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RESEARCH ARTICLE

Optimal reception of multiple phase shift keying and quadrature amplitude modulation signals with non-coherent processing of harmonic interference

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Abstract

Objectives. Analysis of the reception noise immunity of multiple phase shift keying (M-PSK) and quadrature amplitude modulation (M-QAM) signals has demonstrated a significant reduction in the quality of reception of discrete information due to the presence of various types of non-fluctuating interference in a radio communication channel including targeted harmonic interference. Therefore, the development of algorithms for compensating the influence of such forms of interference is an urgent task. While various methods for combatting this kind of interference, these vary in terms of their effectiveness. The aim of the present work is to synthesize and analyze the optimal algorithm for the reception of M-PSK and M-QAM signals with incoherent processing of harmonic interference.

Methods. Various statistical radio engineering and computer simulation methods were used in accordance with optimal signal reception theory.

Results. Synthesis and analysis of the optimal algorithm for receiving M-PSK and M-QAM signals with incoherent processing of harmonic interference were carried out. In addition to calculating the correlation integrals in the receiver, it is necessary to form weight coefficients, whose value depends on the correlation of the interference oscillation (extracted from the received mixture) with a sample of the interference stored in the receiver. The dependences of the bit error probability on the signal-to-noise ratio, interference detuning, and inaccuracy in setting the frequency and level of the interference sample in the receiver were obtained. It is shown that the higher the gain in the noise immunity of reception, the greater the intensity of the harmonic interference.

Conclusions. The synthesized receiver circuit effectively compensates for harmonic interference. However, the efficiency of its operation depends on the detuning of the harmonic interference relative to the center frequency of the spectrum of the useful signal. The scheme for incoherent processing of harmonic interference remains operational even with small (within ±10%) inaccuracies in setting the frequency and the level of the interference copy in the receiver.

Keywords: multiple phase shift keying, quadrature amplitude modulation, harmonic interference, optimal reception, noise immunity

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НАУЧНАЯ СТАТЬЯ

Оптимальный прием многопозиционных сигналов М-ФМ и М-КАМ с некогерентной обработкой гармонической помехи

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Резюме

Цели. Проведенный в работах многих исследователей анализ помехоустойчивости приема многопозиционных сигналов с фазовой (М-ФМ) и квадратурной амплитудной модуляцией (М-КАМ) показал, что качество приема дискретной информации существенно снижается при наличии кроме шумовой помехи еще и нефлуктуационных помех разных видов в канале радиосвязи. Одной из наиболее опасных является прицельная гармоническая помеха, поэтому разработка алгоритмов компенсации влияния такой помехи является актуальной задачей. Существуют различные методы борьбы с такого рода мешающими воздействиями, обладающие большей или меньшей эффективностью. Целью настоящей работы является синтез и анализ оптимального алгоритма приема многопозиционных сигналов М-ФМ и М-КАМ с некогерентной обработкой гармонической помехи.

Методы. Использованы методы статистической радиотехники, теории оптимального приема сигналов и компьютерное моделирование.

Результаты. Выполнен синтез и анализ оптимального алгоритма приема многопозиционных сигналов М-ФМ и М-КАМ с некогерентной обработкой гармонической помехи. Показано, что кроме вычисления корреляционных интегралов в приемнике необходимо формировать весовые коэффициенты, величина которых зависит от степени корреляции помехового колебания, выделенного из принимаемой смеси, с копией помехи, хранящейся в приемнике. Получены зависимости вероятности битовой ошибки от отношения сигнал/шум, расстройки помехи и неточности установки частоты и уровня копии помехи в приемнике. Показано, что выигрыш в помехоустойчивости приема тем выше, чем больше интенсивность гармонической помехи.

Выводы. Синтезированная схема приемника позволяет достаточно эффективно бороться с гармонической помехой. Эффективность ее работы зависит от расстройки гармонической помехи относительно центральной частоты спектра полезного сигнала. Схема некогерентной обработки гармонической помехи сохраняет работоспособность и при небольших (в пределах ±10%) неточностях установки частоты и уровня копии помехи в приемнике.

Ключевые слова: многопозиционная фазовая модуляция, квадратурная амплитудная модуляция, гармоническая помеха, оптимальный прием, помехоустойчивость

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INTRODUCTION

Analysis of the noise immunity of receiving multiple phase shift keying (M-PSK) and quadrature amplitude modulation (M-QAM) signals demonstrates a significant deterioration in the quality of receiving discrete information (up to complete destruction of communication) due to the presence in addition to noise of various kinds non-fluctuating interference in the communication channel [1–10]. This is especially true in cases where such interference is signal-like, for example, harmonic [5–7].

