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# DEVELOPMENT OF A METHOD FOR INCREASING THE INTERRUPTION PROTECTION OF MULTI-ANTENNA SYSTEMS WITH SPECTRALLY EFFECTIVE SPECIAL PURPOSE SIGNALS UNDER THE INFLUENCE OF DESTABILIZING FACTORS

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*The object of research is multi-antenna systems with spectrally efficient special purpose signals. The problematic issue, the solution of which is devoted to this research, is the improvement of immunity to interference of multi-antenna systems with spectrally efficient special purpose signals. A technique for improving the immunity of multi-antenna systems with spectrally efficient special-purpose signals under the influence of destabilizing factors has been developed. A distinctive feature of the proposed methodology is the use of an improved pre-coding procedure, evaluation of the channel state of multi-antenna radio communication systems with spectrally efficient signals by several indicators. The improved channel state estimation procedure consists in estimating channel bit error probability, channel state frequency response, and channel state impulse response. The formation of an estimate of the channel state for each of the assessment indicators takes place on a separate layer of the neural network using the apparatus of fuzzy sets, after which a generalized estimate is formed at the output of the neural network. The novelty of the proposed method also consists in the use of an improved procedure for forecasting the channel state of multi-antenna systems with spectrally efficient signals. The essence of the proposed procedure is the use of fuzzy cognitive models and an artificial neural network to predict the state of the channels of multi-antenna systems with spectrally efficient signals.*

*Based on the results of the research, it was established that the proposed method allows to increase the immunity of multi-antenna systems with spectrally efficient signals according to the 8×8 scheme and 64 subcarriers by 20–25 % compared to the known ones*

*Keywords: radio communication devices, neural networks, fuzzy sets, computational complexity, frequency response*

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## 1. Introduction

The MIMO (Multiple Input Multiple Output) technology has found practical application in many modern telecommunication systems. MIMO technology is used in wireless local area networks of the IEEE 802.11n standard and in WIMA X and LTE wireless mobile communication networks, etc. [1–5].

The essence of MIMO technology is similar to the method of diversity reception, when several uncorrelated copies of the signal are created on the receiving side due to the diversity of antennas in space, by polarization, diversity of signals by frequency or time.

In radio communication systems with MIMO, spatial multiplexing is implemented: the data stream during transmission is divided into two or more sub-streams, each of which is transmitted and received using different antennas.

The interference immunity of multi-antenna radio communication systems is affected by intentional interference and signal fading that occur during multipath propagation of radio waves. Also, one of the limitations of MIMO technology is the low bandwidth of antenna channels.

In order to improve the efficiency of using the radio frequency resource and combat signal fading, together with MIMO technology, spectrally efficient signals with frequency compression (Spectrally Efficient Frequency Division Multiplexing – SEFDM) are used [6–10].

At the same time, the joint use of MIMO and SEFDM technology reduces the energy efficiency of channels and, in turn, leads to a decrease in immunity. This determines the search for new scientific approaches that allow for a given level of bandwidth of the MIMO system channels to ensure the required level of immunity.

All this confirms the relevance of the chosen direction of research.

## 2. Analysis of literary data and statement of the problem

A feature of the multipath channel is its non-stationarity due to the presence of constant changes in the conditions of signal propagation in the channel, which leads to distortions of the transmitted signal. In addition to distortions arising from the special nature of radio wave propagation, the transmitted signal can be affected by intentional and accidental interference.

In the work [3], a method for assessing the state of the MIMO system channel was developed, which is based on receiving a pilot signal at the beginning of a communication session and conducting a further assessment based on the correlation between message blocks. The disadvantages of the proposed method are the evaluation of the channel state of MIMO systems by only one indicator, namely by the probability of a bit error by blind evaluation devices. The method is not intended for evaluation by several indicators of channel state assessment at the same time, does not take into account signal distortion while using multi-frequency modulation while using SEFDM technology.

The work [5] proposed a method for assessing the state of the MIMO system, taking into account the configuration of the MIMO system and the speed of movement of the subscriber terminal, but the specified method does not take into account the influence of interference created by electronic warfare devices, does not take into account multi-frequency multiplexing.

In the work [10], the authors considered the influence of interference on the performance of MIMO systems. At the same time, the assessment of their influence was carried out only on the basis of the probability of a bit error, without taking into account additional transformations in the antenna channels. This does not allow for the development of effective adaptation measures to the situation in the channel, multi-frequency multiplexing is not taken into account.

