METHODS FOR EVALUATING THE NOISE IMMUNITY OF MODEMS

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Improving the noise immunity of a modem as an element of a data transmission system is a crucial problem in communication technology. Creating such systems (with a transmission speed close to the limit) is achieved by an approach that considers all possible types of transformations to which the transmitted signal is subjected. The article is devoted to the analysis of methods for evaluating noise immunity, presenting modern and advanced methods of signal transmission and reception to ensure (under given conditions) the maximum possible probability of correct data reception (minimum error probability). Achieving the maximum effect in this direction is possible thanks to numerous works by researchers finding optimal methods and algorithms for data processing and analysis, conducting experiments, developing new methods of signal processing, ultimately ensuring the gain in the noise immunity of the communication system. The paper evaluates the influence of communication channel characteristics on the noise immunity of modems, considers the recurrent estimation of real communication channel parameters based on optimal polyharmonic filtering, as well as a polyharmonic model of a Gaussian communication channel with optimal parameter estimation and the results of experimental evaluation of the amplitude-frequency and phase-frequency characteristics of a Gaussian communication channel. In addition, various approaches to the application of signal-code constructions, signal ensembles with different manipulation and positionality are presented. The negative impact of interference on the reliability of signal reception and transmitted information in the channel is described, methods for limiting the influence of interference on data transmission systems, methods, and results of modern theoretical and experimental studies that increase noise immunity and transmission speeds are indicated. At the same time, methods for evaluating noise immunity are fully revealed by the works and research presented in this article to comprehensively and broadly assess the possibility of both qualitative improvement of parameters and characteristics of data reception/transmission systems and reduction of negative effects of interference and noise on the communication channel and the communication system as a whole. The development of a new modulation/demodulation system without costly reconstruction, compatible with existing systems, is an important direction related to improving the efficiency of communication systems.

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Introduction

The main parameters of the communication channels are: the transmission frequency, the power of the signal being transmitted at a given frequency, the transmission rate either bit or baud, the type of modulation used, and the encoding method/type [1]. Various combinations of variations of these parameters directly affect the reliability of receiving/transmitting information. When setting the transmission parameters, in order to obtain a set in which the transmission reliability is maximized, it is necessary to take into account the distances between the receiver and the transmitter, it is logical to assume that the greater the distance, the more likely it is that the transmitting signal will be affected externally and it will undergo a change. Such an impact is defined as transmission interference.

The nature of transmission interference can be natural (natural phenomena) or artificial, caused by man-made factors. The influence of various interferences on the reliability of information transmission is considered in [2], especially the influence of narrowband, fluctuation interference and multipath fading in the communication channel. Based on the results of [2], it can be concluded that these types of interference have the most significant impact on the transmission process. Thus, it is necessary to take measures to counteract such interference, one of the ways to counteract it is the use of signal-code structures. These designs should have a minimal possibility of correlation with these interferences, which is possible if they are based on the eigenvectors of the subband matrix, as well as encoding the transmitted information. Encoding introduces a certain redundancy, which makes it possible to ensure greater signal resistance to interference. At the time of decoding the incoming signal, even if it was transmitted in a channel with multipath fading, the probability of transmission error does not increase significantly and this increase can be ignored.

1 Research on Noise Immunity in Data Reception/Transmission

In the study [3], a simulation model of communication devices operating in accordance with the IEEE 802.15.4-2020 and IEEE 802.15.4z-2020 standards was developed, allowing for the evaluation of the bit error probability under the influence of interference with various bandwidths and shifts in the central frequency of the interference signal relative to the useful signal. A comparison of the noise immunity characteristics of different operating modes of communication devices was conducted.

It was found that the mode with an increased pulse repetition frequency, High Pulse Repetition Frequency (HPRF), has approximately 10 times better noise immunity under the influence of narrowband and wideband interference than the basic mode of the standard in Basic Pulse Repetition Frequency (BPRF). Also, in HPRF mode, with an increase in the overlap of the signal by interference, the increase in the interference/signal ratio (bit error ratio - BER) occurs more smoothly. With a shift in interference relative to the central frequency of the signal in HPRF mode, a sharper decrease in BER is observed than in the basic mode.

Based on this, it can be concluded that if the narrowband interference greatly exceeds the signal power, which is defined in the IEEE 802.15.4 standard, then such an excess does not affect the operation of the communication system. However, if we consider a wireless network signal with a bandwidth of 160 MHz, i.e. it is actually broadband interference, then it has the opportunity, at the power level, to affect the operability of the communication system of the same order as the ultra-wideband (UWB) signal of the IEEE 802.15.4 standard.

In wireless communication systems, which include satellite radio systems, mobile phone networks, and Wi-Fi networks, the quadrature amplitude modulation (QAM) method is used to transmit data and voice traffic in order to increase data transmission speed. This method is also used for the same purposes in wired communication systems. Increasing the communication speed along with protecting signals from interference are important tasks that need to be addressed.

The higher the QAM level, the more bits of information can be transmitted by sending a single signal, for example, the QAM256 allows you to transmit 8 bits of information in one signal, and the QAM1024 has 10 bits of information. Thus, there is a direct relationship between the data transfer rate and the modulation order. When viewed in the context of radio communication systems, a direct relationship remains between the modulation order and spectral efficiency, but at the same time there is an inverse relationship to noise and interference, i.e. the higher the spectral efficiency, the less resistant the systems are to noise.

To solve this problem, before starting data transmission, it is necessary to detect the channel. Based on the information received about the channel status, a modulation scheme is selected that will ensure the maximum transmission speed with an acceptable level of interference, therefore, most radio communication systems use dynamic adaptive modulation methods. The advantage of using lower modulation levels increases the reliability of communication quality by reducing the number of errors that occur [4].

In the work [5], an analysis of the noise immunity of receiving signals with frequency shift keying of position M from 2 to 32 in the presence of retransmitted interference in the communication channel for different values of signal-to-noise ratios and values of relative interference intensity was carried out. The study made the following conclusions: 1. It is possible to reduce the probability of a bit error by reducing the intensity of the transmitted interference, and noise immunity by increasing the positivity when receiving signals from M-FSK. 2. Retransmitted interference also affects the noise immunity when receiving a signal. The dependence is direct, i.e. the higher the signal intensity, the lower the noise immunity. The loss of signal energy at the level of 4-6 dB already occurs at $\mu = 0.5$ at Peb = 10^-4. 3. The advantage of using multi-position frequency manipulation in a wide range of the retransmitted interference band, instead of using quadrature amplitude and amplitude-phase, occurs already at $M > 4$. 4. M-FSK signals have high energy characteristics relative to other signals, so they can be used for transmission in channels without imposing strong frequency restrictions.

