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RESEARCH ARTICLE

# Influence of quadrature transformation imbalance on the noise immunity of signal reception with amplitude-phase shift keying

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**Abstract**
**Objectives.** At the present time, amplitude-phase shift keyed (APSK) signals are actively used in satellite communication systems. In particular, they are applied in systems which operate in a limited radio frequency spectrum with increased data transmission quality requirements. Such systems use multi-channel type receivers with maximum likelihood decision on the received symbol (correlation receiver) or quadrature type receivers. The noise immunity of these receivers is directly dependent on the quality of the formation of reference oscillations. These oscillations are reference signals for correlation receivers and in-phase and quadrature components for quadrature receivers. The aim of the work is to analyze the influence of the amplitude and phase parameter spread of the in-phase and quadrature channels on the noise immunity of receiving APSK signals with a circular shape of the signal constellation.
**Methods.** Methods of statistical radio engineering, theory of optimal signal reception, and computer simulation are used.
**Results.** The study established the characteristics of noise immunity of the APSK signal reception depending on the spread of parameters of the quadrature converter. The theoretical calculations were confirmed by the results of modeling the transmission of APSK signals in a Gaussian communication channel. A comparison with systems using quadrature amplitude modulation (QAM) was carried out, in order to assess system stability in the presence of spread parameters among other similar systems.
**Conclusions.** The studies enabled us to conclude that an imbalance of the quadrature reference oscillations can lead to a significant decrease in the noise immunity of radio systems using APSK signals. The minimum energy loss due to imbalance of quadrature reference oscillations is achieved when the imbalance value is less than 10% in amplitude and 2°–3° in phase. The amplitude imbalance of quadrature reference oscillations when receiving QAM signals is more pronounced than in the case of APSK signals. The phase imbalance affects approximately the same.

**Keywords:** amplitude-phase shift keying, quadrature channels, amplitude imbalance, phase imbalance, bit error probability

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НАУЧНАЯ СТАТЬЯ

# Влияние разбаланса квадратурного преобразования на помехоустойчивость приема сигналов с амплитудно-фазовой манипуляцией

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**Резюме**

**Цели.** В настоящее время сигналы с амплитудно-фазовой манипуляцией (АФМ) активно используются в системах спутниковой связи и, особенно, в системах, работающих в условиях ограниченности спектра радиочастот с повышенными требованиями к качеству передачи данных. В этих системах применяются приемники многоканального типа с принятием решения о принимаемом символе по максимуму правдоподобия (корреляционный приемник) или приемники квадратурного типа. Помехоустойчивость этих приемников напрямую зависит от качества формирования опорных колебаний: для корреляционных приемников – эталонных сигналов, а для квадратурных приемников – синфазной и квадратурной составляющих. Цель работы – анализ влияния разброса амплитудных и фазовых параметров синфазного и квадратурного канала на помехоустойчивость приема сигналов АФМ с круговой формой сигнального созвездия.

**Методы.** Использованы методы статистической радиотехники, теории оптимального приема сигналов и компьютерного моделирования.

**Результаты.** Получены характеристики помехоустойчивости приема сигналов АФМ в зависимости от разброса параметров квадратурного преобразователя. Теоретические расчеты подтверждены результатами имитационного моделирования при передаче АФМ-сигналов в гауссовском канале связи. Проведено сравнение с системами, использующими сигналы с квадратурной амплитудной модуляцией (КАМ).

**Выводы.** Проведенные исследования показали, что разбаланс квадратурных опорных колебаний может привести к существенному снижению помехоустойчивости радиосистем, использующих АФМ-сигналы. Минимальные энергетические потери из-за разбаланса квадратурных опорных колебаний достигаются при значении разбаланса менее 10% по амплитуде и 2°–3° по фазе. Амплитудный разбаланс квадратурных опорных колебаний при приеме сигналов КАМ сказывается сильнее, чем при приеме сигналов АФМ. Фазовый разбаланс сказывается приблизительно одинаково.