In the work [11], the authors developed a method for increasing throughput and assessing the channel state of MIMO systems using neural networks. However, the evaluation of the state of the channel is carried out by the method of brute force (a complete search of possible options - brute force [11]), which leads to a large number of calculations. The difficulty of obtaining results by the method of complete search depends on the number of all possible solutions to the problem. If the decision space is very large, then a complete enumeration of all possible values can take years.

In the work [12], the authors developed a method for assessing the state of the MIMO-OFDM system channel using a neural network. This method can be chosen as the basic one, considering the similarity of multiplexing technology with SEFDM technology. The results obtained by the authors showed a significant advantage of neural networks in comparison with known approaches. The authors evaluated the channel by bit error probability, root mean square error, and the least square method. The evaluation of the channel in the proposed method is carried out by a separately taken indicator.

In the work [13], the method of controlling the parameters of the MIMO system and the method of evaluating the channel of the MIMO system using a neural network were developed. The specified technique is intended for evaluation and correction of the parameters of the MIMO system based on the estimation of the probability of a bit error. At the same time, other system parameters are not evaluated.

In the work [14], a method of phase noise compensation was developed, including MIMO systems using neural networks. In this method, the phase noise of the channel and the probability of a bit error are estimated.

In the work [15], a method of hierarchical assessment of the channel state of MIMO systems using artificial neural networks was developed. In the specified method, a sequential assessment of the channel state is carried out by devices of a complete search of the values of the channel state according to the criterion of minimizing the root mean square error. After that, the training of the neural network takes place and a partial search is carried out before evaluating the channel state. However, evaluation by several indicators does not take place, the distortions present in the subcarriers of the multiparticle signal are not taken into account.

In the work [16], a method for predicting the characteristics of the channel state of MIMO systems using neural networks was developed. To train the neural network, 11 characteristics of the channel are evaluated, such as:

– average signal transit time delay;

– characteristics of the distribution medium;

– azimuth of the signal radiation angle;

– azimuth of the angle of signal arrival;

– characteristics of the signal propagation medium in the propagation angle;

– average signal propagation angle;

– the angle of further propagation of the signal, the average angle of arrival of the signal, the characteristics of the signal in the angle of further propagation, etc.

In the specified method, the specified characteristics are evaluated sequentially, instead of parallel, which increases the time of evaluating the channel state. The specified characteristics characterize the energetics of signal losses during propagation, but do not allow to estimate the frequency characteristic and the probability of a bit error in the channel.

In the work [17], a method for assessing the state of the communication channel using MIMO-OFDM technology is proposed. In this article, the estimation of the bit error probability of the MIMO-OFDM system channel state is carried out using the compression algorithm, the line going down on the OFDM pilot carriers. Thus, this method is not intended for multiple channel health assessment.

The work [18] provides an analysis of known approaches to assess the state of a communication channel using MIMO-OFDM technology. The given methods of assessing the state of the communication channel are based on the assessment of a bit error probability. The evaluation methods presented in the paper are not capable of conducting an evaluation on several evaluation indicators at the same time.

Therefore, the analysis of well-known scientific approaches to improve the immunity of radio communication systems with MIMO-SEFDM technology showed that the following is missing in these works [1–18]:

– selection of channel pre-coding methods with MIMO-SEFDM technology;

– obtaining a generalized assessment of the state of channels with MIMO-SEFDM technology;

– constant evaluation of several characteristics in real time of channels with MIMO-SEFDM technology;

– simultaneously evaluate both downlinks and uplinks with MIMO-SEFDM technology;

– prediction of channel state with MIMO-SEFDM technology.

For this purpose, it should be considered expedient to develop a methodology for improving the immunity of multi-antenna systems with spectrally effective special purpose signals under the influence of destabilizing factors. It makes it possible to implement a compromise between the spectral and energy efficiency of radio communication channels.

## 3. The aim and objectives of the research

The aim of the research is to develop a technique for improving the immunity of multi-antenna systems with spectrally efficient special-purpose signals under the influence of destabilizing factors, which allows to increase the immunity of radio communication channels with MIMO-SEFDM technology. This will make it possible to increase the efficiency of radio communication channels with MIMO-SEFDM technology in conditions of destructive influence.

