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DEVISING A METHOD FOR INCREASING THE NOISE IMMUNITY OF SYSTEMS WITH ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING UNDER THE CONDITIONS OF INTER-CHANNEL INTERFERENCE

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Modern communication systems are based on orthogonal frequency division multiplexing (OFDM) technology, which allows reliable transmission of information under multipath conditions. The need to preserve the orthogonal properties of subcarriers leads to high sensitivity of these systems to frequency shifts of the signal. The method of signal formation for the OFDM system has been improved in this work. The use of spectrum-selective shaping pulses after the inverse fast Fourier transform (IFFT) stage at the transmitter side to reduce the level of inter-channel interference during carrier frequency shift was investigated. New pulse shapes were synthesized, obtained by using optimized multiparameter functions with a selective spectrum. The effectiveness of the application of synthesized pulses with a selective spectrum in reducing the influence of the frequency shift of the signal on the interference immunity of the OFDM system was analyzed. A comparison of the probability of a bit error with already existing forms of Nyquist pulses was carried out. In the MATLAB environment, a model of the transmitter and receiver of the OFDM system was developed for the experimental assessment of the influence of the proposed forming pulses on the immunity of the system under the conditions of inter-channel interference with different types of modulation. It was established that the lowest level of bit error probability under the conditions of inter-channel interference was observed for a two-parameter pulse with a selective spectrum and a piecewise linear approximation of the transition region. So, for a signal-to-noise ratio of 15 dB, BPSK modulation and a normalized frequency shift of 0.2, the probability of a bit error for a given pulse is $3\cdot10^{-4}$; for QPSK modulation and a normalized frequency shift of 0.1–10^{-6}; for QAM-16 modulation and a normalized frequency shift of 0.03–$2\cdot10^{-4}$

Keywords: Nyquist shaping pulse, pulse with a selective spectrum, piecewise linear approximation, interchannel interference, OFDM

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1. Introduction

OFDM technology is the basis of modern communication systems. The peculiarity of this technology is the transmission of information in parallel streams with a low data transfer rate, which reduces the effect of delay in a multibeam communication channel. For additional interference resistance, a cyclic prefix can be added to the signal, which is a copy of the last part of the OFDM signal, or a protective interval between symbols can be used.

The transmitted OFDM signal consists of many modulated subcarriers. Due to the orthogonality of the subcarriers, the components of the signal spectrum overlap each other and do not create inter-channel interference, which increases the efficiency of using the frequency resource.

The latter circumstance leads to the high sensitivity of OFDM-based systems to frequency shifts, which are caused, for example, by the Doppler effect or the frequency difference between the transmitter and the receiver. As a result, inter-channel interference occurs, which worsens the immunity of the system. The search for methods to reduce the effect of the frequency shift on the level of inter-channel interference (ICI) is relevant.

2. Literature review and problem statement

To reduce the level of inter-channel interference, there are various techniques. Thus, works [1, 2] propose a method of self-cancellation of subcarriers when forming an OFDM signal. The advantage of the method is the simplicity of implementation, but its disadvantage is the reduction of spectral efficiency due to the redundancy of subcarrier frequencies.

In [3], the use of Nyquist shaping pulses on the transmitter side is proposed. Expressions are also established that determine the probability of a bit error under the conditions of frequency shift and additive white Gaussian noise (AWGN) when applying Nyquist shaping pulses in an OFDM transmitter. The advantages of this method include, in addition to reducing the ICI level, reducing the level of out-of-band radiation of the OFDM signal, which improves compatibility with other radio services. This method is suitable for use in OFDM, where a guard interval between symbols is used instead of a cyclic prefix.

A method similar to [3] is considered in [4], where signal processing with Nyquist pulses is performed in the receiver of the OFDM system. This method is compatible with OFDM signals having a cyclic prefix [5]. Also, in [4], the implementation of the double fast Fourier transform (2-N FFT) in OFDM receivers, which is used in this work, is considered. However, in [4], only the pulse of the "Raised cosine" form is considered and no attention is paid to other forms of pulses.

In [6], processing of the OFDM signal by window functions on the receiver side is considered in the same way. In [6], a rectangular, trapezoidal pulse and a "Raised cosine" pulse are considered.

In [7], a pulse approximated by a second-order polynomial is synthesized. The peculiarity of this pulse is its transformation into other types of pulses when the second parameter changes.

In [8], a dual sinc-pulse with a selective spectrum is considered, but attention is paid to the bit error probability only under the BPSK modulation mode.

In [9], an exponential sinc-pulse is considered, but attention to the probability of bit error is paid only to the BPSK modulation mode.

A piecewise linear and polynomial approximation of the transition region of the Nyquist pulse is proposed in [10]. A piecewise linear approximation of the transition region of the Nyquist pulse is proposed in [11]. However, both studies do not focus on the application of Nyquist pulse data for OFDM technology.

In [12], the piecewise polynomial approximation of the transition region of the Nyquist pulse is considered. However, the study of the probability of a bit error in the OFDM system is performed only for BPSK modulation.

In [13], a linear combination of pulses with a polynomial approximation of the transition region is considered. Bit error probability expressions for BPSK, QPSK, and QAM-16 modulation modes are also given.

In [14], the exponential approximation of the transition region of the Nyquist pulse is considered. However, the study of the probability of a bit error in the OFDM system is performed only for QPSK modulation.

In [15, 16], the application of the IOTA pulse for OFDM/Offset QAM modulation is considered. The advantage of this method is increased localization of the IOTA pulse on each subcarrier in the time and frequency domain since this pulse is obtained from a Gaussian pulse. But its drawback is the complexity of the Gaussian function orthogonalization algorithm.

Thus, the analysis of known methods for reducing the ICI level in OFDM technology revealed insufficient research into the method of increasing the interference resistance of the OFDM system under the conditions of inter-channel interference using multi-parameter signals with a selective spectrum.

