/sources.

Also, the increasing use of UAV/drones and the GPS for their navigation makes these systems interesting targets for the purpose of hijacking or distracting safety/security in airspace surveillance. Thus, the normal navigation performance of drones may be limited due to natural signal noise or intentional RFI, jamming and spoofing. In particular, as for the spoofing of GPS, military GPS signals are encrypted and thus cannot be changed (Spilker et al, 1996), but civilian GPS signals are unencrypted/unauthenticated, and thus a user can arbitrarily generate or

change signals. Namely, by using arbitrarily manipulated signals, it is possible to make a UAV target deviate from the existing path and lead the UAV to a target point designated by the spoofer. In recent years, the Federal Aviation Administration (FAA) announced a plan that the entrance of civilian UAV into the airspace of the US would be permitted by September 2015, and Amazon has been trying to implement a delivery system using drones. In this situation, spoofing could be a serious problem for the operation of UAV. In a hypothetical combat situation, manipulating the enemy's GPS receiver would mean taking control of the drone or devices that rely on GPS positioning. For example, in 2018, Russia accused the US of spoofing a drone and redirecting it to attack a Russian air base in Syria (Simsky, 2019). Also, in the last few years, numerous spoofing incidents have been recorded in the seas near the Russian border, and it is assumed that the drones were "transported" to nearby airports. This type of spoofing may have been a defense mechanism for landing spy drones. Namely, most semi-professional UAV on the market have a built-in geo-fencing mechanism, which automatically lowers them to the ground if they approach airports or other areas with restrictive access.

Modernization and strengthening of aircraft systems through improvements and innovations in design, technology and efficiency is opposed by fragility in the field of cyber security. Cyber security threats are not only an assumption, but some have been realized. An overview of published cyber incidents and potential vulnerabilities of aircraft systems observed by aviation organizations and researchers/hacker community (from 1997 to 2019) is given in the paper (Kožović & Đurđević, 2019). For example, the weaknesses of the ATC system, by introducing a “ghost-plane” into a flight control system, by mimicking the ADS-B signal, by using low-cost technology devices, and software, have been pointed out (Costin & Francillon, 2012). Then, it was shown that radio navigation systems such as the GPS and the ILS (Sathaye et al, 2019) are susceptible to spoofing attacks, and that by spoofing TCAS messages, false messages can create resolution advisories, which forces pilots to resort to collision avoidance maneuvers.

In addition, until recently, the attitude of civil aviation regarding GNSS spoofing was simple (Berz, 2018): "This is not our problem", and this issue was considered to be within the scope of military structures. However, as more attention is paid to common RFI, the approach to spoofing is changing, which was partly initiated by the incident at Hanover Airport in 2010 (Steindl et al, 2013), and which was caused by the interference of GPS repeaters and thus inadequate positioning of the

GNSS system. Today, it is known that there is a whole range of intermediate stages of spoofing, from incorrectly tuned repeaters, all the way to what a skilled, but unreasonable person could do by using cheap and widely available spoofing devices.

Although different parts of the aircraft system are exposed to various attacks, and potentially to spoofing, there are certain security solutions and protocols while different working groups, conferences and organizations, such as ICAO (International Civil Aviation Organization), RTCA (Radio Technical Commission for Aeronautics) and EUROCAE (European Organization for Civil Aviation Equipment), continuously analyze and monitor the development of effective antispoofing detection methods, as well as their integration into flight control, communication and navigation systems. For example, RTCA has set as a goal for next-generation aeronautical equipment, increasing the security of GNSS to risks in the presence of threats, including spoofing. Current directions in solving spoofing by RTCA and EUROCAE primarily relate to the introduction of new requirements for the detection of spoofing GNSS systems, which allows the use of alternative navigation equipment, without significant safety risks (Hegarty et al, 2018).

GPS: background and spoofing overview

GPS: a fundamental concept

The Global Positioning System (GPS) is satellite navigation, i.e. constellation of satellites that emit RF waves in order to accurately determine the position on/near the Earth's surface. They were first used for military purposes (since 1950s), and later (in 1980s) they were made available for wide, civilian use. A common term for different types of globally used satellite navigation systems is GNSS, such as GPS (USA), GLONASS (Russia), BEIDOW (China), etc. GNSS is a system that gives pilots, as well as aircraft systems, precise information about the position of the aircraft, as well as the reference time.

Although the GPS is the only fully operational GNSS "first generation", GLONASS, which covers Russia and neighboring countries, is also available, while Europe is developing a "second generation" GNSS, called the Galileo program, which in 2003 was also signed by China. Today, in addition to GNSS, there are several additional satellite systems, generically called Space Based Augmentation Systems (SBAS) (Sabatini et al, 2017), because they emit additional signals that a particular receiver can decode and use (along with global GNSS signals) in order to improve positioning performance.

The GPS consists of three segments: space[1], control[2] and user.

The GPS uses satellite transmitters whose locations L_i^S (coordinates, $\left(x_i^S, y_i^S \text{ and } z_i^S\right)$ are known (Tippenhauer et al, 2011). Each transmitter is equipped with a very precise synchronized clock for measuring the exact system time, t^S and emits a navigation signal $s_i(t)$, (low auto- / cross-correlation) which contains timestamps and deviations of the satellite from the predicted trajectory. The signal is transmitted at speed *c*.

A receiver V, located at the coordinates L (to be determined) and using an omnidirectional antenna, will receive the combined signal of all satellites in the range:

$$g(L,t)=\sum_i A_i s_i\left(t-\frac{\left|L_i^S-L\right|}{c}\right)+n(L,t) \qquad (1)$$

where A_i is the attenuation that the signal is undergoing on its way from L_i^S to L, $\left|L_i^S-L\right|$ denotes the Euclidean distance between L_i^S and L, and $n(L, t)$ is background noise.

Due to the properties of the signals $s_i(t)$, the receiver can separate the individual terms of sum (equation 1) and extract the relative spreading code phase, the satellite ID, and data content using a replica of the used spreading code. Given the data and relative phase offsets, the receiver can identify the time delay $\frac{\left|L_i^S-L\right|}{c}$ for each satellite, i.e. "ranges": $d_i=L_i^S-L$, from where, knowing the positions of the transmitter, L_i^S, one can find the 3-dimensional position, L of the receiver.

However, the receiver clock is delayed, i.e. has a time offset, δ relative to the exact system time, t^S, so that the receiver gives ″pseudoranges″:

[1] GPS satellites are called NAVSTAR (Navigation Satellite Timing and Ranging).

[2] Control Center (the main checkpoint is Shriver Military Base, Colorado) checks the satellite condition, position, speed and altitude. The precise trajectory of the satellite is updated on average every 4 hours and the data on the updated orbits are sent to the satellites via terrestrial radio antennas.

$$R_i = d_i - c \times \delta = d_i - \Delta \qquad (2)$$

By measuring the distance from each satellite (at least four) and solving the system of nonlinear equations (2) for both L and δ, precise data (position and time) are obtained and then used used for navigation, positioning and accurate time distribution.

Today, GNSS receivers are very cheap and compact devices, and are widely used in various systems (e.g. SCADA), in mobile phones and in many widely used products. The GNSS design allows three basic messages to be broadcasted, namely:

- positioning, velocity and time signal,
- precise ephemeris data, which determine the exact location of an individual satellite,
- an almanac, which determines the locations and orbits of all satellites in the constellation, together with information on the status of the selected tracking satellite.

All types of GNSS satellites broadcast on at least 2 bands: on the frequency L1–encrypted military code, the so-called P(Y) and unencrypted civil code (C/A), as well as frequency L2 (repeat P(Y) code). So, all satellites broadcast on 2 frequencies: 1575.42 MHz and 1227.6 MHz. As the GPS uses a wide range of techniques, the so-called multiple code-sharing approach, low-pass message data is encoded by a high-level pseudo-random sequence which is different for each satellite. Thus, the receiver can distinguish signals (PRN codes) coming from different satellites and message data is transmitted at a speed of 50 bit/s.

Two different encodings are used (Fig. 1) (Warner & Johnston, 2002), i.e. two PRN codes: Coarse/Acquisition (C/A) code (so-called gold code) on 1.023 MHz and precision (P(Y)) on 10.23 MHz. The signals are modulated to a carrier signal, L1 and L2, by the binary phase shift keying method which encodes 1 bit per phase shift (Betz, 2002). Carrier L1 is modulated with both C/A and P codes, while L2 is modulated only with P code; the C/A code is public and used by civilian GPS receivers, while the P code can be encrypted, and is only available to military equipment with the appropriate description key. Each L1 signal is composed of a navigation message which provides detailed data on the ephemeris (orbit data) of the satellite.

ICAO and EUROCAE are developing standards for the next generation of GNSS in civil aviation (Hegarty et al, 2015) and promoting

a discussion on the evolution of the role of the GNSS in aviation, while encouraging the necessary technical and technological development (Berz, 2018). Thus, ICAO has published a version (for verification and validation) of the concept of operations for the use of the Dual-Frequency Multi-Constellation (DFMC) GNSS in aviation (ICAO, 2018), the final version of which should be completed by 2022, while the Minimum Operational Performance Standard (MOPS) for GPS and Galileo on the frequency bands L1/E1 and L5/ E5a, is in the process of defining. The DFMC GNSS is expected to replace the current single-frequency GPS L1-C/A in future civil aviation regulations. Other evolutionary concepts involving the prominence use of the GNSS include the following systems: Advanced Receiver Autonomous Integrity Monitoring (ARAIM), Airbone Separation Assurance System (ASAS) (SkyBrary, 2020) and Multi-dimensional trajectory management (Enea & Porretta, 2012).

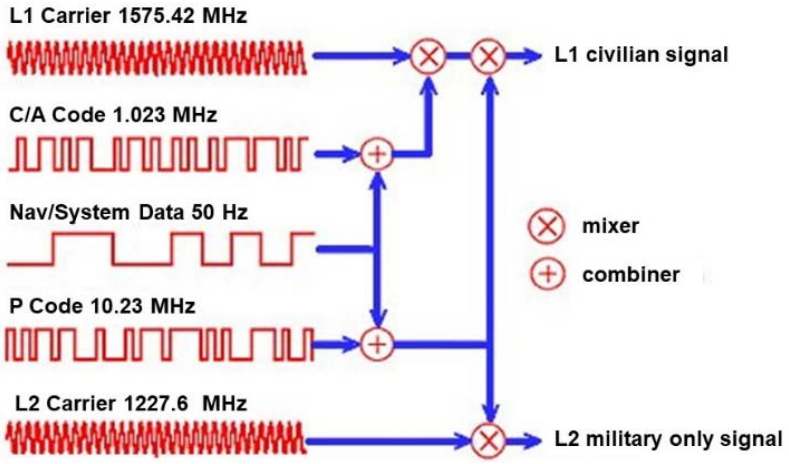


Figure 1 – Structure of a GPS signal (Warner & Johnston, 2002, p.20)
Рис. 1 – Структура сигнала GPS (Warner & Johnston, 2002, p.20)
Слика 1 – Структура ГПС сигнала (Warner & Johnston, 2002, p.20)

GPS spoofing basics

GNSS vulnerabilities (Morales-Ferre et al, 2020) in connection with RFI cause concern and special attention in the field of aviation, i.e. incidents of disappearance of GPS signals in civilian aircraft (especially in areas with political tensions, e.g., Southeast Mediterranean, Black Sea–Caspian Sea axes and Mideast-Canada and the USA via North Pole through Russian airspace) or nearby airports. The reasons for this

can be different, such as solar storms, military exercises, etc., but also intentionally provoked RFI, i.e. jamming (EUROCONTROL, 2019). Near airports, uninformed personal privacy devices could also be the cause of GPS jamming. Consequently, jamming can be considered as a realistic and threatening kind of interference. On the other hand, spoofing is a more subtle and potentially even more dangerous threat, where an ensemble of counterfeit GNSS-like signals are injected into a victim receiver with the purpose of inducing a wrong positioning or timing provision of measure (Nicola et al, 2020). Hence, a much more subtle and dangerous form of a GNSS threat is spoofing, in which false signals are inserted/planted into the "victim's" receiver for the purpose of mispositioning or timing.

Although GNSS spoofing is a potential threat (there are still a few confirmed reports of their exploitation in civil aviation), the technical feasibility of spoofing is realistic, and its potential is great. A noticeable difference between legitimate satellite signals and a spoofing signal can be a discrepancy in time, signal direction, intensity, Doppler shift, or the magnitude of the signal-to-noise ratio. However, most receivers are not equipped to detect these differences. Research in this area (Horton & Ranganathan, 2018) shows that almost every device that uses a civilian GPS signal is vulnerable to spoofing, and the application of spoofing becomes more flexible and cheaper due to the very rapid progress of SDR technologies.

The case of interference at Hanover Airport (in 2010), is an example of real "unintentional" spoofing (Steindl et al, 2013), which shows that the detection/immediate warning of GNSS spoofing is a necessary countermeasure to ensure airport safety and security. Namely, a plane which was located near the threshold of the runway of Hanover Airport, and whose aircraft systems functioned according to the repertoire signals for testing the avionics of business planes in the hangar near the threshold of the runway, had the wrong GPS position during the taxiing and takeoff phase. This scenario, although simple, can be used as a starting point for testing a GNSS receiver or any hardware that depends on precise positioning or time data provided by the receiver. Then, during the FAA's installation of a new GPS-based aircraft landing system at Newark International Airport in 2010, it was observed that ground-based GPS receivers (used to assist GPS receivers on the approaching aircraft) also had several interruptions, almost every day. Also, it was previously reported to the FAA (July, 2003) that the switched-on mobile phone simultaneously affected the operation of three different aircraft GPS receivers, causing a complete signal loss; all three GPS receivers used

three different antennas, installed on a small plane, and a mobile phone was turned on (without making the call), during the incident, as well as subsequent testing (Nguyen, 2004).

The use of the GNSS in aircraft landing and take-off procedures causes the aircraft system to be vulnerable to spoofing. Most commercial aircraft still primarily use the ILS, but there is also a noticeable increase in interest in using the fully automatic landing system, the GBAS (Ground Based Augmentation System), especially in Europe and Russia. However, the introduction of this system, as an international standard, has been slowed down due to the fact that the GBAS system is not authenticated and can be spoofed. As most GNSS receivers used for the GBAS are positioned on the ground (airports), the height of each aircraft can be spoofed, which can potentially lead to an accident. Also, interfering (accidentally or intentionally) with the aircraft's GNSS receiver in approach or departure would be relatively simple and could lead to significant loss of life.

The use of AGC (Automatic Gain Control) to amplify the GNSS signal, which compensates for the strength of the fluctuating signal, also leads to the vulnerability of the receiver to spoofing (Borowski et al, 2012). It is also very important to consider that the receiver does not have the ability to determine where the signal is coming from (from a locally generated false or legitimate source) since the receiver antenna is usually located at one point in space: if the receiver is not protected, the spoofing signal can be inputed directly via the spoofing source. Or, if the spoofer knows the exact location of the target receiver, then the spoofer signals can be superimposed on the authentic signals. Alternatively, stronger asynchronous signals can be used, but this way of spoofing is effective only when the receiver is in the initial phase of operation (reception) or in case it is "forcibly unlocked" by an interfering signal.

There are different forms of GPS signal spoofing, and they can be classified in different ways, such as according to the level of complexation (Humphreys et al, 2008), to simplified, intermediate and sophisticated, or based on their characteristics, to synchronized (spoofing attack in which the false signal is synchronized with authentic GNSS signals) and unsynchronized.

Thus, in the simplest form of spoofing attacks, the receiver (in tracking mode) can receive a false signal when it loses the reception of the signal from the satellite, so that it can be "locked", i.e. swished to the mode of receiving the spoofing signal. The signals are usually not synchronized with the original signals, which allows the use of simple commercial (COTS) components. Detection of this type of spoofing is

relatively simple – the lack of signal synchronization would cause a sudden jump in output signals related to the position of the receiver and time. Also, if the spoofing signals are high, then the monitoring receiver could potentially detect increased activity in the GNSS frequency bands. In a medium-strength (intermediate) spoofing attack, a kind of GNSS simulator is used to produce counterfeit GNSS signals, but they are synchronized with GNSS signals coming from the satellite. Such an attack includes the known location (and path) of the "attacked" receiver, relative to the receiver antenna, to ensure that the false, pseudo-signal band is "aligned" with the authentic codes at the position of the attacked receiver. When the receiver is in the tracking mode, and at the beginning of the attack, the false signals are well enough aligned with the authentic ones, so that the spoofer can take control by gradually increasing the power and successively adjusting the signal. Detection on the target receiver is almost impossible, except when a large number of antennas are used to estimate the signal arrival direction. A more complex version of intermediate spoofing is sophisticated spoofing in which multiple coordinated "intermediate spoofers" could be used to replicate the content and "align" GNSS signals, as well as their spatial distribution, making this form of attack more difficult to detect. However, in this type of attack, the receiver for monitoring at another location (allocated) is likely to have a sharp increase in the value of the output signals related to the position of the receiver and time, since its position differs from the position of the target receiver. Also, if the spoofing signals are high, then the allocated monitoring receiver could potentially detect increased activity in the GNSS frequency bands.

Numerous methods of spoofing detection and mitigation of spoofing attacks on GNSS (Magiera & Katulski, 2015) are proposed such as AGC surveillance, SNR (signal to noise ratio) monitoring, consistency checking of PVT, cryptographic methods (Hegarty et al, 2018), and monitoring of the correlation function of signals and multiple peaks (Turner et al, 2020). For example, one of the suggested methods is based on checking whether the received signals are modulated with the military P(Y) code, which is usually absent in spoofing signals (Psiaki et al, 2011). Despite being effective, this solution uses two receivers and requires that one of them be protected from spoofing, which is not always possible. In general, the effectiveness of the proposed antispoofing method depends on the level of sophistication of the device for generating false signals, i.e. scenarios of spoofing attacks, and tests in this area are performed to find sensitive, fast, robust, and reliable methods for detecting spoofing. As most spoofing scenarios use a single antenna to transmit counterfeit

signals, the spatial characteristics of false signals differ from the characteristics of authentic GPS signals. Therefore, anti-spoofing techniques based on spatial signal processing can be used as generics, and simulations and tests show that they are very effective in detecting spoofing (Jafarnia-Jahromi et al, 2012).

In aviation, specific requirements for recording all GNSS data relevant to GNSS operations are detailed in the ICAO Guidelines (ICAO, 2006). The State is the lead authority for approving GNSS-based operations and should ensure that GNSS data relevant to those operations are recorded, as well as support periodic confirmation that accuracy, integrity, continuity, and availability are maintained within the limits required for approved operations. Airport control towers and units providing access control services must have data/information on the operational status of airport radio navigation systems, which is essential for the approach, landing and take-off of aircraft. The performance of all navigation systems must be in accordance with the requirements of the ICAO GNSS Signal in Space Performance Requirements (ICAO, 2006).

ADS-B: background and vulnerability against the spoofing attack

ADS-B: a fundamental concept

The Automatic Dependent Surveillance - Broadcast (ADS-B) is a modern technological system which combines the existing technical solutions in the field of telecommunications, navigation, and airspace surveillance (Ali, 2016). It is an integral part of the FAA project NextGen and Eurocontrol CASCADE program which should improve the air traffic system in terms of safety, economy, automation, ecology, etc. The special importance of ADS-B technology is emphasized by the allocation of a special category 21 ASTERIX protocol for the exchange of information on aircraft (EUROCONTROL, 2011).

The ADS-B system automatically delivers the necessary data to users (both on the ground and in the air). Its integral part is the GNSS, so that the ADS-B system depends on the accuracy of the positioning system. The ADS-B standard regulates the exchange of broadcast messages between aircraft and ATC ground stations. It can work as a transmitter (ADS-B Out) or a receiver (ADS-B In). The ADS-B In allows the aircraft to receive data which is displayed on the CDTI (Cockpit Display of Traffic Information) interfaces (most often, MFD[3] and EFB[4]

[3] MFD – Multifunction Display

devices), and which are emitted by other aircraft positioned in a relatively close environment. The same information is used for TCAS systems. Within the ADS-B Out system, the status information of the aircraft is handed over.

The ADS-B system consists of three interdependent components:
- ground infrastructure (GBT stations[5] and antenna system),
- aircraft equipment (ADS-B specialized transponder, GPS, receiver, altimeter, CDTI[6], etc.),
- operational procedures (regulatory basis for the implementation and use of the ADS-B system).

Communication within the ADS-B is realized by using the radio system according to standardized communication protocols, such as 1090 MHz extended squitter (1090-ES), 987 MHz Universal Access Transceiver (UAT) and VHF Datalink Mode 4 (VDL-M4), which will be used depends on the type of aircraft (in accordance with the FAA guidelines). Each ADS-B message contains an 8 μs preamble for synchronization and a 56-bit (short) or 112-bit (extended) data block. Thus, an extended ADS-B message has 112 bits which are transmitted using 1090 MHz ("extended squat") data links (FAA, 2010). The ADS-B protocol format with a 112-bit message frames contain a preamble (8.0 μs), which is used to synchronize transmitters and receivers and 112-bit payload which consists of five segments. The first, 5-bit segment contains telecommunication transmission data and refers to the downlink format used to encode broadcast messages, the second, 3-bit segment is the field of choice, while the third, 24-bit segment contains a unique aircraft address. The next 56 bits (ADS-B data) refer to sub-segment data such as flight identification (call sign), position (latitude/longitude), position accuracy, barometric and geometric height, vertical velocity, trajectory angle, and ground spead (Ghose & Lazos, 2015). ADS-B messages are not encrypted: the last 24 bits include a parity check that detects and corrects transmission errors in the messages. ADS-B frames are modulated by pulse modulation with a pulse length of 1 μs. As the ADS-B protocol transmits data at a speed of 1 Mbit/s, the total duration of the ADS-B extended message is 120 μs (including the preamble).

[4] EFB –Electronic Flight Bag
[5] GBT stations – Ground Based Transceivers stations.
[6] CDTI – Cockpit Display of Traffic Information.

Cyber attacks on the ADS-B

The risks faced by the ADS-B system are essentially related to communications realized by RF waves, i.e. they are related to the fact that messages are transmitted as text and have no encryption. Because of that, they are the main targets of malicious hackers (Kožović & Đurđević, 2019). Thus, the security risks faced by the ADS-B relate to ATC–aircraft connections, and if they are not secure, ADS-B messages may be hacked by authorized/unauthorized persons, especially when messages containing sensitive information are interrupted or eavesdropped.

Attacks on the ADS-B, which can have different levels of impact on aircraft systems, include eavesdropping, jamming, message insertion, message deletion, and message modification (Table 1) (Wang et al, 2020).

Table 1 – Different types of attacs on the ADS-B system (Wang et al, 2020, p.3)
Таблица 1 – Различные типы атак на систему ADS-B (Wang et al, 2020, p.3)
Табела 1 – Различите врсте напада на АДС-Б систем (Wang et al, 2020, p.3)

Attack type	Purpose of attack	Way of attack
Eavesdropping	Eavesdrop operating status information of aircraft (aircraft reconnaissance)	Obtain ADS-B data of the corresponding airspace through ADS-*B In*
Jamming	Jam the transmission of an ADS-B message in a specific airspace	By using an ADS-B transmitting device with sufficient high transmit power in the relevant frequency band
Message injection	Inject fake aircraft into a specific flight scenario, confusing ATC systems (aircraft target ghost injection/flooding)	By using a transmitting device with sufficient high transmit power in the relevant frequency band and capable of generating correct modulation and conforming to the ADS-B message format
Message deletion	Delete some or all of the information contained in a message (aircraft disapperance)	By implementation at the physical layer through constructive/destructive interference
Message modification	Modifify the information contained in a message (virtual trajectory modification)	Realized by overshadowing and bit-flipping at the physical layer of the system and can also be achieved by combining two attack methods

Thus, eavesdropping causes minimal damage, because it does not directly damage the ATC system, while deleting messages affects the aircraft surveillance system (the aircraft temporarily disappears from the ATC map), but the aircraft can be identified by radar or multilateral systems. Message modification is a typical "spoofing" attack and has a major impact on the ATC system. For example, a spoofing attack, the so-called "boiled frog" (Chan-Tin et al, 2011), refers to a situation in which an attacker continuously, but to a small extent, changes the information about the position of the aircraft in the CSDP messages. In this case, it is difficult for surveillance technologies such as radar surveillance systems and positioning, to detect small differences which are within the accuracy of adjustment, resulting in inaccurate control of aircraft by air traffic control, as well as delayed system response to prevent collision in the air.