Harmonic interference also affects the reliability of signal reception. The relationship between the interference level coefficient and the reliability of signal reception is inversely proportional, the higher the interference level, the lower the reliability. This relationship was investigated in [6], which presents the results of calculations; it can be assumed that if the frequency at which the signal is transmitted coincides with the frequency of interference, then the greatest damage is done to the transmission process, but in practice the difference between the frequencies can be quite large. Based on the values obtained, it is possible to make a preliminary assessment of the dependence of the reliability of the transmitted information on the level of harmonic interference.

The modern development of the theory of character-by-character data reception determines the direction that should allow the expansion of a variety of signal structures. To do this, it is necessary to study the developed algorithm for character-by-character reception of signal structures based on information-rich digital signals and to generalize for the case of correction codes in non-binary Galois fields excluding the class of their generating polynomials. This approach seems relevant and meets the current trends in the development of the theory of character-based reception.

As shown by the researcher in [7], the use of the symbol-by-symbol reception algorithm provides a significant energy gain of up to 2.5...4.0 dB in relation to the transmission of the considered series of signals without coding.

2 The relationship between the noise immunity of MFSK-DMT modems and the characteristics of the communication channel

As is known, the average value of the electric field strength at the receiving point is determined by the signal-to-noise values in the fading channels. Based on this, in real conditions, it is desirable to use the parameters of the dependence of the maximum allowable bit error probability on the average value of the signal-to-noise ratio that occurs in the channel at certain reliability values. These values are determined based on the depth of slow fluctuations in the channel parameters and may correspond to the variance of the fluctuating signal. It was shown in [8] that in the case of slow multiplicative oscillations, the amplitude of the signal can decay relative to their median values. The magnitude of such attenuations may be stronger than the magnitude of the attenuations that occur in the case of interference, i.e., it can be said that the observed attenuations have higher magnitudes than those observed with a one-sided normal probability distribution of the signal amplitude.

One of the methods for increasing noise immunity [9] is diversity reception, where several signals carrying the same symbol are fed to the input of the demodulator. In practice, frequency, time, spatial, and polarization diversity are widely used. The most well-known method for processing such signals is weighted coherent addition, where the total signal fed to the demodulator is a linear combination of different diversity branches. The maximum effect is achieved when the weight coefficients in each of the subchannels coincide with the complex transfer coefficients of the channel. As a rule, such a priori information does not exist, and obtaining it during demodulation is not possible. The complete opposite of this addition method is demodulation in each of the diversity branches and making a decision through non-coherent addition of the power of elementary signals. The simplicity of this approach leads to a significant decrease in noise immunity.

For digital binary data transmission systems based on optimal DMT modems with finite signals (FS), it is possible to use a filter with a constant amplitude-frequency response (AFR) as a model of a direct communication channel. For such an organization of the reception/transmission system, the noise immunity of the modem can only be estimated by the ratio to additive white Gaussian noise (AWGN). In the field, the AFR and the phase-frequency response (PFR) of the communication channel depend on the frequency. If this dependence occurs, it is not possible to talk about the equivalence of noise immunity for the DMT modem channel. As a result of the fact that the unevenness of both AFR and PFR in the communication channel also increases, the average probability of reception increases. This dependence has been shown in [10, 11].

$$P_{b,KAM,n}=\frac{1}{ldM_{KAM}}\left\{1-\left[1-\left(1-\frac{1}{\sqrt{M_{KAM}}}\right)\mathrm{erfc}\left(\sqrt{\frac{E_b}{G_0}\frac{3ldM_{KAM}k_E(V_s)}{2(MKAM-1}\frac{A_n^2}{\overline{A}_n^2}}\right)\right]^2\right\}, \quad (1)$$

where $A_n=A(f_n), n=\overline{1,N}$, are the values of the AFR of the CC at the central frequencies of the channels, E_b- energy, is the energy per bit of data [10], G_0- power spectral density of AWGN.

The dependencies (1), illustrate the potential noise immunity of the modem.

If no adjustment is made, noise immunity is reduced [11].

As an equivalent model we will adopt the relationship: $f_n=nF_\gamma, n=\overline{0,N-1}$, N=8, and $f_k=kF_\gamma, k=1,2,...$, final values: $A_n(k)=\frac{1}{\sqrt{1+b_k n^2}}, n=\overline{0,7}, k=1,2,...$, $b_k=1/k^2$ – indicator, its values are shown in Table 1.

Table 1

The unevenness index of the LFE frequency response model of the CS, hdB = 10 dB

k	1	2	3	4	5	6	7	8
b_k	1	0.25	0.11	0.06	0.04	0.03	0.02	0.016
$p_{b,KAM}(k)$	$1.08\cdot10^{-1}$	$3.50\cdot10^{-2}$	$1.10\cdot10^{-2}$	$3.59\cdot10^{-3}$	$1.29\cdot10^{-3}$	$5.25\cdot10^{-4}$	$2.46\cdot10^{-4}$	$1.32\cdot10^{-4}$

Substituting $A_n(k)$ into (1), we find the average value of the error probability in the modem.

$$P_{b,KAM}(k)=\frac{1}{2N}\sum_{n=1}^{N}\left\{1-\left[1-0.5\mathrm{erfc}\left(\sqrt{\frac{E_b}{G_0}\frac{15}{16(1+b_k n^2)}}\right)\right]^2\right\}, k=1,2,... \quad (2)$$

Graphs of dependence (2) for various indicators are shown in Figure 1 [11].

