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MATHEMATICAL MODEL OF TRANSMISSION OF STOCHASTIC SIGNALS UNDER INTERFERENCE CONDITIONS

Introduction

The experience gained from combat operations during the large-scale armed aggression of the russian federation against Ukraine makes it possible to conclude that, under modern conditions, information systems for combat control have become the primary means of operational, tactical, and strategic command and control of troops [1–8]. The growing volume of information, limited radio-frequency resources, and the intensive impact of electronic interference significantly affect the performance efficiency of these systems [1, 2, 9–12].

Despite the significant advantages of modern combat information and control systems, such as the integration of intelligence data, weapon systems, and command-and-control assets into a unified information space, the implementation of network-centric operating principles, and high decision-making speed, there remain critical limitations, including dependence on radio-frequency resources, vulnerability to electronic warfare (EW), and insufficient adaptability to dynamically changing electromagnetic environment conditions [1, 2].

Particularly critical are conditions characterized by high information load density, multipath fading, and active interference generated by the enemy's electronic warfare systems [2, 6, 8, 9].

Traditional signal generation and processing methods, including Fourier series, wavelet transforms, and classical linear filtering techniques, do not provide the necessary compromise between spectral compactness, interference immunity, and adaptability under non-stationary interference conditions [6–8]. In this regard, the development of new mathematical approaches capable of significantly reducing the spectral redundancy of stochastic signals without degrading the reliability of information transmission is of particular importance.

Analysis of recent research and publications

Recent studies in the field of spectral efficiency enhancement demonstrate a persistent transition from classical linear signal processing methods toward adaptive nonlinear models capable of accounting for the stochastic nature of signals, channel memory effects, and complex electromagnetic environments. Among such approaches, particular attention is given to methods based on Volterra series, the Karhunen–Loève transform, cognitive spectrum management, and adaptive wideband processing. Classical studies [1–3] substantiated the principles of optimal signal processing, statistical accumulation, and correlation-based interference suppression, which became the foundation of modern adaptive communication and electronic warfare systems. It has been shown that the application of wideband signals is characterized by high interference immunity, low probability of interception, and support for multiple access capabilities [2, 13–17].

Publications [4, 5] propose an improved method for stochastic signal generation based on second-order Volterra series with adaptive adjustment of kernel parameters according to the statistical characteristics of the signal. These studies demonstrate that classical nonlinear models without adaptation may even degrade the spectral characteristics of noise-like signals due to uncontrolled spectral expansion.

Despite significant achievements in individual research areas, the problem of the integrated application of the Karhunen–Loève transform and adaptive Volterra series as a unified processing framework for stochastic signals under the simultaneous influence of Gaussian noise, impulsive interference, and Rayleigh fading remains insufficiently investigated. In addition, the issue of multicriteria optimization with dynamic

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adjustment of weighting coefficients for different combat application scenarios of combat control information systems (CCIS) requires further study [4, 9, 12].

Thus, modern research confirms that the combination of stochastic signals, adaptive nonlinear processing, and intelligent spectral management is one of the most promising directions for the development of next-generation combat control information systems [13–22].

The purpose of the article

The purpose of the article is to develop a mathematical model of stochastic signal transmission in the presence of radio-electronic interference. The model is based on the joint use of the Karhunen–Loève transform and adaptive Volterra series to enhance spectral efficiency, noise immunity, and adaptability of information combat control systems operating under limited radio-frequency resources and dynamic electromagnetic conditions.

Presentation of the main material

Modern CCIS, depending on their scale and level of command, are conventionally classified into tactical systems (Harris Falcon, ROVER, Kropyva), operational-tactical systems (SitaWare, ASCA), and strategic systems (“Dzvin”, ABMS). Regardless of the level of application, the primary requirements for CCIS remain high interference immunity, rapid response capability, efficient utili zation of radio-frequency resources, and the ability to adapt to changing operational conditions.

In control information systems, a significant share of data is transmitted by stochastic or noise-like signals characterized by wide spectral bandwidth, non-uniform energy distribution, and complex statistical structure [2, 6, 17]. EW assets introduce additional nonlinear distortions, multipath fading, and impulsive interference, which cause a decrease in spectral efficiency [1, 2, 8, 9].

As traditional signal processing methods based on linear transformations fail to deliver sufficient performance in combat control information systems (CCIS) that utilize stochastic signals under non-stationary interference conditions, the application of adaptive nonlinear models is emerging as a promising development direction. These models are capable of effectively accounting for the statistical properties of signals and the dynamic variations in communication channel parameters [4, 6–8].

To increase spectral efficiency, a mathematical model of stochastic signal transmission based on the combined use of the Karhunen–Loève transform and adaptive Volterra series is proposed. The model has the following form (1):

$$x(t) = \mathcal{F}_V(\mathcal{T}_{KL}[s(t)]), \tag{1}$$

where $s(t)$,– input stochastic signal; $\mathcal{T}_{KL}$, – Karhunen–Loève transform operator, which provides orthogonalization (decorrelation) and energy compaction; $\mathcal{F}_V$,– nonlinear operator of the Volterra model, which forms the target signal structure for further transmission.