3. The aim and objectives of the study

The purpose of this study is to devise a method for increasing the immunity of the system with orthogonal frequency division of channels based on multi-parameter pulses with a selective spectrum. This will make it possible to increase the immunity of the digital communication system under conditions of inter-channel interference.

To achieve the goal, the following tasks were set:

– to approximate the transition region of pulses with a selective spectrum using multiparameter functions;

– to evaluate the dependence of the ICI and SIR levels on the parameters of the synthesized pulses and determine the optimal values of the parameters;

– to evaluate the theoretical immunity of the OFDM system when using multi-parameter pulses with a selective spectrum;

– to build a software model of the OFDM system with a frequency shift and additive white Gaussian noise (AWGN) in the channel using the MATLAB environment to confirm the theoretical results of the current work.

4. The study materials and methods

The object of this research is the processes of OFDM signal transmission and processing under the conditions of a frequency-shifted channel and AWGN. The subject of the study is the use of pulses with a selective spectrum as forming pulses in the transmitter of the OFDM system to increase the immunity of the OFDM system under conditions of inter-channel interference.

The main hypothesis of the study assumed that the use of multi-parameter pulses with a selective spectrum after the unit of inverse fast Fourier transform in the OFDM system will make it possible to increase its immunity under the conditions of inter-channel interference.

The following limitations and assumptions were adopted during the research:

– the number of subcarriers N=64;

– modulation modes: BPSK, QPSK, and QAM-16;

– channel model: frequency shift and additive white Gaussian noise;

– only one of the techniques of piecewise linear approximation of the transition region of the pulse with a selective spectrum is considered;

– the effect of frequency-selective fading is not taken into account.

The method of multi-parameter piecewise linear and trigonometric approximation of the transition region was used for pulse synthesis. Determination of optimal parameters was carried out according to the criterion of the maximum value of the signal/interference ratio.

To determine the processes taking place in the transmitter and receiver of the OFDM system, the Fourier transform mathematical apparatus was used.

Comparison of theoretical results with experimental data was performed by computer simulation in the MATLAB environment. The model includes an OFDM transmitter, a receiver, and a frequency-shifted additive white Gaussian noise (AWGN) communication channel.

5. The results of investigating the construction of a method for increasing the immunity of the system with orthogonal frequency division of channels

5. 1. Application of pulses with a selective spectrum in a system with orthogonal frequency division of channels

Fig. 1 shows the scheme of application of forming pulses with a selective spectrum in the transmitter of the OFDM system.

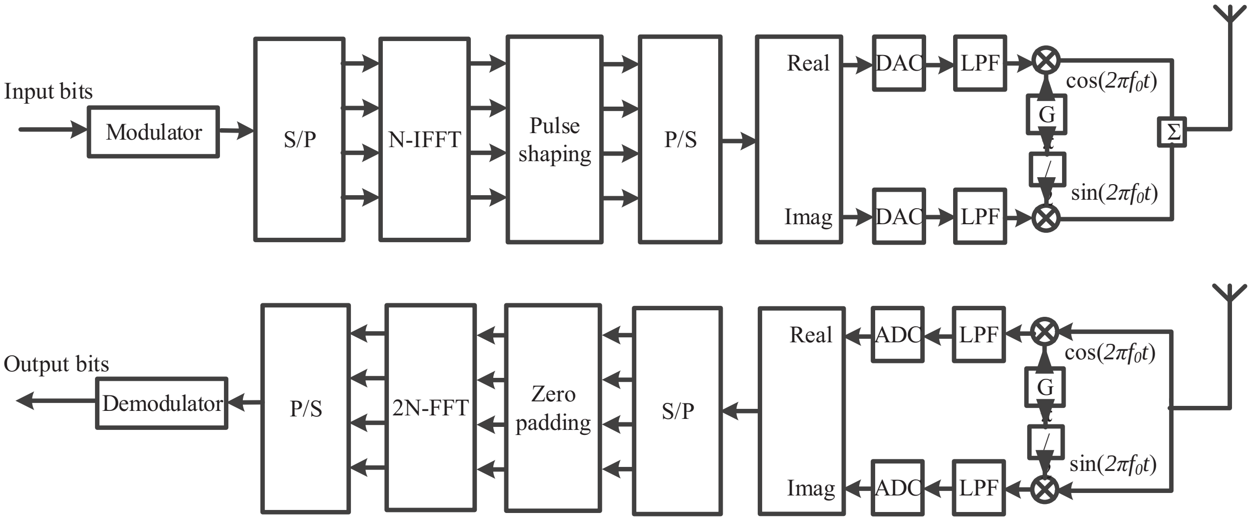


Fig. 1. Principal diagram of the system with orthogonal frequency division of channels using shaping pulses

Signals that can be used for OFDM technology as a forming pulse must satisfy the condition of the absence of inter-channel interference, which can be represented in the following form:

$$S(f)=\begin{cases}UT, & |f|=0;\\ 0, & |f|=1/T,2/T,\ldots,n/T,\end{cases} \tag{1}$$

where $S(f)$ is the spectral density of the signal; $1/T$ is the frequency interval between two subcarriers.