ADS-B spoofing

A spoofing attack on the ADS-B refers to an attack by modifying ADS-B messages, which is realized by inserting fake/falsified messages. It can be considered as an attack from both the ground and the air. An illustration of two different types of spoofing attacks on the ADS-B is given in Fig. 2; namely, a spoofing attack by inserting messages and a spoofing attack on the ground station. In the first type of attack, the attacker uses a cheap SDR to re-broadcast a previously recorded message (so-called repeat attacks) or to transmit a newly generated and correctly modulated fake message (attack by introducing a ghost plane). The main goal of the attack is to falsify the presence of the non-existent, i.e. aircraft-ghost and to cause confusion of the ATC system. In the second type of attack, the attacker modifies the ICAO address in the ADS-B messages using the ADS-B transponder in the air posing as a known/reliable aircraft, thus bypassing surveillance.

Thus, depending on the way the spoofed messages are generated, ADS-B spoofing attacks can be divided into three types (Ying et al, 2019):

- message or IQ data[7] replay attack,
- ghost aircraft injection attack, and
- aircraft spoofing attack.

[7] IQ data/signals (samples or quadrature signals), are a pair of periodic signals wich differ in a phase by 90°; designation I, refers to the in-phase (reference signal), while Q refers to the phase-shifted signal.

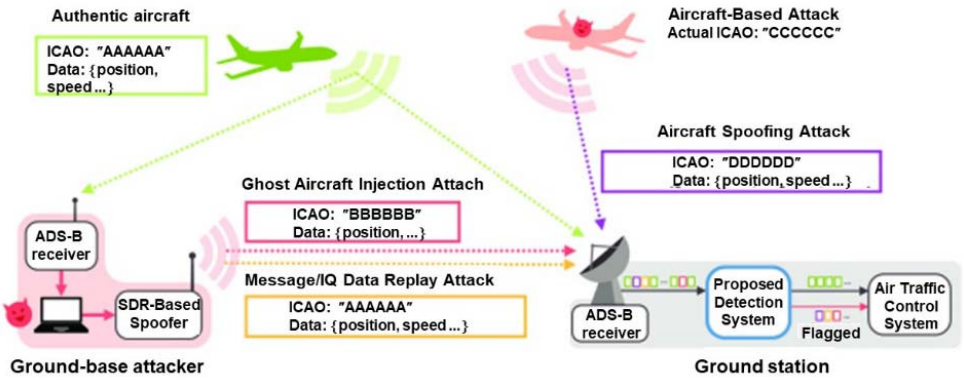


Figure 2 – Illustration of two types of attacks on the ADS-B: the ground-based attack, using a SDR spoofer and an aircraft-based attack where the attacker uses an ADS-B transponder with a changed ICAO address (Ying et al, 2019)
Рис. 2 – Иллюстрация двух типов атаки на ADS-B: наземная атака с использованием спуфера SDR и воздушная атака, при которой злоумышленник использует транспондер ADS-B с измененным адресом ICAO (Ying et al, 2019)
Слика 2 – Илустрација две врсте напада на АДС-Б: напад са земље, коришћењем СДР спуфера и напад из ваздушног простора (авиона), при чему нападач користи АДС-Б транспондер с измењеном ИЦАО адресом (Ying et al, 2019)

In a message/IQ data replay attack, an attacker from the ground records the content of the messages/IQ data of the received authentic ADS-B messages using an SDR, and then transmits the same messages at a later time without changing the message content. This attack is very sophisticated, because the recorded IQ data contains a lot of information, such as those related to the Doppler effect, the transmitter characteristics, and the channel characteristics, which is difficult to mimic otherwise. In a ghost aircraft injection attack, a ground-based attacker, using an SDR device, transmits fake ADS-B messages with arbitrary content of its choice. In particular, an attacker can simulate the trajectories of non-existent aircraft ("ghosts") and generate appropriate ADS-B messages by carefully selecting Doppler displacements, thus making these "aircrafts-ghosts" visible to earth stations. In an aircraft spoofing attack, an aircraft-based attacker (malicious aircraft) attempts to masquerade as a known or trusted aircraft by spoofing the ICAO address and hide its true identity. Since the aircraft is physically present, the masquerading attack will not be detected even if the secondary radar surveillance system is deployed.

To detect spoofing, i.e. for the protection of wireless ADS-B communication, various security methods have been proposed, based on the existing cryptographic techniques (Finke et al, 2013), (Alghamdi et al, 2018). An alternative to this are necryptographic approaches which are based on signal separation (PHY-layer signal separation) (Leonardi et al, 2017), time and position verification (Schäfer et al, 2015), Doppler shift (Schäfer et al, 2016), etc. The most recently developed methods for ADS-B system spoofing detection are based on the predictions of mathematically set models and network analysis. One of these is the method based on a SODA-DNN (Deep Neural Network) spoofing detector (Ying et al, 2019), whose application allows the detection of spoofing attacks with a very high probability and a very small proportion of false alarms, which is a significant improvement over other state-of-the-art detectors.

Conclusion

Systems based on satellite positioning techniques, such as the GNSS and the ADS-B, can be targets of various attacks, including the so-called spoofing attacks – a sophisticated form of attack in which false signals (which imitate authentic satellite signals, but with higher power and different time delay in relation to authentic signals) are emitted. As a result, aircraft will send incorrect information about their position.

One of the most important steps in the modernization of ATC is the transition to the ADS-B wireless communication protocol, of which the GNSS is an integral part. In addition to its advantages, the ADS-B system also has several very important disadvantages, such as dependence on the satellite navigation system (which can be physically damaged, corrupt, or subject to interference) and a very simple protocol, which does not provide full authentication and encryption. All this increases the vulnerability of the ADS-B system to various types of cyber attacks, such as RFI, including spoofing, i.e. deliberately inducing RFI.

Also, the role of GPS/GNSS is constantly increasing, due to the increase in the use of UAV/drones, which is why new concepts of navigation and ATC will be necessary in a "crowded sky" situation, where many unmanned aerial vehicles will share airspace with crews. On the other hand, the increasing use of drones and the GPS for their navigation makes these systems interesting targets for the purpose of hijacking or distracting security/safety in airspace surveillance.

Although the spoofing of the GNSS system is a potential threat - there are still no confirmed reports of their exploitation in civil aviation,

the technical feasibility of spoofing is realistic and the potential is great. Research in this area shows that almost every device that uses L1 civilian GPS is vulnerable to spoofing, and the application of spoofing is becoming more flexible and cheaper due to the very rapid advancement of SDR technology. Therefore, the issues of detection and prevention of spoofing attract the attention of researchers in the field of cyber security, and due to possible more sophisticated spoofing terrorist attacks on the aircraft system, ICAO, RTCA and EUROCAE are proactive in improving the robustness of GPS/GNSS to RFI.

However, the aircraft system is not helplessly exposed to spoofing attacks without any defense; by applying various anti-spoofing methods, GNSS receivers can detect spoofing by looking for signal anomalies or using signals designed to prevent spoofing, and advanced interference mitigation technologies use signal processing algorithms. Certainly, the effectiveness of the proposed antispooffing method depends on the level of sophistication of the device for generating false signals, i.e. scenarios of spoofing attacks, and tests in this area are performed in order to find sensitive, fast, as well as robust and reliable methods for detecting and mitigating spoofing.

References

Alghamdi, F., Alshrahani, A. & Hamza, N. 2018. Effective security techniques for automatic dependent surveillance-broadcast (ADS-B). *International Journal of Computer Applications*, 180(26), pp.23-28 [online]. Available at: https://www.ijcaonline.org/archives/volume180/number26/alghamdi-2018-ijca-916598.pdf [Accessed: 25 December 2020].

Ali, B.S. 2016. System specifications for developing an automatic dependent surveillance-broadcast (ADS-B) monitoring system. *International Journal of Critical Infrastructure Protection*, 15, pp.40-46. Available at: https://doi.org/10.1016/j.ijcip.2016.06.004.

Berz, G. 2018. GNSS spoofing and aviation: an evolving relationship. *Inside GNSS*, 25 September [online]. Available at: https://insidegnss.com/gnss-spoofing-and-aviation-an-evolving-relationship/ [Accessed: 25 December 2020].

Betz, J.W. 2002. Binary offset carrier modulations for radionavigation. *Navigation*, 48(4), pp.227-246. Available at: https://doi.org/10.1002/j.2161-4296.2001.tb00247.x.

Borowski, H., Isoz, O., Eklof, F.M., Lo, S. & Akos, D. 2012. Detecting false signals with automatic gain control. *GPS World*, 1 April [online]. Available at: https://www.gpsworld.com/detecting-false-signals-automatic-gain-control-12804/ [Accessed: 1 April, 2012].

Chan-Tin, E., Heorhiadi, V., Hopper, N., Kim, Y. 2011. The frog-boiling attack: limitations of secure network coordinate systems. *ACM Transactions on information and system security* (TISSEC), 14(3), pp.1-26. Available at: https://doi.org/10.1145/2043621.2043627.

Costin, A. & Francillon, A. 2012. Ghost in the air (traffic): on insecurity of ads-b protocol and practical attacks on ads-b devices. In: *BLACKHAT 2012*, Las Vegas, NV, USA, July 21-26 [online]. Available at: https://www.eurecom.fr/publication/3788 [Accessed: 25 December 2020].

Enea, G. & Porretta, M. 2012. A comparison of 4D-trajectory operations envisioned for NextGen and SESAR, some preliminary findings. In: *Proceedings of the 28th International Congress of Aeronautical Sciences (ICAS)*, Brisbane, Australia, pp.1-14, September 23-28 [online]. Available at: https://www.icas.org/ICAS_ARCHIVE/ICAS2012/PAPERS/310.PDF [Accessed: 25 December 2020].

-EUROCONTROL. 2011. *Coding rules for "Reserved Expansion Field" for ASTERIX Category 021. Apendix A* [online]. Available at: https://www.eurocontrol.int/sites/default/files/2019-06/appendixcat021pt12aed11.pdf [Accessed: 25 December 2020].

-EUROCONTROL. 2019. *EVAIR safety bulletin 20 (summer seasons and full years 2013-2017)*, Brussels, Belgium [online]. Available at: https://www.eurocontrol.int/publication/eurocontrol-voluntary-atm-incident-reporting-evair-safety-bulletin-20 [Accessed: 25 December 2020].

-FAA. 2010. Automatic dependent surveillance broadcast (ADS-B) out performance requirements to support air traffic control (ATC) service (final rule). *14 CFR Part 91, Federal Register,* 75(103), pp.30160-30195 [online]. Available at: https://www.govinfo.gov/content/pkg/FR-2010-05-28/pdf/2010-12645.pdf [Accessed: 25 December 2020].

Finke, C., Butts, J., Mills, R. & Grimaila, M. 2013. Enhancing the security of aircraft surveillance in the next generation air traffic control system. *International Journal of Critical Infrastructure Protection*, 6(1), pp.3-11. Available at: https://doi.org/10.1016/j.ijcip.2013.02.001.

Ghose, N. & Lazos, L. 2015. Verifying ADS-B navigation information through Doppler shift measurements. In: *IEEE/AIAA 34th Digital Avionics Systems Conference (DASC)*, Praue, pp.4A2-1-4A2-11, September 13-17. Available at: https://doi.org/10.1109/DASC.2015.7311412.

Hegarty, C.J., Ligler, G.T., Alexander, K., Chesto, L., Moses, H., Wichgers, J.M., Enge, P., Erlandson, B., Van Dierendonck, A.J., Azoulai, L., Kalyanaraman, S., Heppe, S., Lee, J.C., Wesson, K. & Studenny, J. 2015. RTCA SC-159: 30 Years of Aviation GPS Standards. In: *Proceedings of the 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2015)*, Tampa, FL, pp.877-896, September 14-18 [online]. Available at: https://www.ion.org/publications/abstract.cfm?articleID=13133 [Accessed: 25 December 2020].

Hegarty, C., Odeh, A., Shallberg, K., Wesson, K., Walter, T. & Alexander, K. 2018. Spoofing detection for airborne GNSS equipment. In: *Proceedings of 31st International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2018)*, Miami, FL, pp.1350-1368, September 24-28. Available at: https://doi.org/10.33012/2018.16008.

Horton, E. & Ranganathan, P. 2018. Development of a GPS spoofing apparatus to attack a DJI matrice 100 quadcopter. *Journal of Global Positioning Systems*, 16(art.number:9). Available at: https://doi.org/10.1186/s41445-018-0018-3.

Humphreys, T.E., Ledvina, B.M., Psiaki, M.L., O'Hanlon, B.W. & Kintner, P.M. 2008. Assessing the spoofing threat: development of a portable GPS civilian spoofer. In: *Proceedings of the 21st International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2008)*, Savanna, pp.2314-2325, September 16-19 [online]. Available at: https://gps.mae.cornell.edu/humphreys_etal_iongnss2008.pdf [Accessed: 25 December 2020].

-ICAO. 2018. *Concept of Operations (CONOPS) for Dual-Frequency Multi-Constellation (DFMC) Global Navigation Satellite System (GNSS)* [online]. Available at: https://www.icao.int/Meetings/anconf13/ [Accessed: 25 December 2020]

-ICAO. 2006. *Annex 10 to the Convention on International Civil Aviation. Aeronautical Telecommuncations*, 1(Radio Navigation Aids), Sixth Edition [online]. Available at: https://www.theairlinepilots.com/forumarchive/quickref/icao/annex10.1.pdf [Accessed: 25 December 2020].

Jafarnia-Jahromi, A., Broumandan, A., Nielsen, J. & Lachapelle, G. 2012. GPS vulnerability to spoofing threats and a review of antispoofing techniques. *International Journal of Navigation and Observation*, art.ID:127072. Available at: https://doi.org/10.1155/2012/127072.

-John A. Volpe National Transportation Systems Center. 2001. *Vulnerability assessment of the transportation infrastructure relying on the global positioning system. Final Report*, pp.6-88, August 29, ES3 [online]. Available at: https://rntfnd.org/wp-content/uploads/Vople_vulnerability_assess_2001.pdf [Accessed: 25 December 2020].

Kožović, D. & Đurđević, D. 2019. Syber security in aviation. *Megatrend revija*, 16(2), pp.39-56 (in Serbian). Available at: https://doi.org/10.5937/MegRev1902039K.

Leonardi, M., Piracci, E. & Galati, G. 2017. ADS-B jamming mitigation: a solution based on a multichannel receiver. *IEEE Aerospace and Electronic Systems Magazine*, 32(11), pp.44-51 Available at: https://doi.org/10.1109/MAES.2017.160276.

Magiera, J. & Katulski, R. 2015. Detection and mitigation of GPS spoofing based on antenna array processing. *Journal of Applied Research and Technology*, 13(1), pp.45-57. Available at: https://doi.org/10.1016/S1665-6423(15)30004-3.

Morales-Ferre, R., Richter, P., Falletti, E., de la Fuente, A. & Lohan, E.S. 2020. A survey on coping with intentional interference in satellite navigation for manned and unmanned aircraft. *IEEE Communications Surveys&Tutorials*, 22(1), pp.249-291. Available at: https://doi.org/10.1109/COMST.2019.2949178.

Nguyen, T.X. 2004. *Evaluation of a mobile phone for aircraft GPS interference*. Langley Research Center, Hampton, Virginia [online]. Available at: https://ntrs.nasa.gov/api/citations/20040040193/downloads/20040040193.pdf [Accessed: 25 December 2020].

Nicola, M., Falco, G., Morales-Ferre, R., Lohan, E-S., Fuente, A. de la & Falletti, E. 2020. Collaborative solutions for interference management in GNSS-based aircraft navigation. *Sensors*, 20(15), pp.4085-4108 Available at: https://doi.org/10.3390/s20154085.

Psiaki, M.L., O'Hanlon, B.W., Bhatti, J.A., Shepard, D.P. & Humphreys, T.E. 2011. Civilian GPS Spoofing Detection Based on Dual-Receiver Correlation of Military Signals. In: *Proceedings of ION GNSS 2011*, Portland, pp.2619-2645. September 20-23 [online]. Available at: https://gps.mae.cornell.edu/Paper_E4_2_ION_GNSS_2011b.pdf [Accessed: 25 December 2020].

Sabatini, R., Moore, T., Ramasamy, S. 2017. Global navigation satellite systems performance analysis and augmentation strategies in aviation. *Progress in Aerospace Sciences*, 95, pp.45-98. Available at: https://doi.org/10.1016/j.paerosci.2017.10.002.

Sathaye, H., Schepers, D., Ranganathan, A. & Noubir, G. 2019. Wireless attacks on aircraft instrument landing systems. In: *28th USENIX Security Symposium*, Santa Clara, CA, USA, pp.1-16. August 14-16 [online]. Available at: https://www.usenix.org/conference/usenixsecurity19/presentation/sathaye [Accessed: 25 December 2020].

Schäfer, M., Lenders, V. & Martinovic, I. 2013. Experimental analysis of attacks on next generation air traffic communication. In: Jacobson, M., Locasto, M., Mohassel, P. & Safavi-Naini, R. (Eds.) *Applied Cryptography and Network Security. ACNS 2013. Lecture Notes in Computer Science*, 7954. Springer, Berlin, Heidelberg. Available at: https://doi.org/10.1007/978-3-642-38980-1_16.

Schäfer, M., Lenders, V. & Schmitt, J. 2015. Secure track verification. In: *Proceedings of the 2015 IEEE Symposium on Security and Privacy*, San Jose, CA, USA, pp.199-213, July 20. Available at: https://doi.org/10.1109/SP.2015.20.

Schäfer, M, Leu, P., Lenders, V. & Schmitt, J. 2016. Secure motion verification using the Doppler effect. In: *Proceedings of the 9th ACM Conference on Security & Privacy in Wireless and Mobile Networks (WiSec'16)*, Darmstadt, Germany, pp.135-145, July. Available at: https://doi.org/10.1145/2939918.2939920.

Simsky, M. 2019. What is spoofing and how can you ensure GPS security? *Aerospace testing international,* 30 October [online]. Available at: https://www.aerospacetestinginternational.com/features/what-is-spoofing-and-how-can-you-ensure-gps-security.html [Accessed: 25 December 2020].

-SkyBrary. 2020. *Airborne Separation Assurance Systems (ASAS)* [online]. Available at: https://www.skybrary.aero/index.php/Airborne_Separation_Assurance_Systems_(ASAS) [Accessed: 25 December 2020].

Spilker, J.J., Axelrad, P., Parkinson B.W. & Enge, P. 1996. *Global positioning system: theory and applications, Volume 1*. Washington DC: American Institute of Aeronautics and Astronautics. Available at: https://doi.org/10.2514/4.866388. ISBN: 978-1-56347-106-3.

Steindl, E., Dunkel, W., Hornbostel, A., Haettich, C. & Remi, P. 2013. The impact of interference caused by GPS repeaters on GNSS receivers and services. In: *European Navigation Conference (ENC) GNSS 2013*, Wien, April 22-25 [online]. Available at: https://elib.dlr.de/84739/ [Accessed: 25 December 2020].

Tippenhauer, N.O., Pöpper, C., Rasmussen, K.B. & Capkun, S. 2011. On the requirements for successful GPS spoofing attacks. In: *Proceedings of the 18th ACM Conference on Computer and Communications Security*, Chicago, Illinois, USA, pp.75–86. October 17-21. Available at: https://doi.org/10.1145/2046707.2046719.

Turner, M., Wimbush. S., Enneking, C. & Konovaltsev, A. 2020. Spoofing detection by distortion of the correlation function. In: *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, Portland, Oregon, USA, pp.566-574. April 20-23. Available at: https://doi.org/10.1109/PLANS46316.2020.9110173.

Wang, J., Zou, Y. & Ding, J. 2020. ADS-B spoofing attack detection method based on LSTM. *Journal Wireless Communications and Networking*, art.number:160. Available at: https://doi.org/10.1186/s13638-020-01756-8.

Warner, J.S. & Johnston, R.G. 2002. A simple demonstration that the global positioning system (GPS) is vulnerable to spoofing. *Journal of Security Administration*, 25(2), pp.19-27 [online]. Available at: https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-03-2384 [Accessed: 25 December 2020].

Ying, X., Mazer, J., Bernieri, G., Conti, M., Bushnell, L. & Poovendran, R. 2019. Detecting ADS-B spoofing attacks using deep neural networks. In: *IEEE Conference on Communications and Network Security (CNS)*, Washington DC, USA, June 10-12. Available at: https://doi.org/10.1109/CNS.2019.8802732.

СПУФИНГ В АВИАЦИИ: УГРОЗЫ БЕЗОПАСНОСТИ СИСТЕМ GPS И ADS-B

Деян В. Кожович[а], *Драган* Ж. Джурджевич[б]

[а] БЕН АИР, г. Белград, Республика Сербия

[б] Университет «Мегатренд», факультет гражданской авиации, г. Белград, Республика Сербия

РУБРИКА ГРНТИ: 73.00.00 ТРАНСПОРТ:
73.37.17 Безопасность полетов воздушных судов,
73.37.81 Автоматизированные системы управления и вычислительная техника воздушного транспорта
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В статье представлен краткий обзор последних исследований в области спуфинга/антиспуфинга систем GPS и ADS-B. Системы, которые полагаются на технологию спутникового позиционирования, могут стать мишенью атак с использованием спуфинга, с целью внедрения неверного позиционирования / синхронизации при введении ложных сигналов в радиоприемник «жертвы». Таким образом летательный аппарат приближается к злоумышленнику, который пытается ввести ложную информацию о местоположении в системы, которые обеспечивают навигацию самолетов или беспилотников, с целью их угона или захвата, а также нарушения безопасности при наблюдении за воздушным пространством. В данной связи в ближайшее время потребуются разработки новых концепций как для навигации, так и УВД.

Методы: Используя научный подход, в статье была дана оценка спуфинга / антиспуфинга GPS и ADS-B и того, как спуфинг влияет на кибербезопасность авиационных систем.

Результаты: На основании проведенного методологического анализа доказана значимость изучения спуфинга/антиспуфинга в авиации.

Вывод: Несмотря на то, что спуфинг в авиации представляет собой потенциальную угрозу, его техническая осуществимость вполне реальна и обладает большим потенциалом; он становится более доступным и дешевым вследствие быстрого развития технологий SDR. Реальный риск в будущем – это потенциальные атаки с использованием спуфинга с помощью дронов в воздушном пространстве. Однако авиационная система самолета оснащена антиспуфинг защитой и благодаря применению различных методов антиспуфинг защиты, радиоприемники могут обнаружить атаку. Кроме того, летчики проходят подготовку по обнаружению и решению проблем на каждом этапе полета. Однако в связи с возможностями более изощренных атак спуфинга международные организации, такие как ICAO, активно работают над повышением устойчивости систем GPS и ADS-B и предотвращением спуфинга.

Ключевые слова: ADS-B, авиация, GPS, радиочастотные помехи, спуфинг, антиспуфинг.

СПУФИНГ У АВИЈАЦИЈИ: БЕЗБЕДНОСНЕ ПРЕТЊЕ ПО ГПС И АДС-Б СИСТЕМЕ

Дејан В. Кожовић[а], *Драган* Ж. Ђурђевић[б]

[а] БЕН АИР, Београд, Република Србија

[б] Мегатренд Универзитет, Факултет цивилне авијације, Београд, Република Србија

ОБЛАСТ: сајбер безбедност (информационо-комуникационе технологије), ваздушни саобраћај, контрола летења
ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: У раду су укратко описана недавна истраживања у области ГПС и АДС-Б спуфинга/антиспуфинга. Ови системи, који се ослањају на технологију сателитског позиционирања, могу бити мета спуфинг напада чији је циљ генерисање погрешног позиционирања или временског одређења, тако што се у пријемник „жртве" убацују лажни сигнали. Наиме, нападач покушава да убаци лажне информације у системе који, на пример, омогућавају навигацију авиона или дронова ради отмице или дистракције безбедности/сигурности у надзору ваздушног простора. Због тога су неопходни нови концепти навигације и АТЦ-а.

Методе: Применом научног приступа презентована је евалуација ГПС и АДС-Б спуфинга/антиспуфинга. Наведено је како спуфинг утиче на сајбер безбедност ваздухопловног система.

Резултати: На основу коришћене методолошке анализе објашњен је значај проучавања спуфинга/антиспуфинга у авијацији.

Закључак: Иако спуфинг ГНСС система представља потенцијалну претњу, његова техничка изводљивост је реална, а потенцијал велики јер је флексибилнији и јефтинији због врло брзог напретка СДР технологија. Реалан ризик представљају потенцијални спуфинг напади који би се могли остварити из ваздушног простора, уз коришћење дронова/УАВ. Међутим, применом различитих антиспуфинг техника пријемници авионског система могу детектовати спуфинг. Због могућих софистицираних облика спуфинг напада, међународне организације, попут ИЦАО, проактивно се баве повећањем отпорности ГПС и АДС-Б система на спуфинг.