There are various methods of dealing with this kind of interference, which are more or less effective, for example, those developed in [1, 11–14]. Their technical implementation can be very complex, as in the case of the synthesis of optimal algorithms [1], or simpler, as in [12, 14], but less efficient. The purpose of this work is to synthesize and analyze the optimal algorithm for receiving M-PSK and M-QAM signals with incoherent processing of harmonic interference.

1. ALGORITHM FOR RECEIVING OF M-PSK AND M-QAM SIGNALS WITH INCOHERENT PROCESSING OF HARMONIC INTERFERENCE

Consider the optimal reception of M-PSK and M-QAM signals against the background of white Gaussian noise $n(t)$ with one-sided power spectral density N_0 and harmonic interference

$$s_{\text{int}}(t, \varphi_{\text{int}}) = \mu A_0 \cos(\omega_{\text{int}} t + \varphi_{\text{int}}), \tag{1}$$

with relative intensity μ, frequency $\omega_{\text{int}} = 2\pi f_{\text{int}}$, close to the useful signal frequency, and random initial phase φ_{int}. At the same time, we assume that the initial phase of the useful signal is known, and the distribution of the random variable φ_{int} is uniform in the range $(-\pi, \pi]$. In this case, we can speak of incoherent noise processing.

The signal entering the input of the receiver,

$$x(t) = s_i(t) + s_{\text{int}}(t, \varphi_{\text{int}}) + n(t),$$

is a mixture of interference, noise, and M-PSK signal

$$s_i(t) = A_0 \cos(\omega_0 t + \varphi_i),$$
$$\varphi_i = \frac{i2\pi}{M},\ t \in (0, T_s],\ i = 0, 1, \ldots, M-1, \tag{2}$$

or M-QAM signal

$$s_i(t) = A_{\text{av}}(I_i \cos \omega_0 t - Q_i \sin \omega_0 t),$$
$$t \in (0, T_s],\ i = 0, 1, \ldots, M-1, \tag{2'}$$

where $A_0 = A_{\text{av}} = \sqrt{2E_s / T_s}$ is the signal amplitude; $E_s = kE_b$ is the energy of the channel symbol; E_b is the energy per one bit of information; $k = \log_2 M$; I_i and Q_i are the coefficients that determine the amplitudes of the quadrature signal components; ω_0 is the carrier frequency. In the case of M-QAM signal, the energies and amplitude should be averaged over the ensemble of signals.

For the sake of simplicity, let us denote the sum of the signal and interference as

$$s_{\text{sig,int}}(t, C_i, \varphi_{\text{int}}) = s_i(t) + s_{\text{int}}(t, \varphi_{\text{int}}). \tag{3}$$

Let us specify the a posteriori probability of this process, and, consequently, the joint a posteriori probability of the channel symbol C_i and phase φ_{int} as follows [15, 16]:

$$p_{\text{ps}}[s_{\text{sig,int}}(t, C_i, \varphi_{\text{int}})] = p_{\text{ps}}(C_i, \varphi_{\text{int}}) = K p_{\text{pr}}(C_i) p_{\text{pr}}(\varphi_{\text{int}}) \times$$
$$\times \exp\Big[-\frac{1}{N_0}\int_0^{T_s} s_{\text{sig,int}}^2(t, C_i, \varphi_{\text{int}})dt + \frac{2}{N_0}\int_0^{T_s} x(t) s_{\text{sig,int}}(t, C_i, \varphi_{\text{int}})dt\Big].$$

Here, the symbol K denotes the normalization coefficient, which takes into account all components that do not contain information about the useful signal and non-fluctuating noise, while $p_{\mathrm{pr}}(C_i)$ is the a priori probability of the channel symbol C_i, and $p_{\mathrm{pr}}(\varphi_{\mathrm{int}}) = 1/2\pi$.

$$\begin{aligned}
&\int_0^{T_\mathrm{s}} s_{\mathrm{sig,int}}{}^2(t, C_i, \varphi_{\mathrm{int}})dt = \\
&= \int_0^{T_\mathrm{s}} s_i{}^2(t, C_i)dt + \int_0^{T_\mathrm{s}} s_{\mathrm{int}}{}^2(t, \varphi_{\mathrm{int}})dt + \\
&+2\int_0^{T_\mathrm{s}} s_i(t, C_i)s_{\mathrm{int}}(t, \varphi_{\mathrm{int}})dt = \\
&= E_\mathrm{s} + E_{\mathrm{int}} + 2R_i(\varphi_{\mathrm{int}}),
\end{aligned}$$

where E_{int} is the energy of interference packets of duration T_s; $R_i(\varphi_{\mathrm{int}})$ is the correlation coefficient between the signal and interference.