Accordingly, the Karhunen–Loève transform operator decomposes the input signal $s(t)$, into the basis of eigenfunctions of the covariance function of the process. This makes it possible to reduce the correlation between signal components, concentrate the majority of the energy in a small number of basis functions, and reduce the dimensionality of the data without loss of information content. At the same time, the nonlinear operator of the Volterra model implements the nonlinear transformation (2):

$$z(t) = x(t) + \alpha x^2(t) + \beta x^3(t), \tag{2}$$

where α, β, – model parameters.

This approach modifies the signal structure with the goal of enhancing its spectral compactness and robustness to interference [4, 9–11].

The corresponding optimization functional is given by (3):

$$J = \omega_1 B_{ef}\big(x(t)\big) + \omega_2 BER\big(x(t), n(t)\big) - \\ - \omega_3 SNR_{out} + \omega_4 SNR_{out}\Phi_{adapt}(x)t)), \tag{3}$$

where: ω_i– weight coefficients reflecting the priority of the respective criteria; B_{ef}– effective spectrum width of the signal; BER– ймовірність бітової помилки при дії завади $n(t)$; SNR_{out}– signal-to-noise ratio at the receiver output; Φ_{adapt}– adaptability function that evaluates the system’s ability to adapt to changes in the statistical characteristics of the environment.

Given that CCIS are required to function in electronic warfare conditions involving limited bandwidth and time-varying signal propagation characteristics, while guaranteeing high transmission reliability and adaptability, the use of an adaptive-heuristic method for tuning the weight coefficients is expedient.

This method combines flexibility (reaction to changes in the operating environment) with controllability (by setting initial priorities) and enables automatic reconfiguration of the system according to the interference level, spectrum density, and current requirements for bit error probability in the presence of jamming and the signal-to-noise ratio at the receiver output.

Normalization is a fundamental requirement that makes it possible to interpret the weight coefficients as the relative importance of each criterion for a particular combat application scenario (4):

$$\textstyle\sum_{i=1}^{4} \omega_i = 1. \tag{4}$$

The consolidated values of the weight coefficients are presented in tab. 1.

Table 1

The consolidated values of the weight coefficients

№ з/п	Criterion	Notation	Stealth mode	EW conditions
1	Effective spectrum width	ω_1	0,5	0,2
2	Bit error probability	ω_2	0,2	0,4
3	Signal-to-noise ratio	ω_3	0,2	0,1
4	Adaptability to environment	ω_4	0,1	0,3

Source: developed by the authors.

As shown in Table 1, two representative CCIS application scenarios were analyzed, each demanding a different priority ranking of the optimization criteria:

1. Stealth mode or operation under limited spectrum conditions.

In such situations, the primary goal is to reduce the spectral detectability of the signal in order to lower the probability of interception. Priority is given to minimizing the effective spectrum width, while a minor reduction in other parameters (such as SNR or adaptability) is deemed acceptable.

2. Active electronic warfare (EW) conditions or medium/high-level jamming.

In this case, the main criteria are maintaining reception reliability (minimization of BER) and the signal's ability to adapt to a complex interference environment. Spectral efficiency is of lower priority compared to interference resistance and the flexibility of the signal structure.

Thus, the adaptive-heuristic method for selecting weight coefficients allows dynamic reconfiguration of the system priorities according to the operational context. This capability is critically important for flexible and resilient CCIS operating in a dynamic battlefield environment. The selection of weight coefficients directly influences the compromise between spectral efficiency, transmission reliability, energy feasibility, and system adaptability. However, even under the assumption of an ideal choice of weight coefficient values, there exist both hardware and physical limitations characteristic of CCIS.

Such limitations are as follows:

1. Energy constraint

The system must not exceed the permissible level of average signal power. This is critically important both for limiting radiation in stealth mode and for meeting electromagnetic compatibility requirements in a shared radio-frequency spectrum (5):

$$\int_T |x(t)|^2\, dt \le E_{\max}, \tag{5}$$

where $E_{\max}$, – the maximum allowable energy level of the signal during the transmission period..

Control of signal energy is one of the effective ways to prevent nonlinear distortions in the hardware, especially when using multi-component signals.

2. Reliability constraint

CCIS must guarantee a minimum acceptable level of information loss, particularly in critical modes involving the command and control of combat units (6):

$$BER \le \varepsilon, \tag{6}$$

where ε – is the maximum permissible bit error rate.

3. Constraints on computational implementation complexity

The practical implementation of the combined approach based on the Karhunen–Loève transform and the Volterra model requires substantial computational resources; therefore, it is advisable to introduce constraints on computational implementation complexity. In particular, only those eigencomponents of the Karhunen–Loève transform that contain the dominant portion of the signal energy (typically 90–95 %) are included in the analysis, which makes it possible to significantly reduce dimensionality without substantial loss of informative content.