To solve the given task, it is necessary to solve a number of interrelated research tasks:

– to formalize the operation of the MIMO-SEFDM system;

– to develop an algorithm for the implementation of the method for improving the immunity of multi-antenna systems with spectrally efficient special purpose signals under the influence of destabilizing factors;

– to evaluate the effectiveness of the proposed method.

## 4. Research materials and methods

The object of research is multi-antenna systems with spectrally efficient special purpose signals.

The essence of the proposed method consists in the adaptive selection of rational values of channel parameters of multi-antenna military radio communication systems with spectrally efficient signals, depending on the current implementation of the transmission characteristics of the channels, according to the criterion of the minimum probability of a bit error while meeting the restrictions on the speed of information transmission.

In the course of the conducted research, the general provisions of the theory of artificial intelligence were used to solve the problem of analyzing and forecasting the state of radio communication channels with MIMO-SEFDM technology. Thus, the theory of artificial intelligence is the basis of the mentioned research. The simulation was carried out using MathCad 2014 software (USA) and an Intel Core i3 PC (USA).

The evaluation of the effectiveness and modeling of the work of the method proposed in the research to improve the immunity of multi-antenna systems with spectrally efficient special purpose signals under the influence of destabilizing factors was carried out in the MathCad 14 software (USA).

## 5. Research results on the development of methods for improving the immunity of multi-antenna systems with spectrally efficient special purpose signals

### 5. 1. Formalization of the operation of the MIMO-SEFDM system

The structural diagram of the radio communication system using MIMO with spectrally efficient signals is shown in Fig. 1 [19, 20].

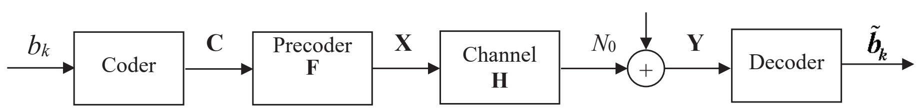


Fig. 1. Generalized description of the system of multi-antenna systems with spectrally efficient signals

In the indicated scheme, on the transmission side, after the coder (which here includes the modulator), the signal is subjected to linear transformation using the matrix **F**. Then the signal enters the MIMO communication channel with spectrally efficient signals with the channel matrix **H**. The matrix **F** of the linear transformation determines linear precoding algorithm.

The type of coder and modulator has a significant impact on the structure of the precoding algorithm. While synthesizing pre-coding algorithms, two architectures of a MIMO communication system with spectrally efficient signals are usually considered:

– MIMO system with spectrally efficient signals with spatial multiplexing. In such a system, independent information streams are transmitted through all antennas, it is possible to separately adapt the transmission speed for each transmission antenna using the information available on the transmission side about the state of the communication channel;

– MIMO system with spectrally efficient signals with space-time coding.

The pre-coding procedure, based on the use of information about the state of the communication channel available on the transmitting side, provides two functions:

– splitting the transmitted signal into independent spatial flows (rays);

– power distribution of emitted signals between these spatial streams (rays).

If the spatial flows (rays) exactly correspond to the eigenvectors of the **H** channel matrix, then mutual interference between these flows does not occur. In this case, the transmission of information through the communication channel is carried out in parallel in several independent spatial channels. In order to implement such an ideal data transfer, it is necessary that accurate information about the current state of the communication channel is available on the transmitting side.

If information about the communication channel is only partially known on the transmitting side, then during pre-coding spatial streams (beams) are formed in such a way as to minimize the level of mutual interference between them. It should be noted that with an increase in the number of transmitting antennas, the number of degrees of freedom increases. This allows for a more significant energy gain from pre-coding, which confirms the additional advantage of using MIMO technology with spectrally efficient signals, compared to classical MIMO technology.

The signal model in a MIMO communication system with spectrally efficient signals with linear precoding can be represented in the following form:

$$\mathbf{Y}=\mathbf{HFC}+N_0, \tag{1}$$

where **H** is the channel matrix, $N_0$ is the white Gaussian noise with power spectral density $G(f)=G_0$, $0<f<\infty$, **F** is the channel precoding matrix, **C** is the channel code matrix.

This model is valid for both spatial multiplexing and space-time coding.

**5. 2. Algorithm for implementing the method of increasing the immunity of multi-antenna systems with spectrally efficient signals**

The problem of increasing the immunity of multi-antenna systems with spectrally efficient special purpose signals can be solved by adaptive selection of rational values of channel parameters of multi-antenna military radio communication systems with spectrally efficient signals, depending on the current implementation of the transmission characteristics of the channels. The minimum bit error probability can be chosen as the efficiency criterion while meeting the restrictions on the speed of information transmission.