Signals with a selective spectrum have a central symmetry of the transition region of the time function. The basic signal satisfying condition (1) is a rectangular pulse:

$$s_1(t)=\begin{cases}U, & |t|\le\dfrac{T}{2};\\ 0, & |t|>\dfrac{T}{2},\end{cases} \tag{2}$$

$$S_1(f)=UT\frac{\sin(\pi Tf)}{\pi Tf}. \tag{3}$$

In [6], a trapezoidal pulse is considered (Fig. 2), which can be written as:

$$s_2(t)=\begin{cases}U, \ 0\le|t|<t_A;\\ \dfrac{U}{\alpha T}\left(0.5T-|t|+0.5\alpha T\right), t_A\le|t|<t_B;\\ 0, \ |t|\ge t_B,\end{cases} \tag{4}$$

where $t_A=(1-\alpha)t_C;\ \ t_B=(1+\alpha)t_C;\ \ t_C=T/2;\ \ 0\le\alpha\le1.$

Pulse (4) has only one parameter α, which determines the width of the transition region. Its spectral density can be written as:

$$S_2(f)=UT\,\mathrm{sinc}(\pi Tf)\,\mathrm{sinc}(\pi\alpha Tf), \tag{5}$$

where $\mathrm{sinc}(x)=\dfrac{\sin(x)}{x}.$

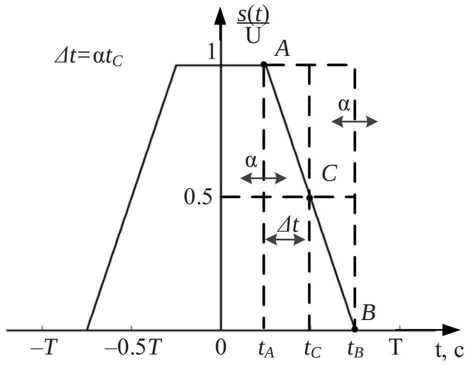


Fig. 2. Nyquist trapezoidal pulse

In literature, the impulse of the "Raised cosine" form (Fig. 3) is widely applied:

$$s_3(t)=\begin{cases}U, \ 0\le|t|<t_A;\\ \dfrac{U}{2}\left(1+\cos\left(\dfrac{\pi}{\alpha T}\left(|t|-(1-\alpha)\dfrac{T}{2}\right)\right)\right), t_A\le|t|<t_B;\\ 0, \ |t|\ge t_B,\end{cases} \tag{6}$$

$$S_3(f)=UT\,\mathrm{sinc}(\pi Tf)\frac{\cos(\pi\alpha Tf)}{1-4\alpha^2T^2f^2}. \tag{7}$$

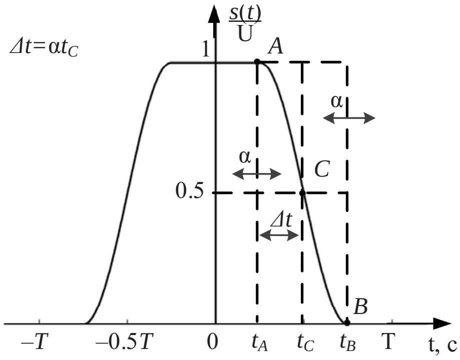


Fig. 3. "Raised cosine" impulse form

The above pulses (4) and (6) have only one parameter, the change of which does not make it possible to effectively synthesize new signals with the necessary properties. In [17], using multiparameter piecewise linear approximation, new classes of signals satisfying the condition of absence of inter-symbol interference were synthesized. These classes of signals after simple dual Fourier transformations [18] can be used in the OFDM system. Therefore, the method of two-parameter piecewise linear approximation of the transition region was applied, as a result of which a new type of pulse was synthesized (Fig. 4):

$$s_4(t)=\begin{cases}U, & 0\le|t|<t_A;\\ (1-\beta)U, & t_A\le|t|<t_C;\\ \beta U, & t_C\le|t|<t_B;\\ 0, & |t|\ge t_B.\end{cases} \qquad (8)$$

Its spectral density is defined as:

$$S_4(f)=UT\operatorname{sinc}(\pi Tf)\left[1-2\beta\left(1-\cos(\alpha\pi Tf)\right)\right]. \qquad (9)$$

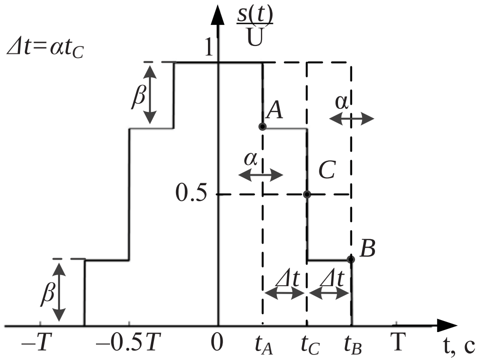


Fig. 4. Two-parameter pulse with piecewise linear approximation

Approximation of the transition region of the pulse by the sum of trigonometric functions made it possible to synthesize another type of two-parameter signal with a selective spectrum (Fig. 5):

$$s_5(t)=\begin{cases}U, & 0\le|t|<t_A;\\ A, & t_A\le|t|<t_B;\\ 0, & |t|\ge t_B,\end{cases} \qquad (10)$$

where:

$$A=0.5U+0.5U\begin{pmatrix}\beta\cos\left[\dfrac{\pi}{2}\cdot\dfrac{t-t_A}{t_C-t_A}\right]+\\ +(1-\beta)\cos\left[\dfrac{3\pi}{2}\cdot\dfrac{t-t_A}{t_C-t_A}\right]\end{pmatrix}.$$

Its spectral density is equal to:

$$S_5(f)=UT\operatorname{sinc}(\pi Tf)\times$$

$$\times\begin{pmatrix}\cos(\alpha\pi Tf)+\dfrac{\beta(2\alpha Tf)^2\cos(\alpha\pi Tf)}{1-(2\alpha Tf)^2}+\\ +\dfrac{(1-\beta)(2\alpha Tf)^2\cos(\alpha\pi Tf)}{3^2-(2\alpha Tf)^2}\end{pmatrix}. \qquad (11)$$

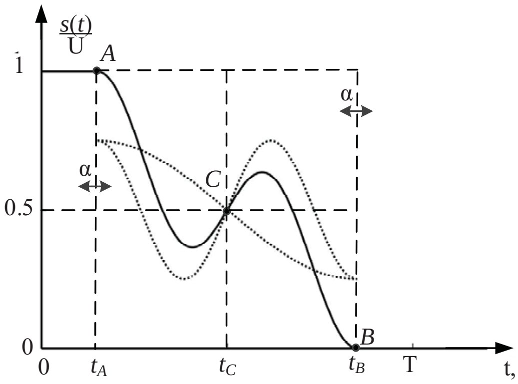


Fig. 5. Two-parameter Nyquist pulse with trigonometric approximation at β=0,5

At β=1, the pulse in Fig. 5 is converted into a pulse of the form "Raised cosine".