**Ключевые слова:** амплитудно-фазовая манипуляция, квадратурные каналы, амплитудный разбаланс, фазовый разбаланс, вероятность битовой ошибки

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Авторы заявляют об отсутствии конфликта интересов.

## INTRODUCTION

Many external and internal factors are used to determine the noise immunity of radio information transmission systems. External factors include radio wave propagation conditions and interference of various origins. Internal factors are operation validity and the stability of technical characteristics of devices included in the system.

In [1–4], the principles of construction and some specific features of implementation of digital television systems according to DVB[1] standards are considered. In the case of enhanced-definition television or high-definition television, high-speed types of modulation are used. These include: quadrature amplitude modulation (QAM) used in DVB-T and DVB-C [2, 4]; and amplitude-phase shift keying (APSK) with circular signal constellation used in DVB-S2 [1, 3]. Receivers of QAM and APSK signals can be designed according to two basic schemes: multichannel type with decision making relating to the received symbol based on maximum likelihood (Fig. 1); and quadrature type (Fig. 2). The noise immunity characteristics are the same for both schemes. An important part of the receivers is the module generating reference oscillations: in-phase and quadrature components, shifted in phase by 90°. Any inaccurate operation of this circuit would cause the loss of orthogonality. This can result in errors while defining the transmitted symbols and, consequently, the reduced noise immunity of the information transmission system. The influence of errors in the scheme for generating quadrature reference oscillation on the reception of QAM signals is studied in [5–12].

[1] DVB. https://www.dvb.org/standards. Accessed May 22, 2023.