*Setting objectives.*

*Given:* parameters of the transceiver $\Psi=\{\psi_i\}$ and channel $i=\overline{1,\ m}$, where $y_1...y_m$ is the number of transmitting and receiving antennas, the type of modulation, the type and parameters of the correction code, the signal power, the signal frequency band, the signal-to-interference ratio (SIR), **H** is the channel matrix.

*It is necessary:* to determine the parameters of multi-antenna military radio communication systems with spectrally efficient signals that minimize the probability of a bit error while fulfilling the limitation on the speed of information transmission.

Restrictions: $\tau_{gr}\leq\tau_{cor}$, where $\tau_{gr}$ is the duration of a group of symbols, $\tau_{cor}$ is the correlation time of fading; the dimension of the ensemble of signals is $2\leq M\leq 64$; the number of transmission antennas $S\leq 8$; the number of receiving antennas $V\leq 8$; the speed of the correction code $R=0.5$–$0.9$; the probability of falsely receiving signals is $P_b\leq 10^{-3}$.

*Assumption:* the channel matrix **H** is known and constant for the time $\tau_{gr}$.

The task of choosing the parameters of multi-antenna military radio communication systems with spectrally efficient signals with the minimum probability of bit error $P_b$ is reduced to a typical optimization problem. The system of equations for solving the optimization problem has the form:

$$\begin{cases} P_b = F_1\left(v_i, \Delta F, M, S, V, n, R, d, h^2, F\right) \rightarrow \min; \\ v_i = F_2\left(P_s, M, n, R, d, F\right) \geq v_{i\ per}, \end{cases} \tag{2}$$

where $v_i$ is the speed of information transmission; D$F$ is the channel bandwidth; $n$ is the length of the code combination, $P_s$ is the signal power, $M$ is the dimension of the signal ensemble, $R$ is the speed of the correction code ($R=k/n$), $k$ is the number of information bits in the code combination of length $n$, $d$ is the value of the code distance, $h^2$ is the ratio signal/noise at the receiver input, **F** is the pre-coding matrix.

Thus, the system of equations (2) for solving the optimization problem is transformed into the form:

$$P_b = F_1(\Psi) = \frac{R \cdot S \cdot V \cdot \log_2 M}{\Delta F \cdot \tau_i} \rightarrow \min_{\Psi \in G};$$

$$G = \begin{cases} \Delta F = \Delta F_{giv};\ M = 2^m;\ 1 \leq m \leq 6; \\ 1 \leq S \leq 8;\ 1 \leq V \leq 8; \\ 7 \leq n \leq 256;\ 1 \leq Q^2 \leq 100; \\ 0.5 \leq R \leq 0.9;\ 0 < \tau_i \leq \tau_{i\ per}; \\ 1 \leq d \leq 19;\ S, V, d, n, m \in Z. \end{cases} \tag{3}$$

$$\Psi = \left[\Delta F, M, S, V, n, R, d, \tau_i, P_b, h^2, F\right];$$

It is advisable to solve the presented problem of conditional discrete optimization by the devices of a directed selection of admissible options using an iterative algorithm.

The proposed method, the scheme of the algorithm for the implementation of which is presented in Fig. 2, consists of the following stages.

*Input of output data.* The parameters of multi-antenna military radio communication systems with spectrally efficient signals and channels are entered $Y=\{y_i\}$, $i=\overline{1,\ 8}$, where $y_1 ...y_8$ is the number of transmitting and receiving antennas. Also, the type of modulation, the size of the ensemble of signals, the duration of the frame at the output of the demodulator, the duration of the frame at the output of the decoder, the speed of the correction code, the value of the code distance, the type of pre-coding encoder.

*Evaluation of channel status.* At this stage, the state of the multi-beam channel is evaluated and its channel matrix is determined using the channel state estimation method developed by the authors [21–23].

*Pre-encoding.*

Let's consider the search for the matrix **F** – the solution of the optimization problem of the optimal precoding parameters in the following form:

$$\mathbf{F} = \mathbf{VT}, \tag{4}$$

where **V** is an unitary matrix from the SVD decomposition, and the desired matrix **T** belongs to the rotation subgroup $SU(M)$ of the unitary group $U(M)$ in the $C^M$ space.