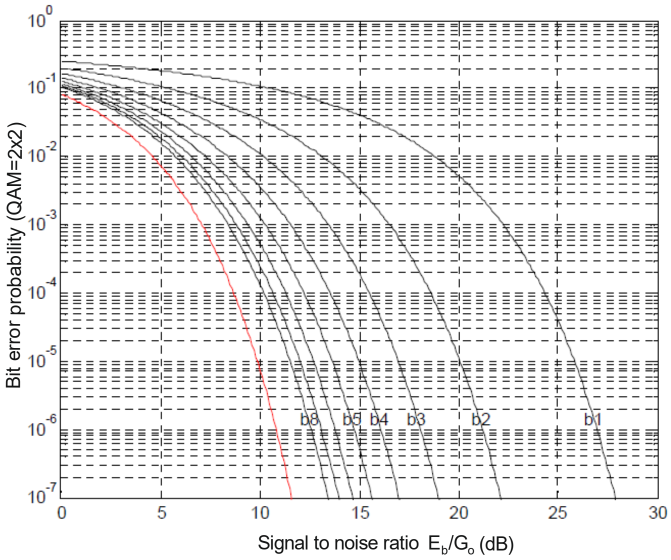

Fig. 1. Dependencies of the bit error probability on the SNR Eb/Go for signals with M_{KAM}=2x2

As shown in the plots of Fig. 1, an increase in the transfer function nonuniformity factor from b_8 to b_1 leads to a sharp rise in the average error probability. Under a fixed signal-to-noise ratio, this results in a considerable degradation of the noise immunity of MFSK-DMT modems with OFS. According to the data in Table 1, b_k from b_8=0.016 to b_1=1, the average probability error increases from $1.32\cdot10^{-4}$ to $1.08\cdot10^{-1}$.

The figure shows that the problem of channel alignment depends on the estimation of the amplitude-frequency and phase-frequency characteristics. A correct and accurate assessment of these characteristics will eventually reduce the average probability of error and, accordingly, increase the noise immunity of the DMT modem, the same task was considered in [10].

In [12], the noise immunity of a speech transmission system based on a modification of the algorithm proposed by Ya.I. Khurgin and V.P. Yakovlev was investigated. The results of the performed calculations and analyses demonstrated that transmission and primary coding systems employing this modification provide a noise immunity gain compared to systems based on V.A. Kotelnikov's theorem: 2.27 dB for a two-channel transmission and processing system, 6.2 dB for a three-channel system, and 9.72 dB for a four-channel system.

The noise immunity gain was determined by comparing the output signal-to-noise ratio of the studied system, QXQ_XQX, with that of the reference system based on Kotelnikov's classical theorem, QKQ_KQK, using the formula G = QX/QKG = Q_X/Q_KG = QX/QK. Thus, according to the conclusions of the study, multichannel transmission systems based on the modification of the algorithm proposed by Ya. I. Khurgin and V. P. Yakovlev exhibit enhanced noise immunity.

In order to analyze the noise immunity of a communication line that can be used in the specified modes of multiparametric adaptation, an adaptive smoothing parameter should be used. This parameter must be used in conjunction with forecasting models. This application leads to a reduction in prediction error, which in turn will allow for more accurate calculations of the expected probability of reception at a given level of reliability. This forecasting method is described more fully in [13], and it is assumed that it will be used in the operation of a multi-stage adaptive system.

Each adaptive line can have its own set of parameters and structure. The parameters can have different dimensions and define different physical values. In order to compare the effectiveness of the lines among themselves, it is necessary to calculate a dimensionless indicator and normalize. One of the ways to calculate such an indicator is based on the application of the E.S. Harrington function. In [13], the possibility of expanding algorithms for controlling communication systems with multi-stage adaptation based on the obtained dimensionless indicator is considered.

3 Recurrent Estimation of Real Communication Channel Parameters Based on Optimal Polyharmonic Filtering

Based on the fact that adaptation implies adjustment based on environmental conditions, in the case of an adaptive modem, it is necessary to constantly monitor the channel state parameters with the selected sampling frequency. The parameters that are monitored can be: cutoff frequency, pulse, amplitude-frequency, and phase characteristics. One of the properties of real communication channels is non-stationarity. In real conditions, communication channels are affected by a large amount of interference, so the solution to the problem of optimal filtering or estimating the parameters of the demodulator [14-18] can be solved based on estimating the optimal parameters for the Gaussian communication channel (GCC) model.

4 Polyharmonic model of Gaussian communication channel

Consider a multichannel digital communication system employing multiple-frequency shift keying (MFSK). Suppose that, during connection establishment, a polyharmonic signal with specified amplitudes and initial phases is transmitted through a Gaussian communication channel (GCC) [19, 20]. In this case, the response of the GCC can be expressed as:

$$s(t)=\sum_{n=0}^{N}A_{n,t}\cos(2\pi f_n t-\phi_{n,t})+\varsigma(t), f_n=f_0+F_n, F_n=n2F_p\ , \qquad (3)$$

where $A_{n,t}, \varphi_{n,t}, n=\overline{0,N}$, – are the amplitudes and initial phases of the GCC.

Applying, detection to s(t) the reference oscillation $u_0(t)=2\cos(2\pi f_0)$ method [10], we arrive at the LFE $s_0(t)$ of the form [11, 21]

$$s_0(t)=\sum_{n=0}^{N}A_{n,t}\cos(2\pi F_n t-\varphi_{n,t})+\xi(t)=0.5c_0+\sum_{n=1}^{N}c_{n,t}\cos(2\pi F_n t)+s_{n,t}\sin(2\pi F_n t)+\xi(t), \qquad (4)$$

where $c_0=2A_0, c_n=A_n\cos\varphi_n, s_n=A_n\sin\varphi_n$.

Moving from the trigonometric to the exponential series, signal $s_0(t)$ in discrete time $t_k=k\Delta t$, we obtain:

$$Sk=\sum_{n=-N/2}^{N/2}\underline{c}_{n,k}\exp\left(j\frac{2\pi 2F_p}{f_d}nk\right)+\xi_k=\sum_{n=0}^{N}\underline{c}_{nk}W_N^{nk}+\xi_k, W_N=e^{j\frac{2\pi}{N}}, N=f_d/2F_p, k=\overline{0,N}\cdot \qquad (5)$$

Using vector-matrix representations [17, 22], the relation (5) is reduced to the following form:

$$s_l=Wc_l+\xi_l, l=1,2,..., \qquad (6)$$

where

$s_l=(s_{l,0},s_{l,1},...,s_{l,N})^T$, $c_l=(c_{l,0},c_{l,1},...,c_{l,N})^T$, $\xi_l=(\xi_{l,0},\xi_{l,1},...,\xi_{l,N})^T$ – are the vectors of the signal, complex parameters of the CC, and observation noise, respectively, $W=\left[W_N^{nk}\right], n,k=\overline{0,N}$ – is the Fourier matrix.

Multiplying the left and right parts of the relation (6) by the transposed complex conjugate matrix W^{*T} and taking into account the condition of its orthogonality, we represent (6) as follows:

$$z_l=c_l+\eta_l, \qquad (7)$$

$z_l=W^{*T}s_l, \eta_l=W^{*T}\xi_l$ – are the transformed complex vectors of the signal and noise.