5. 2. ICI and SIR indicators

When the frequency is shifted in the OFDM system, inter-channel interference occurs, the average level of which can be estimated using the following expression:

$$P_{ICI}=\sum_{\substack{k\neq N/2\\ k=0}}^{N-1}\left|G\left(\frac{k-N/2}{T}+\Delta f\right)\right|^2, \qquad (12)$$

where $G(f)$ is the normalized relative to UT spectral density of the forming pulse; k is the index of the adjacent subcarrier; N is the total number of subcarriers; $1/T$ – frequency interval between subcarriers; Δf is the frequency shift.

In addition to the occurrence of inter-channel interference, the level of the useful signal also changes. Therefore, the signal-to-interference ratio (SIR) is also used to estimate inter-channel interference:

$$SIR=\frac{|G(\Delta f)|^2}{P_{ICI}}. \qquad (13)$$

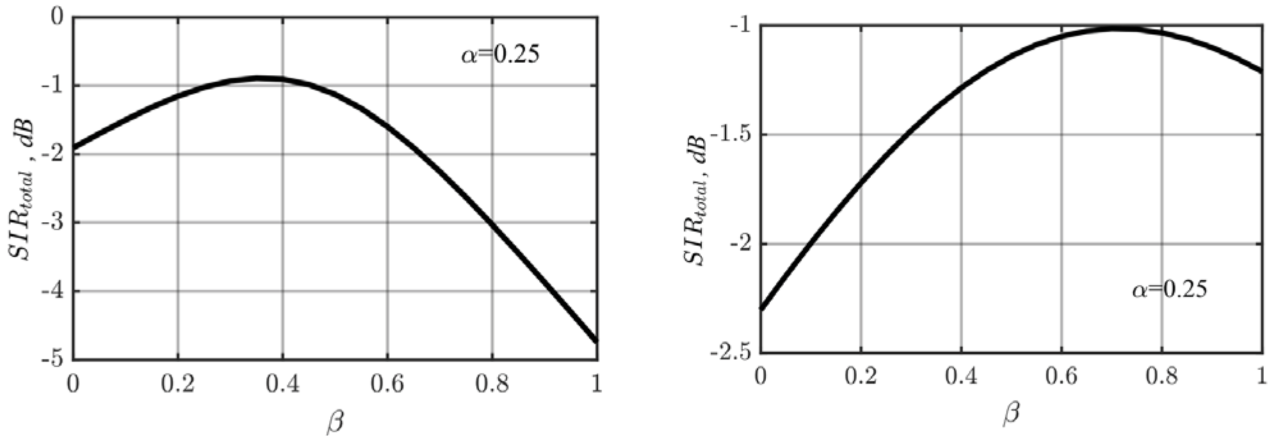
The best spectrum-selective pulse should have the highest signal-to-noise ratio regardless of frequency shift. Therefore, the function optimization criterion according to the parameter β can be represented in the following form:

$$SIR_{total}(\alpha,\beta)=\int_0^1 SIR(\Delta fT\,|\,\alpha,\beta)\,\mathrm{d}(\Delta fT), \qquad (14)$$

$$\beta_{\text{опт}}(\alpha)=\arg\max_{\beta}\left\{SIR_{total}(\alpha,\beta)\right\}.$$

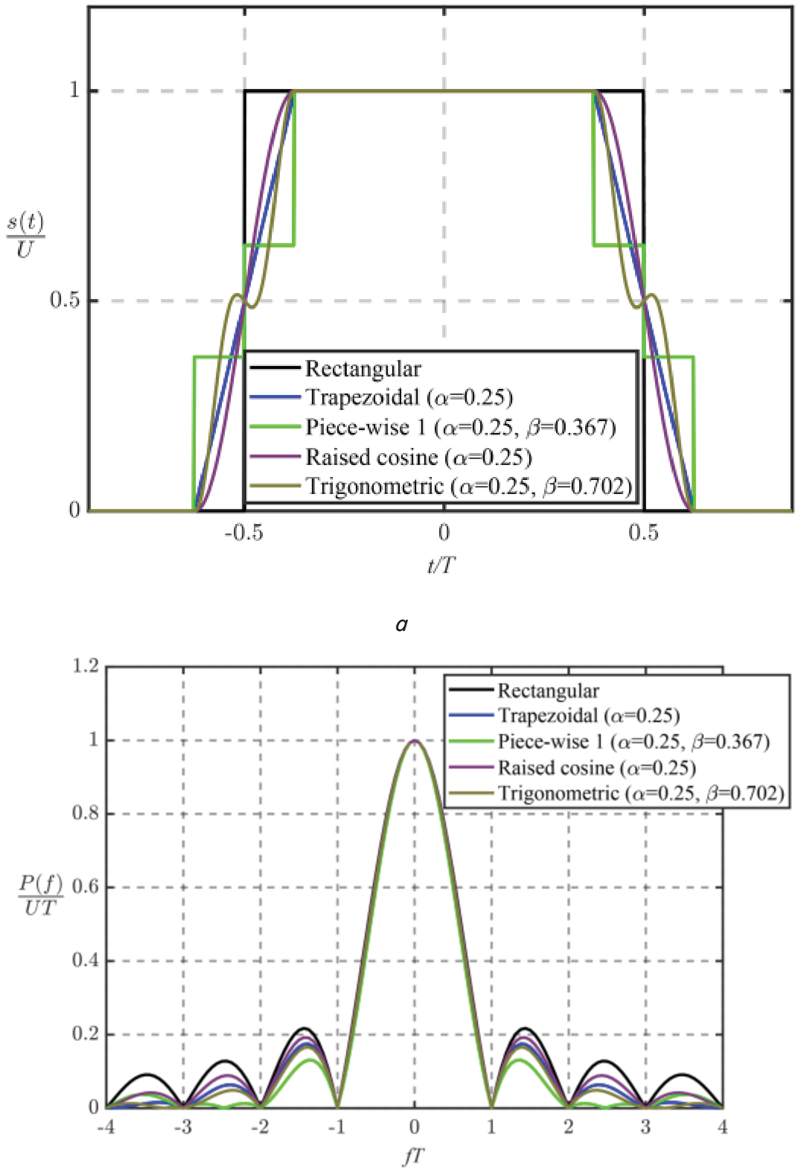
Expressions (12) to (14) were used to plot the dependence of the total SIR on the β parameter at α=0.25 for impulses (8) and (10) (Fig. 6). Thus, for pulse (8), the optimal value β_{opt}=0.362 (Fig. 6, *a*); for pulse (10), the optimal value β_{opt}=0.702 (Fig. 6, *b*). Fig. 7 shows pulses with a selective spectrum (2) to (11) in the time (Fig. 7, *a*) and frequency (Fig. 7, *b*) domains investigated in this work.