Hence,

$$\begin{aligned}
&p_{\mathrm{ps}}(C_i, \varphi_{\mathrm{int}}) = Kp_{\mathrm{pr}}(C_i)\frac{1}{2\pi} \times \\
&\times \exp[-\frac{1}{N_0}(E_s + E_{\mathrm{int}} + 2R_i(\varphi_{\mathrm{int}}))] \times \\
&\times \exp[\frac{2}{N_0}\int_0^{T_\mathrm{s}} x(t)s_{\mathrm{sig,int}}(t, C_i, \varphi_{\mathrm{int}})dt] = \\
&= K_1\frac{1}{2\pi}\exp[-\frac{2}{N_0}R_i(\varphi_{\mathrm{int}})] \times \\
&\times \exp[\frac{2}{N_0}\int_0^{T_\mathrm{s}} x(t)s_{\mathrm{sig,int}}(t, C_i, \varphi_{\mathrm{int}})dt].
\end{aligned}$$

The coefficient K_1 includes terms that do not depend on the value of the symbol C_i or the phase φ_{int}.

To obtain the a posteriori probability of a discrete symbol C_i, it is necessary to average the value $p_{\mathrm{ps}}(C_i, \varphi_{\mathrm{int}})$ over all possible values of the phase φ_{int}. Then we obtain:

$$\begin{aligned}
&p_{\mathrm{ps}}(C_i) = K_1\frac{1}{2\pi} \times \\
&\times \int_{-\pi}^{\pi}(\exp[-\frac{2}{N_0}R_i(\varphi_{\mathrm{int}})]\exp[\frac{2}{N_0}\int_0^{T_\mathrm{s}} x(t)s_{\mathrm{sig,int}}(t, C_i, \varphi_{\mathrm{int}})dt])d\varphi_{\mathrm{int}}.
\end{aligned}$$

Let us introduce the notation for the integrals that describe the degree of correlation between the received process $x(t)$ and signal copies for different values of the channel symbols C_i:

$$\begin{aligned}
&J_0 = \frac{2}{N_0}\int_0^{T_\mathrm{s}} x(t)s_i(t, C_i = 0)dt, \\
&\ldots \qquad (4) \\
&J_{M-1} = \frac{2}{N_0}\int_0^{T_\mathrm{s}} x(t)s_i(t, C_i = M-1)dt.
\end{aligned}$$

Assuming that there is a copy of the interference $s_{\mathrm{int}}(t, \varphi_{\mathrm{int}})$ in the receiver, then the following integrals, in fact, determine the degree of correlation between it and the received interference sample, formed by subtracting the signal copies from the received process $x(t)$:

$$\begin{aligned}
&a_0 = \frac{2}{N_0}\int_0^{T_\mathrm{s}} [x(t) - s_i(t, C_i = 0)]s_{\mathrm{int}}(t, \varphi_{\mathrm{int}})dt, \\
&\ldots \qquad (5) \\
&a_{M-1} = \frac{2}{N_0}\int_0^{T_\mathrm{s}} [x(t) - s_i(t, C_i = M-1)]s_{\mathrm{int}}(t, \varphi_{\mathrm{int}}).
\end{aligned}$$

Then, taking into account (1), (3)–(5), a decision-making algorithm for the value of the channel symbol C_i can be written using the modified Bessel functions $I_0(\cdot)$ as follows:

$$\begin{aligned}
&C_i \Rightarrow \max\left\{p_{\mathrm{ps}}(C_i)\right\} = \\
&= \max\left\{\exp(J_i)\frac{1}{2\pi}\int_{-\pi}^{\pi}\exp(a_i)d\varphi_{\mathrm{int}}\right\} = \\
&= \max\left\{\exp(J_i)I_0(U_i)\right\}, \\
&p_{\mathrm{ps}}(C_i = 0) > \left\{p_{\mathrm{ps}}(C_j \neq 0)\Big|_{j \neq i}\right\},\ i, j = 0, \ldots, M-1. \qquad (6)
\end{aligned}$$

The last expression can be written differently:

$$\exp(J_i)I_0(U_i) > \{\exp(J_j)I_0(U_j)|_{j \neq i}\} \qquad (7)$$

or

$$J_i + \ln(I_0(U_i)) > \{J_j + \ln(I_0(U_j))|_{j \neq i}\},\ i, j = 0, \ldots, M-1.$$

In the case of M-QAM, when comparing the values to find the maximum $\max\{\cdot\}$, the decision thresholds must not be considered as zero, but as equal to the half-difference of the energies of the corresponding signal packets.