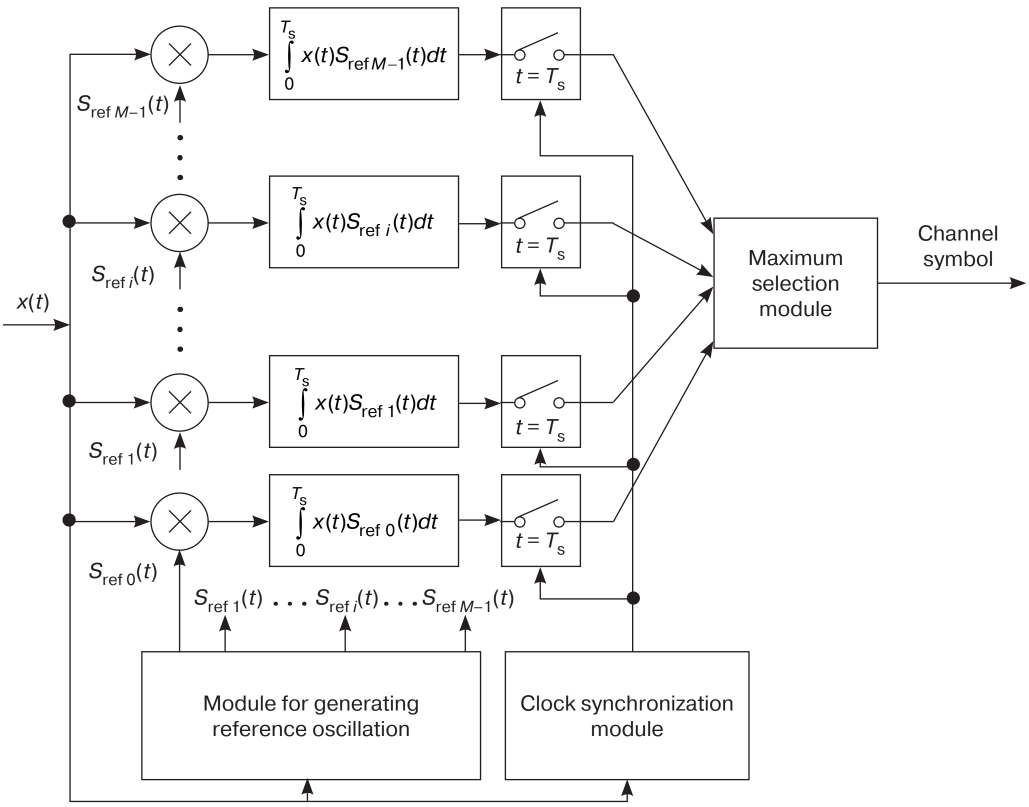



**Fig. 1.** Structural diagram of the multichannel coherent receiver

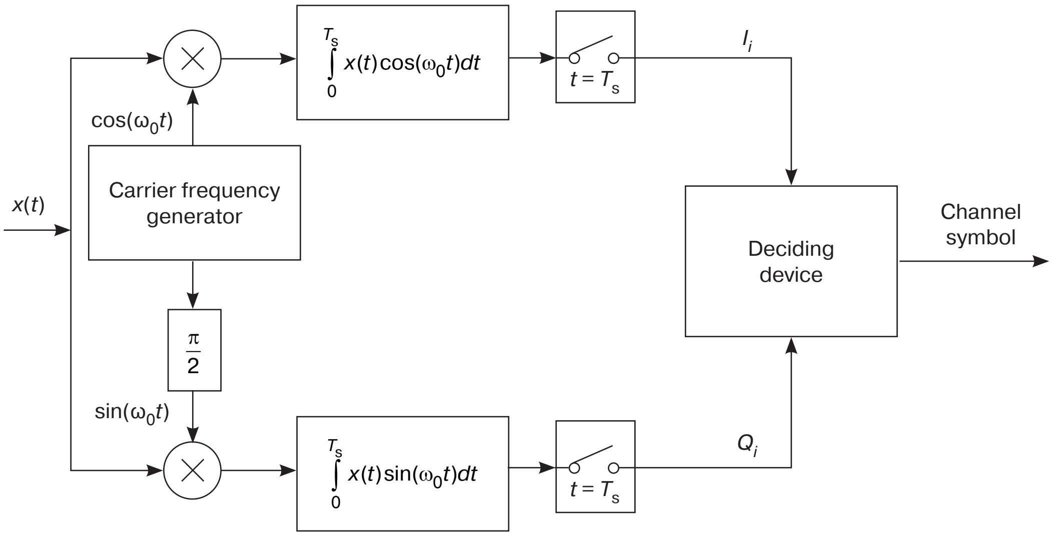



**Fig. 2.** Structural diagram of the quadrature demodulator

The aim of the paper is to evaluate the influence of amplitude and phase imbalance of quadrature reference oscillations when receiving APSK signals with circular signal constellation. The problem may be resolved in two ways: by the methods of statistical radio engineering using theoretical calculations of the bit error probability of a multichannel receiver; and by simulation modeling of a quadrature receiver.

## METHODOLOGY FOR CALCULATING BIT ERROR PROBABILITY

Let us represent the APSK signal in the following quadrature form:

$$s_i(t) = Ar_i\cos(\omega_0 t + \varphi_i) = A(I_i\cos\omega_0 t - Q_i\sin\omega_0 t),\quad t \in (0, T_s],\ i = \overline{0, M-1}, \tag{1}$$

where $t$ is time; $I_i = r_i\cos\varphi_i$; $Q_i = r_i\sin\varphi_i$; $A$ is the signal amplitude average; $\omega_0$ is carrier frequency; $r_i$ and $\varphi_i$ are values determining the amplitude and phase of a signal element; $T_s$ is the channel symbol duration; and $M$ is signal positioning.

Let us assume that the signal reception occurs against the background of white Gaussian noise $n(t)$ with the following parameters:

$$< n(t) > = 0,\ < n(t_1)n(t_2) > = \frac{N_0}{2}\delta(t_2 - t_1),$$

where $N_0$ is the noise power spectral density, $\delta$ is delta function, $t_1$ and $t_2$ are time instants.

Then the signal-to-noise ratio is the following:

$$E_b/N_0 = E_s/(N_0\log_2 M) = A^2T_s/(2N_0\log_2 M),$$

where $E_s$ is the average energy per symbol (assuming all symbols have the similar probability of occurrence), and $E_b$ is the average bit energy.