As can be seen from Fig. 7, *b*, the pulse with piecewise linear approximation is characterized by the lowest level of the main petal of the spectral density and the lowest level of the first two side petals.



a *b*

Fig. 6. Total SIR of a two-parameter pulse: *a* – with piecewise linear approximation; *b* – with trigonometric approximation



b

Fig. 7. Pulses with a selective spectrum: *a* – in the time domain; *b* – in the frequency domain

5. 3. Theoretical bit error probability

Expressions of bit error probability for BPSK, QPSK, and QAM-16 modulations are given in [3]. So, for BPSK modulation, the BER can be written as:

$$P_b=\frac{1}{N}\sum_{m=0}^{N-1}P_b(m), \tag{15}$$

$$P_b(m)=\frac{1}{2}-$$

$$-\int_0^{+\infty}\left(\frac{\sin\left(\sqrt{E_b}\omega c_0^I\right)}{\pi\omega}e^{-\frac{1}{2}\omega^2\sigma^2}\prod_{\substack{k\neq m\\k=0}}^{N-1}\cos\left(\sqrt{E_b}\omega c_{k-m}^I\right)\right)\mathrm{d}\omega,$$

where N is the number of subcarriers; $P_b(m)$ is the probability of a bit error of the m-th subcarrier; E_b is the energy of the bit; c_0^I is the real part of the coefficient of the usable signal at the output of the decision device; c_{k-m}^I is the real part of the inter-channel interference coefficient of the k-th subcarrier at the output of the decision device; σ^2 is the noise variance.

For the case when pulses with a selective spectrum are used as forming pulses in the transmitter of the OFDM system, the coefficient c_{k-m} is defined as [3]:

$$c_{k-m}=P\left(\frac{k-m}{T}+\Delta f\right)e^{j\pi(k-m+\Delta fT)(1+\alpha)},$$

where $1/T$ is the frequency interval between adjacent subcarriers; Δf – frequency shift; α is a parameter that determines the width of the transition region of the forming pulse.

For QPSK, the bit error probability is defined as:

$$P_b=\frac{1}{N}\sum_{m=0}^{N-1}P_b(m), \tag{16}$$

$$P_b(m)=\frac{1}{2}-\int_0^{+\infty}\sin\left(\omega\sqrt{E_b}c_0^I\right)\cos\left(\sqrt{E_b}\omega c_0^Q\right)\gamma(\omega)\mathrm{d}\omega,$$

$$\gamma(\omega)=\frac{e^{-\frac{1}{2}\omega^2\sigma^2}}{\pi\omega}\prod_{\substack{k\neq m\\k=0}}^{N-1}\cos\left(\sqrt{E_b}\omega c_{k-m}^I\right)\cos\left(\sqrt{E_b}\omega c_{k-m}^Q\right),$$

where N is the number of subcarriers; $P_b(m)$ is the probability of a bit error of the m-th subcarrier; $P_b(m)$ is the energy of the bit; c_0^I is the real part of the coefficient of the usable signal at the output of the decision device; c_0^Q is the imaginary part of the coefficient of the usable signal at the output of the decision device; c_{k-m}^I is the real part of the inter-channel interference coefficient of the k-th subcarrier at the output of the decision device; c_{k-m}^Q is the imaginary part of the inter-channel interference coefficient of the k-th subcarrier at the output of the decision device; σ^2 is the noise variance.

For QAM-16, the bit error probability is defined as:

$$P_b=\frac{1}{2N}\sum_{m=0}^{N-1}\left[P_{i1}(m)+P_{i2}(m)\right], \tag{17}$$

$$P_{i1}(m)=\frac{1}{2}-$$

$$-\int_0^{\infty}\begin{aligned}&\cos\left(2\omega dc_0^Q\right)\cos\left(\omega dc_0^Q\right)\times\\&\times\sin\left(2\omega dc_0^I\right)\cos\left(\omega dc_0^I\right)\beta(\omega)\mathrm{d}\omega,\end{aligned}$$

$$P_{i2}(m)=\frac{1}{2}-$$

$$-\int_0^{\infty}\begin{aligned}&2\sin(2\omega d)\sin\left(2\omega dc_0^I\right)\sin\left(\omega dc_0^I\right)\times\\&\times\cos\left(2\omega dc_0^Q\right)\cos\left(\omega dc_0^Q\right)\beta(\omega)\mathrm{d}\omega,\end{aligned}$$

$$\beta(\omega)=\frac{e^{-\frac{1}{2}\omega^2\sigma^2}}{\pi\omega}\prod_{\substack{k\neq m\\k=0}}^{N-1}\begin{aligned}&\cos\left(2\omega dc_{k-m}^I\right)\cos\left(\omega dc_{k-m}^I\right)\times\\&\times\cos\left(2\omega dc_{k-m}^Q\right)\cos\left(\omega dc_{k-m}^Q\right),\end{aligned}$$

$$d=\sqrt{\frac{2E_b}{5}}.$$

With the help of (15) to (17), plots of the theoretical probability of a bit error under the conditions of frequency shift and Gaussian noise were constructed.