The Volterra model is limited to the second or third order, since increasing the order provides only marginal performance improvement while causing a rapid growth in computational complexity. In addition, the required number of arithmetic operations must correspond to the available resources of the target device, such as the computational capabilities of a tactical terminal, mobile communication station, or unmanned platform.

Considering the formulated multicriteria optimization problem of spectral efficiency in combat control information systems, it is advisable to construct a mathematical model for the transmission of stochastic signals under interference conditions.

Figure 1 presents a block diagram of the subject domain of stochastic signal transmission in CCIS, illustrating the key stages of signal generation, transmission, and evaluation under interference conditions.

As can be seen from the figure, the signal transmission process in a combat control information system consists of several sequential stages, each of which performs a specific function in the generation, transformation, and quality assessment of a stochastic signal. At the first stage, the input signal is processed using the Karhunen–Loève transform, which reduces the correlation between signal components and concentrates the signal energy within several principal components. Then, signal processing is performed using the Volterra model, which makes it possible to form a structured nonlinear signal with improved spectral properties. The generated signal is transmitted through a channel that models the communication environment. The signal at the receiver input is the result of the convolution of the transmitted signal with the environmental characteristics and the addition of interference.

The final quality assessment is performed according to several criteria, including power spectral density, bit error probability, SNR, and the adaptability function, which reflects the system's ability to maintain acceptable transmission quality under dynamically changing environmental conditions. Such a structural model forms the basis for the development of a simulation model of combat control information system operation using the proposed methods.

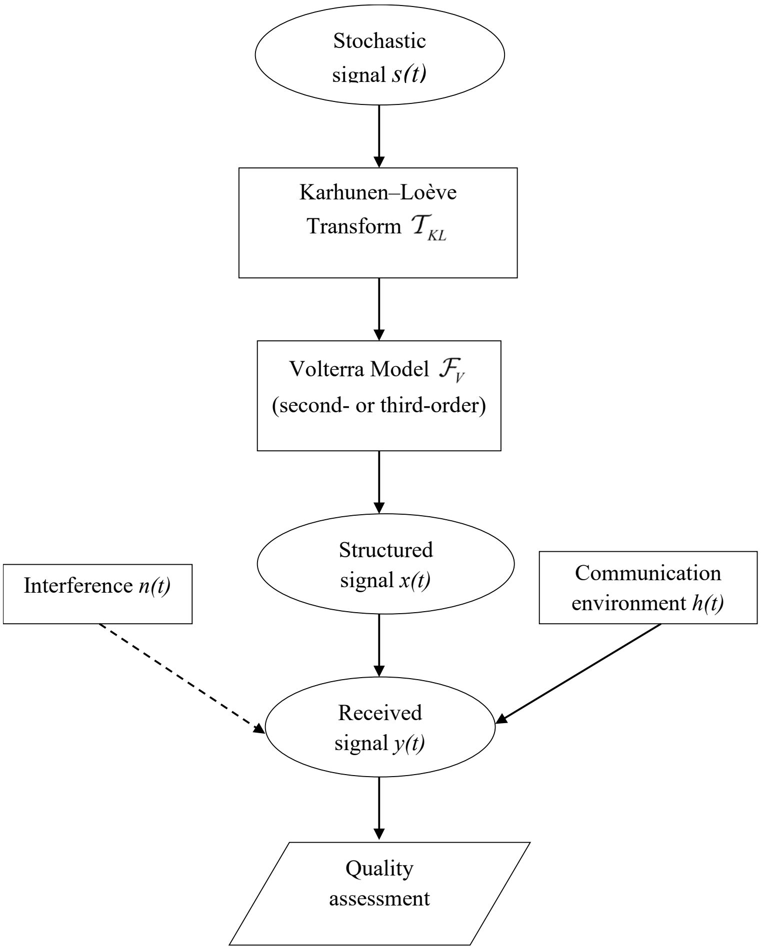

Fig. 1. Block diagram of the subject domain of stochastic signal transmission in CCIS
Source: developed by the authors

Thus, the mathematical model can be represented as a convolutional linear system with a stochastic input (7):

$$y(t) = x(t) * h(t) + n(t), \quad (7)$$

where $y(t)$ – signal at the receiver input; $x(t)$ – structured signal after processing; $h(t)$ – channel impulse response; $n(t)$ – generalized interference impact; $*$ – convolution operator.

In order to validate the effectiveness of the proposed model, simulation modeling of combat control information system operation using the developed methods was performed.

The simulation was performed in the Python 3.11 software environment. The proposed model reproduces the complete signal transmission cycle, including the generation of a stochastic process, its processing, transmission through an interference-affected channel, and the evaluation of signal parameters at the receiver side.