The arguments of the Bessel functions are formed using the quadrature components of the quantities described by expression (5), for example:

$$U_i = \sqrt{X_i^2 + Y_i^2},$$

$$\begin{aligned} X_i &= \frac{2\mu A_0}{N_0}\int\limits_0^{T_\mathrm{s}}[x(t) - s_i(t, C_i)]\cos\omega_{\mathrm{int}}t\,dt, \\ Y_i &= \frac{2\mu A_0}{N_0}\int\limits_0^{T_\mathrm{s}}[x(t) - s_i(t, C_i)]\sin\omega_{\mathrm{int}}t\,dt. \end{aligned} \quad (8)$$

The decision rule for a channel symbol in the presence of harmonic interference with a random initial phase in addition to noise in the communication channel basically coincides with the decision rule for the receiver of M-PSK and M-QAM signals against the background of only white Gaussian noise. However, in addition to calculating the correlation integrals, it is also necessary to form weight coefficients for these integrals (in the form of Bessel functions), the value of which depends on the degree of correlation between the interference oscillation extracted from the received mixture $x(t)$, as well as the sample copy of the interference stored in the receiver. The corresponding block diagram of the receiver shown in Fig. 1 is denoted as follows: 1 – 90° phase shifter; 2 – integrator; 3 – exponent calculation unit; 4 – squaring unit; 5 – modulus calculation unit; 6 – weight coefficients formation unit; 7 – maximum selection unit; 8 – circuit channel symbol estimation; 9 – scheme for generating weight coefficients; 10 – noise copy generator; 11 – unit for generating reference oscillations.

As an example, Fig. 1 shows one additional channel; the rest are constructed in a similar fashion.

2. SIMULATION RESULTS

To evaluate the efficiency of the scheme of incoherent harmonic interference processing, the simulation of reception was performed for 2-PSK, 4-PSK (4-QAM), 8-PSK, and 16-QAM signals. The bit error probability P_{eb} was determined depending on the interference parameters and the receiver settings.

A. Dependence of the bit error probability on the interference detuning

Modeling of optimal receivers for M-PSK and M-QAM signals showed the efficiency of the incoherent interference processing circuit to depend on the detuning Δf_{int} of the interference frequency relative to the center frequency of the useful signal spectrum. Figure 2 illustrates the dependence of the bit error probability P_{eb} on the interference detuning $\Delta f_{\mathrm{int}}T_\mathrm{s}$ at μ = 0.5 and the