5. 4. Experimental bit error probability

In the MATLAB environment, a model was built, the scheme of which is shown in Fig. 8.

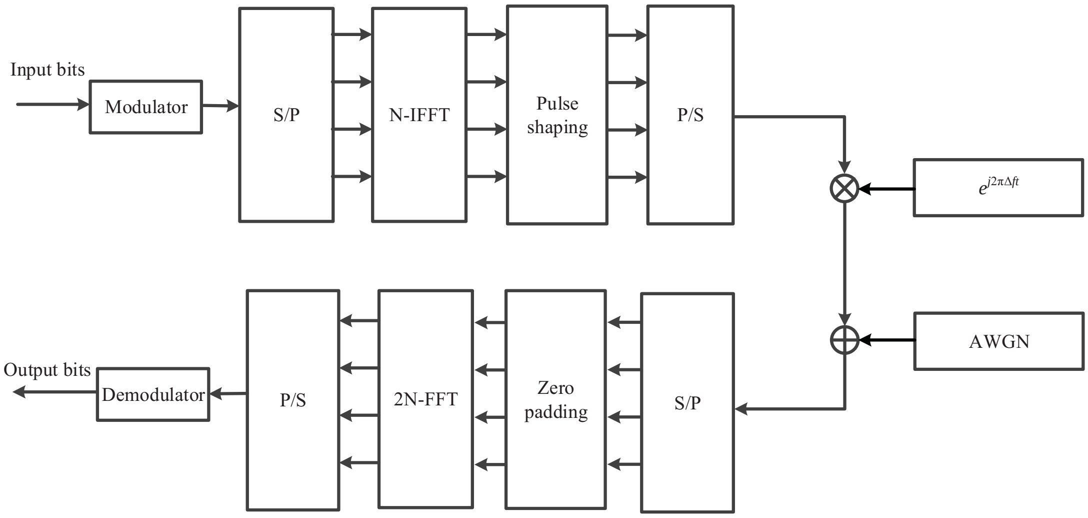


Fig. 8. Experimental model of the system with orthogonal frequency division of channels with frequency shift and additive white Gaussian noise in the communication channel

The parameters of the OFDM system model are summarized in Table 1. Using the above model, the dependence of the OFDM system's interference immunity on the frequency shift and the signal/noise ratio (E_b/N_0) for the investigated pulses was evaluated. Theoretical and simulation results are shown in Fig. 9–11.

As can be seen from Fig. 9–11, the pulse with piecewise linear approximation is characterized by the lowest level of bit error probability of the OFDM system.

Table 1

Parameters of software model of the OFDM system

Number of subcarriers, N	64
Amount of data, bits	1048576
Modulation mode	BPSK, QPSK, QAM-16
Channel model	AWGN+frequency shift
Normalized frequency shift, ΔfT	for BPSK: 0,2
	for QPSK: 0,1
	for QAM-16: 0.03
Relative width of the transition region of the generating pulse, α	0.25