The correlation matrix of the observation noise η_l is reduced to the following form: $R_\eta=M\eta\eta^{*T}=MW^{*T}\xi_l\xi_l^TW=W^{*T}R_\xi W=\sigma_\xi^2 I$.

To solve the problem of optimal estimation parameters, the observation equation (7), we introduce the model [10].

c_l – Wiener vector process, we obtain:

$$c_l=c_{l-1}+\zeta_l, l=1,2,... \qquad (8)$$

where ζ_l - is the model noise with parameters:

$$M\zeta_l = 0,\ M\zeta_l\zeta_l^T = \sigma_\zeta^2 I,\ M\zeta_l\eta_i^T = 0 .$$

Relations (6) - (8) define the model of a Gaussian communication channel (GCC) in the state space [23, 24].

5 Optimal Estimation of Parameters of the Polyharmonic Model of a Gaussian Communication Channel

Based on the observation equations (7) and state equations (8), taking into account the non-correlation of the components of the vector, we use the known Kalman filtering algorithm [17] to obtain η_l optimal estimates of the components of the vector $c_l = (c_{l,0}, c_{l,1}, ..., c_{l,N})^T$ of the polyharmonic model of the GCC [10, 21]:

$$\begin{aligned}&\underline{\bar{c}}n,l = \underline{\bar{c}}_{n,l-1} + \underline{h}_{n,l}(\underline{z}_{n,l} - \underline{\bar{c}}_{n,l-1}),\ \underline{h}_{n,l} = V_{n,l}/(V_{n,l} + \sigma_\zeta^2),\\ &V_{n,l} = D_{n,l-1} + \sigma_\zeta^2,\ D_{n,l} = V_{n,l} - \underline{h}_{n,l}V_{n,l},\ n = \overline{0, N},\ l = 1, 2, ...\end{aligned} \tag{9}$$

In (9) – is the a priori variance of the filtering error, $D_{n,l}$ s the a posteriori variance $\underline{h}_{n,l}$, $V_{n,l}$ - is the Kalman filter gain for the nth component. The filter operation starts under the conditions: $\underline{\bar{c}}_{n,0} = 0,\ D_{n,0} = \sigma_\zeta^2$.

Based on the estimates of the complex quantities $\underline{\bar{c}}_{n,l}$ he estimates of the amplitudes $\bar{A}_{n,l} = |\underline{\bar{c}}|$ of the AFR and the phases $\bar{\varphi}_{n,l} = \arg \underline{\bar{c}}_{n,l}$ of the PFR in relation (3) are calculated.

6 Experimental Evaluation of the AFR and PFR of the GCC

The results of testing the operability of the method for recurrent estimation of the GCC parameters based on a known polyharmonic signal were obtained in [21] using the MATLAB system and are illustrated in Figure 2.

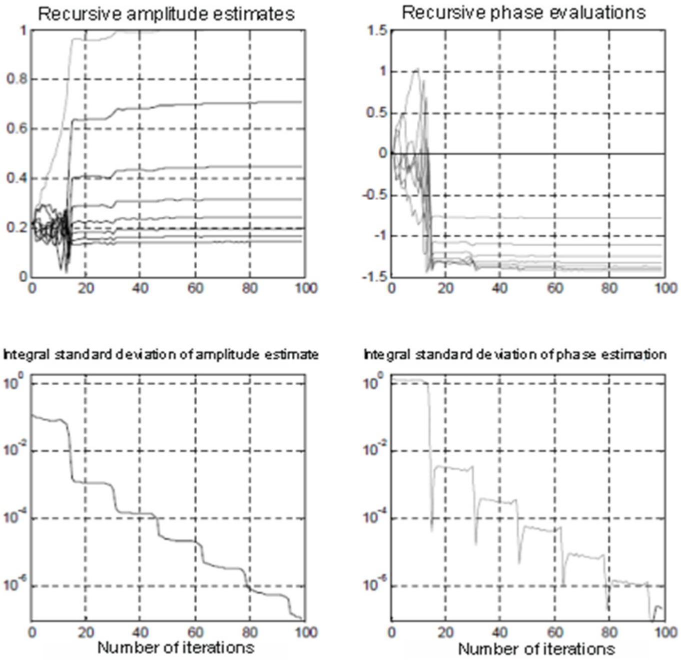

Fig. 2. Results of an experimental study of the algorithm for recurrent estimation of the parameters of the polyharmonic model of the GCC

Here, according to algorithm (9), the graphs of recurrent estimates of the amplitudes {} (top right graph) at zero SN hdB=0.

The lower graphs show the current integral root-mean-square deviations (RMSD) of the amplitude and phase estimates from their a priori values, determined as follows:

$$\text{skoAk} = \frac{1}{L}\sum_{n=0}^{L-1}\left(\bar{A}_{n,k} - A_n\right)^2,\quad \text{sko}\phi_k = \frac{1}{L}\sum_{n=0}^{L-1}\left(\bar{\phi}_{n,k} - \phi_n\right)^2,\ k = \overline{0, K-1}, \tag{10}$$

where L=100 - is the number of iterations.

As a model of the LFE of the CC, a first-order filter with a complex transfer coefficient of the form: where – AFR, a – PFR of the LFE model of the CC. For digital implementation, N=8 channels were selected at frequencies. The values of the estimated amplitudes and phases of the LFE model of the CC are presented in Table 2.

Table 2

Estimated parameters of the NCE model of the GKS

n	0	1	2	3	4	5	6	7
A_n	1	0.7071	0.4472	0.3162	0.2425	0.1961	0.1644	0.1414
φ_n	0	-0.785	-1.107	-1.249	-1.326	-1.373	-1.406	-1.429

As a test signal at the input of the LFE of the CC, a polyharmonic signal of the following form was used.

Then the response of the GCC model is equal to: $z_k^* = z_k + \xi_k = \sum_{n=0}^{N-1} A_n \cos(\pi nk / N - \varphi_n) + \xi_k$.

As a noise signal, uncorrelated Gaussian noise with an average power of σ2=1σ2=1 was simulated [10] uncorrelated gaussian noise with average power.

The results of estimating the parameters from Table 2 are shown in Figure 2.

The presence of modulation noise resulting from multilevel signal modulation does not allow us to accurately estimate the phase of the clock oscillation when using modern methods for reconstructing multi-position signals with quadrature amplitude modulation (QAM).

The task of optimally estimating the values of the constant delay time of a signal in the presence of additive noise can be determined within the framework of the generally accepted clock synchronization problem. Based on the initial conditions of the problem, it is assumed that the noise that affects and distorts the signal is basically additive white Gaussian noise. The signal is transmitted in a channel, which in turn is a Nyquist channel. These limitations make it possible to calculate the effect of additive noise with maximum accuracy.