Кључне речи: АДС-Б, авијација, ГПС, радио-фреквенцијске интерференције, спуфинг, антиспуфинг.

Paper received on / Дата получения работы / Датум пријема чланка: 30.12.2020.
Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 11.03.2021.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 12.03.2021.

VOJNOTEHNIČKI GLASNIK / MILITARY TECHNICAL COURIER, 2021, Vol. 69, Issue 2

CARBONATION OF MINERALS AND SLAGS UNDER HIGH PRESSURE IN AN AUTOCLAVE

Carlos F. Matus[a], *Srećko* R. Stopić[b], *Bernd* G. Friedrich[c]

[a] Refratechnik Cement GmbH,
Göttingen, Federal Republic of Germany,
e-mail: carlos.matus@refra.com,
ORCID ID: https://orcid.org/0000-0002-3474-5989

[b] RWTH Aachen University, IME Process Metallurgy and Metal Recycling, Aachen, Federal Republic of Germany,
e-mail: sstopic@ime-aachen.de, **corresponding author**,
ORCID iD: https://orcid.org/0000-0002-1752-5378

[c] RWTH Aachen University, IME Process Metallurgy and Metal Recycling, Aachen, Federal Republic of Germany,
e-mail: bfriedrich@ime-aachen.de,
ORCID iD: https://orcid.org/0000-0002-2934-2034

DOI: 10.5937/vojtehg69-30203; https://doi.org/10.5937/vojtehg69-30203

FIELD: Chemical technology
ARTICLE TYPE: Original scientific paper

Abstract:

Introduction/purpose: Carbonation of minerals (olivine and wollastonite) and secondary materials such as slag under high pressure in autoclaves has high importance due to environmetal problems.

Methods: The most important for this process is to have a good knowledge of the behavior of carbon dioxide in water solution under high pressure, the precipitation of silica, dissolution of metals such as nickel and magnesium as well as subsequent filtration.

Results: The carbonation process of olivine und slag under high pressure (from 40 to 80 bar) in an autoclave was successfully performed at 175°C, with and without additivies.

Conclusion: A comparative analysis has confirmed better carbonation of slag (max. 300 kg/ton) in comparison to that of olivine (max. 70 kg/ton) under the same conditions.

Key words: carbonation, olivine, slag, autoclave, additives.

ACKNOWLEDGMENT: This research was funded by BMBF (Federal Ministry of Education and Research) in Berlin, grant number 033RCO14B (CO2MIN Project in period from 01.06.2017 to 31.12.2020).

Introduction

Carbon dioxide has the fourth highest presence in Earth's atmosphere after nitrogen, oxygen and argon and plays a significant role in global warming due to the greenhouse effect. Because of the significant increase of CO_2 emissions, carbonation is a promising process in which carbon oxide reacts with compounds with high metal oxide compositions to form chemically stable and insoluble metal carbonates. The choice of experimental parameters (temperature, pressure, solid/liquid ratio, mixing rate, time) for carbonation in an autoclave is of high importance. Although it is reported in literature (Gadikota et al, 2014, pp.4679-4693) that a higher temperature favors mineral dissolution and carbonation, there exists an optimum level of a temperature range. The carbon dioxide solubility is reduced if the temperature is too high. On the other hand, low temperature slows mineral dissolution. The authors suggested that higher conversion was achieved with higher temperature but with a limit to 185°C. They performed an olivine experiment with varied temperatures at partial pressure of 141 bar, for 3 hours with an additive of 1.0M NaCl + 0.64 $NaHCO_3$ with 15 wt% solid, and at a stirring speed of 800 rpm. The final carbonation rates at 90, 125, 150, and 185°C were found to be 3.0, 28.2, 70.5 and 85.3%, rspectively. An increase in reaction time from 3 hours to 5 hours does not influence the carbonation efficiency.

The slag carbonation between 40°C to 160°C with partial pressure set at 48 bar and a reaction time of 1 hour (Chang et al, 2011) confirmed that conversion increased with increasing temperature because of a higher carbonation rate of calcium at higher temperatures. In this experiment, blended hydraulic cement BHC slag showed a more unique route because this conversion decreased after the temperature had exceeded 100°C. It could be caused by the reduction of carbon dioxide dissolution as reaction temperature increased.

It is expected that higher olivine to carbonate conversion is achieved with increased pressure of carbon dioxide (Santos et al, 2016, pp.1-6). From his experiment, the conversion rate is almost doubled (from 8% to 16%) when the total pressure was doubled from 60 to 120 bar after 3 hours of reaction time. The reason behind it was that a higher carbonic acid concentration improved mineral dissolution and, at the same time, promoted carbonate precipitation.

The liquid to solid ratio L/S represents the weight ratio of water to solid in aqueous carbonation slurry. The optimal proposed L/S ratio was 10 mL/g (Rahmani et al, 2014, pp.5953-5958). Although a high L/S ratio

was advantageous for decreasing water treatment and saving energy during dehydration, additional water is required to extract calcium and magnesium in the indirect carbonation process. The reduction of the L/S ratio also has small contribution to the overall conversion rate, which suggested it could result in more calcium and magnesium ions in the solution and, therefore, stronger ionic strength.

As the L/S ratio increased, the carbonation rate also increased because aqueous carbonation was dominant (Chang et al, 2012, pp.97-106). As the L/S increased more, however, the conversions did not increase because the excess amount of the aqueous medium formed a mass transfer barrier, and, as a result, the ionic strength was lower. There was a limit to the liquid to solid ratio between 10-20 mL/g for the carbonation process because a large amount of water could limit the conversion rate. Dunite carbonation in a batch-tubular reactor was performed with an increased S/L ratio of 2.8 g/ml (Agrawal & Mehra, 2020). The results revealed the precipitation of magnesite under diffusion limited conditions. The SiO_2 formation and magnesite precipitation fill the pore space and the fractured zone on the rock surface.

The positive role of the added $NaHCO_3$ in olivine carbonation was confirmed, but not investigated in detail (Stopic et al, 2018, pp.193-207). The synthesis of magnesium carbonate was studied using olivine under a partial pressure of carbon dioxide higher than 100 bar at 175°C. The combination of organic acids such as oxalic acid and ascorbic acid accelerates the carbonation of olivine, reducing the formation of the silicate passive layer (Stopic et al, 2019, pp.135-147). The synthesis of nanosilica was studied via olivine carbonation using the size fraction between 20 and 63 μm with the solid/liquid ratios of 1:10 at 175 °C and a partial pressure of CO_2 higher than 100 bar in an autoclave in the presence of additives such as sodium bicarbonate, and oxalic and ascorbic acid. Under the above-mentioned conditions, ideally spherical particles of silica below 500 nm with amorphous grains were produced during carbonation. An increase in stirring speed from 600 rpm to 1800 rpm in an autoclave leads to the increased formation of magnesium carbonate and silica. An increased stirring speed has a positive influence on the separation of the formed silica-rich layer of the non-reacted magnesium silicate. On the other hand, the pressure in an autoclave was increased from 120 to 170 bar with an increasing stirring speed from 600 to 1800 rpm, which is an additional support for the silica separation and precipitation from the solution. The use of strong turbulence for better mixing of reactants to avoid the formation of a silica passivation layer was mostly studied in literature (Stockmann et al, 2014, pp.31439-

31445). Using a strong mixing device, such as a high gravity rotary reactor, might also help to resolve this issue.

A new mechanism model for metal extraction (nickel, iron, magnesium) from olivine-bearing ore by avoiding silica gel formation during leaching with hydrochloric acid including a carbonation pre-treatment was proposed (Matus et al, 2020, pp.811-827). This study explains additionally the behavior of metals such as nickel, magnesium, and iron during the carbonation of olivine-bearing ore and the leaching of a carbonated solid product.

In accordance with the previously mentioned analysis of the reaction parameters, an experiment was designed in order to reach maximum carbonation efficiency. This paper will explain the carbonation of olivine and the carbonation of slag under chosen experimental conditions. A comparison of their carbonation efficiencies will be mentioned in order to choose the most suitable material for scale up experiments.

Experimental

Material

The samples of olivine (Norway), ladle slag, and electric arc furnace slag (Germany) were studied for carbonation in water solution under high pressure conditions in an autoclave. It should be noted that, despite different particle sizes, the results of the XRF analysis are very similar in the case of different olivine Steinsvik. The characterization was performed by the X-ray fluorescence (XRF) technique, type PW2404 (Malvern PANalytical, Malvern, UK). Milling was performed using a Roller Mill, Type LWBP 2/2 (Karl Merz Maschinenfabrik GmbH, 1972 (year of manufacture), Heschingen, Germany). Sieving was performed using a Sieving Maschine, Type Prüf 86 (Siebtechnik GmbH, Mühlheim an der Ruhr, Germany). In the case of slag, all tests were run with a particle size < 63 µm, since a slag particle size analysis was not part of this work. The presence of calcium oxide and magnesium oxide is the most important parameter for the carbonation process. Because of different behaviors of metal silicate and metal oxide through carbonation, the mineralogical composition mostly influences high carbonation efficiency. The maximum content of calcium oxide and magnesium oxide in electric arc furnace (EAF) slag amounts to 55.90%, in contrast to its minimum presence found in mineral olivine (43.67 %). Because of this situation, the maximum carbonation value was expected for EAF and the minimum carbonation value for olivine. Besides the chemical compositions of the studied samples, the particle size and the active surface area have an

important role in a higher carbonation level. A higher amount of silicon in the sample can be later included in a newly formed passive layer as a barrier for the carbonation process in an autoclave. Some part of iron can also be carbonated. Aluminium and manganese are not included in the carbonation process.

Table 1 – Chemical compositions of the samples used in the carbonation process
Таблица 1 – Химический состав образцов, используемых в процессе карбонизации
Табела 1 – Хемијски састав узорака који се користе у процесу карбонизације

Sample	Chemical composition (%)						
	NiO	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	MnO
Olivine-Steinsvik	0.4	43.45	0.24	7.41	0.51	47.34	0.11
Ladle Slag	-	5.19	42.45	12.45	27.56	7.65	2.69
Electric arc furnace slag	-	11.17	44.83	0.12	6.36	32	0.19
Wollastonite	-	1.52	45.42	0.41	0.13	52.56	0.19

The used samples are shown in Figure 1:

Olivine, Norway	Ladle slag, Germany	Electric arc furnace slag, Germany

Figure 1 – The used samples in the carbonation process
Рис. 1 – Используемые образцы в процессе карбонизации
Слика 1 – Коришћени узорци у процесу везивања угљен-диоксида

Procedure

The treatment of olivine first included the operations such as milling, sieving, and carbonation under high pressure conditions with an additional filtration and a chemical analysis of solid and liquid. The carbonation tests were carried out in a 9.9 L autoclave (Hastelloy C22 pressure reactor) of a kiloclave Type 3E (Büchi, Switzerland) with electric

heating and water cooling (as shown in Figure 2) at 175◦C with 71.5 bar pure grade CO_2 in the presence of additives such as sodium bicarbonate, oxalic acid, and ascorbic acid. The planned experiments in this work will show how the the previously mentioned results from the experiments performed in the 0.25 L and 1.0 L autoclave relate to the 10 L autoclave experiment and validate the obtained results.

Figure 2 – Autoclave for the carbonation process
Рис. 2 – Автоклав для процесса карбонизации
Слика 2 – Аутоклав за везивање угљен-диоксида

For the carbonation of samples, the stabilization initial pressure is of great importance. The stabilization pressure is the pressure set at the beginning of the experiment by CO_2 injection. This pressure was set at room temperature. The adjustment was made by continuously adding gas until the pressure stabilized in the system. Since there is reduction in the pressure in the system during gas introduction due to the chemical reaction of CO_2 with water, it is important to perform stabilization. In this regard, it was observed that the higher the stabilization, the higher carbonation levels were obtained. However, this also depended on the grain size and the returned liquid. The Büchi software, Switzerland, was

used for the analysis of pressure, temperature, and stirring speed in an autoclave.

Reaction parameters

In the carbonation tests, the increase of the carbonation degree by changing the influencing parameters was investigated. Some parameters were kept constant as they were found to be suitable according to the previously mentioned literature. In the case of the tests with olivine ore, the solid/liquid ratio and the stirring speed were kept constant.

The following listed carbonation parameters are shown in Table 2.

Table 2 – List of the reaction parameters (Additives: 0.64 M sodium bicarbonate, 0.04 M oxalic acid & 0.01M ascorbic acid, 600 rpm, solid/Liquid= 1 kg/8L)
Таблица 2 – Список реакционных параметров (добавки: 0,64 М бикарбонат натрия, 0,04 М щавелевая кислота и 0,01 М аскорбиновая кислота, 600 оборотов в минуту, соотношение твердое вещество / жидкость = 1 кг / 8 л)
Табела 2 – Листа реакционих параметара (додаци: 0,64 М натријум-карбоната, 0,04 М оксалне киселине и 0,01 М аскорбинске киселине, при 600 обртаја у минути и односу чврстог материјала и раствора 1kg/8 l)

Material	Particle size (μm)	Initial stabilizing pressure (bar)	Max. Pressure (bar)	Time (hours)	Temperature (°C)
Olivine	<11, <20, 20-63, <63	15-30	40-80	2-4	100, 175
Ladle Slag, EAF-slag, wollastonite	<63	15-20	50	4	100, 175

By calculating the degree of carbonation, it is possible to determine the maximum CO_2 absorption capacity of the feedstock. It must be taken into account that not all of the studied material is capable of absorbing CO_2. Therefore, only the proportion of MgO is considered for olivine and the proportion of MgO and CaO for slag. The loss on ignition gives a global estimate of the experiment efficiency, since the higher the loss on ignition, the more CO_2 was absorbed in percentage terms.

The particle size plays a decisive role in the success of olivine carbonation. The smaller the particle size, the higher the degree of carbonation achieved (as shown in Figure 3). The carbonation reaction of magnesium silicate from olivine was presented with Equation 1:

$$Mg_2SiO_4 + 2\ CO_2 \rightarrow 2\ MgCO_3 + SiO_2 \quad (1)$$

An increase in pressure of carbon dioxide increases carbonation efficiency. The maximum carbonation efficiency of olivine at 175 °C amounts to 70 kg CO_2/ton.

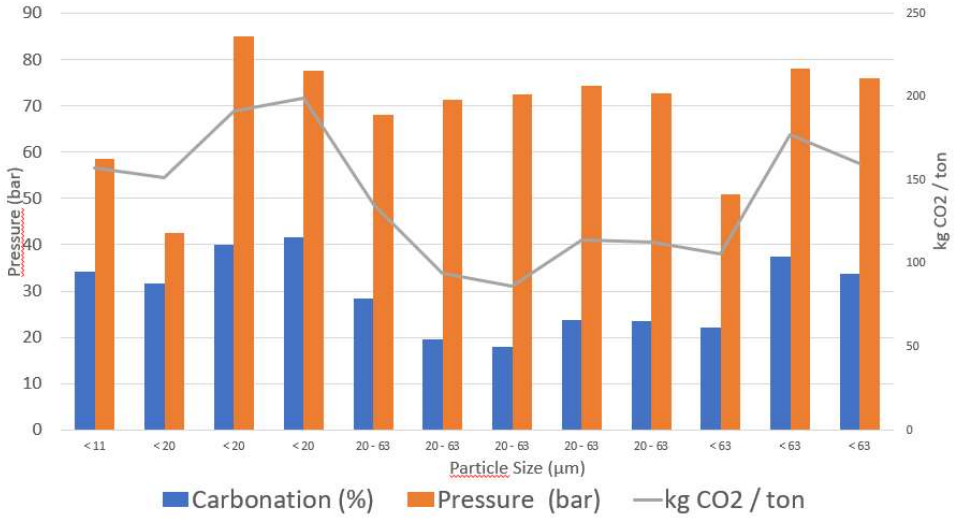


Figure 3 – Degrees of carbonation for different particle sizes of olivine in the presence of additives at 175°C, 600 rpm, S/L=1/8
Рис. 3 – Степень карбонизации при различной величине частиц оливина с добавками при 175 ° С, 600 оборотов в минуту, соотношение твердое вещество / жидкость = 1 кг / 8 л)
Слика 3 – Степени везивања угљен-диоксида за различите величине честица оливина у присуству додатака на 175°C, при 600 обртаја у минути и односу чврстог материјала и раствора 1:8

The result of the test with a decreased particle size smaller than 11 µm is different from the expected value. Here, the carbonation degree was 34.28% despite an extremely small particle size. This raises a possibility that there is a critical particle size between 0-20µm above which further grinding of olivine is no longer worthwhile. The carbonation of slags and wollastonite was performed in the presence and absence of additives, as shown in Figure 4.

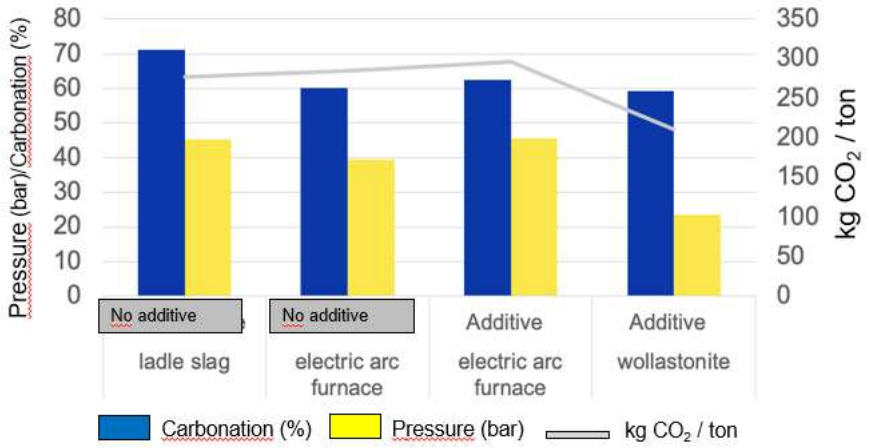


Figure 4 – Degrees of carbonation for different types of slags at 175°C, 600 rpm, S/L=1/8
Рис. 4 – Степень карбонизации для различных видов шлаков при 175 ° С, 600 оборотов в минуту, соотношение твердое вещество / жидкость = 1 кг / 8 л)
Слика 4 – Степени везивања угљен-диоксида за различите типове шљака на 175°С,при 600 обртаја у минути и односу чврстог материјала и раствора 1/8

After a confirmation that EAF slag is suitable for carbonation, it was investigated whether the addition of additives affects the degree of carbonation. As shown in Figure 4, the carbonation degree of EAF slag both without additives and in the presence of additives amounts to 60.13%, which confirms no influence and significance of their using in slag carbonation. This result was confirmed in the case of wollastonite carbonation.

$$CaSiO_3 + CO_2 = CaCO_3 + SiO_2 \quad (2)$$

The maximum carbonation efficiency was obtained for ladle slag (about 70 % or 300 kg CO_2/ton) at 175 °C in the absence of additives. However, only one test was run with this slag because solids cemented to the bottom of the reactor and the cleaning of the reactor was very difficult. To free the carbonated ladle slag from the reactor, a two-hour leaching process at 100°C with acetic acid was necessary.

In the case of electric arc furnace slag (EAF slag), the degree of carbonation is somewhat lower than for ladle slag. However, no cementation problems were encountered with EAF slag, making this slag suitable for the carbonation test. The disadvantage of EAF slag is the

formation of small stones during the carbonation tests. This caused some problems during the subsequent filtration process.

Conclusion

Carbonation of minerals and slag in an autoclave seems to be a prominent solution to the problem of rising carbon dioxide levels in the air. Carbonation of olivine and slag was successfully performed at 175°C under high pressure conditions (40-80 bar) in a 10 L autoclave. A comparative analysis has confirmed better carbonation of slag (max. 300 kg CO_2/ton) in comparison to that of olivine (max. 70 kg CO_2/ton) under the same conditions. The presence of additives such as sodium bicarbonate and oxalic and ascorbic acid is very important for olivine carbonation, but without influence in the case of slag, which is very important regarding an efficient cost-effectiveness analysis.

One challenge of mineral carbonation is to make it economically feasible. The obtained results will help to design future mineral carbonation experiments in scale up conditions.

References

Agrawal, A.K. & Mehra, A. 2020. Dunite carbonation in batch-tubular reactor. *Environmental Science and Pollution Research*, 27, pp.31439-31445. Available at: https://doi.org/10.1007/s11356-020-09426-4.

Chang, E-E., Pan, S-Y., Chen, Y-H., Tan, C-S. & Chiang, P-C. 2012. Accelerated carbonation of steelmaking slags in a high-gravity rotating packed bed. *Journal of Hazardous Materials*, 227-228, pp.97-106. Available at: https://doi.org/10.1016/j.jhazmat.2012.05.021.

Chang, E-E., Pan, S-Y., Chen, Y-H, Chu, H-W., Wang, C-F. & Chiang, P-C. 2011. CO_2 sequestration by carbonation of steelmaking slags in an autoclave reactor. *Journal of Hazardous Materials*, 195, pp.107-114. Available at: https://doi.org/10.1016/j.jhazmat.2011.08.006.

Gadikota, G., Matter, J., Kelemen, P. & Park, A-h.A. 2014. Chemical and morphological changes during olivine carbonation for CO_2 storage in the presence of NaCl and $NaHCO_3$. *Physical Chemistry Chemical Physics*, 16(10), pp.4679-4693. Available at: https://doi.org/10.1039/C3CP54903H.

Matus, C., Stopic, S., Etzold, S., Kremer, D., Wotruba, H., Dertmann, C., Telle, R., Friedrich, B. & Knops, P. 2020. Mechanism of Nickel, Magnesium, and Iron Recovery from Olivine Bearing Ore during Leaching with Hydrochloric Acid Including a Carbonation Pre-Treatment. *Metals*, 10(6), art.number:811, pp.811-827. Available at: https://doi.org/10.3390/met10060811.

Rahmani, O., Junin, R., Tyrer, M. & Mohsin, R. 2014. Mineral carbonation of red gypsum for CO_2 sequestration. *Energy & Fuels*, 28(9), art.number:708. Available at: https://doi.org/10.1021/ef501265z.

Santos, R.M., Knops, P.C.M., Rijnsburger, K.L. & Chiang, Y.W. 2016. CO2 energy reactor–integrated mineral carbonation: perspectives on lab-scale investigation and products valorization. *Frontiers in Energy Research*, 4(art.number:5), pp.1-6. Available at: https://doi.org/10.3389/fenrg.2016.00005.

Stockmann, G.J., Wolff-Boenisch, D., Bovet, N., Gisslason, S.R., Oelkers, E.H. 2014. The role of silicate surfaces on calcite precipitation kinetics. *Geochimica et Cosmochimica Acta*, 135, pp.231-250. Available at: https://doi.org/10.1016/j.gca.2014.03.015.

Stopic, S., Dertmann, C., Koiwa, I., Kremer, D., Wotruba, H., Etzold, S., Telle, R., Knops, P. & Friedrich, B. 2019. Synthesis of Nanosilica via Olivine Mineral Carbonation under High Pressure in an Autoclave. *Metals*, 9(6), art.number:708, pp.135-147. Available at: https://doi.org/10.3390/met9060708.

Stopic, S., Dertmann, C., Modolo, G., Kegler, P., Neumeier, S., Kremer, D., Wotruba, H., Etzold, S., Telle, R., Rosani, D., Knops, P. & Friedrich, B. 2018. Synthesis of Magnesium Carbonate via Carbonation under High Pressure in an Autoclave. *Metals*, 8(12), art.number:993, pp.193-207. Available at: https://doi.org/10.3390/met8120993.

КАРБОНИЗАЦИЯ МИНЕРАЛОВ И ШЛАКОВ ПОД ВЫСОКИМ ДАВЛЕНИЕМ В АВТОКЛАВЕ

Карлос Ф. Матус[а], *Сречко* Р. Стопич[б], **корреспондент**, *Бернд* Г. Фридрих[б]

[а] Refratechnik Cement GmbH,
г.Геттинген, Федеративная Республика Германия

[б] Технический университет города Ахен,
Институт металлургических процессов и рециклирования металлов,
г. Ахен, Федеративная Республика Германия

РУБРИКА ГРНТИ: 61.00.00 ХИМИЧЕСКАЯ ТЕХНОЛОГИЯ.
ХИМИЧЕСКАЯ ПРОМЫШЛЕННОСТЬ:
61.13.21 Химические процессы
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Карбонизация минералов (оливина и волластонита) и вторичных материалов под высоким давлением в автоклавах очень важно для охраны окружающей среды.