The results of the simulation are presented in Table 2 and Fig. 2. Analysis of the obtained results indicates that the application of the combined approach based on the Karhunen–Loève transform and the Volterra model makes it possible to significantly improve the characteristics of stochastic signals in combat control information systems. Despite the complexity of the transmission channel, the presence of Gaussian noise, impulsive interference, and Rayleigh fading effects, it was possible to achieve a noticeable reduction in spectral bandwidth, an increase in spectral efficiency, and preservation of signal integrity at acceptable levels of normalized mean square error (NMSE).

Table 2

The results of the simulation

№ з/п	Signal Type	Spectral Bandwidth (kHz)		Spectral Efficiency (bit/Hz)		Signal-to-Noise Ratio under Interference (dB)		Normalized Mean Square Error (%)
		Before	After	Before	After	Before	After	
1	White noise	486,00	465,86	1,97	2,06	-18,31	-16,81	51,74
2	PRN (GPS-like)	486,00	465,75	1,98	2,06	-18,28	-16,78	51,48
3	Rayleigh fading	486,00	466,77	1,97	2,06	-19,77	-18,27	72,04
4	*m* – sequence	486,00	468,78	1,97	2,05	-18,92	-17,42	57,46

Source: developed by the authors

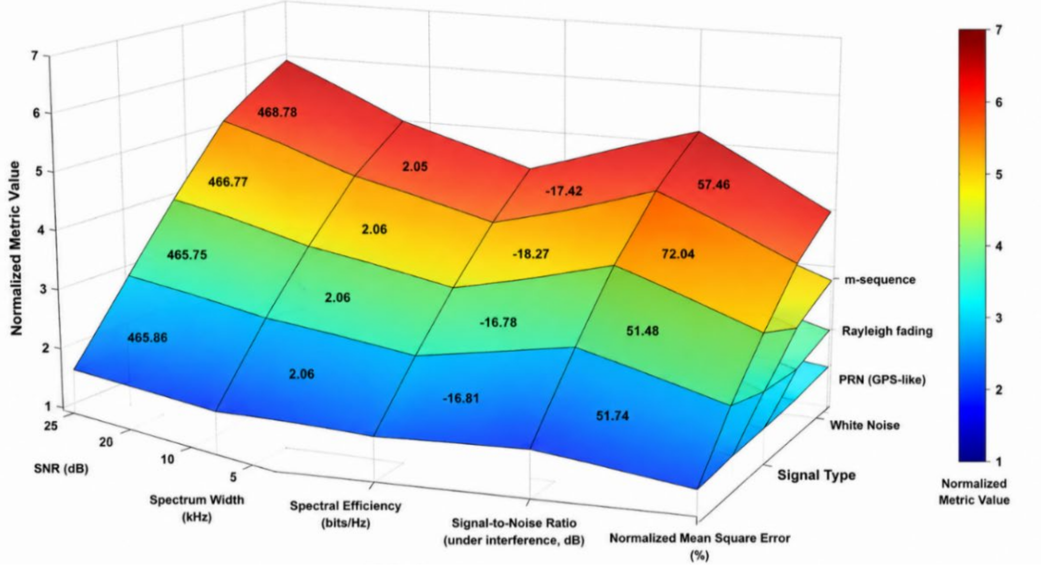

Fig. 2. The results of the simulation Source: developed by the authors

In order to substantiate the advantages of the developed stochastic signal processing method, namely the method based on the combination of the Karhunen–Loève transform and Volterra series, a number of traditional approaches widely used in digital signal processing were selected for comparative efficiency analysis:

1. Fourier-series-based filtering
2. Signal processing using the wavelet transform method
3. Classical Volterra model without preliminary decorrelation
4. Standalone application of the Karhunen–Loève transform
5. *Z*-transform

ithin the scope of this study, the Z-transform is implemented in the form of a first-order cascaded filter in order to analyze its capability to preserve the signal structure during transmission, but without additional spectral compaction or adaptation to interference conditions. In addition, the simulation included a reference control scenario in which the input signal passed through the interference channel without any preliminary processing, decorrelation, or nonlinear modeling. This made it possible to evaluate the lower performance bound of the system and quantitatively determine the gain provided by the application of signal processing methods.

An m-sequence generated using a seventh-order linear feedback shift register (LFSR) was selected as the test signal. Such a signal represents a pseudorandom binary sequence characterized by white-noise-like properties, high autocorrelation selectivity, and uniform spectral occupancy. This type of signal is typical for combat control information systems and is also widely used in navigation protocols, frequency-hopping spread spectrum (FHSS) systems, and code-based communication methods, which ensures the objectivity and relevance of the conducted comparative analysis.