Based on this, in order to minimize the effects of distortion, it is necessary to use a clock synchronization method that allows each pair of adjacent symbols to be converted to a binary signal. The method should provide centering taking into account the zero point and the weights. This method was considered in [25] and its application made it possible to more accurately determine the moment of decision-making and increase the noise immunity of the digital communication line demodulator by about 0.5-0.7 dB.

Multi-position frequency shift keying (M-FSK) is an attractive signal construction for communication systems not limited by the width of the occupied spectrum, since at high orders of modulation it is capable of providing a significant energy gain (up to 4 dB compared to traditional PSK modulation). In addition, the advantages of M-FSK include constant power and zero peak factor. There is a possibility of increasing the spectral efficiency of higher-order modulations by narrowing the spectrum by 10-15% without significant deterioration in noise immunity [26].

It can be argued that the mathematical expectation of the number of frames in a single interval of episodic synchronization, as well as the number of intervals of episodic synchronization, are determined by the values of the continuity and duration of the synchronization pulse. non-stationary unintended pulse interference and has little effect on the beginning of the first pulse of non-stationary unintended pulse interference in the observation interval. This statement is based on an analysis of the effect of episodic synchronization of channel-level frames with nonstationary unintended pulse interference. For this synchronization, a model of the functioning of the communication channel based on OFDM technology has been constructed and discussed in detail in [27, 31].

The nature of the obtained dependences of the probability of erroneous reception of various parts of the frame and the frame as a whole on the duration of the pulse of non-stationary unintentional pulse interference is determined by the structure of the frame. Therefore, it can be argued that for the situation under consideration, the number of characters in the synchronization group, its type and the actual size of the service part of the frame, as well as the ratio between the size of the service and information parts of the frame are crucial. The influence of non-stationary unintentional pulse interference on the service part of the frame can lead to the fact that the probability of erroneous reception of the frame will be higher than when such non-stationary unintentional pulse interference affects only the information part of the frame. The pulse duration of an unsteady unintended pulse interference takes about 10-15% of the frame duration, which is given in [27-30].

Transmission based on matrix orthogonalization allows increasing the rate of decay of the side lobes of the power spectral density compared to OFDM, as well as increasing the duration of channel signals without changing the transmission rate of binary message elements and the frequency band occupied by the transmitted signal. The method of transmitting binary messages considered in [35] provides good frequency efficiency without using a spectrum shaper and high noise immunity.

In the case of a sliding window, it is possible to reduce interference to the requirements of a dynamically changing environment, regardless of the amount and type of interference, for which it is necessary to decompose the broadband signal into its narrowband components. This decomposition is not possible without using data sets of digital bandpass filters. In the case of matching the length of the sliding window to the length of the bandwidth, it is necessary to normalize the interference correlation interval to the value that was obtained as a result of measurements, and actually synthesize the broadband signal from its narrowband components. This method is described in more detail in [32-34], the peculiarity is that when a broadband signal is restored, signals from the output narrowband channels affected by interference are not destroyed.

The use of the functions of pre-detection registration of a group telemetry signal in ground-based reception and recording equipment opens up new possibilities in the processing of telemetry information. In [35], a method was developed that allows sequential restoration of the bit stream of telemetry information. The method is based on the singular spectral decomposition of a group telemetry signal, which reduces the likelihood of bit error and increases the reliability of incoming data. And using the method proposed in [1, 36], in turn, will reduce the energy consumption for transmitting discrete information over data transmission channels, reduce downtime and increase the reliability of transmitted information.

7 Conclusion

For the first time, a theoretical analysis of the influence of the unevenness of the amplitude-frequency characteristic of the communication channel on the deterioration of the noise immunity of a modem with multi-frequency modulation and optimal finite signals was carried out. Based on the polyharmonic model of a non-stationary frequency-limited Gaussian communication channel using the Kalman filtering method, the problem of optimal recurrent estimation of the amplitudes and phases of the transfer function of the channel was solved. Experimentally, using matrix computations in the MATLAB environment, the high accuracy of the obtained estimates was confirmed.

To synthesize an adaptive modem with improved spectral-energy efficiency, it is necessary to estimate the parameters and frequency characteristics of the communication channel under noisy conditions. Recurrent estimates of sample amplitudes and phases obtained based on their optimal polyharmonic filtering reach their true values in 50 iterations (6.25 ms) with a root-mean-square error of 0.01 at an SNR equal to 0 dB.

References

[1] P. I. Kuzin, E. I. Kuzina, “Changing the adaptation parameters when receiving information in data transmission systems,” *Information systems and technologies: theory and practice: Collection of scientific papers*. St. Petersburg: St. Petersburg State Forest Engineering University named after S. M. Kirov, 2024, pp. 58-63. (in Russian)

[2] N. R. Abdyraeva, D. B. Bakytbekov, A. D. Poletaev, “Evaluation of noise immunity of information transmission system under conditions of multipath fading in the channel,” *Bulletin of Science and Practice*. 2025. Vol. 11, No. 4, pp. 160-166. DOI 10.33619/2414-2948/113/24. (in Russian)

[3] Yu. E. Korchagin, K. D. Titov, Yu. G. Petrov, P. A. Kondratovich, “Study of noise immunity of ultra-wideband communication facilities of the IEEE 802.15.4 standard under the influence of broadband interference,” *Journal of Radio Electronics*. 2024. No. 11. P. 13. DOI 10.30898/1684-1719.2024.11.14. (in Russian)

[4] K. R. Romanova, Yu. A. Polevoda, “Analysis of noise immunity of the communication channel during image transmission,” *Issues of Electromechanics. Proceedings of VNIIEM*. 2024. Vol. 199, No. 2, pp. 48-51. (in Russian)

[5] A. E. Troitskaya, Yu. A. Polevoda, G. V. Kulikov, “Noise immunity of reception of signals with multi-position frequency manipulation against the background of retransmitted interference,” *Russian Technological Journal*. 2024. Vol. 12, No. 5, pp. 33-41. DOI 10.32362/2500-316X-2024-12-5-33-41. (in Russian)

[6] V. V. Zvonarev, A. V. Pitrin, A. S. Popov, “Calculation of the bit error probability for incoherent reception of a signal with four-position relative phase manipulation in the presence of harmonic interference,” *Proceedings of MAI*. 2024. No. 135. P. 23 (in Russian)