Методы: Наиболее важным в данном процессе является познание того, как себя ведет диоксид углерода в водном растворе под высоким давлением, как происходит растворение металлов таких как никель и магний, а также их последующая фильтрация.

Результаты: Процесс карбонизации оливина и шлака под высоким давлением (от 40 до 80 бар) был успешно проведен при 175 °C в автоклаве с добавками и без них.

Выводы: Сравнительный анализ показал, что карбонизация шлака (макс. 300 кг / т) по сравнению с карбонизацией оливина (макс.70 кг/ т) в одинаковых условиях производится намного лучше.

Ключевые слова: карбонизация, оливин, шлак, автоклав, добавки.

ВЕЗИВАЊЕ УГЉЕН-ДИОКСИДА СА МИНЕРАЛИМА И ШЉАКОМ ПРИ ВИСОКОМ ПРИТИСКУ У АУТОКЛАВУ

Карлос Ф. Матус[а], *Срећко* Р. Стопић[б], **аутор за преписку**,
Бернд Г. Фридрих[б]

[а] Refratechnik Cement GmbH, Гетинген, Савезна Република Немачка

[б] Технички универзитет у Ахену, Институт за процесну металургију и рециклирање метала, Ахен, Савезна Република Немачка

ОБЛАСТ: хемијске технологије
ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Везивање угљен-диоксида са минералима (оливин и воластонит) и секундарним материјалима при високом притиску у аутоклаву врло је важно за заштиту животне средине.

Методе: За овај процес најважније је понашање угљен-диоксида у воденом раствору при високом притиску и растварање метала као што су никал и магнезијум, као и наредна филтрација.

Резултати: Процес везивања угљен-диоксида са оливином и шљаком успешно је изведен у аутоклаву на 175°C између 40 и 80 бара у присуству и одсуству адитива.

Закључак: Упоредна анализа је потврдила боље везивање угљен-диоксида са шљаком (максимално 300 kg/t) у поређењу са оливином (максимално 70 kg/t) при истим условима.

Кључне речи: везивање угљен-диоксида, оливин, шљака, аутоклав, додаци.

Paper received on / Дата получения работы / Датум пријема чланка: 07.01.2021
Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 01.03.2021.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 03.03.2021.

HIGH ENERGY MICROWAVE WEAPON - ELECTROMAGNETIC BOMB

Goran M. Banjac[a], *Vladimir* D. Đorđević[b], *Miladin* Z. Živković[c], *Abdellah* Ferdjali[d]

[a] University of Defence in Belgrade, Military Academy, Department of Air Defence, Belgrade, Republic of Serbia, e-mail: gbbanjac@yahoo.com, **corresponding author**, ORCID iD: https://orcid.org/0000-0002-3547-9723

[b] University of Defence in Belgrade, Military Academy, Department of Air Defence, Belgrade, Republic of Serbia, e-mail: ketidjole@ptt.rs, ORCID iD: https://orcid.org/0000-0003-0669-0770

[c] University of Defence in Belgrade, Military Academy, Department of Air Defence, Belgrade, Republic of Serbia, e-mail: miladin32dus@yahoo.com, ORCID iD: https://orcid.org/0000-0002-3060-4011

[d] Polytechnic Military School, Algiers, People's Democratic Republic of Algeria, e-mail: ferdjali.abdellah@gmail.com, ORCID iD: https://orcid.org/0000-0002-1748-1715

DOI: 10.5937/vojtehg69-29007; https://doi.org/10.5937/vojtehg69-29007

FIELD: Electromagnetics
ARTICLE TYPE: Professional paper

Abstract:

Introduction/purpose: Technological progress has led to the actualization of the problem of construction and use of high-energy microwave weapons, especially electromagnetic bombs. However, in the recent military-professional literature, this issue is little represented.

Methods: The available existing literature on the subject was analyzed.

Results: It has been established that the general principles of functioning and theoretical bases have been widely available and known for many years. Numerous experiments in specialized institutions have confirmed the electromagnetic pulse effectiveness. This is especially true of sensitivity of devices based on semiconductor technology. Also, it is assumed that, at the current technological level, technical solutions are widely available to a large number of entities. The most common model of

electromagnetic bomb dealt with in the literature is the realization of the use of a compression flux generator and an oscillator with a virtual cathode. According to the authors, this variant would ensure that the final product has realistic physical dimensions and sufficient strength to be useful. Another problem identified in the literature is the massive absence of adequate protection measures against the effects of electromagnetic pulses. This applies not only to the civilian but also to the military sector and imposes the need to invest significant resources in order to subsequently increase resilience.

Conclusion: The available literature indicates that it is possible to make an electromagnetic bomb of acceptable physical dimensions and power. It is assumed that it would generate an electromagnetic pulse with a power of about 10 GW and a frequency of 5 GHz. In combination with high-precision weapons, even protected devices would be successfully disabled. The wide presence of semiconductor technology in all spheres of life makes this weapon extremely effective and it is realistic to expect its much wider application in the coming period.

Keywords: high energy microwave weapon, electromagnetic bomb, electromagnetic pulse, explosively pumped flux compression generators, vircator.

Introduction

The harmful effects of electromagnetic pulses have been known for a long time. The most famous example is the activation of a warhead with a power of 1.45 megatons, at an altitude of 250 miles above the Pacific Ocean. The consequences of this experiment were much more serious than expected. The impact of electromagnetic pulses was felt in Hawaii, 1445 km from the explosion center. The consequences were the destruction of street lighting, alarm systems and telecommunication systems. Six satellites at such a distance for which the possibility of affecting them had not even been considered were completely destroyed. After this event, the effect of the electromagnetic pulse becomes extremely relevant from the aspect of military use. Further research has yielded more accurate knowledge about the consequences of using such weapons. Thus, a nuclear warhead, with a power of 1-2 megatons, activated at an altitude of 250 miles, would release an electric field of 10-50 kV / m, which would cause damage to a larger continental part of the United States (Miller, 2005, p.390).

Numerous laboratory research studies have significantly contributed to understanding the mechanisms of influence of electromagnetic impulses. In them, the electromagnetic pulse is not generated as a product of a nuclear explosion, but is created by certain high-frequency

high-power devices. Although they can be used more than once, these technical solutions, due to their dimensional limitations, have not found wider application outside specialized scientific research institutions.

Technical solutions called high-energy microwave weapons stand out today as very important for military use. These are devices capable of emitting directed high-frequency electromagnetic energy. Their pulse power is 100 MW-100 GW, and the operating frequency is 1-300 GHz (Ni et al, 2005, p.2). Progress in their development in recent decades has been most pronounced in the domain of reducing physical dimensions, while maintaining and increasing power. Currently, such systems have a spatially limited scope, but create an electric field strong enough to disable integrated electrical circuits (Miller, 2005, p.391). There are different types of their construction and use, and a special focus is on a solution realized in the form of an electromagnetic bomb. It is made as a disposable device, whose main functional units are realized using a compression coaxial flux generator, a high-frequency generator with a virtual cathode oscillator, and an antenna system based on a helix antenna.

Explosively Pumped Flux Compression Generators

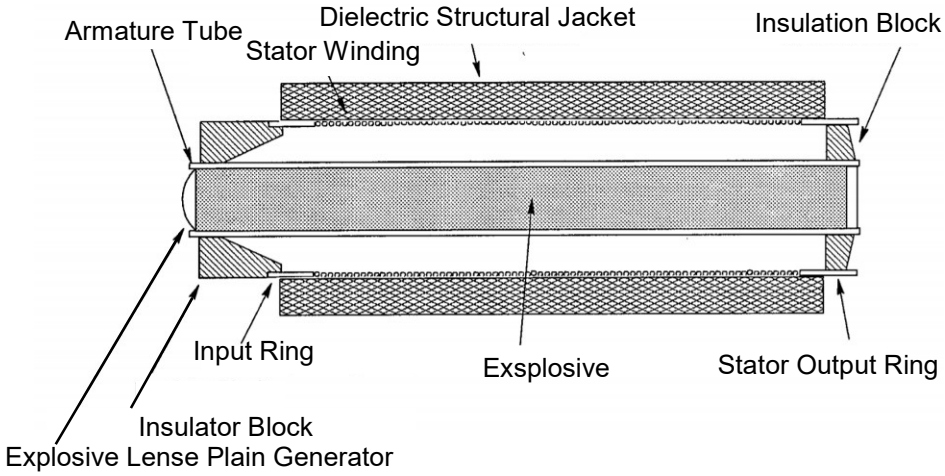
The main problem in the construction of such weapons is the provision of an adequate power source. It is easily overcome if the concept of a disposable weapon, i.e. electromagnetic bomb (e-bomb) is adopted. A popular approach to the problem is the choice of an Explosively Pumped Flux Compression Generator. Its advantage is the well-known working principle, technical simplicity and high efficiency. In addition, estimates indicate that it can be made by any country with a developed information technology sector (Miller, 2005, p.392).

The idea its construction is based on is to use the power of explosion to quickly compress the magnetic field, thus ensuring the conversion of explosion energy into electromagnetic field energy. An explanation of this can be easily found in the available literature, and is illustrated by a simplified cross-section in Figure 1 (Kopp, 1996, p.3).

The basis of the construction is an electric coil wound on a copper pipe, in which there is a shaped explosive charge. The coil represents the generator stator. On the outside, there is an additional sheath made of dielectric material so that the electromagnetic field is better directed. The central explosive charge extends along the entire length of the copper pipe.

On the side of the charge, from which the detonation path begins, there is an explosive lens which should provide a certain law of formation

and propagation of the explosive wave. This deforms the copper tube into a regular conical shape. The aim of this is to spread the copper tube evenly over the entire diameter of the stator, thus causing a short circuit between the stator windings. This deformation will move with the explosive wave towards the stator output contacts, Figure 2 (Kopp, 1996, p.3).



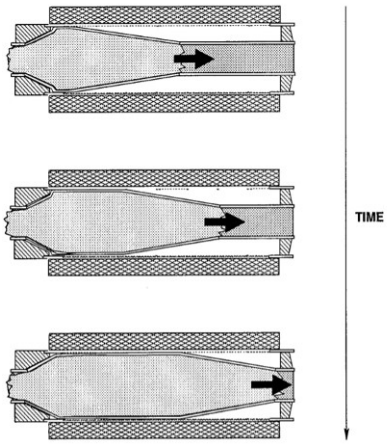
Picture 1 – Construction of Explosively Pumped Flux Compression Generators
Рис. 1 – Конструкция генераторов сжатия потока с взрывной накачкой
Слика 1 – Конструкција експлозијом покретаног флуксног генератора

Immediately before the activation of the explosive charge, the coil is supplied with high-power current, of the order of mega amperes (for which another, smaller flux generator can be used). Due to the flow of current, a large, rapidly decreasing electromagnetic field is created. The activation of the explosive charge is timed to correspond to the moment of reaching the current peak in the stator windings.

The explosive generator with the lens is activated and forms an explosive wave that deforms the copper tube into a conical shape, which spreads over the inner diameter of the stator windings, short circuits them and "traps" the current in the device.

The short circuit moving along the generator body has the effect of compressing the magnetic field while reducing the inductance of the

stator winding. The result is the formation of a rapidly growing impulse, the maximum of which is reached immediately before the physical destruction of the generator itself.



Picture 2 – Deformations of a copper pipe under the action of an explosive wave
Рис. 2 – Деформации медной трубы под воздействием взрывной волны
Слика 2 – Деформације бакарне цеви под дејством експлозивног таласа

According to the available results, the maximum is reached in a few milli or micro seconds. Also, for a current peak of 10 MA, an output power of several tens of MJ is provided (Kopp, 1996, p.5). In this way, an electromagnetic field of 1 kV / m is created at a distance of approximately 2 km, or 10 kV / m at a distance of 175 meters. A field of this strength would ensure the safe destruction of all electrical systems (Miller, 2005, p.392). However, the main problem is the low frequency of this pulse, usually below 1 MHz, which does not provide sufficient efficiency on targets of smaller dimensions (such as integrated circuits).

Oscillator with a virtual cathode

There are several possible solutions how to provide a high frequency pulse of sufficient power from the output pulse of the flux generator. The available literature offers several different HF sources, the characteristics of which can be seen in Table 1 (Ni et al, 2005, p.3).

It is interesting that the most common choice from the aspect of making an e-bomb is a variant of a device with a virtual cathode oscillator (vircator). Although it does not provide the highest output power, nor can

it cover higher frequencies of the microwave spectrum and has low efficiency, it is a popular solution for making e-bombs. The main reason is a simple construction and small dimensions, which is why it has a great possibility of practical use. It should be noted that the realization in the variant of the axial vircator stands out in terms of efficiency (Kopp, 1996, p.5).

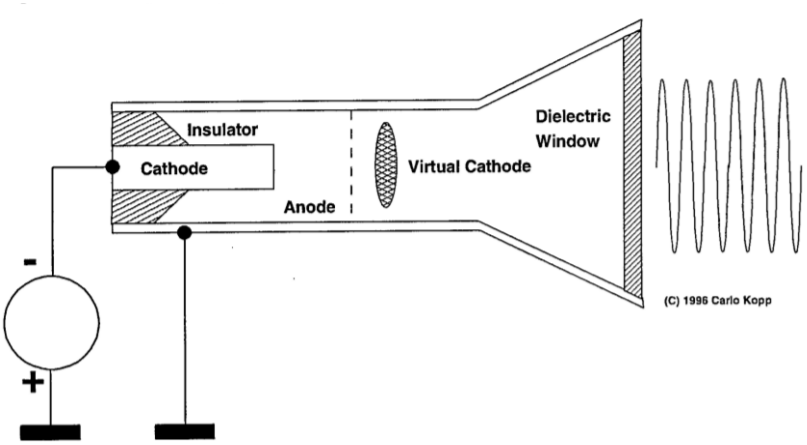
Table 1 – Different sources of HF energy
Таблица 1 – Различные источники ВЧ энергии
Табела 1 – Различити извори ВФ енергије

Device name	P (GW)	F (GHz)	τ (ns)	η (%)
Virtual cathode oscillator	1.2	5.9	-	-
Freedom electronic laser	>1	40	-	30
Axial driven cathode oscillator	7.5	1.17	-	-
Plasma auxiliary slow wave oscillator	4-8	-	-	15-25
Single pulse looping-wave oscillator	1.5	8.-12.5	60	30
Looping-wave oscillator	1	10	2	30
Field radiation oscillator	0.06	7	-	25
Looping-wave oscillator	1.5	X band	60	50
Repeating pulse looping-wave oscillator	1	10	2	30
Relativity magnetron	0.1	-	1000	-
Improved cyclotron tube	2	12.5	50	-
Polarized radiation microwave tube	0.06	7	700	25

Kop offers a simple explanation of the principles on which the operation of the vircator is based, Figure 3. The basic idea is to accelerate a strong jet of electrons to the mesh anode which is grounded to the device body. Most electrons will pass through the anode and form a charged space behind it. This charged area represents the virtual cathode.

The virtual cathode will oscillate at the appropriate frequency, which can be adjusted by manipulating its position in the cavity. The output power ranges from 170 kW to 40 GW, and the frequency range covers the decimeter and centimeter wavelength range.

Although it has a very low efficiency, which is only 1%, the simplicity of design, small dimensions, and the absence of external magnetic field makes this a popular solution (Dražan & Vrána, 2009, p.622).



Picture 3 – Simplified presentation of the construction and principle of operation of the vircator
Рис. 3 – Упрощенное представление конструкции и принципа работы виркатора.
Слика 3 – Упрошћени приказ конструкције и принципа рада виркатора

Kopp cites pulse duration as the biggest limitation in using a vircator. It is usually of the order of microseconds and is limited by the melting time of the anode and the stability of the oscillation frequency which are conditioned by the emitted power.

Antenna system

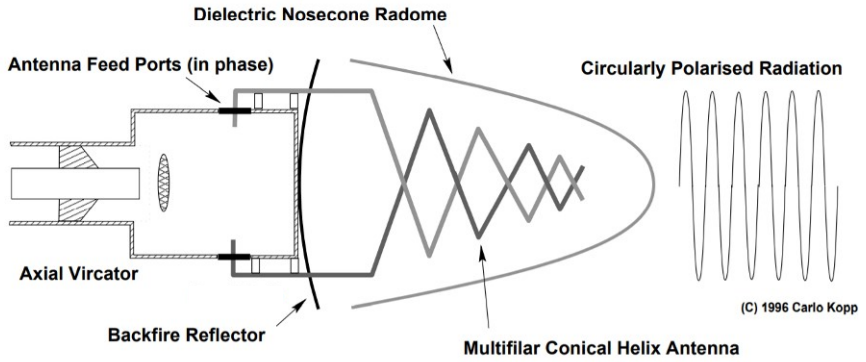
The next step in the construction of the e-bomb is the selection of an appropriate antenna system. The main problem here is the high output power of the vircator and ensuring the maximum utilization of the transmitting antenna.

Practical problems as an optimal choice impose the choice of a circularly polarized antenna. This brings the following advantages in relation to solutions with linear polarization:

- reflection - the signal strength is not reduced because it is emitted in all planes, so its reflection is not mostly expressed on one plane;
- absorption - due to broadcasting in all planes, the probability of coupling with the target device is higher;
- phase - since these are signals of higher frequencies, this type of polarization provides a higher probability of coupling regardless of the position and shape of the target object as well as obstacles;

- multi-path problem - the problem arises when the basic and reflected signals reach the receiver almost at the same time. This can have the problem of creating dead spots and reducing the total power at the reception. Circularly polarized antennas are less susceptible to this problem;
- visibility line - when the line of sight is disturbed by obstacles such as vegetation and smaller buildings, circular polarization has a better ability to establish a coupling with the target object; and
- influence of atmospheric conditions - thanks to the characteristics described above, there is greater resistance to the influence of rain, snow and other microconditions on signal absorption.

As an optimal solution, Krop states the use of a narrowing helix or a conical spiral antenna. According to the shown solution, Figure 4 (Kopp, 1996, p.10), the connection is by means of probes in the resonant cavity of the vircator, which are directly connected to the antenna.



Picture 3 – An example of a link between a vircator and an antena
Рис. 4 – Пример связи между виркатором и антенной
Слика 4 – Пример везе виркатора и антене

Effect of electromagnetic pulse on electric circuits

The importance of the problem of the influence of EMP on the operation of electrical circuits is shown by the fact that it is the subject of work of specialized institutions. For example, in Sweden, there is The Microwave Test Facility, whose task was originally to test the impact of high-frequency signals on aircraft, and later to start testing with commercial electrical devices.

The influence of EMP is considered through: impulse characteristics, coupling mode, and mechanism of influence. The quantities through which EMP is defined and through which its influence on electric circuits is estimated are: pulse growth time (v/s), electric field strength (V/m), and frequency (Hz), (Miller, 2005, p.387). Growth time is a basic factor in terms of "bypassing" overload protection. The strength of the electric field directly indicates the amount of energy that can be transmitted, and the frequency indicates transmission efficiency. Tests have shown that integrated circuits are more sensitive to higher frequency EMP, while physically larger electrical systems (such as power grids) are more sensitive to lower frequency EMPs. EMPs at frequencies from 200 MHz to 5 GHz[1] are considered the most dangerous for electrical systems.

Coupling is the way EMP is introduced into an electrical system, and can be accomplished in two ways (Vasilevich & Pershenkov, 2016, pp.621-629). The first is through the front door, i.e. the points that are intended to be the inputs / outputs of electrical circuits. The simplest example of this is the transceiver antennas of various devices. The second way is through the back door or through the points whose purpose is to connect parts of the system into a functional whole (signal transmission, power supply elements, etc.). In this case, the correlation with the frequency spectrum of the pulse is very important. Because EMP covers a wide range of frequencies, it easily penetrates parasitic antennas and connects to electrical systems.

Regardless of the type of coupling, these two authors further list four basic levels of influence on electrical systems. As such, they single out: upset, lock-up, latch-up, and burnout.

The first two ways are interfering with the operation of electrical devices and as such are found in foreign literature under the name soft kill. Uupset is the temporary interference with one or more electrical nodes in a device. Due to the appearance of parasitic voltages, the device does not function normally. The malfunction is rectified when the source of interference is switched off. The lock-up is similar to the previous case, except that now, in addition to stopping the interference, it is also necessary to turn off or reset the device.

With greater power, permanent damage and destruction of electrical devices is achieved. This influence is found in the literature under the name hard-kill. The only way to eliminate the consequences of such actions is to repair or replace certain parts of the circuit. A latch-up is an

[1] This is the frequency area with the largest number of radars, TV systems, mobile telephony systems, etc.

extreme variant of locking in which, due to the level of induced voltage, certain nodes in circuits either self-destruct or turn off. Burnout is the most extreme form of impact on electric circuits. It takes place physically through the form of a short circuit or even the physical burning of certain nodes, the melting of capacitors, resistors or conductive paths. Incineration is most often localized at points where more conductors intersect, more bases, collectors or emitters are connected. Damage occurs because, due to the described phenomenon, the components of the circuit are heated to a temperature exceeding 300 ° C.

The main factors, important for the damage of semiconductor elements, are the following:

- occurrence of voltages and overload currents in electric circuits,
- breakdown of dielectrics and air insulation between and near conductive roads,
- formation of short circuits in parasitic thyristor structures, and
- the induced EMP recombination currents.

Which of the mechanisms will exert a key effect depends mostly on the distance of the target from the EMP source, its frequency, the vulnerability of the target itself, the degree of EMP connection, as well as the entry points.

These authors give a tabular overview, Table 2, of the voltage quantities required for the physical destruction of certain elements realized in semiconductor technology. What can be seen is that semiconductor elements are extremely sensitive and that it is necessary to achieve voltage induction of the order of several tens of volts in order to ensure the safe destruction of such elements. Computers and integrated circuits are especially sensitive, for which a voltage of only 10V is sufficient. In contrast, "older technology" based on pipe technology is much more resistant.

Table 2 – Voltage levels required to damage various semiconductor components
Таблица 2 – Уровни напряжения, необходимые для повреждения различных полупроводниковых компонентов
Табела 2 – Напонски нивои неопходни за оштећење различитих полупроводничких компоненти

Types of semiconductor devices	Breakdown voltage
Silicon high frequency bipolar transistors	15V-65V
Gallium Arsenide Field Effect Transistors	10V
High density Dynamic Random Access Memories (DRAM)	7V
Generic CMOS logic	7V-15V
Microprocessors running off 3.3 V or 5 V power suppliesV	3.3V-5V

Numerous experiments are being conducted to better understand the impact of EMP. The importance of this question shows that there have been specialized institutes in the world for decades that deal with research in this field. One example is the Swedish microwave test facility. They are capable of producing electromagnetic pulse frequency up to 15GHz and pulse power up to 10GV (Bäckström et al, 2002).

An interesting resistance test of the computer network resistance to the influence of EMP was conducted in this institution (Arnesen et al, 2005). The subject of the test were LAN and WLAN networks, implemented on three desktops and five laptops. A field of maximum strength of 29 kV/m at a frequency of 1.3GHz and 17.5 kV/m at a frequency of 2.86 GHz was used as a source of interference. The tested equipment was distributed in three different radiation areas (according to intensity).

The results of this study were as follows. Parts of the equipment tested showed varying degrees of failure, from interference to failure (which could have been instantaneous or manifested with a delay of 5 minutes). Wireless networks are extremely sensitive because AP[2] were damaged by a field of strength in 175 V/m. The operation of LAN networks was already disrupted with a field of 2 kV/m, while interference of higher intensity[3] occurred with a field of over 4 kV/m. The physical damage of the electrical components started at 8 kV/m, and the power field of 12 kV/m had the effect of certain destruction. Computers have shown varying degrees of sensitivity. Laptops are up to ten times more resistant than desktops, but there were also differences depending on the specific type and manufacturer.

It is interesting to note that parts of the network equipment are significantly more resistant than computers themselves. Although the LAN was already disrupted at 500 V/m, its operation was interrupted for fields of 8 V/m, there was no physical damage to the parts of this equipment.[4]

These and similar experiments indicate that it is possible to make EMP of sufficient power to affect electrical devices. This data, in addition to the possibility of making an e-bomb, also indicates the problem of designing a successful protection against this type of threat.