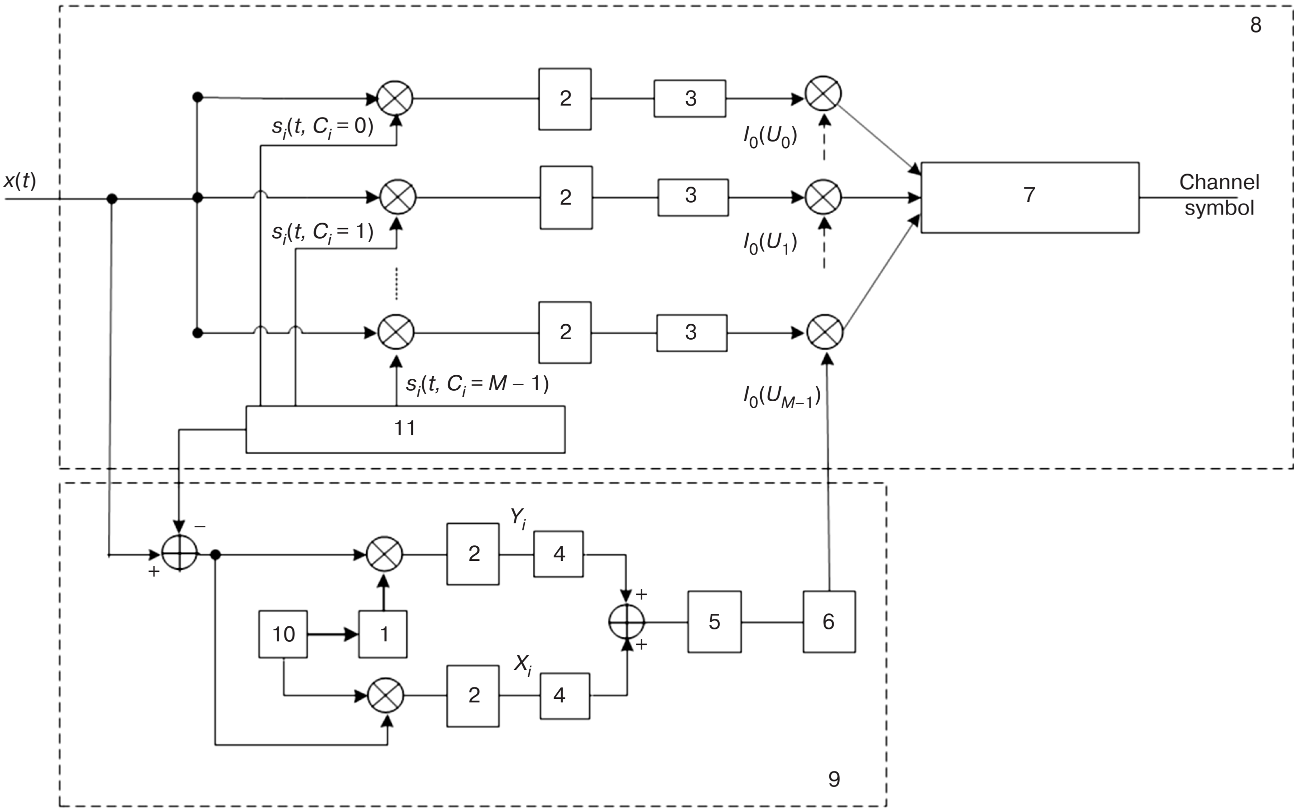

Fig. 1. Block diagram of the optimal receiver of M-PSK and M-QAM signals with incoherent processing of harmonic interference

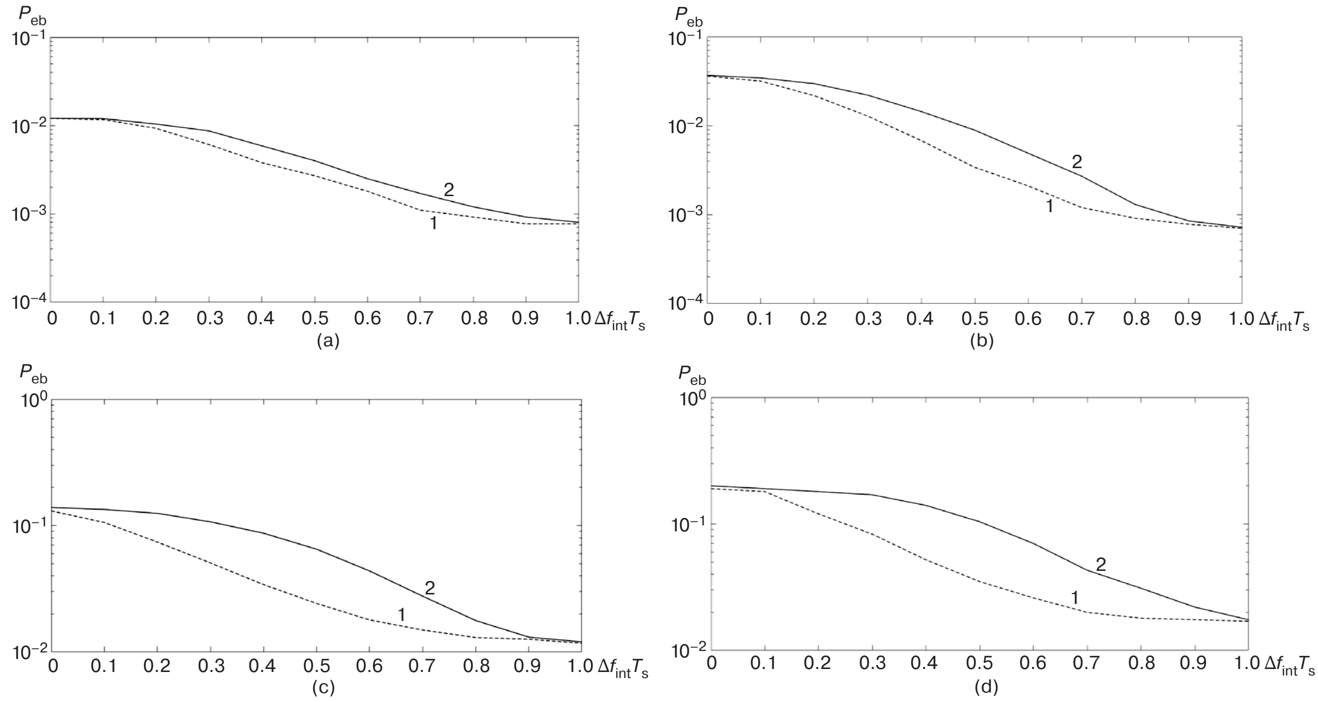

Fig. 2. Dependences of the bit error probability on the interference detuning with (1) and without (2) interference processing: (a) 2-PSK, (b) 4-PSK (4-QAM), (c) 8-PSK, and (d) 16-QAM