The multichannel receiver correlators (Fig. 1) compute convolution integrals:

$$J_i = \frac{2}{N_0}\int_0^{T_s} x(t)s_{\text{ref}\,i}(t)dt,\ i = \overline{0, M-1} \tag{2}$$

of the input process $x(t) = s_i(t) + n(t)$ with the reference signals $s_{\text{ref}\,i}(t)$, and ideally, $s_{\text{ref}\,i}(t) = A_{\text{ref}}\,(I_i\cos\omega_0 t - Q_i\sin\omega_0 t)$, with the amplitude of the reference signal $A_{\text{ref}} = A$.

We set the amplitude and phase imbalance values for quadrature reference oscillations through the amplitude coefficient $a$ and the phase shift $\theta$ in one of the channels, as follows:

$$S_{\text{ref}\,i}(t) = A(I_i\cos\omega_0 t - aQ_i\sin(\omega_0 t + \theta)). \tag{3}$$

In order to calculate the error probability, the methods described in [13, 14] are used. According to them, the error probability for receiving any $m$th channel symbol is equal to

$$P_{\text{es}\,m} = 1 - \prod_{\substack{i=0\\ m\neq i}}^{M-1}\left(1 - Q\left(\frac{m_{mi}}{\sqrt{D_{mi}}}\right)\right),\ Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{\frac{-t^2}{2}}dt, \tag{4}$$

where $m_{mi}$ are the mathematical expectations and $D_{mi}$ are the dispersions of linear combinations of processes (2).

Calculating and averaging all $i \neq m;\ i, m = \overline{0, M-1}$ combinations enables us to find the error probability average for symbol reception and then the bit error probability when using Gray coding [15], as follows:

$$P_{\text{eb}} = P_{\text{es}}/\log_2 M.$$

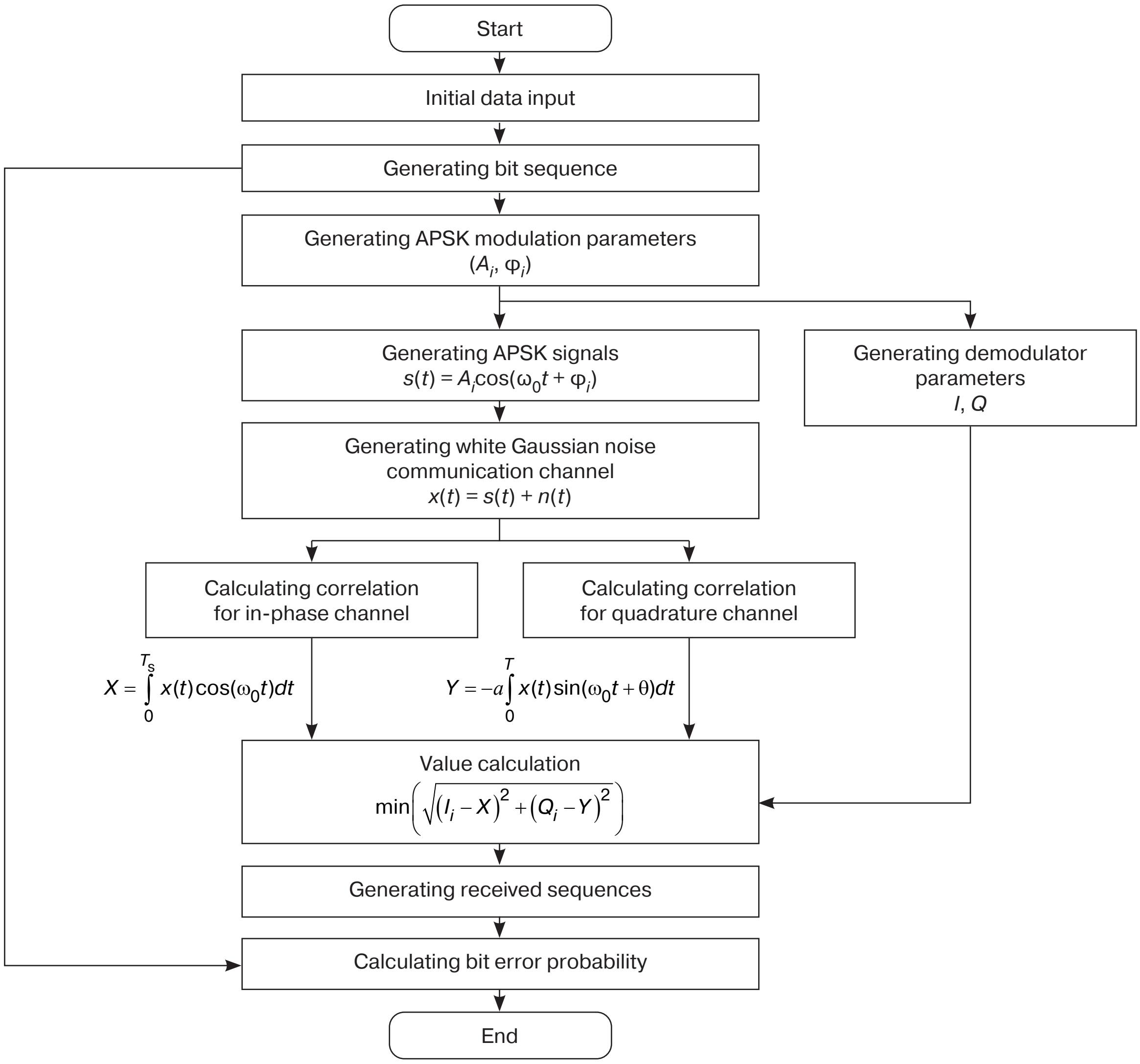



**Fig. 3.** Algorithm for simulation modeling of the APSK signal transmission system in a Gaussian noise channel

In (4), $m_{mi}$ and $D_{mi}$ with allowance for (1) and (3) are defined as follows:

$$m_{mi} = \frac{2E_s}{N_0}\Bigg(r_m{}^2\cos^2\varphi_m - r_m r_i\cos\varphi_m\cos\varphi_i - ar_m\sin(\theta - \varphi_m)\times (r_m\sin\varphi_m - r_i\sin\varphi_i) - \frac{r_m^2 - r_i^2}{2}\Bigg), \quad (5)$$

$$D_{mi} = \frac{2E_s}{N_0}\Big(\big(r_m\cos\varphi_m - r_i\cos\varphi_i\big)^2 + a^2\big(r_m\sin\varphi_m - r_i\sin\varphi_i\big)^2 - 2a\sin\theta\big(r_m\cos\varphi_m - r_i\cos\varphi_i\big)\times \big(r_m\sin\varphi_m - r_i\sin\varphi_i\big)\Big). \quad (6)$$

In order to verify theoretical results, a simulation model of the APSK signal transmission system in a Gaussian noise channel. This includes quadrature converter modules with the possibility of introducing amplitude $a$, and developing phase $\theta$ imbalances. The modeling algorithm is shown in Fig. 3.

## CALCULATION AND STIMULATION RESULTS

### Influence of the amplitude imbalance of quadrature channels

The calculations assume that there is no phase imbalance, $\theta = 0$. In this case Eqs. (5) and (6) take the following form:

$$m_{mi} = \frac{2E_s}{N_0}\Bigg(r_m\cos\varphi_m(r_m\cos\varphi_m - r_i\cos\varphi_i) + ar_m\sin\varphi_m(r_m\sin\varphi_m - r_i\sin\varphi_i) - \frac{r_m^2 - r_i^2}{2}\Bigg),$$

$$D_{mi} = \frac{2E_s}{N_0}\Big(\left(r_m \cos\varphi_m - r_i \cos\varphi_i\right)^2 + $$
$$+ a^2\left(r_m \sin\varphi_m - r_i \sin\varphi_i\right)^2\Big).$$

The dependencies of bit error probability on the amplitude imbalance at $E_b/N_0 = 13$ dB for 16-APSK and 32-APSK signals are shown in Fig. 4. The dependencies of the bit error probability on the signal-to-noise ratio at fixed values $a$ are shown in Fig. 5. Note that the case $a = 1$ stands for the absence of imbalance.