[2] Acces point
[3] Interference was performed at frequencies of 1.3 and 2.86 GHz
[4] For a frequency signal of 2.857 GHz

Electromagnetic pulse protection

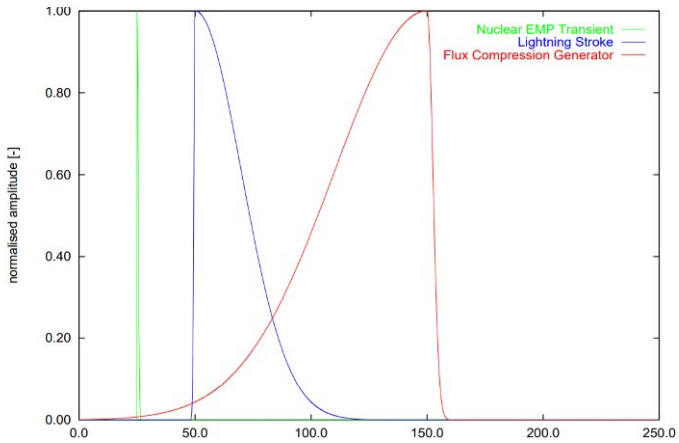
Protection measures and their efficiency depend on several factors, and armor protection and grounding have proven to be the most effective. The best example of armor protection is the use of a Faraday cage. This type of protection is realized by complete shielding, protected device, conductive material.

This ensures the distribution of electricity on the surface of the armor, which cancels the electric field inside it. Although efficient, this system has disadvantages that arise from the need to provide power and signal flow to the protected device. This causes the need to make holes in the armor, which will represent imperfections in the electrostatic armor. These openings will be "open doors", for all EMP wavelengths smaller than their dimensions and thus reduce the effectiveness of this type of protection. In addition, the use of conductors represents additional points for coupling with EMP.The problem with signal flow is successfully solved by using optical cables, while the issue of power supply still remains one of the main problems.

Although there are standard protection solutions, they must be adapted to the specific mode of threat, i.e. the type of electromagnetic pulse. The best example of this is a graphical representation of different types of electromagnetic pulses, Figure 5 (Kopp, 1996, p.3). What can be seen, as the most obvious difference, is the time of growth and duration.

Thus, the EMP caused by a nuclear explosion almost immediately reaches its maximum value and lasts extremely short, which dictates the specific conditions for the design of protection systems. In contrast, the EMP created by the flux generator gradually reaches its maximum value and lasts longer. The fact that these diffences are significant is indicated by the results of the research conducted in the USA, to which Kopp refers.

According to them, the protection measures developed for the purpose of preventing the impact of EMP caused by a nuclear strike are not sufficiently effective in preventing the effects of pulses generated by the use of high-energy microwave weapons.



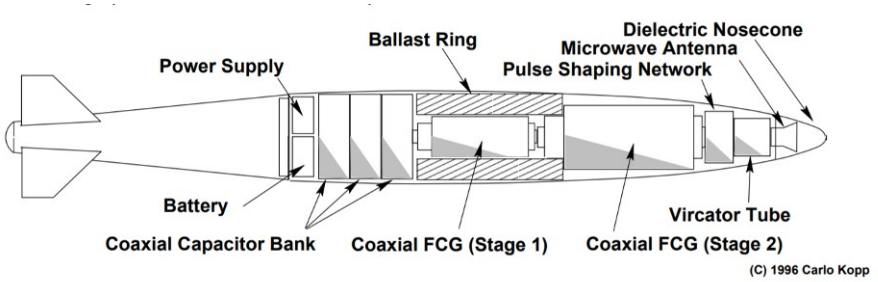
Picture 4 – Forms of electromagnetic pulses
Рис. 5 – Формы электромагнитных импульсов
Слика 5 – Облици електромагнетних импулса

The most economically viable is the design and installation of protection during the construction of devices themselves, while the costs of subsequent protection are significantly higher. As an example, various studies on the sensitivity to the use of EMP conducted in the United States can be cited (Foster et al, 2008, p.23). According to them, the estimated costs of installing protection in the existing elements of the high-energy electric, gas and telecommunication network range between 20 and 30 billion US $. Between $ 800 million and $ 1.5 billion need to be set aside to protect the most basic parts of the power system (such as high-voltage transformers). Strengthening most military systems would amount to an additional 10% of the cost, and strengthening only the military energy network an additional 10% of the cost. What everyone agrees on is that there are a very large number of systems without any protection, not only in the civilian but also in the military sphere. The problem is still extremely current because recent estimates suggest that the achieved level of resistance to electromagnetic pulse is still low and requires a more vigorous approach in eliminating this danger (Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, 2017)

Example of an electromagnetic bomb model

Back in 1996, Kopp presented an assessment of the dimensions and manner of realization of the applicable e-bomb. According to him,

this can be realized in the housing of the dimensions of an air bomb type Mk.84, Figure 6 (Kopp, 1996, p.10).



Picture 5 – An e-bomb placed in Mk.84 air bomb
Рис. 6 – Электронная бомба, размещенная в авиабомбе Mk.84
Слика 6 – Е-бомба смештена у тело авио-бомбе Мк.84

The air bomb body, 3.8 m long and 0.46 m in diameter, would successfully accommodate an e-bomb realized on a two-stage compression flux generator, with a virtual cathode generator. This would provide a usable model whose biggest problem would be a limited field of action, which can be overcome by high probability of kill. Also, by reducing the activation height, the lethal area is reduced, but the strength of the electric field is increased. In this way, targets of greater resistance can be destroyed.

Michael Abrams gave an estimate of how much EMP power could be achieved (Abrams, 2003). With the application of technical solutions stated by Kop, such a bomb would have a power of 10 GW, a frequency of 5 GHz and would have a deadly footprint with a diameter of 400-500 m. In this area, it would create a field of several kilowatts per meter. This would have an extremely distructive effect, even if the electrical devices in the targeted area had a certain degree of protection.

Conclusion

The trend of digitalization of all spheres of society has brought a wide presence of semiconductor technology. Besides numerous advantages, however, this undoubtedly brings certain weaknesses. The biggest one, extremely interesting from the aspect of both attack and protection, is the sensitivity to electromagnetic pulse effects. This area is important because the mechanisms of affecting electrical devices are well known and confirmed by numerous experiments.

The theoretical basis and technology of making an applicable model of an e-bomb are known and available to a wider number of subjects. The optimal choice of technical solutions, such as a flux generator for a power source and a vircator for an HF generator, would ensure the production of an e- bomb with real physical dimensions, a power of about 10 GW and a frequency of 5 GHz. In combination with high-precision weapons, satisfactory delivery accuracy would be achieved and thus limited power would be compensated. A large number of lucrative targets, ranging from radar and missile systems, through communication systems, to modern battle tanks, would justify the development and use of such weapons.

The high efficiency of e-bombs indicates the importance of this problem not only in the civilian but also in the military sphere. The main reason is the declining awareness of the importance of installing protection measures; and if they exist, they are not fully effective in protection against EMP produced by the e-bomb. A certain problem is a dominant trend of commercialization of the military sector, which leads to the growing presence of electrical components, which are not sufficiently protected. This is important because it is realistic to expect wider application of such weapons systems in the coming period. Also, timely protection, installed in the design phase, is significantly less financially burdensome compared to the cost of the entire project.

References

Abrams, M. 2003. Dawn of the E-Bomb. *IEEE Spectrum*, 40(11), pp.24-30. Avalable at: https://doi.org/10.1109/MSPEC.2003.1242953.

Arnesen, O.H., Krogager, E., Backstrom, M., Bo-Sande, S., Godo, J., & Harkonen, S. 2005. High power microwave effects on civilian equipment. In: *Proceedings of 28th General Assembly of the URSI*, India, New Delhi, October 23-29.

Bäckström, M., Lövstrand, K.G. & Nordström, B. 2002. The swedish microwave test facility: technical features and experience from system testing. In: *Proceedings of 27th General Assembly of the URSI*, The Netherlands, Maastricht, August 17-24 [online]. Available at: https://www.ursi.org/proceedings/procGA02/papers/p0451.pdf [Accessed: 28 September 2020].

Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. 2017. *Assessing the Threat from Electromagnetic Pulse (EMP): Executive Report* [online]. Available at: http://www.firstempcommission.org/uploads/1/1/9/5/119571849/executive_report_on_assessing_the_threat_from_emp_-_final_april2018.pdf [Accessed: 28 September 2020].

Dražan, L. & Vrána, R. 2009. Axial Vircator for Electronic Warfare Applications. *Radioengineering*, 18(4), pp.618-626 [online]. Available at: https://www.radioeng.cz/fulltexts/2009/09_04_618_626.pdf [Accessed: 28 September 2020].

Foster, J.S., Gjelde, E., Graham, W.R., Hermann, R.J., Kluepfel, H.M., Lawson, R.L., Soper, G.K., Wood, L.L. & Woodard, J.B. 2008. *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures*. Fort Belvoir, Virginia: Defense Technical Information Center [online]. Available at: https://apps.dtic.mil/sti/citations/ADA484672 [Accessed: 28 September 2020].

Kopp, C. 1996. *The electromagnetic Bomb – a Weapon of Electric mass destruction.* Fort Belvoir, Virginia: Defense Technical Information Center [online]. Available at: https://apps.dtic.mil/sti/citations/ADA332511 [Accessed: 28 September 2020].

Miller, C.R. 2005. *Electromagnetic Pulse Threats in 2010*. Fort Belvoir, Virginia: Defense Technical Information Center [online]. Available at: https://apps.dtic.mil/sti/citations/ADA463475 [Accessed: 28 September 2020].

Ni, G., Gao, B. & Lu, J. 2005. Research on High Power Microwave Weapons. In: *Asia-Pacific Microwave Conference Proceedings*, Suzhou, China, p.4, December 4-7. Available at: https://doi.org/10.1109/APMC.2005.1606492.

Vasilevich, S.V. & Pershenkov, V.S. 2016. Electromagnetic pulse effects and damage mechanism on the semiconductor electronics. *Facta universitatis - series: Electronics and Energetics*, 29(4), pp.621-62. Available at: https://doi.org/10.2298/FUEE1604621S.

ВЫСОКОЭНЕРГЕТИЧЕСКОЕ СВЧ-ОРУЖИЕ − ЭЛЕКТРОМАГНИТНАЯ БОМБА

Горан М. Баняц[а], **корреспондент**, *Владимир* Д. Джорджевич[а], *Миладин* З. Живкович[а], *Абделла* Ферджали[б]

[а] Университет обороны в г. Белград, Военная академия, кафедра противовоздушной обороны, г. Белград, Республика Сербия

[б] Политехническое военное училище, г. Алжир, Алжирская Народная Демократическая Республика

РУБРИКА ГРНТИ: 78.00.00 ВОЕННОЕ ДЕЛО:
78.25.00 Вооружение и военная техника;
78.25.23 Новейшие разрабатываемые средства вооруженной борьбы и защиты от них

ВИД СТАТЬИ: профессиональная статья

Резюме:

Введение/цель: Технический прогресс привел к актуализации вопроса о создании и применении высокоэнергетического СВЧ-оружия, в частности электромагнитных бомб. Однако в новейшей военно-профессиональной литературе этот вопрос недостаточно освещен.

Методы: В данной статье представлен анализ имеющейся литературы по данной теме.

Результаты: Выявлено, что общие принципы функционирования и теоретические основы широко доступны и известны на протяжении многих лет. Многочисленные эксперименты в специализированных учреждениях подтвердили эффективность электромагнитного импульса. Особенно касательно чувствительности устройств на основе полупроводниковой техники. Также предполагается, что на текущем технологическом уровне технические решения широко доступны большому количеству организаций. В изученной литературе наиболее распространенной моделью электромагнитной бомбы является использование генератора сжатия потока и генератора с виртуальным катодом. По мнению авторов, этот вариант гарантирует, что конечный продукт будет обладать достаточной мощностью и реалистичными физическими размерами для того чтобы иметь ценность использования. Еще одна проблема, обозначенная в литературе, касается вопроса об отсутствии соответствующих мер защиты от воздействия электромагнитных импульсов. Это относится не только к гражданскому, но и к военному сектору и требует инвестирования значительных ресурсов для последующего повышения сопротивления.

Выводы: В доступной литературе указывается, что можно разработать электромагнитную бомбу приемлемых физических размеров и мощности. Предполагается, что она будет генерировать электромагнитный импульс мощностью около 10 ГВт и частотой 5 ГГц. В сочетании с высокоточным оружием даже защищенные устройства можно будет успешно вывести из строя. Широкое присутствие полупроводниковых технологий во всех сферах жизни делает это оружие чрезвычайно эффективным, следовательно, можно ожидать его широкого применения в ближайшем периоде.

Ключевые слова: СВЧ-оружие высокой энергии, электромагнитная бомба, электромагнитный импульс, генераторы сжатия потока с взрывной накачкой, виркатор.

ВИСОКОЕНЕРГЕТСКО МИКРОТАЛАСНО ОРУЖЈЕ – ЕЛЕКТРОМАГНЕТНА БОМБА

Горан М. Бањац[а], **аутор за преписку**, *Владимир* Д. Ђорђевић[а], *Миладин* З. Живковић[а], *Абделлах* Фердјали[б]

[а] Универзитет одбране у Београду, Војна академија, Катедра противваздухопловне одбране, Београд, Република Србија

[б] Политехничка војна академија, Алжир, Народна Демократска Република Алжир

ОБЛАСТ: електромагнетика
ВРСТА ЧЛАНКА: стручни рад

Сажетак:

Увод/циљ:Технолшки напредак довео је до актуелизације питања конструкције и коришћења високоенергетског микроталасног оружја, а посебно електромагнетене бомбе. Међутим, у новијој војностручној литератури ова проблематика је ретко заступљена.

Методе: Извршена је анализа постојеће доступне литературе из предметне проблематике.

Резултати: Установљено је да су општа начела функционисања и теоријске основе доступни и познати већ дужи низ година. Бројни експерименти у специјализованим установама потврдили су ефикасност утицаја електромагнетног импулса, што се превасходно односи на осетљивост уређаја базираних на полупроводничкој технологији. Такође, претпоставља се да су, на садашњем технолошком нивоу, техничка решења доступна великом броју субјеката. Као најчешћи модел електромагнетне бомбе, у литератури се истиче реализација коришћењем компресионог флукс-генератора и осцилатора са виртуелном катодом. Ова варијанта могла би да обезбеди да коначни производ има реалне физичке димензије и довољну снагу, као и употребну вредност. Још један од проблема који је идентификован у обрађеној литератури јесте масовније одсуство адекватних мера заштите од дејства електромагнетног импулса. То се не односи само на цивилни, него и на војни сектор и намеће потребу улагања знатних средстава ради накнадног повећања отпорности.

Закључак: Доступна литература указује на могућност израде електромагнетне бомбе прихватљивих физичких димензија и снаге. Претпоставља се да би њом био генерисан електромагнетни импулс снаге око 10 GW и фреквенције 5 GHz. У комбинацији са високопрецизним оружјем могли би се успешно ометати чак и заштићени уређаји. Широка заступљеност полупроводничке технологије чини овакво оружје изузетно

ефикасним, паје реално очекивати његову значајнију примену у наредном периоду.

Кључне речи: високоенергетско микроталасно оружје, електромагнетна бомба, електромагнетни импулс, компресиони флукс-генератор, виркатор.

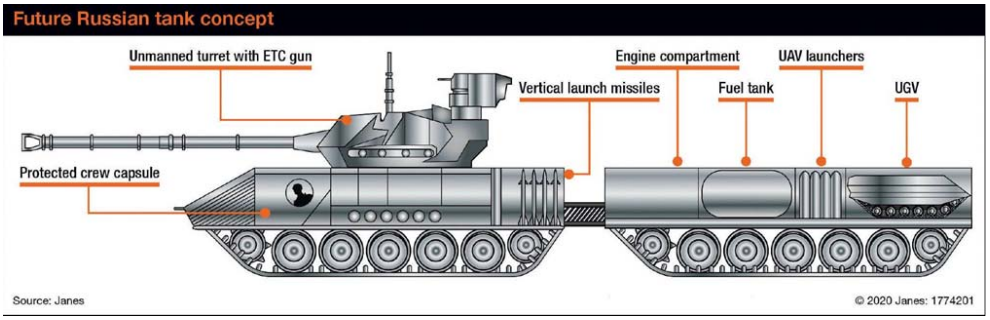
Paper received on / Дата получения работы / Датум пријема чланка: 24.10.2020.
Manuscript corrections submitted on / Дата получения исправленной версии работы / Датум достављања исправки рукописа: 16.03.2021.
Paper accepted for publishing on / Дата окончательного согласования работы / Датум коначног прихватања чланка за објављивање: 18.03.2021.

Идеје о будућим руским оклопним концептима[1]

Током приказа наоружања *Armiya* 2020, изнета је радикално нова идеја о тенку који би заменио основни борбени тенк *T-14 Armata*. У чланку, који је објављен 25. августа 2020. године, будући концепт тенка приказали су експерти из руског 38. института за истраживање и тестирање оклопног оружја и опреме.

Институт је одговоран за основни правац развоја оклопних возила, као и за тестирање различитих оклопних возила руских копнених трупа.

Извештај руске агенције TASS наговештава да ће руски тенк *T-14 Armata* остати у наоружању до 2040. године, али да је потребно поставити основе за даљи развој и замену тенка.



„Експерти 38. института виде ново борбено возило као опцију зглобног возила састављеног од два дела. Предњи борбени модул може бити опремљен контролним одељењем са три члана посаде у заштићеној оклопној капсули. Средњи део модула би био опремљен безпосадном куполом са монтираним електро-термохемијским топом са аутоматским пуњачем", изјавио је пуковник Yevgeny Gubanov, заменик директора Института.

Поред електротермохемијског топа, предњи модул возила садржао би и ћелију за вертикално лансирање ракета домета до 12 км са системом за навођење. Предњи део модула био би заштићен реактивним оклопом на његовом предњем делу где би се налазило и „заслепљујуће ласерско оружје", као и „електромагнетски пулсни генератор".

[1] Jane's Defence International December 2020

Други модул зглобног возила носио би мотор, гасну турбину снаге до 3.000 КС, као и одвојени део за лансирање невођених ваздушних и копнених возила. Експерти објашњавају да би употреба зглобног концепта умањила тежину возила која би морала бити много већа због употребе нове врсте оклопа и наоружања. Експерти Института наводе да би други зглобни модул могао носити и људство уместо невођених беспилотних летелица и возила, а да би оба модула могла бити опремљена камерама које „гледају" кроз оклоп.

Историјат

Дводелни тенковски пројекти разматрани су и раније, нарочито са шведским тенковима *UDES XX5* и *UDES XX20* – зглобним лаким тенковима које су развијале тадашње шведске компаније *AB Hägglunds* и *Söner*. *UDES XX5 имао* је шасију *Bv 206* на којој се налазио топ, иако се тада радило само о демонстрацији мобилности пројекта. Када се испоставило да је дизајн приказао одличне теренске карактеристике, одлучено је да се изради потпуни демонстрациони пројекат са борбеном масом до 20 т. Тестирано возило добило је назив *UDES XX20* (ознака XX је означавала експериментално возило), а његова маса износила је до 26 т. У јануару 1982. године испоручила га је уговорна компанија *HB Utveckling AB,* а тестирано је до марта 1984. године.

Возило је имало два дела. Магацин се налазио у предњем делу, иако је постојала идеја да се угради аутоматски пуњач, а да се магацин са гранатама нађе на задњем модулу. Међутим, испоставило се да је било потребно да се топ сваки пут врати назад у позицију за пуњење након сваког испаљеног хица, а затим врати у првобитну позицију ка циљу, што је успоравало циклус нишањења и пуњења.

Тестови возила показали су различите резултате. *UDES XX20* је био изузетно покретан, савладавао је препреке на лакшим и средње тешким теренима, као и по снегу, боље од других тенкова.

Један од тенкова бољих карактеристика којим ће Русија опремити своје копнене снаге до 2027. године је Т-90М, док је следећи тенк који ће ући у састав копнених снага Т-14 Armata

Шведски прототип могао је да се креће и када би предњи модул изгубио гусеницу, али су оправке тенка биле компликованије од оправки класичних тенкова. Појавили су се и други проблеми. Возилу је било потребно више времена за прелазак из статичног, осматрачког режима у положај за отварање ватре, што је доводило до ризика губљења покретних мета. Такође, неки облици мобилности показали су се лошији у односу на конвенционална возила. На пример, окретање у месту било је немогуће због тога што је сваки модул имао своју путању окретања, што је значило да је било скоро немогуће окренути цело возило у малом кругу, већ је захтевало неколико дуготрајнијих маневара.Возило је било нешто више у односу на тенкове конвенционалног дизајна, па се могло лакше приметити док је у покрету, а имало је и већу горњу површину. С друге стране, било је могуће умањити ширину возила, што би значило мању предњу површину која би била боље заштићена.

Поред тога, предложени дизајн је подразумевао аутоматски пуњач и магацин на задњем модулу, што би ефикасније штитило посаду од експлозије и накнадног изгоревања муниције. На крају, од овог пројекта се одустало због механичке сложености оваквог возила које би захтевало много веће оперативне трошкове одржавања и производње.

Није познато да су руски инжењери покушали производњу дводелног тенка, иако је Русија развијала различите пројекте за своју фамилију топова/хаубица *DT-10/20/30*, као што су топ-минобацач *Magnolia* на платформи *DT-20PM* и вишецевне лансере ракета *Grad* и *Smerch* на платформи *DT-30PM*.

Током осамдесетих година прошлог века, совјети су разматрали идеју тенка са четири гусенице и два мотора познатог по ознаци *Object 490*, „Перспективни тенк 21. века”, односно *PT21C*.

Спецификације возила биле су врло амбициозне у сваком погледу; укључивале су ватрену моћ, ниво преживљавања и мобилности који су били импресивни и по садашњим стандардима. Ипак, овакав концепт је напуштен, пре свега због тога што је био врло зависан од термалних и ТВ камера у смислу ситуационе свесности.

У то време совјетска оптоелектронска технологија је знатно заостајала за западном, па није било могуће произвести тенк *PT21C* без одговарајућих кључних компонената. Међутим, данас је ова индустрија толико напредовала да је могуће реализовати овакве егзотичне дизајне.

Анализа

Концепт 38. института има неколико елемената који се могу анализирати. На први поглед, употреба зглобне шасије изгледа логично, јер би омогућила возилу да достигне много већу тежину од класичних тенкова а да и даље задржи добар, ако не и бољи, степен мобилности. На пример, зглобни *DT-30PM,* који није оклопљен а има масу до 60 тона може да се креће на снегу и леду. Међутим, када је у питању тенковска

мобилност, возило би морало да се креће и по меком тлу, као што су иловача и песак, као и на чврстим подлогама.

Зглобно возило би захтевало сложен пренос брзина с обзиром на то да се снага преноси са задњег модула ка предњем преко покретног зглоба који би морао да се дели на два погонска ланчаника. Ипак, зглобност нуди и различите повољности, укључујући уже радијусе окретања и могућност окретања без већег потиска на подлогу по којој се креће. Зглобност, такође, омогућава да предњи и задњи модул остану на својим подлогама иако се налазе на нагибу који је на 30 степени од централне линије возила.

Зглобно возило се теоретски може и одвојити, тако да сваки модул ради независно. Ипак, одвајање посадног модула од погонског у овом случају би било немогуће.

Може се закључити да зглобна возила постижу већу брзину на тешким деоницама и мање се заглављују, али њихова већа дужина компликује транспорт и употребу у просторима који су ограничени.

Институт наводи да би погон возила имао снагу до 3.000 КС. Уколико се претпостави да би маса возила била до 60 тона (10 тона тежа од било ког познатог руског тенка) то би водило до односа снаге/масе од 50 КС/т. Уколико се претпостави да би возило тежило до 80 тона, резултат би био 37,5 КС/т.

Логично је очекивати да би возило захтевало невероватну количину пасивног и реактивног оклопа да би преживело противоклопне претње 2040. године. Једно од могућих решења је и заштићена капсула за посаду са релативно танким оклопом на остатку возила. У сваком случају, с обзиром на потенцијалне претње, возило би морало бити тешко, па би зглобни дизајн и јак погон могао доћи до изражаја.

Одабир гасне турбине није у складу са развојем руских тенкова, првенствено у погледу трошкова. Године 1987. америчка војска је утврдила да би покретање оклопне дивизије опремљене тенковима *M1 Abrams* на даљину до 160 км захтевало 821.000 литара горива у односу на 605.500 литара колико би било потребно за покретање исте такве јединице опремљене тенковима *M60* са дизел моторима. Додатна тежина тенка *M1 Abrams,* као и потрошња гасне турбине, резултирају великом потрошњом горива, па и великим трошковима одржавања флоте.