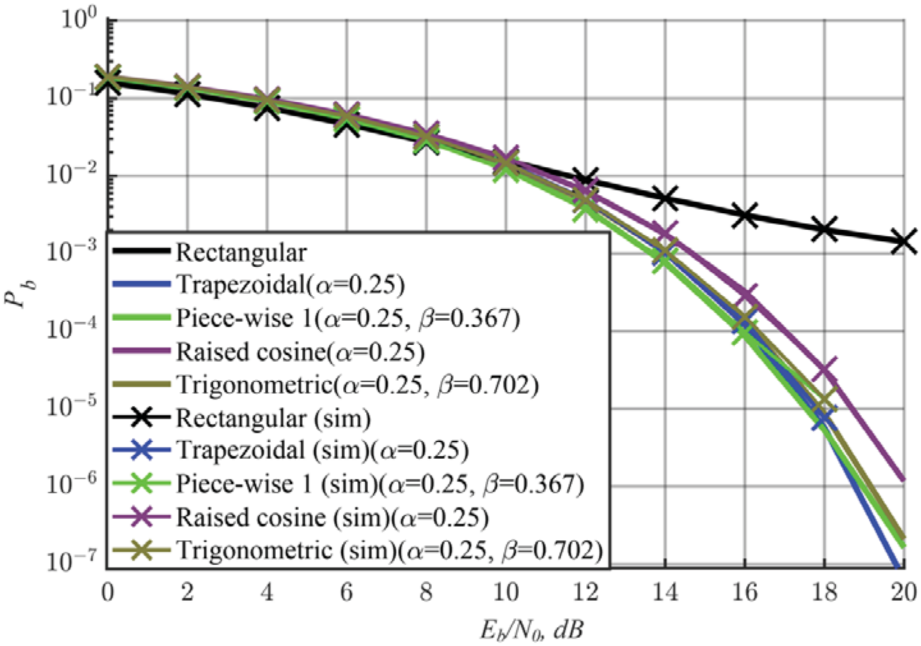


Fig. 9. Bit error probability for modulation OFDM BPSK

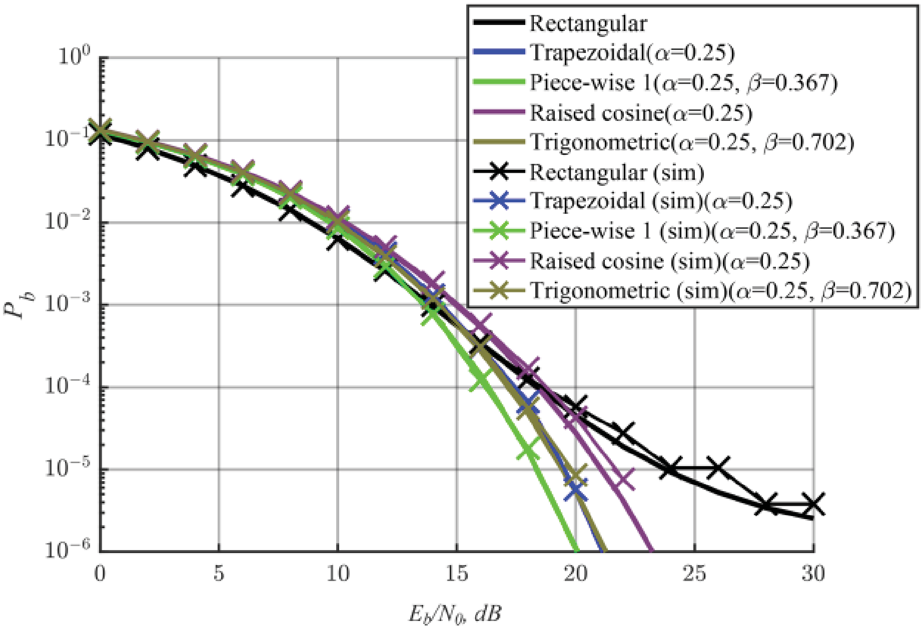


Fig. 10. Bit error probability for modulation OFDM QPSK

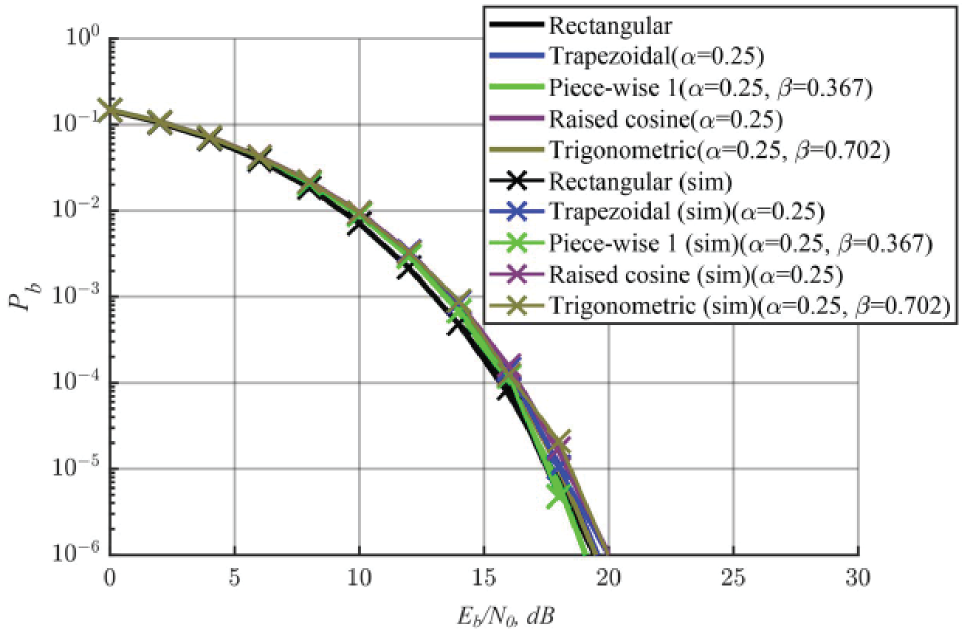


Fig. 11. Bit error probability for modulation OFDM QAM-16

6. Discussion of results of research into the construction of a method for increasing the immunity of the system with orthogonal frequency division of channels

In contrast to known methods, the one for increasing the interference resistance of the OFDM system based on forming pulses with a selective spectrum involves the use of pulses with a selective spectrum after the inverse fast Fourier transform unit in the transmitter.

In the work, theoretical and experimental studies on the interference resistance of the OFDM system using five pulses with a selective spectrum were carried out. It was established (Fig. 9–11) that the application of a pulse with piecewise linear approximation provides the lowest level of bit error probability for three types of digital modulation BPSK, QPSK, and QAM-16.

The results on improving the interference resistance of the OFDM system using forming pulses with a selective spectrum indicate that the pulse with piecewise linear approximation, proposed in [11, 17], has the lowest probability of a bit error in comparison with such pulses as a trapezoidal pulse [6] and the "Raised cosine" impulse [3]. So, with a signal-to-noise ratio of 15 dB, BPSK modulation and a normalized frequency shift of 0.2, the probability of a bit error for a given pulse is $3\cdot10^{-4}$; for QPSK modulation and a normalized frequency shift of 0.1, 10^{-6}; for QAM-16 modulation and a normalized frequency shift of 0.03, $2\cdot10^{-4}$.

For the practical use of the results, the following limitations and assumptions are adopted:

– the relative width of the transition region of the forming pulse with a selective spectrum should be α=0.25;

– the value of the second pulse parameter with piecewise linear approximation should be β_{opt}=0.362;

– the communication channel must be without frequency-selective fading.

The improved method for increasing the immunity of the system with orthogonal frequency division of channels on the basis of forming pulses with a selective spectrum can be implemented in software and hardware systems of OFDM signal processing.

Disadvantages of the improved method for increasing the immunity of the system with orthogonal frequency division of channels on the basis of forming pulses with a selective spectrum is the processing of a double number of readings of the input signal in the unit of fast Fourier transform in the receivers of the OFDM system.

Further research should be focused on finding other ways of approximating the transition region of pulses with a selective spectrum and optimizing their parameters.