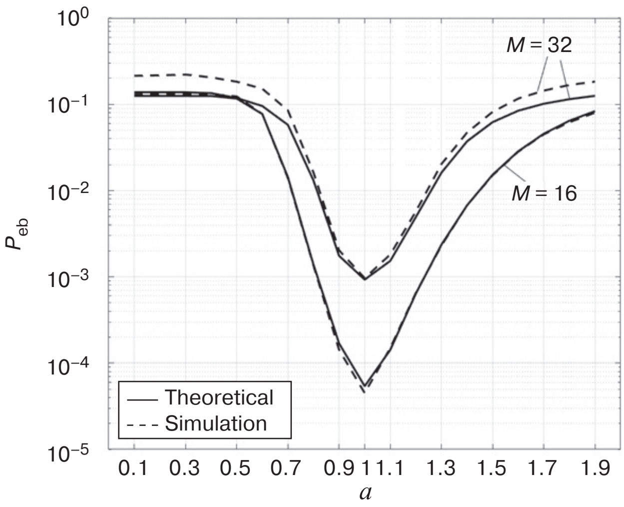


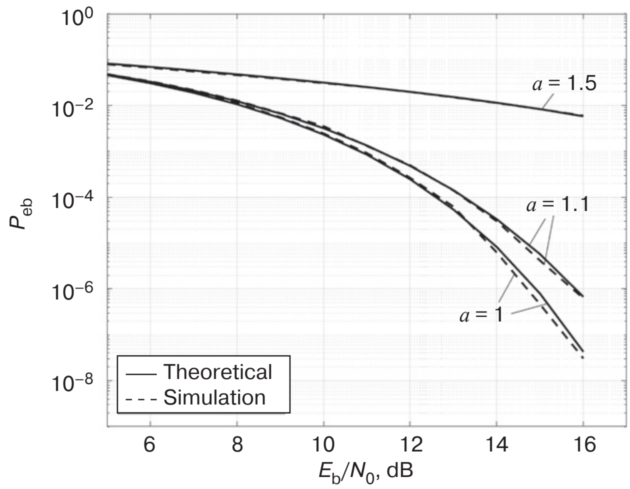

**Fig. 4.** Dependencies of the bit error probability on the amplitude imbalance of quadrature channels

It can be seen that in the case of both signals, low amplitude imbalance of quadrature channels ±10% affects the information reception quality insignificantly. This value may be considered acceptable. In particular, at $P_{eb} = 10^{-3}$ and $a = 1.1$, energy losses would not exceed 0.5 dB. At an amplitude imbalance of 20% ($a = 0.8$ and 1.2), the bit error probability increases by an order of magnitude. Greater imbalance ($a = 1.5$) is unacceptable and results in the reception failure. This is due to the fact that the bit error probability increases by several orders of magnitude while energy losses increase by 8–10 dB.

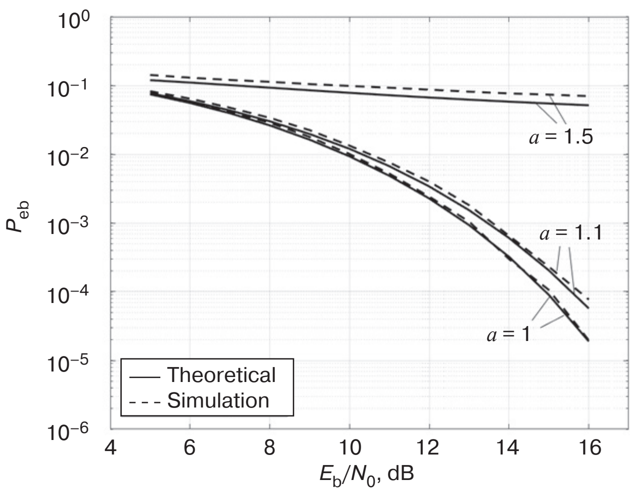
It should be also noted that the difference in the results for multichannel (theoretical calculation) and quadrature (simulation modeling) receivers is insignificant, thus indicating approximately the same stability of schemes against the amplitude imbalance of quadratures.