Поред тога, модерни дизел мотори могу достићи исти ниво убрзања и вуче, а по габариту су мањи од гасне турбине. На пример, дизел мотор *MT 883* компаније *MTU* од 1.500 КС захтева 4,53 кубних метара простора у односу на 8,4 кубних метара за турбину *AGT-1500* тенка *M1 Abrams*. На основу овакве рачунице више би се исплатило поставити дизел агрегат на зглобну платформу са одговарајућим преносом брзина.

Када је у питању оружје возила, комбинација електротермохемијског топа са ракетама са вертикалним лансирањем претпостављала би класичан напад на тенкове, али и напад на циљеве ван линије хоризонта. Обе врсте напада захтевале би постојање напредних сензора, али и прикупљање информација о циљевима путем одвојених средстава. Оваква

врста захватања циљева већ постоји у руској војсци, тако да употреба ракета дугог домета на зглобним тенковима није нереална.

Прошли експерименти су показали да је електротермохемијски топ ефикасан, али и да је повећање брзине гранате на истом калибру топа мање од убрзања гранате кроз класичан топ већег калибра.

Америчка војска је почетком 2000-тих покушала да за свој „будући борбени систем" развије електротермохемијски топ 105 мм са даљинама гађања до 50 км, омогућавајући његову употребу као хаубицу са цикличним брзинама паљбе од 20 до 40 граната у минути. Уколико 38. институт разматра револуционарни дизајн онда би перформансе тог топа могле бити сличне америчким по програму „Будући борбени систем".

Драган М. Вучковић (*Dragan* M. Vučković),
e-mail: draganvuckovic64@gmail.com,
ORCID iD: https://orcid.org/0000-0003-1620-5601

Нови израелски пасивни радар[2]

Израелска компанија *Aerospace Industries' Elta Systems* приказала је, 27. октобра 2020. године, нови пасивни кохерентни локациони систем – *Passive Coherent Location (PCL)* који генерише слику ситуације у ваздушном простору користећи технологију откривања циља без активног емитовања. Он поседује и некооперативне одашиљаче – ФМ радио-станице или торњеве за дигитално аудио-емитовање чије се емисије одбијају од летелица које лете изнад њих.

Рефлексије се примају једна по једна, са мреже, или са антена, омогућавајући 3Д омнидирекционално покривање више циљева у реалном времену. Овај систем је једноставан за монтирање и може бити постављен на границама, али и у градским срединама. Инсталација укључује један или више сензора ради постизања редунданције и побољшаног покривања посебних проблематичних области. Локације система су повезане у централни систем путем посебних дата-линкова.

Овај систем може бити постављен независно или као додатни слој поред радара за ваздушну контролу. Пројектован је за откривање авиона, беспилотних летелица и квадкоптера, а за разлику од електронског и комуникационог надзора може открити, лоцирати и пратити циљеве који не емитују активно.

Сваки регион у некој земљи има своју радио-станицу, а често и више од једне. Емисије радио-станица погађају, поред осталог, авионе у ваздушном простору. Систем добија повратне сигнале и путем дигиталног процесуирања ствара мапу циљева.

[2] Jane's Defence International December 2020

Емисије се одбијају од летелица ради локације мета

За ефикасан рад система потребно је да у одређеној области постоји радио-станица, при чему није битно колико је близу праћеног циља.

Компанија *IAI-Elta* развија ову технологију већ 10 година. Проблем је, углавном, био у процесуирању сигнала, јер постоје десетине циљева и стотине радио-станица. Систем прима десетине хиљада одбијених емисија на основу којих гради слику летелица у ваздушном простору.

Релативно ниска фреквенција цивилних радио-станица – око 100 MHz, знатно је нижа од фреквенција које користи највећи број радара. Овакве фреквенције омогућавају откривање циљева који имају мали радарски одраз, а с обзиром на то да нема одашиљања скоро је немогуће открити сензоре који су прикривени и имуни на ометање.

Очекује се да ће систем бити оперативан за годину дана.

Драган М. Вучковић (*Dragan* M. Vučković),
e-mail: draganvuckovic64@gmail.com,
ORCID iD: https://orcid.org/0000-0003-1620-5601

Ласерски убица дронова[3]

Компанија Rafael Advanced Defense Systems спровела је прву ватрену демонстрацију свог система за сузбијање беспилотних летелица – *Drone Dome-L counter-unmanned aircraft systems* (*C-UASs*), користећи ласерско оружје велике снаге.

Слика вишеструког напада беспилотних летелица током демонстрације система компаније Rafael Advanced Defence Systems' Drone Dome-L у јужном делу Израела, током децембра 2019. године.

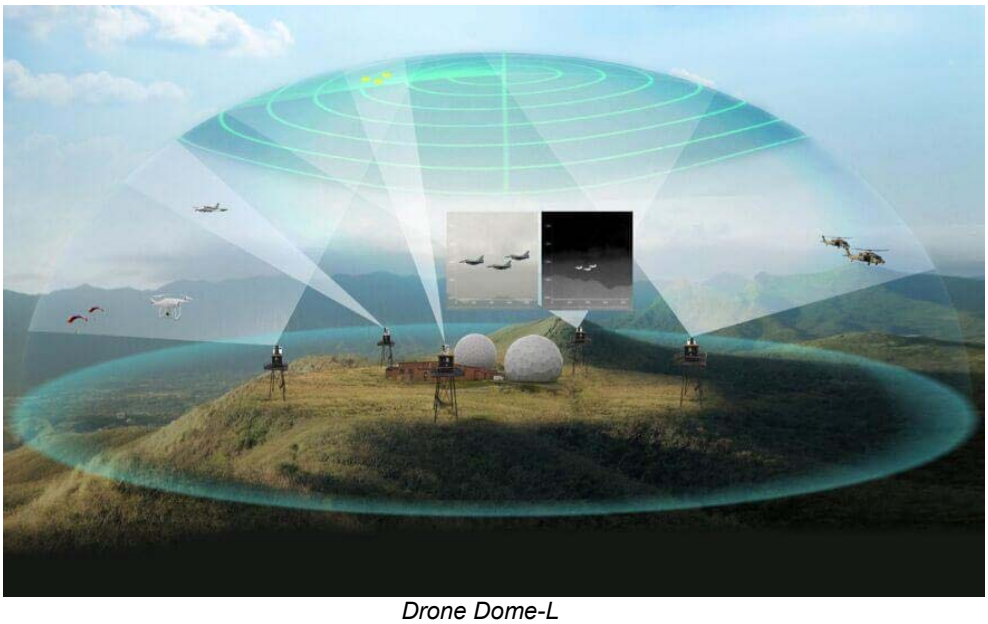
Демонстрација употребе овог система спроведена је децембра 2019, али је објављена тек у фебруару 2020. године. Током демонстрације приказано је праћење и ласерско пресретање „већег броја маневришућих беспилотних летелица". Овом догађају претходили су двогодишњи тестови који су резултирали демонстрацијом вишеструког пресретања.

Компанија Rafael је употребила квадкоптере класе *Phantom* у улози мете, али нису објављене даљине пресретања ни време које је било потребно ласеру да неутрализује мете.

[3] Jane's Defence International April 2020

Drone Dome-L је модуларни систем који функционише у кругу од 360 степени, у свим временским условима против непријатељских микро и мини беспилотних летелица. Основна конфигурација овог система подразумева мултимисијски хемисферни радар *RADA RPS-42 S-band*, систем надзора великог домета *SPEED ER*, комуникациони пакет, лаки, потпуно програмабилни преносиви ометач *C-Guard RD* и систем детекторских сензора широког појаса који је развила компанија Netline. Током 2017. године компанија је додала ласерски усмеривач зрака . Систем се може упарити са различитим екстерним системима, а подржава и будући развој.

RPS-42 је четворопанелни (неротирајући) тактички систем надзора у кругу од 360 степени по азимуту и 90 степени по елевацији. Оптимизован је за детекцију, праћење и класификацију свих класа беспилотних летелица. Поседује активни радар са електронским скенирањем, чији је радијус откривања циљева до 30 км, а детектује циљеве величине 0,002 квадратна метра на даљини до 3,2 км и на висинама од 9,14 до 9,144 м.



Drone Dome-L

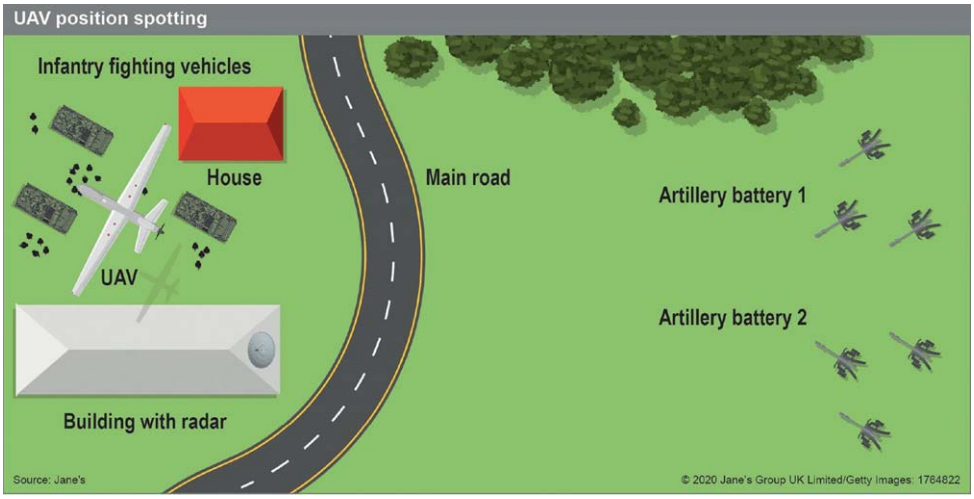
Широкопојасни сензор *NetSense* открива низ разних трансмисија са брзим скенирањем у фреквенцијама од 20 MHz до 6 GHz, док ометач *C-Guard RD* блокира врло високе и ултрависоке фреквенције канала на беспилотним летелицама путем реактивне ометајуће технологије (са по 400 W укупне излазне снаге) и напада све могуће везе на стандардним

(индустријским, научним и медицинским) и Wi-Fi таласима. На овом нивоу беспилотна летелица је неутрализована путем активације дирекционог уређаја *GPS/GNSS* и ометањем радио-фреквенција.

Драган М. Вучковић (*Dragan* M. Vučković),
e-mail: draganvuckovic64@gmail.com,
ORCID iD: https://orcid.org/0000-0003-1620-5601

Употреба руске БПЛ *Orlan-10*[4]

Америчке трупе на ратиштима у Ираку и Авганистану успоставиле су нове границе употребе беспилотних летелица (бпл) – од извиђачких задатака до атентата на мете великог значаја. Пре тога, БПЛ су секористиле углавном у шпијунским мисијама, на пример изнад Северне Кореје и Вијетнама.



БПЛ „уочавају позиције" летом изнад потенцијалне мете и слањем њених координата

Развој технологије током осамдесетих година омогућио је смањивање димензија БПЛ и дуже трајање летова. Коришћене су у извиђачким мисијама на Косову током 1999. године ради прикупљања обавештајних података о српским снагама и покретима избеглица, као и о оштећеним српским оклопним снагама.

Прва наоружана америчка БПЛ уведена је у оперативну употребу 2000. године. Вођена је радио-таласима уместо преко сателита, што је

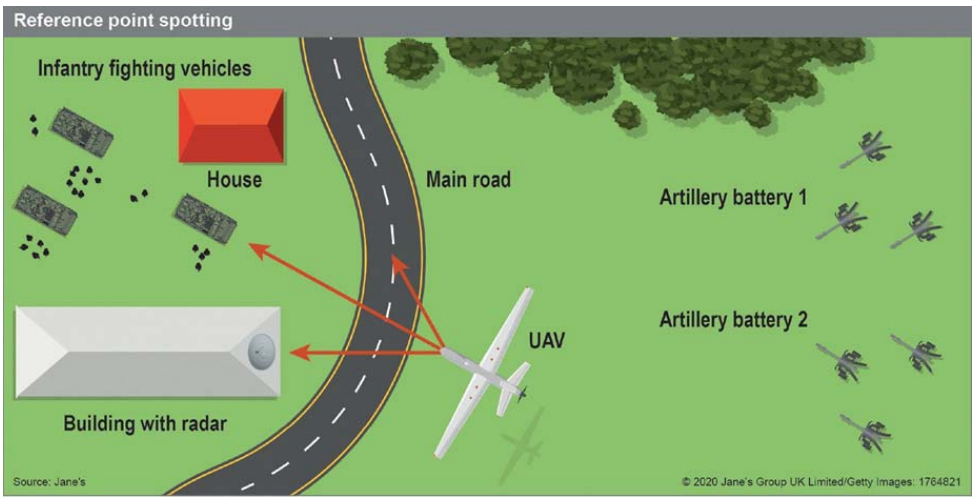
[4] Jane's Defence International May 2020

приморало пратеће особље да буде знатно ближе ратним операцијама. Наоружавање и сателитско навођење БПЛ омогућило је америчком председнику Бараку Обами да прошири своју борбу против тероризма далеко од америчких граница без присуства америчког особља у просторима ратних дејстава.

Беспилотне летелице доминантно је користила Америка и њени савезници, док руске трупе нису ушле у Украјину 2014. и 2015. године. Снаге Доњетске Народне Републике биле су подржане руским БПЛ и осигурале тактичку предност у односу на украјинску војску. Тада су се појавили и нови извештаји који су указивали на то да су руске БПЛ биле коришћене за ометање комуникација и радара. Тиме је потврђена намера Русије да користи БПЛ на тактичком нивоу.

Употреба тактичких БПЛ била је демонстрирана 2016. године, а детаљи су се накнадно сазнали у серији брифинга руског специјалног технолошког центра на војној артиљеријској академији „Михаловски". Радило се о „стварању извиђачког ватреног комплекса употребом БПЛ *Orlan-10"*.

Експеримент је био заснован на тактичком нивоу. Наиме, БПЛ је била упарена са три батерије од по четири самоходне хаубице 122 мм *2S1 Gvozdika*. Различите улоге добиле су *2S1* – једна батерија била је одређена за контрабатирање, а друге две за напад на циљеве. Батерије су подржане једном јединицом која је користила БПЛ *Orlan-10*.



БПЛ снимају „референтне тачке" коришћењем детаљних мапа

Беспилотна летелица *Orlan-10* била је опремљена системом *Shelest*. У презентацији је објашњено да је *Shelest* био коришћен путем БПЛ ради обезбеђивања 24-часовног надзора украјинских контрабатирајућих радара

AN/TPQ-48. У тренутку испаљивања артиљеријских плотуна *Shelest* би био укључен. Употреба овог система заварала је украјинске радаре и онемогућила их у добијању позиције батерије која је тада гађала.

Употреба батерија *2S1* интересантна је због старости самог система. Наиме, систем *2S1* је заснован на гусеничару *MT-Lbu* који је произведен између 1969. и 1991. године и наоружан је олученом хаубицом 122 мм *2A31* која је настала од вучног топа-хаубице *D-30*. Хаубица *2A31* омогућава возилу да нападне циљеве на даљинама до 15.200 м конвенционалном муницијом чији се домет повећава употребом ракетних граната на 21.900 м.

Министарство одбране Русије наводи да систем има каденцу ватре од само 3 до 5 граната у минути. Мада има могућност испаљивања граната са ласерским вођењем та опција је врло ретко у употреби.

Батерија *2S1* није најмоћнији руски артиљеријски систем. Наиме, она има слабију ватрену моћ и мањи домет у односу на веће самоходне хаубице 152 мм *2S3 Akatsiya* и *2S19 Msta-S*. Ипак, може бити сасвим погодно решење у областима без непосредне опасности и где није неопходна велика подршка.

Батерије *2S1* су, заједно са БПЛ *Orlan-10,* употребљене ради лоцирања и напада на циљеве дању и ноћу. Прва акција забележена током презентације била је против радара *AN/TPQ-48* који се налазио на крову једне зграде. Презентација је показала скриншот са екрана оператора БПЛ, као и неколико слика локације мете које су снимиле БПЛ.

Скриншот је такође показао серије сателитских *GLONASS* координата. Видело се да су први хици исправљени сигналом са БПЛ, што значи да су прве гранате артиљеријског баража промашиле, али је већ следећа тура пала на циљ. Презентација је показала да је испаљено 38 граната на циљ и да је радар био уништен. Тада је речено и да је по стандардној руској доктрини, ради уништавања овакве врсте циљева, било потребно између 200 и 300 граната.

Нису објављени детаљи у вези с начином циљања БПЛ *Orlan-10.,* Међутим, у једном чланку, објављеном 2016. године, наведено је да БПЛ *Orlan-10* није у могућности да користи напредне методе циљања као што су ласерско озрачивање или триангулација. Коришћена је метода прелета саме БПЛ изнад мете на коју је дејствовала артиљерија где је БПЛ снимала дејство или је артиљерији пружала информацију о референтним тачкама као што су, на пример, неки рељефни репери или раскршћа путева. Када је у питању коришћење путне инфраструктуре неопходно је поседовати и врло детаљне саобраћајне мапе.

Ниједна од поменутих метода не захтева коришћење скупих артиљеријских навођених пројектила, а БПЛ омогућава спровођење артиљеријског напада и коректурне ватре употребом конвенционалне муниције у врло кратком периоду. Са само две батерије *2S1* могуће је испалити 10 граната на циљ за само 60 секунди.

Падобранац лансира БПЛ Orlan-10 током војне вежбе 2018. године

Следећа акција приказана презентацијом описана је као „уништавање групе циљева артиљеријском ватром у осматрачком ватреном нападу". Циљ се састојао од неколико оклопних возила *MT-LB* и *BMP* који су се налазили ускладиштени у згради. На презентацији је речено да су две батерије напале ускладиштена возила, док је трећа била у приправности ради контрабатирања.

Детаљно је објашњена ватрена мисија. Основни топови батерија су испалили по један хитац. Након корекције следио је плотун. Уништење циља спроведено је након испаљивања две до четири гранате по топу. Укупно је испаљено 112 граната, а уништено најмање три оклопна возила и непознат број украјинских трупа, што је касније потврдила и Организација за безбедност и сарадњу у Европи.

Трећа мисија била је усмерена против објеката описаних као „тешко утврђена позиција у бившој војној касарни". Радило се о фортификацији и припремљеним позицијама за минобацаче 120 мм, као и за оклопна возила и рововима за трупе. Стандардно су испаљени пробни хици ради усклађивања ватре са БПЛ *Orlan-10*. Након тога, сваки циљ је индивидуално гађан засебним ватреним мисијама са по две до четири гранате. Једном када је циљ уништен, топови су почињали ватрену мисију по следећем циљу. Укупно је испаљено 120 граната на циљ површине 400×400 м и уништени су минобацачки положаји, као и остали фортификовани објекти.

Презентацијом је касније детаљно приказано неколико сличних сценарија и забележено да је за време експеримента изведено 109 летова

БПЛ и 12 ватрених мисија са укупно 960 испаљених граната 122 мм. Двадесет и три мисије спроведене су ради радио-пресретања и прикупљања података, а затим и потврде ефикасности претходних ватрених мисија. Укупни резултати показују да су уништене три балистичке ракете кратког домета *Tochka-U* муницијом са БПЛ, четири радара *AN/TPQ-48*, 17 гусеничара, 20 точкаша и један магацин са муницијом.

Закључено је да је потребно формирати јединице опремљене беспилотним летелицама на нивоу пука ради одржавања највишег стања приправности артиљеријских јединица које у том случају не би зависиле од подршке следећих ешелона.

Драган М. Вучковић (*Dragan* M. Vučković),
e-mail: draganvuckovic64@gmail.com,
ORCID iD: https://orcid.org/0000-0003-1620-5601

Нова „паметна" тканина за војнике[5]

Прототип „паметне" тканине за војнике коју је произвела Европска агенција за одбрану улази у финалну фазу тестирања.

Овај пројекат, под називом *Smart TextILE (STILE),* укључује шпанско удружење текстилне индустрије, две португалске истраживачке организације *CITEVE* и Институт наука и иновација у механичком и индустријском инжењерингу. Циљ је да се произведе наноматеријал са уграђеним различитим сензорима.

Овај материјал пројектован је за контролу телесне температуре и откривање биолошких претњи, као и за интеграцију ових функција ради даљинског очитавања параметара. Данас је сензорска технологија толико напредовала на нанометарском нивоу да је таква интеграција врло могућа. Међутим, „текстроника" уграђена у тканину – материјал који одговора на спољну средину, ипак је врло скуп процес.

Нови материјал који се носи испод балистичких плоча интегрише шест функција и карактеристика: мултиспектралну камуфлажу у статичним и покретним позицијама, надзор хемијских, биолошких и радиолошких претњи, отпорност на ватру, одбијање воде и прљавштине, решење за одбијање комараца, надзор пулса и рада срца, регулацију телесне температуре преко надзора спољне температуре и комуникације.

Материјал је врло лак, не више од 1 до 2 кг, тако да не смета војницима када се на њега дода и балистичка заштита.

Прави изазов за производњу овакве тканине био је да се изради материјал који би задржао своје функције и након више прања. Други изазов био је избегавање искључења једне или више функција када су друге активиране, као што је термална регулација у односу на управљање камуфлажом.

[5] Jane's Defence International July 2020

Тканина шаље све параметре, као што је број срчаних откуцаја или температура тела, у реалном времену до војника преко апликације његовог паметног телефона. Војник тада може одлучити како ће се „кожа" даље понашати у односу на спољну средину. Ови подаци се затим могу послати и у командни центар на даљу анализу.

Следећа фаза испитивања почиње у јулу 2020. године, када пројекат улази у своју завршну фазу. Тада следе испитивања у контролисаном лабораторијском окружењу, а након тога и на терену.

Драган М. Вучковић (*Dragan* M. Vučković),
e-mail: draganvuckovic64@gmail.com,
ORCID iD: https://orcid.org/0000-0003-1620-5601

Руска војска добија амфибијски тенк[6]

Руско Министарство одбране одлучило је да набави самоходне противтенковске топове (СПТ) *2S25M Sprut-SDM1*, мада још није познат њихов број.

Sprut-SDM1 (Извор: Army Recognition)

За сада је познато да ће 242. тренажни центар ваздушнодесантних снага први добити нове примерке *Sprut-SDM1* током 2021. године.

[6] Defense News December 2020 Global Security army industry

Основна варијанта СПТ, *Sprut-SD*, званично је усвојена 2006. године. Оружани систем је заснован на борбеним возилима пешадије за ваздушнодесантне снаге – *BMD-4*. Међутим, 2010. године, Министарство одбране је зауставило даље набавке возила *Sprut-SD* због лошег квалитета израде и слабе оклопне заштите.

Ради повећања борбеног преживљавања модернизованог топа, руска индустрија је развила много јачу балистичку заштиту за СПТ *Sprut-SDM1*. Оружани систем има интегрисан дигитални систем за контролу ватре који повећава тачност гађања и омогућава посади напад на мете мале брзине на малим висинама, на пример хеликоптере и беспилотне летелице. СПТ је добио вођену ракету *Invar-M* која се лансира из цеви топа. Развијена је и варијанта ракете са термобаричном високоексплозивном бојевом главом ради напада на пољске фортификације.

Ово пловеће ваздушнодесантно возило опремљено је основним топом 125 мм који представља стандардно наоружање руских тенкова са пуним капацитетом граната. Систем је намењен за подршку ваздушнодесантних трупа на бојишту. До сада су ваздушнодесантне трупе имале подршку само у облику самоходних минобацача *Nona-S* 120 мм које нису могле да се боре против тенкова.

Верзија СПТ могла је попунити ту празнину. Модернизована верзија система опремљена је новим системом за управљање ватром и термалном камером који су слични решењима која постоје на тенку *T-90MS,* што ову платформу доводи до нивоа основног борбеног тенка. У ствари, *Sprut-SDM1* је лаки амфибијски тенк. Тренутно је у тренду развој оваквих возила, а већина платформи је скоро једнака модернизованом тенку *Sprut-SDM1* по ватреној моћи. Међутим, ниједна држава нема лаке тенкове који имају способност ваздушног десантирања и пловности.

Ваздушнодесантне трупе наоружане овим возилом моћи ће да дејствују против стандардног оклопа, док са борбеним возилима пешадије *BMD-2* ту могућност нису имале. До сада су ваздушнодесантне трупе располагале само са две врсте противтенковског оружја – ручним ракетним бацачима и противтенковским вођеним ракетама. Прво оруђе има домет до 400 м, док стандардни бојеви комплет вођених противтенковских ракета не прелази три до четири ракете.