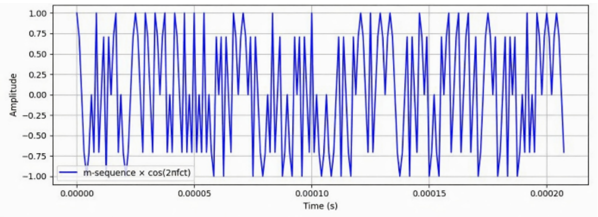

Fig. 3. Fragment of the m-sequence before processing Source: developed by the authors

Fig. 3 shows a fragment of an m-sequence modulated onto a 120 kHz carrier frequency before processing. The signal demonstrates the characteristic noise-like structure inherent to pseudorandom sequences combined with a harmonic carrier. The signal amplitude varies according to the binary *m*-sequence, while the high-frequency component is formed by harmonic modulation.

The parameters of the test signal are presented in Table 3.

Table 3

Parameters of the Test Signal for Comparative Analysis

№ з/п	Parameter	Value	Description
1	Signal type	*m*-sequence (LFSR, $n = 7$)	Pseudorandom binary sequence with white-noise-like properties
2	Signal length	1024 samples	Discretized signal realization
3	Sampling frequency	960 kHz	Determines the maximum spectral bandwidth
4	Carrier frequency	120 kHz	Used for radio-frequency modulation
5	Modulation	Harmonic ($\cos(2\pi f\_ct)$)	Carrier-modulated representation
6	Signal centering	Yes	Removal of the mean value
7	Normalization	Yes	Energy normalization (RMS = 1)
8	Transmission channel type	Rayleigh fading	Impulse response of 100 samples with exponential decay
9	Channel noise	Gaussian, SNR ≈ 10 дБ	Basic additive interference
10	Impulsive interference	Amplitude ≈ 5, random points	Active EW or technical interference

Source: developed by the authors.

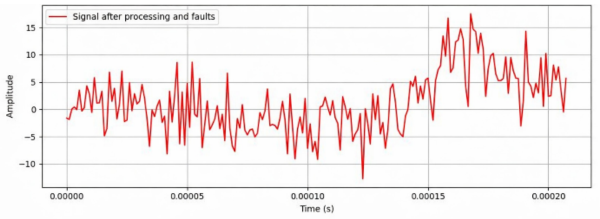

Fig. 4. Fragment of the m-sequence after processing with the proposed method.
Source: developed by the authors

Fig. 4 shows a fragment of the m-sequence after passing through the complete processing chain according to the developed method, which combines the Karhunen–Loève Transform (KLT) and the Volterra model.

Despite the presence of interference, the signal structure at the output is partially preserved. This demonstrates the ability of the proposed method to maintain the integrity of the information even under complex interference conditions. The graph shows violations of periodicity and amplitude fluctuations; however, the overall shape of the signal is not completely destroyed, which allows correct decoding at the receiver.

The adaptability of the stochastic signal processing model (i.e., its ability to maintain stable characteristics under the influence of various types of interference) using the combined application of the Karhunen–Loève Transform and Volterra series is estimated at approximately 0,3 (30 %).

Thus, Fig. 4 clearly demonstrates the effectiveness of the proposed method for increasing the robustness of stochastic signals in combat control information systems.

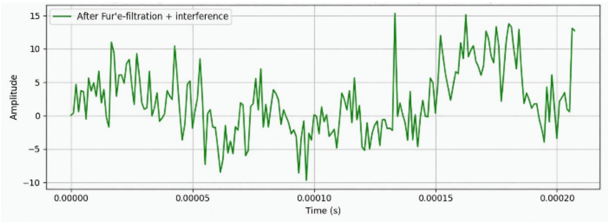

Fig. 5. Fragment of the m-sequence after processing with the Fourier filtering method.
Source: developed by the authors

Fig. 5 shows a fragment of the m-sequence after processing by the Fourier filtering method and subsequent transmission through the interference channel. The signal was pre-processed in the frequency domain using Fourier series to smooth the signal and limit its spectrum, and then passed through a channel affected by Rayleigh fading, impulse interference, and additive noise.

The graph clearly demonstrates that Fourier filtering effectively reduced the high-frequency components but failed to ensure robustness against impulse and phase distortions. As a result, the signal structure is significantly deformed, which substantially complicates its further decoding.

In contrast to the proposed method based on the combined use of the Karhunen–Loève Transform and Volterra series, classical Fourier processing does not provide the necessary adaptability to a complex interference environment. This significantly limits its effectiveness in combat control information systems.

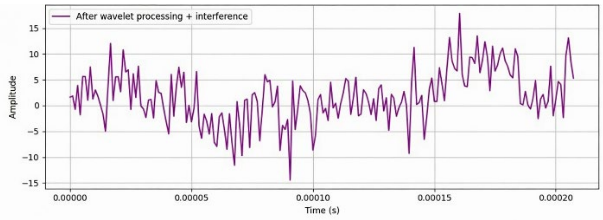

Fig. 6. Fragment of the m-sequence after processing with the wavelet transform method. Source: developed by the authors

Fig. 6 illustrates a fragment of the m-sequence after processing by the wavelet transform method and subsequent transmission through the interference channel. Discrete wavelet transform with threshold filtering of high-frequency components was used for preliminary signal processing. The signal was then subjected to the influence of a channel with multipath propagation, noise, and impulse bursts, modeling the real operating conditions of a combat environment.