signal-to-noise ratio *SNR* = 7 dB. Here, it can be seen that the greatest gain in noise immunity is observed at the detuning $\Delta f_{int}T_s = 0.5$. Thus, for the 2-PSK signal, the error probability decreases by 1.3 times, for 4-PSK (4-QAM)—by 2.5 times, for 8-PSK—by 2.7 times, and for 16-QAM—by 2.8 times. With targeted interference ($\Delta f_{int}T_s = 0$), the scheme turns out to be inefficient, while for $\Delta f_{int}T_s = 1$, there is no gain due to the frequency of the interference coinciding with the frequency of the first zero of the signal spectrum; hence, it can be seen that such interference does not affect reception noise immunity.

Let us now carry out a more detailed analysis of the case when the interference frequency does not coincide with the center frequency of the useful signal spectrum, and when, as follows from Fig. 2, the non-coherent interference processing scheme provides a gain in noise immunity.

B. Dependence of the bit error probability on the signal-to-noise ratio

Figure 3 shows the dependence of the bit error probability P_{eb} on the signal-to-noise ratio SNR (dB) at $\Delta f_{int}T_s = 0.5$. The dashed lines correspond to the case when the incoherent interference processing circuit is switched on. For comparison, solid lines show the curves obtained without interference processing.

The positive effect of such processing is clearly visible: the probability of bit error is significantly reduced. This is especially noticeable at high interference intensities $\mu = 0.5$ and 0.9. Thus, for $\mu = 0.5$ and $P_{eb} = 10^{-2}$ switching on the scheme of incoherent interference processing results in an energy gain of no more than 0.5 dB, for 4-PSK (4-QAM)—about 2 dB, and for 8-PSK and 16-QAM—more than 5 dB.

Comparison of the efficiency of the synthesized algorithm with the adaptive algorithm applied in [12, 17] showed that the optimal signal and interference processing provides the best noise immunity parameters over the entire range of interference level changes.

C. Influence of inaccurate setting of the frequency of the copy of the interference in the receiver

Algorithm (7) assumes that the interference frequency in the receiver in known as a sample. Naturally, this assumption is often not fulfilled. Let us consider how the deviation of the frequency of the copy of the interference $\Delta f_{int.rec.}$ installed in the receiver affects the value of the error probability P_{eb}. Figure 4 shows graphs illustrating this dependence for different signals at SNR = 7 dB. Here, the abscissa shows the value $\Delta f_{int.rec.}T_s$ normalized to the symbol transmission rate of the useful signal.

Naturally, the interference processing is the most effective when the frequency of the interference $\Delta f_{int.rec.}T_s = 0$ is precisely known in the receiver. Small inaccuracies in the setting of the frequency of the interference copy $\Delta f_{int.rec.}T_s = \pm 0.1$ in the receiver slightly reduce the noise immunity of signal reception; although this decrease is stronger, the greater the intensity of the interference, at $\mu = 0.9$ and detuning $\Delta f_{int.rec.}T_s = \pm 0.5$; for 2-PSK, the error probability already increases by a factor of 5, while for 8-PSK, it decreases by a factor of 7–10.