Приказ пловности амфибијског тенка Sprut-SDM1

На овај начин руска војска наставља успешну традицију употребе лаких амфибијских тенкова као што је био *ПТ-76* који је успешно дејствовао против америчких трупа у Вијетнаму, а који су, запленивши га, успешно користили и Израелци у ратовима против арапских држава.

Драган М. Вучковић (*Dragan* M. Vučković),
e-mail: draganvuckovic64@gmail.com,
ORCID iD: https://orcid.org/0000-0003-1620-5601

ПОЗИВ И УПУТСТВО АУТОРИМА
ПРИГЛАШЕНИЕ И ИНСТРУКЦИЯ ДЛЯ АВТОРОВ РАБОТ
CALL FOR PAPERS AND INSTRUCTIONS FOR AUTHORS

ПОЗИВ И УПУТСТВО АУТОРИМА О НАЧИНУ ПРИПРЕМЕ ЧЛАНКА

Упутство ауторима о начину припреме чланка за објављивање у Војнотехничком гласнику урађено је на основу Правилника о категоризацији и рангирању научних часописа Министарства просвете, науке и технолошког развоја Републике Србије ("Службени гласник РС", број 159/20). Примена овог Правилника првенствено служи унапређењу квалитета домаћих часописа и њиховог потпунијег укључивања у међународни систем размене научних информација.

Војнотехнички гласник / Vojnotehnički glasnik / Military Technical Courier (втг.мо.упр.срб, www.vtg.mod.gov.rs, ISSN 0042-8469 – штампано издање, e-ISSN 2217-4753 – online, UDC 623+355/359, DOI: 10.5937/VojnotehnickiGlasnik; https://doi.org/10.5937/VojnotehnickiGlasnik), јесте мултидисциплинарни научни часопис Министарства одбране и Војске Србије. Часопис објављује научне и стручне чланке из области основних истраживања (математике, рачунарских наука и механике) и технолошког развоја (електронике, телекомуникација, информационих технологија, машинства, материјала и хемијских технологија), као и техничке информације о савременим системима наоружања и савременим војним технологијама. Часопис прати јединствену интервидовску техничку подршку Војске на принципу логистичке системске подршке, области основних, примењених и развојних истраживања, као и производњу и употребу средстава наоружања и војне опреме. Часопис објављује и остала теоријска и практична достигнућа која доприносе усавршавању свих припадника српске, регионалне и међународне академске заједнице, а посебно припадника војски и министарстава одбране.

Уређивачка политика Војнотехничког гласника заснива се на препорукама Одбора за етичност у издаваштву (COPE Core Practices), као и на најбољим прихваћеним праксама у научном издаваштву. Војнотехнички гласник је члан COPE (Committee on Publication Ethics) од 2. маја 2018. године.

Министарство просвете, науке и технолошког развоја Републике Србије утврдило је дана 18. 12. 2020. године категоризацију Војнотехничког гласника, за 2020. годину:

за област основна истраживања:
– на листи часописа за математику, рачунарске науке и механику:
категорија национални часопис **(М53)**,

за област технолошки развој:
– на листи часописа за електронику, телекомуникације и информационе технологије:
категорија истакнути национални часопис **(М52)**,
– на листи часописа за машинство:
категорија истакнути национални часопис **(М52)**,
– на листи часописа за материјале и хемијске технологије:
категорија истакнути национални часопис **(М52)**.

Усвојене листе домаћих часописа за 2020. годину могу се видети на сајту Војнотехничког гласника, страница *Категоризација часописа* (Министарство

просвете, науке и технолошког развоја Републике Србије још увек није објавило званичну категоризацију научних часописа за 2021. годину).

Детаљније информације могу се пронаћи и на сајту Министарства просвете, науке и технолошког развоја Републике Србије.

Подаци о категоризацији могу се пратити и на сајту КОБСОН-а (Конзорцијум библиотека Србије за обједињену набавку).

Категоризација часописа извршена је према Правилнику о категоризацији и рангирању научних часописа Министарства просвете, науке и технолошког развоја Републике Србије ("Службени гласник РС", број 159/20).

У складу са овим правилником и табелом о врсти и квантификацији индивидуалних научноистраживачких резултата (у саставу Правилника), објављени рад у Војнотехничком гласнику вреднује се са 2 бода (категорија М51), 1,5 бод (категорија М52) и 1 бод (категорија М53).

Часопис се прати у контексту Српског цитатног индекса – СЦИндекс (база података домаћих научних часописа) и Руског индекса научног цитирања (РИНЦ). Подвргнут је сталном вредновању (мониторингу) у зависности од утицајности (импакта) у самим базама и, посредно, у међународним (Clarivate Analytics) цитатним индексима. Детаљи о индексирању могу се видети на сајту Војнотехничког гласника, страница *Индексирање часописа*.

Војнотехнички гласник омогућава и примењује Creative Commons (CC BY) одредбе о ауторским правима. Детаљи о ауторским правима могу се видети на сајту часописа, страница *Ауторска права и политика самоархивирања*.

Радови се предају путем онлајн система за електронско уређивање АСИСТЕНТ, који је развио Центар за евалуацију у образовању и науци (ЦЕОН).

Приступ и регистрација за сервис врше се на сајту www.vtg.mod.gov.rs, преко странице *АСИСТЕНТ* или *СЦИНДЕКС*, односно директно на линку aseestant.ceon.rs/index.php/vtg.

Детаљно упутство о регистрацији и пријави за сервис налази се на сајту www.vtg.mod.gov.rs, страница *Упутство за АСИСТЕНТ*.

Потребно је да се сви аутори који подносе рукопис за објављивање у Војнотехничком гласнику региструју у регистар ORCID (Open Researcher and Contributor ID), према упутству на страници сајта *Регистрација за добијање ORCID идентификационе шифре*.

Војнотехнички гласник објављује чланке на српском, руском и енглеском језику (arial, српска ћирилица или српска латиница, величина слова 11 pt, проред Single).

Поступак припреме, писања и уређивања чланка треба да буде у сагласности са *Изјавом о етичком поступању* (http://www.vtg.mod.gov.rs/izjava-o-etickom-postupanju.html).

Чланак треба да садржи сажетак са кључним речима, увод, разраду, закључак, литературу и апстракт са кључним речима на енглеском и руском језику (без нумерације наслова и поднаслова). Обим чланка треба да буде око једног ауторског табака (16 страница формата А4 са проредом Single), а највише 24 странице.

Чланак треба да буде написан на обрасцу за писање чланка, који се у електронској форми може преузети са сајта на страници *Образац за писање чланка*.

Наслов

Наслов треба да одражава тему чланка. У интересу је часописа и аутора да се користе речи прикладне за индексирање и претраживање. Ако таквих речи нема у

наслову, пожељно је да се придода и поднаслов. Наслов треба да буде преведен и на енглески и руски језик.

Ови наслови исписују се испред сажетка на одговарајућем језику.

Текући наслов

Текући наслов се исписује са стране сваке странице чланка ради лакше идентификације, посебно копија чланака у електронском облику. Садржи презиме и иницијал имена аутора (ако аутора има више, преостали се означавају са „et al.“ или „и др.“), наслове рада и часописа и колацију (година, волумен, свеска, почетна и завршна страница). Наслови часописа и чланка могу се дати у скраћеном облику.

Име аутора

Наводи се пуно име и презиме (свих) аутора. Веома је пожељно да се наведу и средња слова аутора. Имена и презимена домаћих аутора увек се исписују у оригиналном облику (са српским дијакритичким знаковима), независно од језика на којем је написан рад.

Назив установе аутора (афилијација)

Наводи се пун (званични) назив и седиште установе у којој је аутор запослен, а евентуално и назив установе у којој је аутор обавио истраживање. У сложеним организацијама наводи се укупна хијерархија (нпр. Универзитет одбране у Београду, Војна академија, Катедра природно-математичких наука). Бар једна организација у хијерархији мора бити правно лице. Ако аутора има више, а неки потичу из исте установе, мора се, посебним ознакама или на други начин, назначити из које од наведених установа потиче сваки од наведених аутора. Афилијација се исписује непосредно након имена аутора. Функција и звање аутора се не наводе.

Контакт подаци

Адреса или е-адреса свих аутора даје се поред имена и презимена аутора.

Категорија (тип) чланка

Категоризација чланака обавеза је уредништва и од посебне је важности. Категорију чланка могу предлагати рецензенти и чланови уредништва, односно уредници рубрика, али одговорност за категоризацију сноси искључиво главни уредник.

Чланци у *Војнотехничком гласнику* класификују се на научне и стручне чланке.

Научни чланак је:

– оригиналан научни рад (рад у којем се износе претходно необјављени резултати сопствених истраживања научним методом);

– прегледни рад (рад који садржи оригиналан, детаљан и критички приказ истраживачког проблема или подручја у којем је аутор остварио одређени допринос, видљив на основу аутоцитата);

– кратко или претходно саопштење (оригинални научни рад пуног формата, али мањег обима или прелиминарног карактера);

– научна критика, односно полемика (расправа на одређену научну тему, заснована искључиво на научној аргументацији) и осврти.

Изузетно, у неким областима, научни рад у часопису може имати облик монографске студије, као и критичког издања научне грађе (историјско-архивске,

лексикографске, библиографске, прегледа података и сл.), дотад непознате или недовољно приступачне за научна истраживања.

Радови класификовани као научни морају имати бар две позитивне рецензије.

Ако се у часопису објављују и прилози ваннаучног карактера, научни чланци треба да буду груписани и јасно издвојени у првом делу свеске.

Стручни чланак је:

– стручни рад (прилог у којем се нуде искуства корисна за унапређење професионалне праксе, али која нису нужно заснована на научном методу);

– информативни прилог (уводник, коментар и сл.);

– приказ (књиге, рачунарског програма, случаја, научног догађаја, и сл.).

Језик рада

Језик рада може бити српски, руски или енглески.

Текст мора бити језички и стилски дотеран, систематизован, без скраћеница (осим стандардних). Све физичке величине морају бити изражене у Међународном систему мерних јединица – SI. Редослед образаца (формула) означава се редним бројевима, са десне стране у округлим заградама.

Сажетак

Сажетак јесте кратак информативан приказ садржаја чланка који читаоцу омогућава да брзо и тачно оцени његову релевантност. У интересу је уредништава и аутора да сажетак садржи термине који се често користе за индексирање и претрагу чланака. Саставни делови сажетка су увод/циљ истраживања, методи, резултати и закључак. Сажетак треба да има од 100 до 250 речи и треба да се налази између заглавља (наслов, имена аутора и др.) и кључних речи, након којих следи текст чланка.

Кључне речи

Кључне речи су термини или фразе које адекватно представљају садржај чланка за потребе индексирања и претраживања. Треба их додељивати ослањајући се на неки међународни извор (попис, речник или тезаурус) који је најшире прихваћен или унутар дате научне области. За нпр. науку уопште, то је листа кључних речи Web of Science. Број кључних речи не може бити већи од 10, а у интересу је уредништва и аутора да учесталост њихове употребе буде што већа. Кључне речи дају се на језику на којем је написан чланак (сажетак) и на енглеском језику. У чланку се пишу непосредно након сажетка.

Систем АСИСТЕНТ у ту сврху користи специјалну алатку KWASS: аутоматско екстраховање кључних речи из дисциплинарних тезауруса/речника по избору и рутине за њихов одабир, тј. прихватање односно одбацивање од стране аутора и/или уредника.

Датум прихватања чланка

Датум када је уредништво примило чланак, датум када је уредништво коначно прихватило чланак за објављивање, као и датуми када су у међувремену достављене евентуалне исправке рукописа наводе се хронолошким редоследом, на сталном месту, по правилу на крају чланка.

Захвалница

Назив и број пројекта, односно назив програма у оквиру којег је чланак настао, као и назив институције која је финансирала пројекат или програм, наводи се у посебној напомени на сталном месту, по правилу при дну прве стране чланка.

Претходне верзије рада

Ако је чланак у претходној верзији био изложен на скупу у виду усменог саопштења (под истим или сличним насловом), податак о томе треба да буде наведен у посебној напомени, по правилу при дну прве стране чланка. Рад који је већ објављен у неком часопису не може се објавити у Војнотехничком гласнику (прештампати), ни под сличним насловом и измењеном облику.

Табеларни и графички прикази

Пожељно је да наслови свих приказа, а по могућству и текстуални садржај, буду дати двојезично, на језику рада и на енглеском језику.

Табеле се пишу на исти начин као и текст, а означавају се редним бројевима са горње стране. Фотографије и цртежи треба да буду јасни, прегледни и погодни за репродукцију. Цртеже треба радити у програму word или corel. Фотографије и цртеже треба поставити на жељено место у тексту.

За слике и графиконе не сме се користити снимак са екрана рачунара програма за прикупљање података. У самом тексту чланка препоручује се употреба слика и графикона непосредно из програма за анализу података (као што су Excel, Matlab, Origin, SigmaPlot и други).

Навођење (цитирање) у тексту

Начин позивања на изворе у оквиру чланка мора бити једнообразан.

Војнотехнички гласник за референцирање (цитирање и навођење литературе) примењује Харвардски систем референци, односно Харвардски приручник за стил (Harvard Referencing System, Harvard Style Manual). У самом тексту, у обичним заградама, на месту на којем се врши позивање, односно цитирање литературе набројане на крају чланка, обавезно у обичној загради написати презиме цитираног аутора, годину издања публикације из које цитирате и, евентуално, број страница. Нпр. (Petrović, 2012, pp.10–12).

Детаљно упутство о начину цитирања, са примерима, дато је на страници сајта *Упутство за Харвардски приручник за стил*. Потребно је да се позивање на литературу у тексту уради у складу са поменутим упутством.

Систем АСИСТЕНТ у сврху контроле навођења (цитирања) у тексту користи специјалну алатку CiteMatcher: откривање изостављених цитата у тексту рада и у попису референци.

Напомене (фусноте)

Напомене се дају при дну стране на којој се налази текст на који се односе. Могу садржати мање важне детаље, допунска објашњења, назнаке о коришћеним изворима (на пример, научној грађи, приручницима), али не могу бити замена за цитирану литературу.

Листа референци (литература)

Цитирана литература обухвата, по правилу, библиографске изворе (чланке, монографије и сл.) и даје се искључиво у засебном одељку чланка, у виду листе

референци. Референце се не преводе на језик рада и набрајају се у посебном одељку на крају чланка.

Војнотехнички гласник, као начин исписа литературе, примењује Харвардски систем референци, односно Харвардски приручник за стил (Harvard Referencing System, Harvard Style Manual).

Литература се обавезно пише на латиничном писму и набраја по абецедном редоследу, наводећи најпре презимена аутора, без нумерације.

Детаљно упутство о начину пописа референци, са примерима, дато је на страници сајта *Упутство за Харвардски приручник за стил*. Потребно је да се попис литературе на крају чланка уради у складу са поменутим упутством.

Нестандардно, непотпуно или недоследно навођење литературе у системима вредновања часописа сматра се довољним разлогом за оспоравање научног статуса часописа.

Систем АСИСТЕНТ у сврху контроле правилног исписа листе референци користи специјалну алатку RefFormatter: контрола обликовања референци у складу са Харвардским приручником за стил.

Изјава о ауторству

Поред чланка доставља се *Изјава о ауторству* у којој аутори наводе свој појединачни допринос у изради чланка. Такође, у тој изјави потврђују да су чланак урадили у складу са *Позивом и упутством ауторима* и *Изјавом о етичком поступању часописа*.

Сви радови подлежу стручној рецензији.

Списак рецензената Војнотехничког гласника може се видети на страници сајта *Списак рецензената*. Процес рецензирања објашњен је на страници сајта *Рецензентски поступак*.

Адреса редакције:
Војнотехнички гласник
Вељка Лукића Курјака 33
11042 Београд
e-mail: vojnotehnicki.glasnik@mod.gov.rs.

Главни и одговорни уредник
мр *Небојша* Гаћеша, дипл. инж.
nebojsa.gacesa@mod.gov.rs,
https://orcid.org/0000-0003-3217-6513,
тел: војни 40-260 (011/3603-260),
066/8700-123

ПРИГЛАШЕНИЕ И ИНСТРУКЦИЯ ДЛЯ АВТОРОВ О ПОРЯДКЕ ПОДГОТОВКИ СТАТЬИ

Инструкция для авторов о порядке подготовки статьи к опубликованию в журнале «Военно-технический вестник» разработана согласно Регламенту о категоризации и ранжировании научных журналов Министерства образования, науки и технологического развития Республики Сербия («Службени гласник РС», № 159/20). Применение этого Регламента способствует повышению качества отечественных журналов и их более полному вовлечению в международную систему обмена научной информацией.

Военно-технический вестник (**Vojnotehnički glasnik / Military Technical Courier**), втг.мо.упр.срб, www.vtg.mod.gov.rs/index-ru.html, ISSN 0042-8469 – печатное издание, e-ISSN 2217-4753 – online, UDK 623+355/359, DOI: 10.5937/VojnotehnickiGlasnik; https://doi.org/10.5937/VojnotehnickiGlasnik, является мультидисциплинарным научным журналом Министерства обороны и Вооруженных сил Республики Сербия.. В журнале публикуются научные и профессиональные статьи, исследующие такие области как: математика, компьютерные науки и механика, а также области технологического развития: электроника, телекоммуникации, информационные технологии, машиностроение, материалы и химические технологии, в журнале также публикуется: техническая информация о современных системах вооружения и современных военных технологиях. Журнал следит за единой межвидовой технической поддержкой вооруженных сил, основанной на принципах системной логистики, за прикладными и инновационными научными исследованиями, в том числе, в области производства вооружения и военной техники. В журнале публикуются и прочие теоретические и практические достижения, которые способствуют повышению квалификации представителей сербского, регионального и международного академического сообщества, особенно военнослужащих Министерства Обороны и Вооружённых сил.

Редакционная политика журнала «Военно-технический вестник» основана на рекомендациях Комитета по этике научных публикаций (COPE Core Practices), а также на лучшей практике в научно-издательской деятельности. «Военно-технический вестник» является членом COPE со 2 мая 2018 года.

Министерством образования, науки и технологического развития Республики Сербия утверждена 18 декабря 2020 г. категоризация журнала «Военно-технический вестник» за 2020 год:

Категории в области основных исследований:

– Область математика, компьютерные науки, технические науки:
национальный журнал **(M53)**.

Категории в области технологического развития:

– Область электроники, телекоммуникаций и информационных технологий:
высококачественный национальный журнал **(M52)**.

– Область механики:
высококачественный национальный журнал **(M52)**.

– Область материалов и химической технологии:
высококачественный национальный журнал **(M52)**.

С информацией относительно категоризации за 2020 год можно ознакомиться на странице сайта «Военно-технического вестника» *Категоризация Вестника*

(Министерством просвещения, науки и технологического развития Республики Сербия пока не произведено официального ранжирования научных журналов за 2021 год).

Более подробную информацию можно найти на сайте Министерства образования, науки и технологического развития Республики Сербия.

С информацией о категоризации можно ознакомиться и на сайте КОБСОН (Консорциум библиотек Республики Сербия по вопросам объединения закупок).

Категоризация Вестника проведена согласно Регламенту о категоризации и ранжировании научных журналов Министерства образования, науки и технологического развития Республики Сербия («Службени гласник РС», № 159/20)

В соответствии с вышеуказанным Положением и таблицей с показателями классификации и категоризации индивидуальных научно-исследовательских результатов, являющейся неотъемлемой частью Положения, научная статья, опубликованная в «Военно-техническом вестнике», оценивается следующим способом: 2 балла (категория М51), 1,5 балла (категория М52) и 1,5 балл (категория М53).

Журнал соответствует стандартам Сербского индекса научного цитирования (СЦИндекс/SCIndeks) – наукометрической базы данных научных журналов Республики Сербия, а также Российского индекса научного цитирования (РИНЦ). Журнал постоянно подвергается мониторингу и оценивается количественными наукометрическими показателями, отражающими его научную ценность, в т.ч. опосредованно в международных индексах цитирования (Clarivate Analytics).

С информацией об индексировании можно ознакомиться на странице сайта журнала *Индексирование Вестника*.

«Военно-технический вестник» обеспечивает читателям возможность открытого доступа, в соответствии с положениями об авторских правах, утверждёнными Creative Commons (CC BY). С инструкцией об авторских правах можно ознакомиться на странице *Авторские права и политика самоархивирования*, перейдя по ссылке http://www.vtg.mod.gov.rs/index-ru.html.

Рукописи статей направляются в редакцию журнала с использованием online системы ASSISTANT, запущенной Центром поддержи развития образования и науки (ЦПРОН).

Регистрация в системе и оформление прав доступа выполняется по адресу http://www.vtg.mod.gov.rs/index-ru.html, через страницу *ASSISTANT* или *СЦИНДЕКС* (aseestant.ceon.rs/index.php/vtg).

С инструкцией по регистрации и правам доступа можно ознакомиться по адресу http://www.vtg.mod.gov.rs/index-ru.html, на странице *Инструкция по ASSISTANT*.

Все авторы, предоставляющие свои рукописи для публикации в редакцию журнала «Военно-технический вестник» должны пройти предварительную регистрацию в реестре ORCID (Open Researcher and Contributor ID). Эта процедура осуществляется в соответствии с инструкцией, размещенной на странице сайта *Регистрация в реестре ORCID для присвоения идентификационного кода*.

«Военно-технический вестник» публикует статьи на сербском, русском или английском языках (Arial, шрифт 11 pt, пробел Single).

Процесс подготовки, написания и редактирования статьи должен осуществляться в соответствии с принципами *Этического кодекса* (http://www.vtg.mod.gov.rs/etichyeskiy-kodyeks.html).

Статья должна содержать резюме с ключевыми словами, введение, основную часть, выводы, список использованной литературы и резюме с ключевыми словами на английском языке (без нумерации заголовков и подзаголовков). Объём статьи не должен превышать один авторский лист (16 страниц формата А4 с пробелом Single).

Статья должна быть набрана на компьютере с использованием специально подготовленного редакцией макета, который можно скачать на странице сайта *Правила и образец составления статьи*.

Заголовок

Заголовок должен отражать тему статьи. В интересах журнала и автора необходимо использовать слова и словосочетания, удобные для индексации и поиска. Если такие слова не содержатся в заголовке, то желательно их добавить в подзаголовок. Заголовок должен быть переведён на английский язык. Название заголовка (подзаголовка) пишется перед резюме на соответствующем языке.

Текущий заголовок

Текущий заголовок пишется в титуле каждой страницы статьи с целью упрощения процесса идентификации, в первую очередь копий статьей в электронном виде. Заголовок содержит в себе фамилию и инициал имени автора (в случае если авторов несколько, остальные обозначаются с «et al.» или «и др.»), название работы и журнала (год, том, выпуск, начальная и заключительная страница). Заголовок статьи и название журнала могут быть приведены в сокращенном виде.

ФИО автора

Приводятся полная фамилия и полное имя (всех) авторов. Желательно, чтобы были указаны инициалы отчеств авторов. Фамилия и имя авторов из Республики Сербия всегда пишутся в оригинальном виде (с сербскими диакритическими знаками), независимо от языка, на котором написана работа.

Наименование учреждения автора (аффилиация)

Приводится полное (официальное) наименование и местонахождение учреждения, в котором работает автор, а также наименование учреждения, в котором автор провёл исследование. В случае организаций со сложной структурой приводится их иерархическая соподчинённость (напр. Военная академия, кафедра военных электронных систем, г. Белград). По крайней мере, одна из организаций в иерархии должна иметь статус юридического лица. В случае если указано несколько авторов, и если некоторые из них работают в одном учреждении, нужно отдельными обозначениями или каким-либо другим способом указать в каком из приведённых учреждений работает каждый из авторов. Аффилиация пишется непосредственно после ФИО автора. Должность и специальность по диплому не указываются.

Контактные данные

Электронный адрес автора указываются рядом с его именем на первой страницы статьи.

Категория (тип) статьи

Категоризация статьей является обязанностью редакции и имеет особое значение. Категорию статьи могут предлагать рецензенты и члены редакции, т.е. редакторы рубрик, но ответственность за категоризацию несет исключительно главный редактор. Статьи в журнале распределяются по следующим категориям:

Научные статьи:

– оригинальная научная статья (работа, в которой приводятся ранее неопубликованные результаты собственных исследований, полученных научным методом);

– обзорная статья (работа, содержащая оригинальный, детальный и критический обзор исследуемой проблемы или области, в который автор внёс определённый вклад, видимый на основе автоцитат);

– краткое сообщение (оригинальная научная работа полного формата, но меньшего объёма или имеющая предварительный характер);

– научная критическая статья (дискуссия-полемика на определённую научную тему, основанная исключительно на научной аргументации) и научный комментарий.