7. Conclusions

1. Two new types of pulses with a selective spectrum have been synthesized based on the piecewise linear and trigonometric approximation of the transition region.

2. The optimal parameters of two-parameter pulses with piecewise linear and trigonometric approximation were determined. So, at α=0.25, the optimal parameter for the first pulse is β_{opt}=0.362, and for the second – β_{opt}=0.702.

3. A theoretical study of the bit error probability of the OFDM system under the conditions of frequency shift and additive white Gaussian noise for five types of pulses with a selective spectrum and three types of BPSK, QPSK, QAM-16 modulation was carried out. It was established that the lowest BER level characterizes a two-parameter pulse with a piecewise linear approximation, regardless of the chosen modulation mode.

4. A software model of the OFDM system with a frequency shift and AWGN was built in the MATLAB environment to confirm the theoretical results of the current study. Analysis of simulation data also revealed that the two-parameter pulse with piecewise linear approximation is characterized by the lowest level of bit error probability.

Conflicts of interest

The author declares that he has no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

References

1. Singh, P., Sahu, O. P. (2015). An Overview of ICI Self Cancellation Techniques in OFDM Systems. 2015 IEEE International Conference on Computational Intelligence & Communication Technology. doi: https://doi.org/10.1109/cict.2015.113
2. Kumar, N., Kaur, G., Sohi, B. S. (2015). Comparative Analysis of Various Inter-Carrier Interference Cancellation Methods. International Journal of Wireless and Microwave Technologies, 5 (3), 18–32. doi: https://doi.org/10.5815/ijwmt.2015.03.02
3. Tan, P., Beaulieu, N. C. (2009). Analysis of the effects of Nyquist pulse-shaping on the performance of OFDM systems with carrier frequency offset. European Transactions on Telecommunications, 20 (1), 9–22. doi: https://doi.org/10.1002/ett.1316
4. Muschallik, C. (1996). Improving an OFDM reception using an adaptive Nyquist windowing. IEEE Transactions on Consumer Electronics, 42 (3), 259–269. doi: https://doi.org/10.1109/30.536046
5. ETSI TS 136 211 V17.1.0 LTE. Evolved Universal Terrestrial Radio Access (E-UTRA). Physical channels and modulation. URL: https://www.etsi.org/deliver/etsi_ts/136200_136299/136211/17.01.00_60/ts_136211v170100p.pdf
6. Muller-Weinfurtner, S. H., Huber, J. B. (2000). Optimum Nyquist windowing for improved OFDM receivers. Globecom ’00 - IEEE. Global Telecommunications Conference. Conference Record (Cat. No.00CH37137). doi: https://doi.org/10.1109/glocom.2000.891232
7. Song, R., Guo, X., Leung, S. H. (2011). Optimum Second Order Polynomial Nyquist Windows for Reduction of ICI in OFDM Systems. Wireless Personal Communications, 65 (2), 455–467. doi: https://doi.org/10.1007/s11277-011-0267-x
8. Kamal, S., Azurdia-Meza, C. A., Lee, K. (2016). Suppressing the effect of ICI power using dual sinc pulses in OFDM-based systems. AEU - International Journal of Electronics and Communications, 70 (7), 953–960. doi: https://doi.org/10.1016/j.aeue.2016.04.013
9. Kamal, S., Azurdia-Meza, C. A., Lee, K. (2017). Improved Nyquist-I Pulses to Enhance the Performance of OFDM-Based Systems. Wireless Personal Communications, 95 (4), 4095–4111. doi: https://doi.org/10.1007/s11277-017-4044-3
10. Balan, A. L., Alexandru, N. D. (2012). Two improved nyquist filters with piece-wise rectangular-polynomial frequency characteristics. AEU - International Journal of Electronics and Communications, 66 (11), 880–883. doi: https://doi.org/10.1016/j.aeue.2012.03.006
11. Alexandru, N. D., Balan, A. L., Diaconu, F., Dimian, M. (2013). Development of Improved Nyquist Filters with piecewise linear frequency characteristics. 2013 36th International Conference on Telecommunications and Signal Processing (TSP). doi: https://doi.org/10.1109/tsp.2013.6614023
12. Alexandru, N. D., Balan, A. L. (2014). Investigation of the mechanism of improvement in improved Nyquist filters. IET Signal Processing, 8 (1), 95–105. doi: https://doi.org/10.1049/iet-spr.2013.0050
13. Sharique, M., Chaturvedi, A. K. (2015). Transmitter Pulse Shaping to Reduce OOB Power and ICI in OFDM Systems. Wireless Personal Communications, 83 (2), 1567–1578. doi: https://doi.org/10.1007/s11277-015-2464-5
14. Xiao, J., Yu, J., Cao, Z., Li, F., Chen, L. (2013). Flipped-exponential Nyquist pulse technique to optimize the PAPR in optical direct detection OFDM system. Optics Communications, 286, 176–181. doi: https://doi.org/10.1016/j.optcom.2012.08.053
15. Jayaprakash, A., Reddy, G. R. (2015). Discrete Ambiguity Function Based Analysis of Filter Bank Multicarrier Systems. IETE Technical Review, 32 (5), 330–346. doi: https://doi.org/10.1080/02564602.2015.1015941
16. Kongara, K. P., Smith, P. J., Mann, S. (2008). A comparison of CP-OFDM with IOTA-OFDM under typical system imperfections. IET Seminar Digests. doi: https://doi.org/10.1049/ic.2008.0694
17. Сукачев, Э. А. (2016). Введение в теорию сигналов Найквиста. Одесса: Освіта України, 108.
18. Proakis, J. G., Salehi, M. (2008). Digital Communications. McGraw-Hill. URL: https://edisciplinas.usp.br/pluginfile.php/5636847/mod_resource/content/1/digital%20commun%205th%20-%20proakis%2C%20salehi.pdf