[7] L. E. Nazarov, “Study of noise immunity of symbol-by-symbol reception of digital information-intensive signals with correction coding in non-binary Galois fields,” *Physical Foundations of Instrument Engineering*. 2024. Vol. 13, No. 1 (51), pp. 20-25. DOI 10.25210/jfop-2401-LWRKKL. (in Russian)

[8] V. V. Zelenevsky, Yu. V. Zelenevsky, A. V. Popov, A. B. Nakonechny, “Statistical analysis of communication reliability in a single-beam data transmission channel,” *Bulletin of the Institute of Engineering Physics*. 2025. No. 1 (75), pp. 30-33. (in Russian)

[9] D. S. Gagarina, V. V. Egorov, A. E. Timofeev, “Soft demodulation of frequency-diversified signals,” *Wave electronics and infocommunication systems: Collection of articles of the XXVIII International scientific conference*. In 3 parts, May 12-16. St. Petersburg: St. Petersburg State University of Aerospace Instrumentation. 2025, pp. 78-82. (in Russian)

[10] V. G. Sannikov, A. V. Aleshintsev, “Multi-frequency modem as one of the main elements of the "Intelligent Building" system for remote control of objects,” *T-Comm*. 2015. Vol. 9, No. 6, pp. 21-27. (in Russian)

[11] V. G. Sannikov, “Intelligent modem based on multi-frequency modulation,” *Journal of Radio Electronics*. 2015. No. 1, pp. 2-23. (in Russian)

[12] V. T. Dmitriev, H. Sh. Wu, “Determination of the noise immunity gain of a multi-channel transmission system based on a modification of the Khurgin-Yakovlev algorithm,” *Information technology. Radio electronics. Telecommunications (ITRT-2024): Proceedings of the XI International Correspondence Scientific and Technical Conference*, Tolyatti, November 29, 2024. Tolyatti: Publishing and Printing Center PVGUS, pp. 445-451. (in Russian)

[13] A. E. Alekaev, P. I. Kuzin, E. I. Kuzina, “Methodology for predicting the interference level through the use of multistage adaptation,” *Telecommunications*. 2024. No. 7, pp. 10-21. DOI 10.31044/1684-2588-2024-0-7-10-21. (in Russian)

[14] A. S. Adzhemov, V. G. Sannikov, “General Theory of Communications. Textbook for Universities,” Moscow: Goryachaya Liniya - Telecom, 2018. 624 p.

[15] G. Van Trees, “Theory of Detection, Estimation and Modulation,” Moscow: Sov. Radio. Vol. 1, 744 p., Vol. 2, 343 p. 1972, 1975.

[16] N. E. Kirillov, “Noise-Immune Message Transmission over Linear Channels with Randomly Changing Parameters,” Moscow: Svyaz, 1971. 256 p.

[17] B. Sklyar, “Digital Communications. Theoretical Foundations and Practical Applications,” Moscow: Williams Publishing House, 2003. 1104 p.

[18] Yu.A. Tamm, “Adaptive Correction of the PD Signal,” Moscow: Svya, 1978. 144 p.

[19] R. Kennedy, “Communication Channels with Fading and Scattering,” Moscow: Sov. Radio, 1973. 116 p.

[20] V. B. Kreindelin, “New methods of signal processing in wireless communication systems,” St. Petersburg: Link, 2009. 276 p. (in Russian)

[21] V. G. Sannikov, A. V. Alyoshintsev, “Structure and efficiency of an adaptive multi-frequency modem with optimal finite signals,” *Electrosvyaz*. 2016. No. 6. Pp. 58-63. (in Russian)

[22] Lyons Richard, “Digital signal processing,” Second edition. Moscow: Binom-Press, 2011. 650 p.

[23] V. K. Marigodov, E. F. Baburov, “Synthesis of optimal radio systems with adaptive predistortion and signal correction,” Moscow: Radio and Communications, 1985. 268 p. (in Russian)

[24] A.V. Shvedov, D.V. Gadasin, A.V. Alyoshintsev, “Segment routing in data transmission networks,” *T-Comm*, 2022, vol. 16, No. 5, pp. 56-62. (in Russian)

[25] V. G. Dovbnja, D. S. Koptev, “Clock synchronization method for signal demodulators with quadrature amplitude shift keying,” *Infocommunications and space technologies: status, problems and solutions: collection of scientific articles based on the materials of the VIII All-Russian scientific and practical conference dedicated to the 60th anniversary of the South-West State University*, Kursk, March 21-22, 2024. Kursk: South-West State University, pp. 26-37. (in Russian)

[26] M. M. Medvedev, S. S. Shavrin, “Noise immunity of M-FSK manipulation during transmission through a channel with AWGN,” *Design and technology of electronic means*. 2024. No. 3, pp. 15-20. (in Russian)

[27] Yu. N. Kopalov, P. A. Maslakov, A. V. Parshutkin, “Model of functioning of the communication channel with orthogonal frequency division (OFDM) under conditions of episodic synchronization with a flow of unintentional impulse interference,” *Proceedings of the A.F. Mozhaisky Military Space Academy*. 2024. No. 694, pp. 67-75. (in Russian)

[28] D.S. Chirov, E.O. Lobova, “Wideband hf signals dispersion distortion compensator based on digital filter banks. Theory and approbation,” *T-Comm*. 2020. Vol. 14. No. 4, pp. 57-65.

[29] A.S. Kryukovsky, D.S. Lukin, D.V. Rastyagaev, Yu.I. Skvortsova, “The numerical modeling of propagation of space-time frequency-modulated radiowaves in ionospheric to medium,” *T-Comm*. 2015. Vol 9. No.9, pp. 40-47.