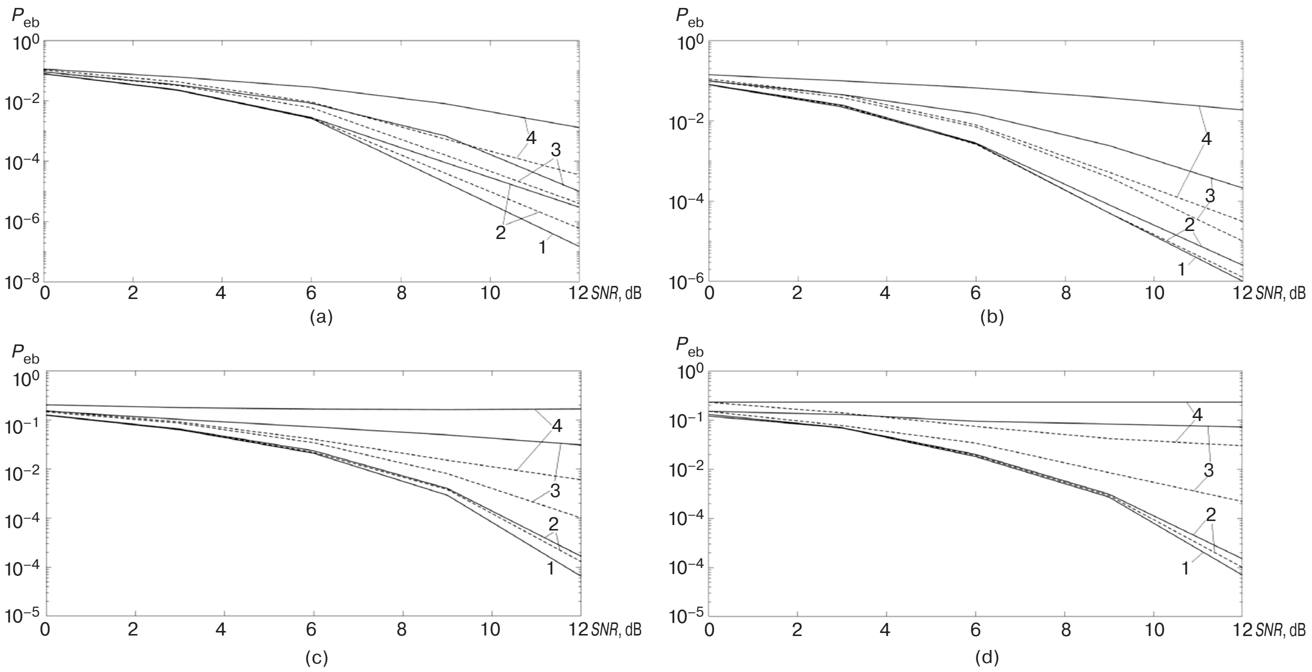

Fig. 3. Dependences of the bit error probability on the signal-to-noise ratio at μ = 0 (1), μ = 0.1 (2), μ = 0.5 (3), μ = 0.9 (4): (a) 2-PSK, (b) 4-PSK (4-QAM), (c) 8-PSK, and (d) 16-QAM