Visually, the graph shows strong smoothing of the signal and significant distortions of its amplitude structure. The useful energy component is practically lost, while impulse interference passes through with almost no suppression. This indicates that, although wavelet transform is effective for noise suppression tasks, it does not provide sufficient robustness against short-duration active interference without additional adaptive mechanisms.

In comparison with the proposed method based on the combined application of the Karhunen–Loève Transform and Volterra series, wavelet processing proves to be significantly less effective for use in combat control information systems.

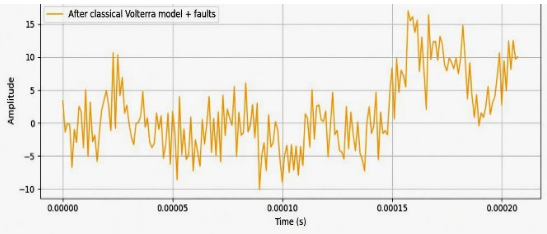

Fig. 7. Fragment of the m-sequence after processing with the Volterra series method. Source: developed by the authors

Fig. 7 shows a fragment of the m-sequence after processing by the Volterra series method (without the use of the Karhunen–Loève Transform) and subsequent transmission through the interference channel. This method allows taking into account the nonlinear interactions between signal elements; however, due to the absence of preliminary decorrelation of the input data, spectral redundancy is not fully eliminated.

The graph reveals noticeable amplitude fluctuations and distortions of the signal structure caused by impulse and noise interference. Despite partial smoothing and improvement compared to the unprocessed signal, the method remains sensitive to environmental distortions. Thus, it provides only an average level of interference resistance.

Application of the Volterra series alone is significantly inferior to the combined method, which simultaneously reduces redundancy and adapts to the interference environment.

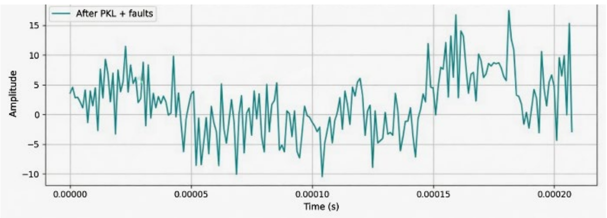

Fig. 8. Fragment of the m-sequence after processing with the Karhunen–Loève Transform method. Source: developed by the authors

Fig. 8 shows a fragment of the m-sequence after processing by the Karhunen–Loève Transform (KLT) method without subsequent nonlinear processing, and after passing through the interference channel. The KLT provides effective reduction of spectral redundancy through orthogonal decomposition and projection of the signal onto principal components. This allows decorrelating the input data and concentrating the signal energy in a smaller number of parameters.

As can be seen from the graph, in the absence of an adaptive nonlinear stage (e.g., the Volterra model), the signal remains sensitive to channel distortions. Noticeable amplitude spikes, structural instability, and fluctuations caused by Rayleigh fading and impulse interference are clearly visible. Although the overall shape of the signal is partially preserved, the NMSE level remains high.

Although the Karhunen–Loève Transform is an effective tool for signal compression and decorrelation, its standalone application is insufficient to achieve full interference immunity in a complex environment. To ensure robust performance, it must be combined with adaptive nonlinear methods, particularly the Volterra series model.

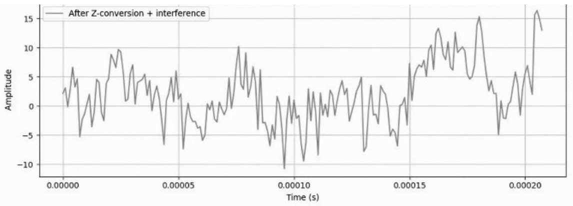

Fig. 9. Fragment of the m-sequence after processing by the Z-transform method implemented as a first-order FIR filter. Source: developed by the authors

Fig. 9 presents the results of processing the *m*-sequence after applying the *Z*-transform implemented as a first-order linear digital FIR filter, which is equivalent to a system with a transfer function in the *Z*-domain and corresponds to simple linear filtering without feedback. The graph shows that after transmission through an interference-affected channel characterized by Rayleigh fading, additive noise, and impulsive interference, the signal structure is almost completely lost. Although the filter partially smooths the signal waveform, it is incapable of either decorrelating the signal or adapting to nonlinear and impulsive distortions.

As a result, this method demonstrates low interference immunity, while the NMSE reaches approximately 100 %, indicating almost complete destruction of the information content. Formally, the method may demonstrate high spectral efficiency due to spectral "compression"; however, this effect is not associated with actual preservation or recovery of useful information.

Thus, the *Z*-transform used as a standalone method is unsuitable for combat information systems and cannot serve as an alternative to adaptive processing approaches.