Однако, в некоторых областях знаний научная работа в журнале может иметь форму монографического исследования, а также критического обсуждения научного материала (историко-архивного, лексикографического, библиографического, обзора данных и т.п.) – до сих пор неизвестного или недостаточно доступного для научных исследований. Работы, классифицированные в качестве научных, должны иметь, по меньшей мере, две положительные рецензии.

В случае если в журнале объявляются и приложения, не имеющие научный характер, научные статьи должны быть сгруппированы и четко выделены в первой части номера.

Профессиональные статьи:

– профессиональная работа (приложения, в которых предлагаются опыты, полезные для совершенствования профессиональной практики, но которые не должны в обязательном порядке быть обоснованы на научном методе);

– информативное приложение (передовая статья, комментарий и т.п.);

– обзор (книги, компьютерной программы, случая, научного события и т.п.).

Язык работы

Работа может быть написана на сербском, русском или английском языке.

Текст должен быть в лингвистическом и стилистическом смысле упорядочен, систематизирован, без сокращений (за исключением стандартных). Все физические величины должны соответствовать Международной системе единиц измерения – СИ. Очередность формул обозначается порядковыми номерами, проставляемыми с правой стороны в круглых скобках.

Резюме

Резюме является кратким информативным обзором содержания статьи, обеспечивающим читателю быстроту и точность оценки её релевантности. В интересах редакции и авторов, чтобы резюме содержало термины, часто используемые для индексирования и поиска статьей. Составными частями резюме являются введение/цель исследования, методы, результаты и выводы. В резюме должно быть от 100 до 250 слов, и оно должно находится между титулами (заголовок, ФИО авторов и др.) и ключевыми словами, за которыми следует текст статьи.

Ключевые слова

Ключевыми словами являются термины или фразы, адекватно представляющие содержание статьи, необходимые для индексирования и поиска. Ключевые слова необходимо выбирать, опираясь при этом на какой-либо международный источник (регистр, словарь, тезаурус), наиболее используемый внутри данной научной области. Число ключевых слов не может превышать 10. В интересах редакции и авторов, чтобы частота их встречи в статье была как можно большей. Ключевые слова даются на языке, на котором написана статья (резюме), и на английском языке. В статье они пишутся непосредственно после резюме.

Программа ASSISTANT предоставляет возможность использования сервиса KWASS, автоматически фиксирующего ключевые слова из источников/словарей по выбору автора/редактора.

Дата получения статьи

Дата, когда редакция получила статью; дата, когда редакция окончательно приняла статью к публикации; а также дата, когда были предоставлены необходимые исправления рукописи, приводятся в хронологическом порядке, как правило, в конце статьи.

Выражение благодарности

Наименование и номер проекта, т.е. название программы благодаря которой статья возникла, совместно с наименованием учреждения, которое финансировало проект или программу, приводятся в отдельном примечании, как правило, внизу первой страницы статьи.

Предыдущие версии работы

В случае если статья в предыдущей версии была изложена устно (под одинаковым или похожим названием, например, в виде доклада на научной конференции), сведения об этом должны быть указаны в отдельном примечании, как правило, внизу первой страницы статьи. Работа, которая уже была опубликована в каком-либо из журналов, не может быть напечатана в «Военно-техническом вестнике» ни под похожим названием, ни в изменённом виде.

Нумерация и название таблиц и графиков

Желательно, чтобы нумерация и название таблиц и графиков были исполнены на двух языках (на языке оригинала и на английском). Таблицы подписываются таким же способом как и текст и обозначаются порядковым номером с верхней стороны. Фотографии и рисунки должны быть понятны, наглядны и удобны для репродукции. Рисунки необходимо делать в программах Word или Corel. Фотографии и рисунки надо поставить на желаемое место в тексте. Для создания изображений и графиков использование функции снимка с экрана (скриншота) не допускается. В самом тексте статьи рекомендуется применение изображений и графиков, обработанных такими компьютерными программами, как: Excel, Matlab, Origin, SigmaPlot и др.

Ссылки (цитирование) в тексте

Оформление ссылок на источники в рамках статьи должно быть однообразным. «Военно-технический вестник» для оформления ссылок, цитат и списка использованной литературы применяет Гарвардскую систему (Harvard Referencing System, Harvard Style Manual). В тексте в скобках приводится фамилия цитируемого автора (или фамилия первого автора, если авторов несколько), год издания и по необходимости номер страницы. Например: (Petrović, 2010, pp.10-20). Рекомендации

о способе цитирования размещены на странице сайта *Инструкция по использованию Гарвардского стиля*. При оформлении ссылок, цитат и списка использованной литературы необходимо придерживаться установленных норм. Программа ASSISTANT предоставляет при цитировании возможность использования сервиса CiteMatcher, фиксирующего пропущенные цитаты в работе и в списке литературы.

Примечания (сноски)

Примечания (сноски) к тексту указываются внизу страницы, к которой они относятся. Примечания могут содержать менее важные детали, дополнительные объяснения, указания об использованных источниках (напр. научном материале, справочниках), но не могут быть заменой процедуры цитирования литературы.

Литература (референции)

Цитированной литературой охватываются, как правило, такие библиографические источники как статьи, монографии и т.п. Вся используемая литература в виде референций размещается в отдельном разделе статьи.

Названия литературных источников не переводятся на язык работы.

«Военно-технический вестник» для оформления списка использованной литературы применяет Гарвардскую систему (Harvard Style Manual). В списке литературы источники указываются в алфавитном порядке фамилий авторов или редакторов. Рекомендации о способе цитирования размещены на странице сайта *Инструкция по использованию Гарвардского стиля*. При оформлении списка использованной литературы необходимо придерживаться установленных норм.

При оформлении списка литературы программа ASSISTANT предоставляет возможность использования сервиса RefFormatter, осуществляющего контроль оформления списка литературы в соответствии со стандартами Гарвардского стиля.

Нестандартное, неполное и непоследовательное приведение литературы в системах оценки журнала считается достаточной причиной для оспаривания научного статуса журнала.

Авторское заявление

Авторское заявление предоставляется вместе со статьей, в нем авторы заявляют о своем личном вкладе в написание статьи. В заявлении авторы подтверждают, что статья написана в соответствии с *Приглашением и инструкциями для авторов*, а также с *Кодексом профессиональной этики журнала*.

Все рукописи статей подлежат профессиональному рецензированию.

Список рецензентов журнала «Военно-технический вестник» размещён на странице сайта *Список рецензентов*. Процесс рецензирования описан в разделе *Правила рецензирования*.

Почтовый адрес редакции:
«Војнотехнички гласник»
ул. Велька Лукича Куряка 33
11042 Белград, Республика Сербия
e-mail: vojnotehnicki.glasnik@mod.gov.rs.

Главный и ответственный редактор
Кандидат технических наук *Небойша* Гачеша
nebojsa.gacesa@mod.gov.rs
https://orcid.org/0000-0003-3217-6513
тел: +381 11 3603 260, +381 66 8700 123

CALL FOR PAPERS AND ARTICLE FORMATTING INSTRUCTIONS

The instructions to authors about the article preparation for publication in the Military Technical Courier are based on the Regulations on categorization and ranking of scientific journals of the Ministry of Education, Science and Technological Development of the Republic of Serbia (Official Gazette of the Republic of Serbia, No 159/20). This Regulations aims at improving the quality of national journals and raising the level of their compliance with the international system of scientific information exchange.

The Military Technical Courier / Vojnotehnički glasnik (www.vtg.mod.gov.rs/index-e.html, втг.мо.упр.срб, ISSN 0042-8469 – print issue, e-ISSN 2217-4753 – online, UDC 623+355/359, DOI: 10.5937/VojnotehnickiGlasnik; https://doi.org/10.5937/VojnotehnickiGlasnik) is a multidisciplinary scientific journal of the Ministry of Defence and the Serbian Armed Forces. The journal publishes scientific and professional papers covering fundamental research (mathematics, computer science and mechanics) and technological development (electronics, telecommunications, information technologies, mechanical engineering, material science and chemical technologies) as well as technical data on modern weapon systems and military technologies. The journal covers inter-service technical support to the Army on the principle of logistic system support; fundamental, applied and development research; production and use of weapons and military equipment. Also, the journal publishes other theoretical and practical achievements leading to professional development of all members of Serbian, regional and international academic communities as well as members of the military and ministries of defence in particular.

The editorial policy of the Military Technical Courier is based on the COPE Core Practices and the journal articles are consistent with accepted best practices in their subject areas. As of 2 May 2018, the Military Technical Courier is a member of COPE (Committee on Publication Ethics).

The Ministry of Education, Science and Technological Development of the Republic of Serbia classified the Military Technical Courier for the year 2020, on December 18, 2020

in the field fundamental research:
– on the list of periodicals for mathematics, computer sciences and mechanics,
category: national journal **(M53)**,
in the field technological development:
– on the list of periodicals for electronics, telecommunications and IT,
category: quality national journal **(M52)**,
– on the list of periodicals for mechanical engineering,
category: quality national journal **(M52)**,
– on the list of periodicals for materials and chemical technology,
category: quality national journal **(M52)**.

The approved lists of national periodicals for the year 2020 can be viewed on the website of the Military Technical Courier, page *Journal categorization* (The Ministry of Education, Science and Technological Development of the Republic of Serbia has not yet published the official evaluation of scientific journals for 2021).

More detailed information can be found on the website of the Ministry of Education, Science and Technological Development of the Republic of Serbia.

The information on the categorization can be also found on the website of KOBSON (Consortium of Libraries of Serbia for Unified Acquisition).

The periodical is categorized in compliance with the Regulations on categorization and ranking of scientific journals of the Ministry of Education, Science and Technological Development of the Republic of Serbia (Official Gazette of the Republic of Serbia, No 159/20). More detailed information can be found on the website of the Ministry of Education, Science and Technological Development.

In accordance with the Regulations and the table about types and quantification of individual scientific and research results (as a part of the Regulations), a paper published in the *Military Technical Courier* scores 2 (two) points (category M51), 1,5 (one and a half) point (category M52) and 1 (one) point (category M53).

The journal is in the Serbian Citation Index – SCIndex (data base of national scientific journals), in the Russian Index of Science Citation/Российский индекс научного цитирования (RINC/РИНЦ) and is constantly monitored depending on the impact within the bases themselves and indirectly in the international (e.g. Clarivate Analytics) citation indexes. More detailed information can be viewed on the website of the Military Technical Courier, page *Journal indexing*.

Military Technical Courier enables open access and applies the Creative Commons Attribution (CC BY) licence provisions on copyright. The copyright details can be found on the *Copyright notice and Self-archiving policy* page of the journal's website.

Manuscripts are submitted online, through the electronic editing system ASSISTANT, developed by the Center for Evaluation in Education and Science – CEON.

The access and the registration are through the Military Technical Courier site http://www.vtg.mod.gov.rs/index-e.html, on the page *ASSISTANT* or the page *SCINDEKS* or directly through the link (aseestant.ceon.rs/index.php/vtg).

The detailed instructions about the registration for the service are on the website http://www.vtg.mod.gov.rs/index-e.html, on the page *Instructions for ASSISTANT*.

All authors submitting a manuscript for publishing in the Military Technical Courier should register for an ORCID ID following the instructions on the web page *Registration for an ORCID identifier*.

The Military Technical Courier publishes articles in Serbian, Russian or English, using Arial and a font size of 11pt with Single Spacing.

The procedures of article preparation, writing and editing should be in accordance with the *Publication ethics statement* (http://www.vtg.mod.gov.rs/publication-ethics-statement.html).

The article should contain the abstract with keywords, introduction, body, conclusion and references (without heading and subheading enumeration). The article length should not exceed 24 pages of A4 paper format.

The article should be formatted following the instructions in the Article Form which can be downloaded from website page *Article form*.

Title

The title should be informative. It is in both Journal's and author's best interest to use terms suitable for indexing and word search. If there are no such terms in the title, the author is strongly advised to add a subtitle. The title should be given in English as well.

The titles precede the abstract and the summary in an appropriate language.

Letterhead title

The letterhead title is given at a top of each page for easier identification of article copies in an electronic form in particular. It contains the author's surname and first name

initial (for multiple authors add “et al”), article title, journal title and collation (year, volume, issue, first and last page). The journal and article titles can be given in a shortened form.

Author’s name

Full name(s) of author(s) should be used. It is advisable to give the middle initial. Names are given in their original form (with diacritic signs if in Serbian).

Author’s affiliation

The full official name and seat of the author’s affiliation is given, possibly with the name of the institution where the research was carried out. For organizations with complex structures, give the whole hierarchy (for example, University of Defence in Belgrade, Military Academy, Department for Military Electronic Systems). At least one organization in the hierarchy must be a legal entity. When some of multiple authors have the same affiliation, it must be clearly stated, by special signs or in other way, which department exactly they are affiliated with. The affiliation follows the author’s name. The function and title are not given.

Contact details

The postal addresses or the e-mail addresses of the authors are given in the first page.

Type of articles

Classification of articles is a duty of the editorial staff and is of special importance. Referees and the members of the editorial staff, or section editors, can propose a category, but the editor-in-chief has the sole responsibility for their classification.

Journal articles are classified as follows:

Scientific articles:

– Original scientific papers (giving the previously unpublished results of the author’s own research based on scientific methods);

– Review papers (giving an original, detailed and critical view of a research problem or an area to which the author has made a contribution demonstrated by self-citation);

– Short communications or Preliminary communications (original scientific full papers but shorter or of a preliminary character);

– Scientific commentaries or discussions (discussions on a particular scientific topic, based exclusively on scientific argumentation) and opinion pieces.

Exceptionally, in particular areas, a scientific paper in the Journal can be in a form of a monograph or a critical edition of scientific data (historical, archival, lexicographic, bibliographic, data survey, etc.) which were unknown or hardly accessible for scientific research.

Papers classified as scientific must have at least two positive reviews.

If the journal contains non-scientific contributions as well, the section with scientific papers should be clearly denoted in the first part of the Journal.

Professional articles:

– Professional papers (contributions offering experience useful for improvement of professional practice but not necessarily based on scientific methods);

– Informative contributions (editorial, commentary, etc.);

– Reviews (of a book, software, case study, scientific event, etc.)

Language

The article can be in Serbian, Russian or English.

The grammar and style of the article should be of good quality. The systematized text should be without abbreviations (except standard ones). All measurements must be in SI units. The sequence of formulae is denoted in Arabic numerals in parentheses on the right-hand side.

Abstract and summary

An abstract is a concise informative presentation of the article content for fast and accurate evaluation of its relevance. It contains the terms often used for indexing and article search. A 100- to 250-word abstract has the following parts: introduction/purpose of the research, methods, results and conclusion.

Keywords

Keywords are terms or phrases showing adequately the article content for indexing and search purposes. They should be allocated heaving in mind widely accepted international sources (index, dictionary or thesaurus), such as the Web of Science keyword list for science in general. The higher their usage frequency is, the better. Up to 10 keywords immediately follow the abstract and the summary, in respective languages.

For this purpose, the ASSISTANT system uses a special tool KWASS for the automatic extraction of key words from disciplinary thesauruses/dictionaries by choice and the routine for their selection, i.e. acceptance or rejection by author and/or editor.

Article acceptance date

The date of the reception of the article, the dates of submitted corrections in the manuscript (optional) and the date when the Editorial Board accepted the article for publication are all given in a chronological order at the end of the article.

Acknowledgements

The name and the number of the project or programme within which the article was realised is given in a separate note at the bottom of the first page together with the name of the institution which financially supported the project or programme.

Article preliminary version

If an article preliminary version has appeared previously at a meeting in a form of an oral presentation (under the same or similar title), this should be stated in a separate note at the bottom of the first page. An article published previously cannot be published in the *Military Technical Courier* even under a similar title or in a changed form.

Tables and illustrations

All the captions should be in the original language as well as in English, together with the texts in illustrations if possible. Tables are typed in the same style as the text and are denoted by Arabic numerals at the top. Photographs and drawings, placed appropriately in the text, should be clear, precise and suitable for reproduction. Drawings should be created in Word or Corel.

For figures and graphs, proper data plot is recommended i.e. using a data analysis program such as Excel, Matlab, Origin, SigmaPlot, etc. It is not recommended to use a screen capture of a data acquisition program as a figure or a graph.

Citation in the text

Citation in the text must be uniform. The Military Technical Courier applies the Harvard Referencing System given in the Harvard Style Manual. When citing sources within your paper, i.e. for in-text references of the works listed at the end of the paper, place the year of publication of the work in parentheses and optionally the number of the page(s) after the author's name, e.g. (Petrovic, 2012, pp.10-12). A detailed guide on citing, with examples, can be found on Military Technical Courier website on the page *Instructions for Harvard Style Manual*. In-text citations should follow its guidelines.

For checking in-text citations, the ASSISTANT system uses a special tool CiteMatcher to find out quotes left out within papers and in reference lists.

Footnotes

Footnotes are given at the bottom of the page with the text they refer to. They can contain less relevant details, additional explanations or used sources (e.g. scientific material, manuals). They cannot replace the cited literature.

Reference list (Literature)

The cited literature encompasses bibliographic sources such as articles and monographs and is given in a separate section in a form of a reference list.

References are not translated to the language of the article.

In compiling the reference list and bibliography, the Military Technical Courier applies the Harvard System – Harvard Style Manual. All bibliography items should be listed alphabetically by author's name, without numeration. A detailed guide for listing references, with examples, can be found on Military Technical Courier website on the page *Instructions for Harvard Style Manual*. Reference lists at the end of papers should follow its guidelines.

In journal evaluation systems, non-standard, insufficient or inconsequent citation is considered to be a sufficient cause for denying the scientific status to a journal.

Authorship Statement

The Authorship statement, submitted together with the paper, states authors' individual contributions to the creation of the paper. In this statement, the authors also confirm that they followed the guidelines given in *the Call for papers* and the *Publication ethics and malpractice statement of the journal*.

All articles are peer reviewed.

The list of referees of the Military Technical Courier can be viewed at website page *List of referees*. The article review process is described on the *Peer Review Process* page of the website.

Address of the Editorial Office:
Vojnotehnički glasnik / Military Technical Courier
Veljka Lukića Kurjaka 33
11042 Belgrade, Republic of Serbia
e-mail: vojnotehnicki.glasnik@mod.gov.rs.

Editor in chief
Nebojša Gaćeša MSc
nebojsa.gacesa@mod.gov.rs
https://orcid.org/0000-0003-3217-6513
tel.: +381 11 3603 260, +381 66 8700 123

Ликовно-графички уредник
Марија Марић, e-mail: marija.maric@mod.gov.rs

Техничко уређење
мр *Небојша* Гаћеша, e-mail: nebojsa.gacesa@mod.gov.rs,
https://orcid.org/0000-0003-3217-6513

Лектор
Добрила Милетић, професор,
e-mail: miletic.dobrila@gmail.com

Превод на енглески
Јасна Вишњић, професор,
e-mail: jasnavisnjic@yahoo.com, https://orcid.org/0000-0003-1728-4743

Превод на руски
др Карина Авагјан,
e-mail: karinka2576@mail.ru

Превод на немачки
Гордана Богдановић
e-mail: gordana.bogdanovic@yahoo.com

Превод на француски
Драган Вучковић,
e-mail: draganvuckovic64@gmail.com, https://orcid.org/0000-0003-1620-5601

ЦИП – Каталогизација у публикацији:
Народна библиотека Србије, Београд

623+355 / 359
355 / 359

ВОЈНОТЕХНИЧКИ гласник : научни часопис Министарства одбране Републике Србије = Military Technical Courier : scientific periodical of the Ministry of Defence of the Republic of Serbia / одговорни уредник Небојша Гаћеша. - Год. 1, бр. 1 (1953) - - Београд (Браће Југовића 19) : Министарство одбране Републике Србије, 1953- (Београд : Војна штампарија). - 24 cm

Доступно и на: http://www.vtg.mod.gov.rs
Тромесечно. - Друго издање на другом медијуму: Vojnotehnički glasnik (Online) = ISSN 2217-4753
ISSN 0042-8469 = Војнотехнички гласник
COBISS.SR-ID 4423938

Цена: 600,00 динара,
Тираж: 100 примерака

На основу мишљења Министарства за науку, технологију и развој Републике Србије, број 413-00-1201/2001-01 од 12. 9. 2001. године,
часопис „Војнотехнички гласник“ је публикација од посебног интереса за науку.

УДК: Народна библиотека Србије, Београд

Художественный редактор
Мария Марич, e-mail: marija.maric@mod.gov.rs

Технический редактор
Кандидат технических наук *Небойша* Гачеша, e-mail: nebojsa.gacesa@mod.gov.rs,
https://orcid.org/0000-0003-3217-6513

Корректор
Добрила Милетич,
e-mail: miletic.dobrila@gmail.com

Перевод на английский язык
Ясна Вишнич,
e-mail: jasnavisnjic@yahoo.com, https://orcid.org/0000-0003-1728-4743

Перевод на русский язык
Д.филол.н. *Карина* Кареновна Авагян,
e-mail: karinka2576@mail.ru

Перевод на немецкий язык
Гордана Богданович,
e-mail: gordana.bogdanovic@yahoo.com

Перевод на французский язык
Драган Вучкович,
e-mail: draganvuckovic64@gmail.com, https://orcid.org/0000-0003-1620-5601

CIP – Каталогизация в публикации: Национальная библиотека Сербии, г. Белград

623+355 / 359
355 / 359

ВОЕННО-ТЕХНИЧЕСКИЙ вестник: научный журнал Министерства обороны Республики Сербия=
Military Technical Courier : scientific periodical of the Ministry of Defence of the Republic of Serbia / главный редактор Небойша Гачеша. – Первый выпуск (1953) – г. Белград (ул. Браче Юговича, д. 19): Министерство обороны Республики Сербия, 1953- (Белград: Военная типография). - 24 см
Размещено на сайте: http://www.vtg.mod.gov.rs
Ежеквартально - Издание в электронном виде: Военно-технический вестник (Online) = ISSN2217-4753
ISSN 0042-8469 = Военно-технический вестник
COBISS.SR-ID 4423938

Цена: 600,00 динаров
Тираж: 100 экземпляров

На основании решения Министерства науки и технологий Республики Сербия, № 413-00-1201/2001-01 от 12. 9. 2001 года, журнал «Военно-технический вестник» объявлен изданием, имеющим особое значение для науки.

УДК: Национальная библиотека Сербии, г. Белград

Graphic design editor
Marija Marić, e-mail: marija.maric@mod.gov.rs

Copy editing
Nebojša Gaćeša MSc, e-mail: nebojsa.gacesa@mod.gov.rs,
https://orcid.org/0000-0003-3217-6513

Proofreader
Dobrila Miletić BA,
e-mail: miletic.dobrila@gmail.com

English translation and polishing
Jasna Višnjić BA,
e-mail: jasnavisnjic@yahoo.com, https://orcid.org/0000-0003-1728-4743

Russian translation and polishing
Karina Avagyan PhD,
e-mail: karinka2576@mail.ru

German translation and polishing
Gordana Bogdanović,
e-mail: gordana.bogdanovic@yahoo.com

French translation and polishing
Dragan Vučković,
e-mail: draganvuckovic64@gmail.com, https://orcid.org/0000-0003-1620-5601

CIP – Catalogisation in the publication: National Library of Serbia, Belgrade

623+355 / 359
355 / 359

ВОЈНОТЕХНИЧКИ гласник : научни часопис Министарства одбране Републике Србије = Military Technical Courier : scientific periodical of the Ministry of Defence of the Republic of Serbia / одговорни уредник Небојша Гаћеша. - Год. 1, бр. 1 (1953) - - Београд (Браће Југовића 19) : Министарство одбране Републике Србије, 1953-(Београд : Војна штампарија). - 24 cm

Доступно и на:
http://www.vtg.mod.gov.rs
Тромесечно. - Друго издање на другом медијуму:
Vojnotehnički glasnik (Online) = ISSN 2217-4753
ISSN 0042-8469 = Војнотехнички гласник
COBISS.SR-ID 4423938

Price: 600.00 RSD
Printed in 100 copies

According to the Opinion of the Ministry of Science and Technological Development No 413-00-1201/2001-01 of 12th September 2001, the *Military Technical Courier* is a publication of special interest for science.

UDC: National Library of Serbia, Belgrade

ГОДИНА

GODINA

ЛЕТ

YEARS