[30] S.S. Adjemov, E.M. Lobov, N.A. Kandaurov, E.O. Lobova, V.I. Lipatkin, “Algorithms of estimating and compensating the dispersion distortions of wideband signals in the HF channel,” *H&ES Reserch*. 2021. Vol. 13. No. No5. P. 5774. doi: 10.36724/2409541920211355774

[31] D.V. Gadasin, A.V.Shvedov, I.A. Kuzin, “Three-dimensional reconstruction of an object from a single image using deep convolutional neural networks ,” *T-Comm*, 2022. Vol. 16, No. 7, pp. 29-35. (in Russian)

[32] V. A. Vershinin, “Parallel transmission of binary messages by narrow-band orthogonalized signals,” *Questions of science*. 2025. No. 1, pp. 51-57. (in Russian)

[33] E. M. Lobov, D. N. Shubin, A. D. Grigorieva, “Method and device for interference suppression based on a bank of digital filters,” *Electrosvyaz*. 2025. No. 5, pp. 25-33. DOI 10.34832/ELSV.2025.67.5.004. (in Russian)

[34] D.V. Gadasin, A.V. Schvedov, “Application of a transport task for load balancing in conditions of source data fuzziness,” *T-Comm*, 2024. Vol. 18, No.1, pp.13-20. (in Russian)

[35] A.S. Dunikov, R.V. Mitronin, P.N. Dolgikh, “Method of sequential reconstruction of telemetry information bit stream based on singular-spectral decomposition of pre-detector recording of group telemetry signal,” *Radio Engineering*. 2025. Vol. 89, No. 4, pp. 109-120. DOI 10.18127/j00338486-202504-10. (in Russian)

[36] D.V. Gadasin, “Building a binary tree of the minimum prices,” *T-Comm*, 2024. Vol. 18, No. 11, pp. 38-44. (in Russian)

МЕТОДЫ ОЦЕНКИ ПОМЕХОУСТОЙЧИВОСТИ МОДЕМОВ

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Аннотация

Повышение помехоустойчивости модема, как элемента системы передачи данных является важнейшей проблемой техники связи. Создание такого рода систем (со скоростью передачи близкой к предельной) реализуется подходом учитывающим всевозможные виды преобразований, которым подвержен передаваемый сигнал. Статья посвящена анализу методов оценки помехоустойчивости с приведением современных наиболее совершенных способов передачи и приёма сигнала с целью обеспечить (при заданных условиях) максимально возможную вероятность правильного приёма данных (минимальной вероятности ошибки). Достижение максимального эффекта (в этом направлении) возможно благодаря многочисленным работам исследователей с нахождением оптимальных методов и алгоритмов обработки и анализа данных, проводимым экспериментам, разработкой новых способов обработки сигналов, в итоге обеспечивающих выигрыш помехоустойчивости системы связи. В работе приводится оценка влияния характеристик канала связи на помехоустойчивость модемов, рассмотрена рекуррентная оценка параметров реального канала связи на основе оптимальной полигармонической фильтрации, а также полигармоническая модель гауссовского канала связи с оптимальной оценкой параметров и результаты экспериментальной оценки амплитудно - частотной и фазо-частотной характеристики гауссовского канала связи. Помимо этого приведены различные подходы в применении сигнально - кодовых конструкций, ансамблей сигналов с различной манипуляцией и позиционностью. Описано негативное влияние помех на достоверность приёма сигнала и передаваемой информации в канале, указаны способы ограничения влияния помех на системы передачи данных, методы и результаты современных теоретических и экспериментальных исследований, позволяющих повысить помехоустойчивость и скорости передачи. При этом методы оценки помехоустойчивости полноценно раскрываются работами и исследованиями, приведенными в данной статье с целью всесторонней, широкой оценки возможности как по качественному улучшению параметров и характеристик систем приёма/передачи данных, так и по уменьшению негативных воздействий помех и шумов на канал связи и систему связи в целом. Разработка новой системы модуляции/демодуляции без дорогостоящей реконструкции, совместимой с действующими системами важное направление, связанное с повышением эффективности систем связи.

Ключевые слова: *помехоустойчивость, многоканальная система, отношение сигнал-шум. достоверность, адаптация, вероятность ошибки, BER, МЧМ модем*

Литература

1. *Кузин П. И., Кузина Е. И.* Изменение параметров адаптации при приеме информации в системах передачи данных // Информационные системы и технологии: теория и практика: Сборник научных трудов. Санкт-Петербург: Санкт-Петербургский государственный лесотехнический университет им. С.М. Кирова, 2024. С. 58-63.
2. *Абдыраева Н. Р., Бакытбеков Д. Б., Полетаев А. Д.* Оценка помехоустойчивости системы передачи информации в условиях многолучевых замираний в канале // Бюллетень науки и практики. 2025. Т. 11, № 4. С. 160-166. DOI 10.33619/2414-2948/113/24.
3. *Корчагин Ю. Э., Титов К. Д., Петров Ю. Г., Кондратович П. А.* Исследование помехоустойчивости сверхширокополосных средств связи стандарта IEEE 802.15.4 при воздействии широкополосных помех // Журнал радиоэлектроники. 2024. № 11. 13 с. DOI 10.30898/1684-1719.2024.11.14.
4. *Романова К. Р., Полевода Ю. А.* Анализ помехоустойчивости канала связи при передаче изображения // Вопросы электромеханики. Труды ВНИИЭМ. 2024. Т. 199, № 2. С. 48-51.
5. *Троицкая А. Е., Полевода Ю. А., Куликов Г. В.* Помехоустойчивость приема сигналов с многопозиционной частотной манипуляцией на фоне ретранслированной помехи // Russian Technological Journal. 2024. Т. 12, № 5. С. 33-41. DOI 10.32362/2500-316X-2024-12-5-33-41.
6. *Звонарев В. В., Питрин А. В., Попов А. С.* Расчет вероятности битовой ошибки при некогерентном приёме сигнала с четырёхпозиционной относительной фазовой манипуляцией в присутствии гармонической помехи // Труды МАИ. 2024. № 135. 23 с.
7. *Назаров Л. Е.* Исследование помехоустойчивости посимвольного приема цифровых информационно-емких сигналов с корректирующим кодированием в недвоичных полях Галуа // Физические основы приборостроения. 2024. Т. 13, № 1(51). С. 20-25. DOI 10.25210/jfop-2401-LWRKKL.
8. *Зеленевский В. В., Зеленевский Ю. В., Попов А. В., Наконечный А. Б.* Статистический анализ надежности связи в однолучевом канале передачи данных // Известия Института инженерной физики. 2025. № 1(75). С. 30-33.
9. *Гагарина Д. С., Егоров В. В., Тимофеев А. Е.* Мягкая демодуляция частотно-разнесенных сигналов // Волновая электроника и инфокоммуникационные системы: Сборник статей XXVIII Международной научной конференции. В 3-х частях, 12-16 мая 2025 года. Санкт-Петербург: Санкт-Петербургский государственный университет аэрокосмического приборостроения. 2025. С. 78-82.
10. *Санников В. Г., Алешинцев А. В.* Многочастотный модем как один из основных элементов системы "Интеллектуальное здание" при удаленном управлении объектами // T-Comm: Телекоммуникации и транспорт. 2015. Т. 9, № 6. С. 21-27.
11. *Санников В. Г.* Интеллектуальный модем на основе многочастотной модуляции // Журнал радиоэлектроники. 2015. № 1. С. 2-23.
12. *Дмитриев В. Т., Ву Х. Ш.* Определение выигрыша помехоустойчивости многоканальной системы передачи на основе модификации алгоритма Хургина - Яковлева // Информационные технологии. Радиоэлектроника. Телекоммуникации (ITRT- 2024): Материалы XI Международной заочной научно-технической конференции, Тольятти, 29 ноября 2024 года. Тольятти: Издательско-полиграфический центр ПВГУС, 2025. С. 445-451.