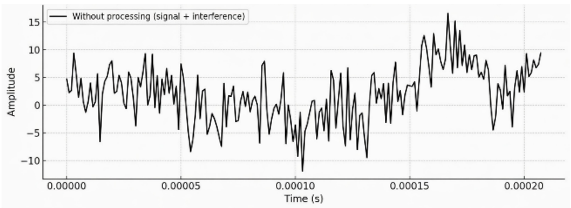

Fig. 10. Fragment of the m-sequence without processing after transmission through an interference-affected channel.
Source: developed by the authors

Figure 10 shows a fragment of the signal that was transmitted without any preliminary processing. The graph clearly demonstrates the dominance of noise components, significant amplitude bursts, and multipath propagation effects. As a result, the signal-to-noise ratio reaches approximately −34.5 dB, while the normalized mean square error exceeds 95%.

Under such conditions, reliable signal recovery or correct decoding at the receiver side becomes practically impossible. This clearly demonstrates that, without specialized signal processing methods, the signal is almost completely destroyed under interference воздействие. The obtained results once again confirm the effectiveness and necessity of applying the developed method in combat control information systems.

The generalized simulation results are presented in Table 4.

Table 4

Comparative analysis of signal processing method efficiency

№	Method	SE (bit/Hz)	SNR (dB)	NMSE (%)	Signal characteristics
1	Without processing	~2,00	−34,5	98,21	Signal structure lost, high noise level
2	Z-transform	~2,10	−20,0	100,5	Signal smoothed, but completely destroyed
3	Wavelet filtering	~2,02	~0,0	≈100,0	Threshold processing leads to complete signal loss
4	Classical Volterra model	~2,05	−17,4	~55,7	Noticeable improvement, signal structure partially preserved
5	Standalone KLT	~2,05	−17,5	~56,9	Redundancy reduction without interference suppression
6	KLT + Volterra	~2,06	−16,8	~50,5	Best compromise between accuracy and robustness
7	Fourier filtering	~2,15	−19,4	75,6	Spectral compression achieved, but vulnerable to phase and impulsive interference

Source: developed by the authors

In order to ensure the reliability of the simulation results, each signal processing configuration was subjected to repeated statistical trials. In particular, the simulation was performed 1000 times for each signal type (m-sequence, PRN, and Rayleigh fading) and for each processing method (KLT, Volterra model, combined Karhunen–Loève transform and Volterra-series approach, *Z*-transform, wavelet filtering, Fourier filtering, and the reference case without processing). Such an approach makes it possible to take into account the stochastic nature of interference, including Gaussian noise, impulsive disturbances, and multipath fading effects, which vary from one iteration to another. The number of realizations was determined empirically through convergence analysis of the average values of the key performance metrics: spectral efficiency (SE), signal-to-noise ratio (SNR), and normalized mean square error (NMSE). With a smaller number of repetitions, an increased variance of the obtained results was observed, making objective comparison difficult. However, after 1000 iterations, the metric values stabilized within a statistical deviation not exceeding 2 %, which was considered a sufficient sample size for comparative analysis. The reliability of the simulation results is estimated at no less than 98 %, while the variability of the obtained values remains within the expected statistical limits. This confirms the logical consistency between the behavior of each processing method and its underlying structural properties.

Conclusions

The article presents a mathematical model for the transmission of stochastic signals under radio-electronic interference conditions based on the combined application of the Karhunen–Loève transform and an adaptive nonlinear Volterra-series model. The proposed approach is aimed at reducing spectral redundancy and improving the spectral efficiency of combat control information systems by matching nonlinear processing with the statistical structure of the signal already at the signal formation stage.

The results of the simulation study confirmed the effectiveness of the developed model for various types of stochastic signals. In particular, it was established that:

1. The application of the combined method provides an increase in spectral efficiency of up to 4,6 %.
2. Preliminary signal decorrelation using the Karhunen–Loève transform in combination with a second-order Volterra nonlinear model significantly improves interference immunity and reduces the normalized mean square error (NMSE) compared to classical processing methods.
3. Adaptive tuning of the weighting coefficients of the multicriteria optimization functional enables flexible reconfiguration of system priorities depending on the operational scenario.

The obtained results also make it possible to formulate the main limitations of the proposed approach:

1. The efficiency of the method decreases for signals with a low correlation level and without pronounced dominant spectral components.
2. The results are sensitive to the correct selection of the number of principal KLT components and the parameters of the Volterra kernel model.
3. For short signal realizations or signals with a high noise level, increased sensitivity to statistical fluctuations is observed.
4. The algorithm requires adaptive parameter reconfiguration to ensure stable operation under dynamically changing interference conditions.

At the same time, the research results indicate several promising directions for further development of the proposed approach, including:

1. The application of tensor factorization and regularization methods to further reduce computational complexity/
2. The development of algorithms for automatic adaptive selection of the number of principal KLT components depending on the current signal statistics.
3. The integration of machine learning methods for real-time adaptive tuning of the Volterra kernel parameters.