Let's note that for **F** in the form of the restriction $\varepsilon_n(Tr(\mathbf{Fx}(\mathbf{Fx})^{\mathbf{H}})) = P_{symb} * M$ is automatically fulfilled, since as a result of multiplication by the unitary matrix, the Euclidean norm of the vector **x** does not change.

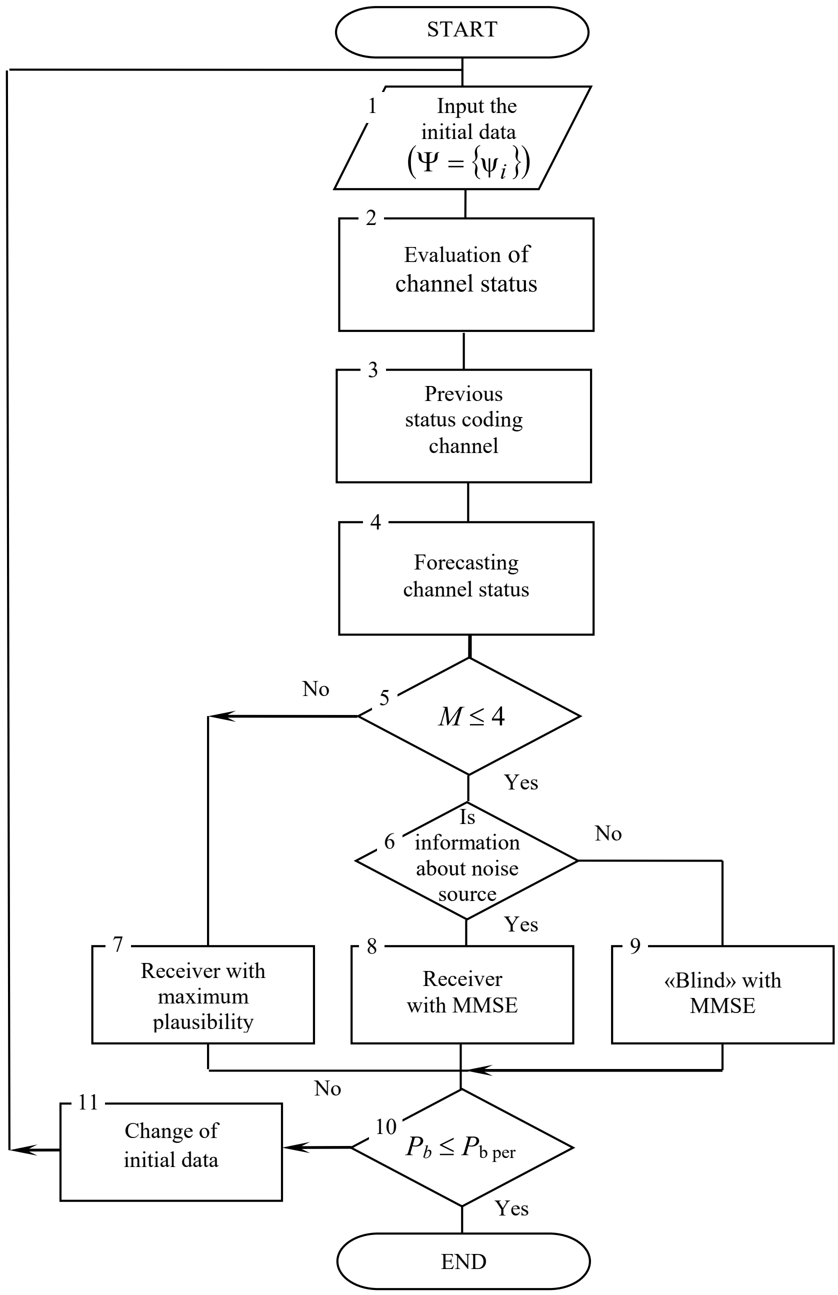


Fig. 2. Scheme of the algorithm for implementing the proposed method

The problem of finding the optimal pre-coding parameters for a representative set of matrices, characteristic, according to the collected statistics, for a given combination of an antenna group and a collocation vector, is solved with respect to **T** numerically:

1) *each formula must be typed separately:*

$$\mathbf{T}_{opt}\left(SNR,H\right)=\arg\min_{\mathbf{T}}\left(\varepsilon_n\left(SER\left(SNR,\mathbf{H},\mathbf{T}\right)\right)\right),$$
$$\mathbf{T}\in SU\left(M\right). \qquad (5)$$

Then, the found optimal value of $\mathbf{T}_{opt}$ is recorded in the database of the RCD as the recommended second element of the pre-coding (5) for this combination of the group antenna and the collocation vector. The main: $\mathbf{T}_{opt}$ numerical search is conducted in advance outside the communication session. Let's propose a parametric representation for the matrices $T$ for the cases $M2$ and $M4$, within which let's search for a solution to problem (5) using the sorting method.