## Influence of phase imbalance of quadrature channels

During the calculations it was assumed that there is no amplitude unbalance: $a = 1$. In this case, Eqs. (5) and (6) take the form:




(a)




(b)

**Fig. 5.** Dependencies of the bit error probability on signal-to-noise ratio at amplitude imbalance of quadrature channels:
(a) for 16-APSK, (b) for 32-APSK

$$m_{mi} = \frac{2E_s}{N_0}\Big(r_m{}^2 \cos^2\varphi_m - $$
$$- r_m r_i \cos\varphi_m \cos\varphi_i - r_m \sin(\theta - \varphi_m) \times $$
$$\times (r_m \sin\varphi_m - r_i \sin\varphi_i) - \frac{r_m^2 - r_i^2}{2}\Big),$$

$$D_{mi} = \frac{2E_s}{N_0}\Big(\left(r_m \cos\varphi_m - r_i \cos\varphi_i\right)^2 + $$
$$+ \left(r_m \sin\varphi_m - r_i \sin\varphi_i\right)^2 - $$
$$- 2\sin\theta\left(r_m \cos\varphi_m - r_i \cos\varphi_i\right) \times $$
$$\times \left(r_m \sin\varphi_m - r_i \sin\varphi_i\right)\Big).$$

The dependencies of the bit error probability on phase imbalance θ at ratio $E_b/N_0$ = 13 dB for 16-APSK and 32-APSK signals are shown in Fig. 6. The dependencies of the bit error probability on the signal-to-noise ratio at fixed values of phase imbalance are shown in Fig. 7.

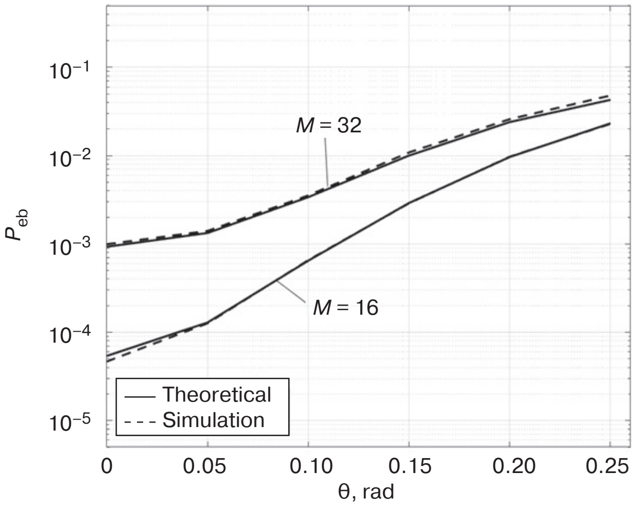



**Fig. 6.** Dependencies of the bit error probability on phase imbalance of quadrature channels

At phase imbalance θ = 0.1 rad (~5°) for $P_{eb} = 10^{-3}$, energy losses of 2 dB for $M$ = 16 and 3 dB for $M$ = 32 can be observed. With the imbalance increasing up to 0.15 rad (~8°), the losses are 4.5 dB or more. In the case of signals 16-APSK and 32-APSK, a phase imbalance of quadrature channels no more than 0.03–0.05 rad, i.e., 2°–3° can be considered acceptable. This can be judged by the graphs given in Fig. 5.