Thus, the developed mathematical model confirms the practical feasibility of controlled formation of stochastic signals with improved spectral efficiency and interference immunity under conditions of limited radio-frequency resources and intensive radio-electronic confrontation.

Use of artificial intelligence tools

The authors con-firm that artificial intelligence tools were used exclusively as auxiliary instruments for translation, language editing, and stylistic improvement of the manuscript, as well as to support the search, selection, and analytical processing of relevant scientific literature. Artificial intelligence technologies were not used in the development of the proposed method, in performing calculations or experiments, or in the generation of scientific results and conclusions presented in this paper.

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МАТЕМАТИЧНА МОДЕЛЬ ПЕРЕДАЧІ СТОХАСТИЧНИХ СИГНАЛІВ В УМОВАХ ЗАВАД

У статті розроблено математичну модель передачі стохастичних сигналів в умовах радіоелектронних завад на основі комбінованого застосування перетворення Кархунена–Лоєва та адаптивних рядів Вольтерра. Актуальність дослідження зумовлена сучасними вимогами до інформаційних систем бойового управління, які в умовах широкомасштабної збройної агресії проти України стали основним засобом оперативного, тактичного та стратегічного керування військами. Традиційні лінійні методи обробки сигналів не забезпечують необхідного компромісу між спектральною компактністю, завадостійкістю та адаптивністю в умовах нестаціонарних завад, багатопроменевих замирань та активних радіоелектронних перешкод, а також не враховують повною мірою стохастичну природу сигналів, ефекти пам'яті каналів та нелінійні спотворення, що виникають під впливом завад.Для вирішення поставленої задачі запропоновано комбіноване застосування перетворення Кархунена–Лоєва для попередньої декореляції та ущільнення енергії стохастичних сигналів із подальшою адаптивною нелінійною обробкою за допомогою рядів Вольтерра другого порядку. Адаптивність системи забезпечується завдяки багатокритеріальному функціоналу оптимізації з динамічним налаштуванням вагових коефіцієнтів залежно від сценарію бойового застосування (стелс-режим або активне радіоелектронне протиборство). Модель описує процес передачі сигналу через канал з урахуванням імпульсної характеристики середовища та узагальненого завадового впливу. Результати дослідження отримано шляхом імітаційного моделювання в середовищі Python 3.11. Проведено порівняльний аналіз запропонованого підходу з традиційними методами обробки сигналів (Фур'є-фільтрація, вейвлет-перетворення, Z-перетворення, класична модель Вольтерра та окреме застосування перетворення Кархунена–Лоєва) для різних типів стохастичних сигналів. Запропонований підхід забезпечує підвищення спектральної ефективності, завадостійкості та адаптивності інформаційних систем бойового управління, що створює передумови для його практичного впровадження в безпроводові системи бойового управління, засоби захищеного зв'язку та сенсорні мережі, де особливого значення набувають вимоги до надійності, конфіденційності та ефективного використання радіочастотного спектра.

Ключові слова: стохастичні сигнали, спектральна ефективність, перетворення Кархунена–Лоєва, ряди Вольтера, інформаційні системи управління; радіоелектронні завади.

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MATHEMATICAL MODEL OF TRANSMISSION OF STOCHASTIC SIGNALS UNDER INTERFERENCE CONDITIONS

This article is devoted a mathematical model of stochastic signal transmission under conditions of radio-electronic interference based on the combined application of the Karhunen–Loev transform and adaptive Volterra series. The relevance of the study is due to modern requirements for combat control information systems, which in the conditions of large-scale armed aggression against Ukraine have become the main means of operational, tactical and strategic control of troops. Traditional linear signal processing methods do not provide the necessary compromise between spectral compactness, noise immunity and adaptability under condi-

tions of non-stationary interference, multi-path fading and active radio-electronic interference, and also do not fully take into account the stochastic nature of signals, channel memory effects and nonlinear distortions arising under the influence of interference. To solve the problem, a combined application of the Karhunen–Loev transform for preliminary decorrelation and energy densification of stochastic signals with subsequent adaptive nonlinear processing using second-order Volterra series is proposed. The adaptability of the system is ensured by a multi-criteria optimization functional with dynamic adjustment of weight coefficients depending on the combat application scenario (stealth mode or active electronic warfare). The model describes the process of signal transmission through the channel, taking into account the impulse response of the environment and the generalized interference effect. The results of the study were obtained by simulation modeling in the Python 3.11 environment. A comparative analysis of the proposed approach with traditional signal processing methods (Fourier filtering, wavelet transform, Z-transform, classical Volterra model and separate application of the Karhunen–Loev transform) for different types of stochastic signals is carried out. The proposed approach provides increased spectral efficiency, noise immunity and adaptability of combat control information systems, which creates the prerequisites for its practical implementation in wireless combat control systems, secure communication facilities and sensor networks, where they are of particular importance.

Keywords: stochastic signals, spectral efficiency, Karhunen–Loev transform, Voltaire series, information control systems; radio electronic interference.

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