For $M2$, let's look for $T$ in the $SU(2)$ group, thus, according to the matrix representation of the $SU(2)$ element in the form [24–32]:

$$\mathbf{T}_{\alpha,\vartheta,\psi}=\begin{bmatrix} ae^{i,\vartheta} & \sqrt{1-\alpha^2 e^{-i\psi}} \\ -\sqrt{1-\alpha^2 e^{-i\psi}} & ae^{-i,\vartheta} \end{bmatrix} \qquad (6)$$

where $\alpha\in[0;1]$, $\vartheta\in[0;2\pi]$; $\psi\in[0;2\pi]$.

For $M=4$, let's look for $\mathbf{T}$ in the $SU(2)\times SU(2)\in SU$ subgroup [24], thus, according to the matrix representation of the $SU(2)\times SU(2)$ element in the form [25]:

$$\mathbf{T}_{a,b,\vartheta,\psi,\omega,\delta}=$$
$$=\begin{bmatrix} ae^{i\vartheta} & \sqrt{1-\alpha^2 e^{-i\psi}} \\ -\sqrt{1-\alpha^2 e^{-i\psi}} & ae^{-i\vartheta} \end{bmatrix}\otimes$$
$$\otimes\begin{bmatrix} be^{i\vartheta} & \sqrt{1-b^2 e^{-i\psi}} \\ -\sqrt{1-b^2 e^{-i\psi}} & be^{-i\vartheta} \end{bmatrix}, \qquad (7)$$

where $\alpha,b\in[0;1]$, $\vartheta\in[0;2\pi]$; $\psi\in[0;2\pi]$; $\omega\in[0;2\pi]$; $\delta\in[0;2\pi]$

The sign $\otimes$ denotes the Kronecker product of matrices;

2) *forecasting the state of the channels of multi-antenna military radio communication systems with spectrally efficient signals.*

The procedure for forecasting the state of the channels of multi-antenna military radio communication systems with spectrally efficient signals will be considered based on, in this case, fuzzy cognitive models and an artificial neural network are used [22, 23];

3) *Selection of SCC parameters.*

The SCC selection algorithm for each own channel consists of the selection, depending on the interference situation, the type of modulation, the selection of the correction code and the selection of the manipulation code.

During the creation of SCC, two-dimensional modulation methods were widely developed, in which ensembles of signals can be represented by dots in two-dimensional Euclidean space. Despite the fact that, theoretically, while transmitting information from the channel, one-dimensional types of modulation have the same potential as two-dimensional ones, one-dimensional modulation is used much less often in the formation of SCC. The application of multidimensional signals is limited by the complexity of implementing such SCC.

The work [12] shows that systems with high energy efficiency, which are necessary to fulfill the conditions of the method, which ensure win for $\beta_E$ and loss for $\beta_F$, are systems with SCC that use multi-position phase (MP-$P$) manipulation. In this procedure, the optimal SCC is searched using fuzzy cognitive models based on the approach proposed by the authors in the works [22, 23, 28, 33, 34];

4) *selection of the method of signal processing during reception.*

At this stage, one of the methods of signal processing in the receiver of the MIMO system is selected: detection with maximum likelihood; reception with minimum mean square error (MMSE) or so-called «blind» reception of signals.

After choosing a method of signal processing, the fulfillment of the requirements for ensuring the specified probability of false reception of signals is checked.

**5. 3. Evaluation of the effectiveness of the proposed technique for improving the immunity of multi-antenna systems with spectrally efficient signals**

For the 8×8 MIMO system with four-position quadrature modulation for the relay channel, statistical modeling was carried out in the *MathCad* environment and 64 subcarriers on each antenna channel. Fig. 3 shows the results of the effectiveness of the proposed method. Fig. 4 shows a comparison of the proposed technique in terms of the efficiency of pre-coding with the ones known by the criterion of the minimum probability of a bit error.