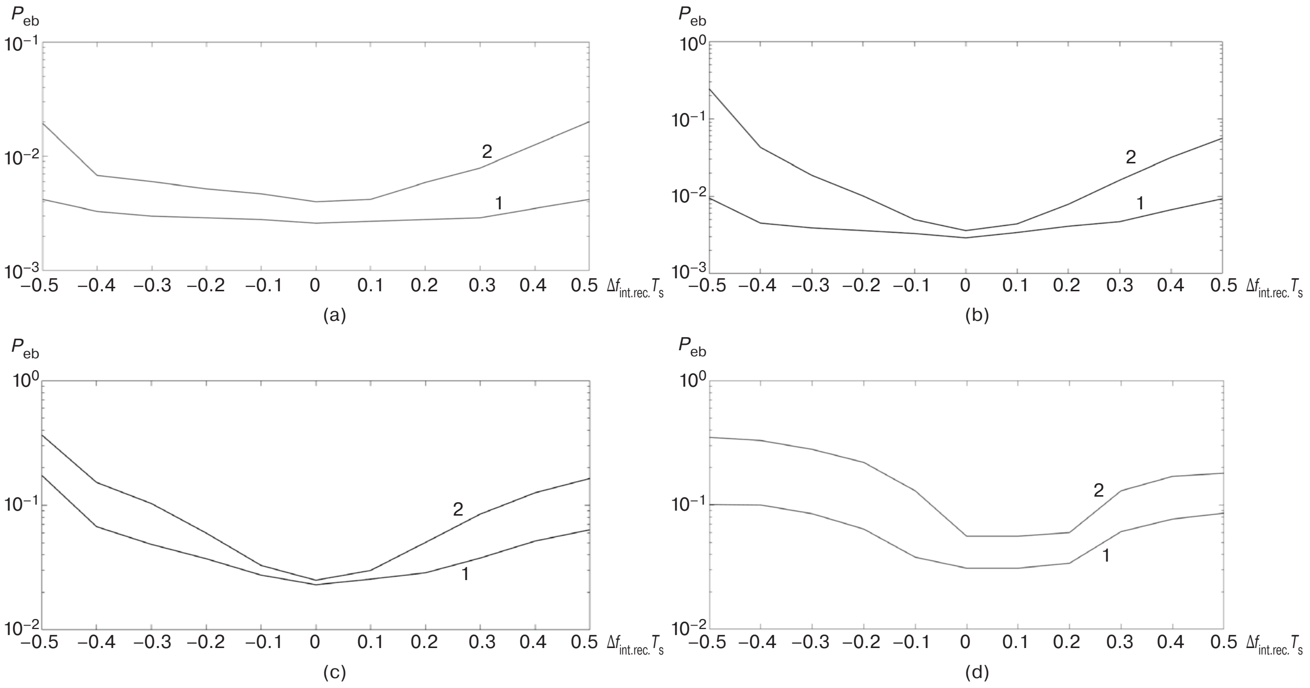

Fig. 4. Influence of the inaccuracy of setting the frequency of the interference copy in the receiver at μ = 0.5 (1), μ = 0.9 (2): (a) 2-PSK, (b) 4-PSK (4-QAM), (c) 8-PSK, and (d) 16-QAM

D. Influence of inaccurate setting of the level of the interference copy in the receiver

Algorithm (7) assumes that the interference level in the receiver is known. Let us consider how the deviation of the level of the copy of the interference $\Delta\mu_{\text{int.rec.}}$, installed in the receiver, affects the value of the error probability P_{eb}. Figure 5 shows graphs illustrating this dependence for different signals at SNR = 7 dB and nominal interference intensity $\mu = 0.9$.

From Fig. 5, the value of the error probability can be seen to be minimal at the intensity deviation $\Delta\mu_{\text{int.rec.}} = 0$. While small inaccuracies in setting the interference copy level in the receiver $\Delta\mu_{\text{int.rec.}} = \pm 0.1$ reduce the noise immunity of signal reception slightly, almost the same (2–3 times) increase in bit error probability is observed for all signals at $\Delta\mu_{\text{int.rec.}} = \pm 0.4$.

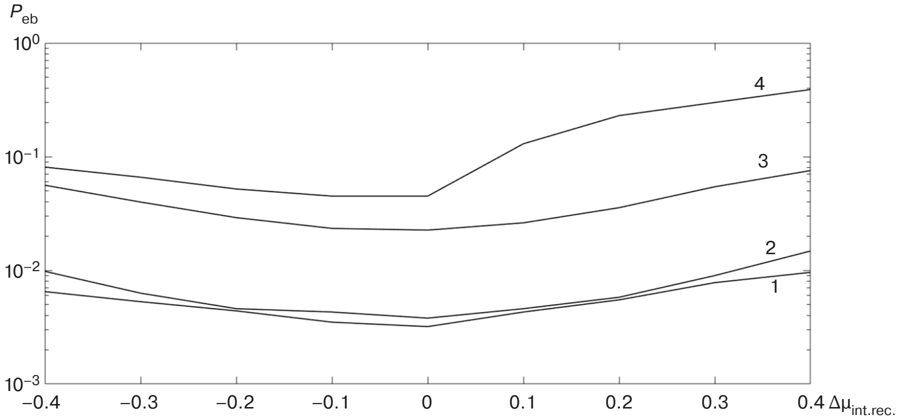

Fig. 5. Influence of the inaccuracy of setting the level of the interference copy in the receiver for 2-PSK (1), 4-PSK (4-QAM) (2), 8-PSK (3), and 16-QAM (4)

CONCLUSIONS

From the analysis of the data obtained, the following conclusions can be drawn:

1. The noise immunity of reception M-PSK and M-QAM signals is improved by optimal non-coherent processing of harmonic interference using an additional threshold correction circuit in the receiver's decision-making unit.
2. The efficiency of the circuit depends on the detuning of the harmonic interference frequency relative to the center frequency of the useful signal spectrum. The greatest gain in noise immunity is observed at the detuning $\Delta f_{int}T_s = 0.5$ (energy gain from 0.5 dB for 2-PSK to more than 5 dB for 8-PSK and 16-QAM at $\mu = 0.5$).
3. The higher the gain in the noise immunity of reception, the greater the intensity of the harmonic interference.
4. The scheme of non-coherent processing of harmonic interference remains operational even with small inaccuracies in the setting of the frequency ($\Delta f_{int.rec.}T_s = \pm 0.1$) and level ($\Delta\mu_{int.rec.} = \pm 0.1$) of the interference copy in the receiver.

Authors' contributions

G.V. Kulikov—the research idea, consultations on the issues of conducting all stages of the study.

T.T. Do—synthesis and analysis of the M-PSK signal receiver.

A.A. Lelyukh—synthesis and analysis of the M-QAM signal receiver.

V.D. Nguyen—computer simulation.

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