13. *Алекаев А. Е., Кузин П. И., Кузина Е. И.* Методика прогнозирования уровня помех за счет применения многоступенчатой адаптации // Телекоммуникации. 2024. № 7. С. 10-21. DOI 10.31044/1684-2588-2024-0-7-10-21.
14. *Аджемов А. С., Санников В. Г.* Общая теория связи. Учебник для вузов. М.: Горячая линия – Телеком, 2018. 624 с.
15. *Ван Трис Г.* Теория обнаружения, оценок и модуляции / Пер. с англ. под ред. проф. В.И. Тихонова. М.: Сов. Радио. 1972. Том 1, 744 с., 1975. Том 2, 343 с.
16. *Кириллов Н. Е.* Помехоустойчивая передача сообщений по линейным каналам со случайно изменяющимися параметрами. М.: Связь. 1971. 256 с.
17. *Скляр Б.* Цифровая связь. Теоретические основы и практическое применение / Пер. с англ. М.: ИД "Вильямс". 2003. 1104 с.
18. *Тамм Ю. А.* Адаптивная коррекция сигнала ПД. М.: Связь. 1978. 144 с.
19. *Кеннеди Р.* Каналы связи с замираниями и рассеянием / Пер. с англ. под ред. И. А. Овсеевича. М.: Сов. Радио. 1973. 116 с.
20. *Крейнделин В. Б.* Новые методы обработки сигналов в системах беспроводной связи. СПб: Линк. 2009. 276 с.
21. *Санников В. Г., Алешинцев А. В.* Структура и эффективность адаптивного многочастотного модема с оптимальными финитными сигналами // Электросвязь. 2016. № 6. С. 58-63.
22. *Ричард Лайонс.* Цифровая обработка сигналов. Второе издание. Пер с англ. М.: ООО "Бином-Пресс", 2011. 650 с.
23. *Маригодов В. К., Бабуров Э. Ф.* Синтез оптимальных радиосистем с адаптивным предыскажением и корректированием сигналов. М.: Радио и связь. 1985. 268 с.
24. *Шведов А.В., Гадасин Д.В., Алёшинцев А.В.* Сегментная маршрутизация в сетях передачи данных // T-Comm: Телекоммуникации и транспорт. 2022. Том 16. №5. С. 56-62.
25. *Довбня В. Г., Коптев Д. С.* Способ тактовой синхронизации для демодуляторов сигналов с квадратурной амплитудной манипуляцией // Инфокоммуникации и космические технологии: состояние, проблемы и пути решения: сборник научных статей по материалам VIII Всероссийской научно-практической конференции, посвящённой 60-летию Юго-Западного государственного университета, Курск, 21-22 марта 2024 года. Курск: Юго-Западный государственный университет. 2024. С. 26-37.
26. *Медведев М. М., Шаврин С. С.* Помехоустойчивость M-FSK манипуляции при передаче через канал с АБГШ // Проектирование и технология электронных средств. 2024. № 3. С. 15-20.
27. *Копалов Ю. Н., Маслаков П. А., Паршуткин А. В.* Модель функционирования канала связи с ортогональным частотным разделением (OFDM) в условиях эпизодической синхронизации с потоком непреднамеренных импульсных помех // Труды Военно-космической академии имени А.Ф.Можайского. 2024. № 694. С. 67-75.
28. *Чиров Д. С., Лобова Е. О.* Компенсатор дисперсионных искажений широкополосных сигналов декаметрового диапазона, построенный на базе банка цифровых фильтров. Теория и эксперимент // T-Comm: Телекоммуникации и транспорт. 2020. Том 14. №4. С. 57-65.
29. *Крюковский А. С., Лукин Д. С., Растягаев Д. В., Скворцова Ю. И.* Численное моделирование распространения пространственно-временных частотно-модулированных радиоволн в анизотропной среде // T-Comm: Телекоммуникации и транспорт. 2015. Т. 9. № 9. С. 40-47.
30. *Аджемов С. С., Лобов Е. М., Кандауров Н. А., Лобова Е. О., Липаткин В. И.* алгоритмы оценки и компенсации дисперсионных искажений широкополосных сигналов ионосферных радиолиний связи // Наукоемкие технологии в космических исследованиях Земли. 2021. Т. 13. № 5. С. 57-74.
31. *Гадасин Д. В., Шведов А. В., Кузин И. А.* Трехмерная реконструкции объекта по одному изображению с использованием глубоких свёрточных нейронных сетей // T-Comm: Телекоммуникации и транспорт. 2022. Т. 16, № 7. С. 29-35. DOI 10.36724/2072-8735-2022-16-7-29-35.
32. *Вершинин В. А.* Параллельная передача двоичных сообщений узкополосными ортогонализованными сигналами // Вопросы науки. 2025. № 1. С. 51-57.
33. *Лобов Е. М., Шубин Д. Н., Григорьева А. Д.* Метод и устройство подавления помех на базе банка цифровых фильтров // Электросвязь. 2025. № 5. С. 25-33. DOI 10.34832/ELSV.2025.67.5.004.
34. *Гадасин Д. В., Шведов А. В.* Применение транспортной задачи для балансировки нагрузки в условиях нечеткости исходных данных // T-Comm: Телекоммуникации и транспорт. 2024. Т. 18, № 1. С. 13-20. DOI 10.36724/2072-8735-2024-18-1-13-20.
35. *Дуников А. С., Митронин Р. В., Долгих П. Н.* Метод последовательного восстановления битового потока телеметрической информации на основе сингулярно-спектрального разложения додетекторной записи группового телеметрического сигнала // Радиотехника. 2025. Т. 89, № 4. С. 109-120. DOI 10.18127/j00338486-202504-10.
36. *Гадасин Д. В.* Построение бинарного дерева минимальной цены // T-Comm: Телекоммуникации и транспорт. 2024. Т. 18, № 11. С. 38-44. DOI 10.36724/2072-8735-2024-18-11-38-44.

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