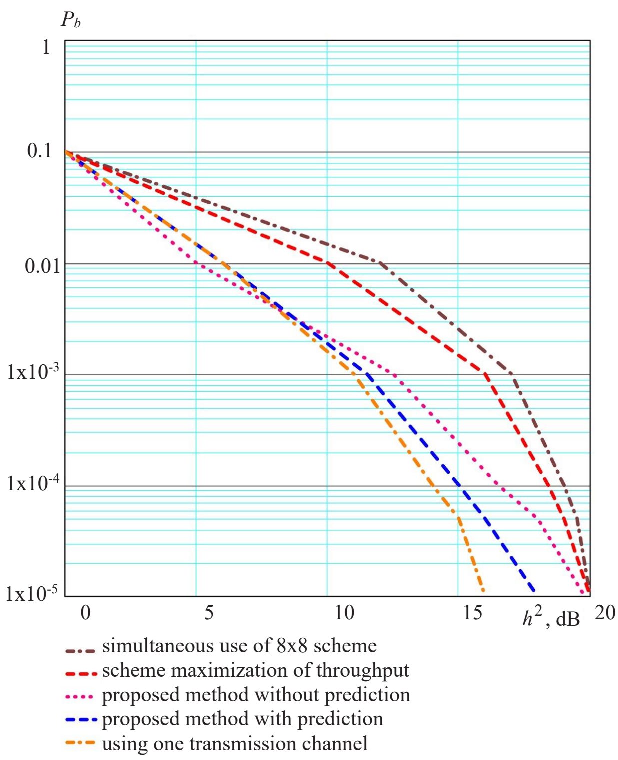


Fig. 3. Results of the evaluation of the proposed method effectiveness

The simulation results show that the proposed method makes it possible to implement state forecasting of MIMO system channels with spectrally efficient signals. It also allows adaptive switching of the number of channels, pre-coding of channels while keeping the probability of a bit error below a given limit. At the same time, it is possible to work at low values of the signal/noise ratio in modes with a limited number of parallel transmission channels.

The evaluation of the effectiveness of the proposed method allows to state that it allows to increase the immunity of MIMO systems with spectrally efficient signals according to the 8×8 scheme and 64 subcarriers at $P_b=10^{-5}$ by 20–25 % compared to the known ones.

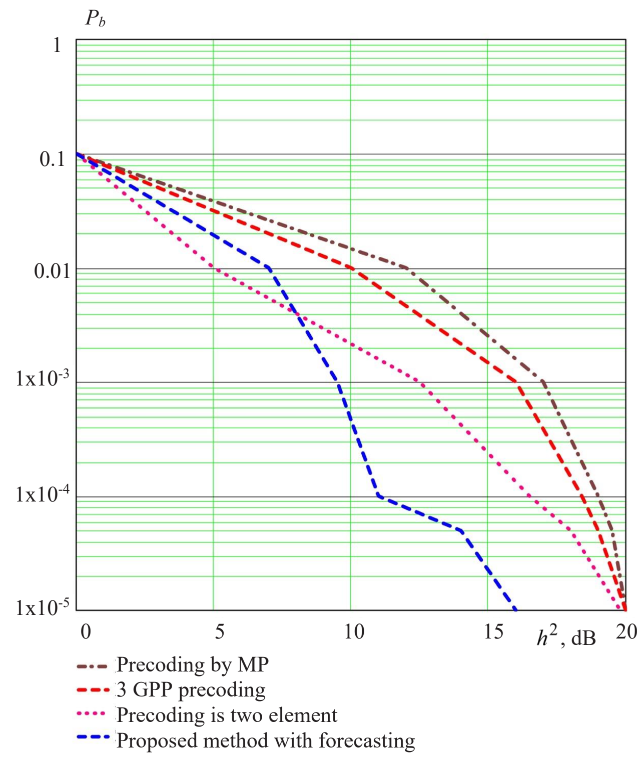


Fig. 4. Results of the effectiveness evaluation of the proposed method in terms of the effectiveness of preliminary coding

## 6. Discussion of the results of the development of methods for improving the immunity of multi-antenna systems with spectrally efficient signals

Let's propose a method for improving the immunity of multi-antenna systems with spectrally efficient special-purpose signals. The advantage of this method over the known ones is the following:

– formalization of the process of functioning of multi-antenna systems with spectrally effective signals under the influence of destabilizing factors, taking into account previous coding (Fig. 1, expression (1));

– an improved assessment procedure, in which the method of assessing the condition of the channel is included [21–23];

– improved pre-coding procedure (expressions (4)–(6));

– an improved forecasting procedure based on fuzzy cognitive models and an artificial neural network [22, 23];

– an adequate assessment of the destructive impact on the immunity of multi-antenna systems with spectrally efficient signals (graphic dependences in Fig. 3 and Fig. 4).

The operation of the proposed method was simulated in the MathCad 14 software environment.

The main advantages of the proposed method are:

– the use of a complex channel condition assessment indicator that takes into account most of the known assessment parameters;

– unambiguousness of the received assessment of the channel state;

– wide scope of use (radio communication and radar systems);

– the simplicity of mathematical calculations;

– an increased operational efficiency of the channel state assessment due to the use of the theory of artificial intelligence;

– the possibility of adapting to the signal situation in the channel and forecasting the state of the channel;

– the possibility of synthesis of the optimal structure of the radio communication tool.

The disadvantages of the proposed method include:

– the loss of informativeness while assessing the channel state due to a comprehensive assessment;

– lower accuracy of evaluation of a single channel condition assessment parameter;

– lower accuracy of the assessment at the initial stage, which is associated with the untrained neural network and the lack of a base of the signal situation;

– this technique is not advisable to use in radio communication systems if it is necessary to obtain an accurate assessment of the channel state by a separate indicator.

The specified method is advisable to use in radio stations with a programmable architecture, which functions in conditions of active radio electronic suppression.

This technique allows:

– to identify the structure of the obstacle, its type and the law of production;

– to assess the condition of the channel;

– to use effective signal-code designs to ensure channel immunity;

– to ensure effective use of the radio frequency resource of programmable radio communications;

– to increase the speed of assessment of communication channels;

– to reduce the use of computing resources of radio communication devices with a programmable architecture;

– to develop measures aimed at improving immunity.

The limitations of the research are:

– the availability of the base of the radio-electronic situation of application region;

– a sufficient qualification of personnel operating radio stations;

– an availability of minimal computing resources of the radio station for the correct operation of the software.

It is advisable to use the method proposed in the work in the development of software for modules (blocks) for the evaluation of promising radio communication tools, which is based on the interfaces of the open architecture version of SCA 2.2.

This research is a further development of the research carried out by the authors, which is aimed at the development of method principles of operational management of the radio resource of radio communication systems.

## 7. Conclusions

1. The MIMO-SEFDM system was formalized. The specified formalized description allows to describe the processes that occur during the process of information transmission in the channels of the MIMO-SEFDM system and to determine the measures aimed at increasing the energy efficiency of the MIMO-SEFDM system.

2. The proposed algorithm for the implementation of the method of improving the immunity of multi-antenna systems with spectrally effective special purpose signals under the influence of destabilizing factors.

The difference of the proposed algorithm for the implementation of the method lies in the choice of parameter values of the MIMO system and spectrally effective signals (rational parameters of pre-coding). Also, signal parameters for each channel of the MIMO system, depending on the current state of the transmission characteristics of the channel. The choice is made taking into account the results of forecasting according to the criterion of the minimum probability of a bit error while meeting the restrictions on the speed of information transmission. The specified selection is carried out using the theory of artificial intelligence, which is the basis of improved procedures.

Rational values of signal parameters for a specific channel state are determined from a finite number of admissible options, which allows to simplify the practical implementation of the equipment of multi-antenna military radio communication systems with spectrally efficient signals.

Signal parameters whose values are determined while solving the optimization problem are: pre-coding parameters, number of subcarriers, signal-code design parameters, signal processing method, and transmitter power.

3. Implementation of the developed methodology ensures: minimization of the probability of a bit error; minimization of transmitter power; improvement of electromagnetic compatibility of radio-electronic devices; increasing the confidentiality of information transmission; minimization of energy consumption.

The obtained results can be applied in adaptive transceivers of multi-antenna military radio communication systems with spectrally efficient signals, which will allow to significantly increase their immunity in conditions of intentional interference and selective blackouts.

The specified technique allows to increase the immunity of channels of multi-antenna military radio communication systems with spectrally efficient signals by 20–25 %, which is confirmed by the simulation results.

## Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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