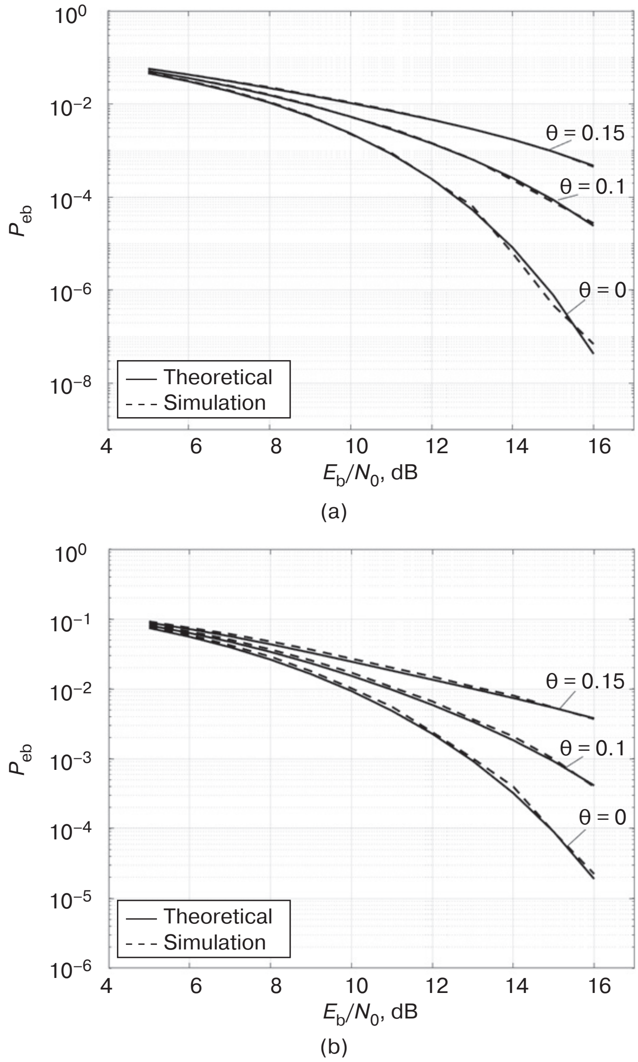



**Fig. 7.** Dependencies of the bit error probability on the signal-to-noise ratio at phase imbalance in quadrature channels: (a) for 16-APSK, (b) for 32-APSK

## COMPARISON OF RESULTS FOR QAM AND APSK SIGNALS

The comparative dependencies of the probability $P_{eb}$ on the amplitude imbalance coefficient $a$ of quadrature channels for APSK and QAM signal receivers of the same positioning [2] are shown in Fig. 8. As can be seen, in the ideal case ($a$ = 1) QAM signal has slightly better noise immunity. However, the steeper slope of graphs in the region $0.7 < a < 1.3$ indicates a greater sensitivity of QAM receiver against the amplitude imbalance value.

It follows from Fig. 9 that the influence of phase imbalance of quadrature channels on the reception of APSK and QAM signals [5] is approximately equal.

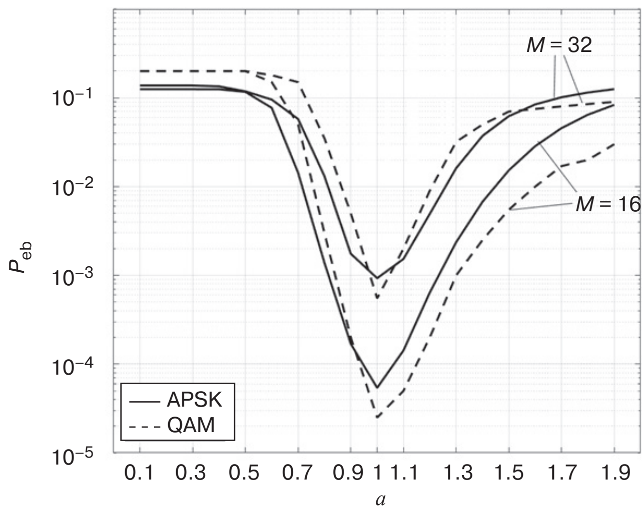



**Fig. 8.** Dependencies of the bit error probability on amplitude imbalance for APSK and QAM signals ($E_b/N_0$ = 13 dB)

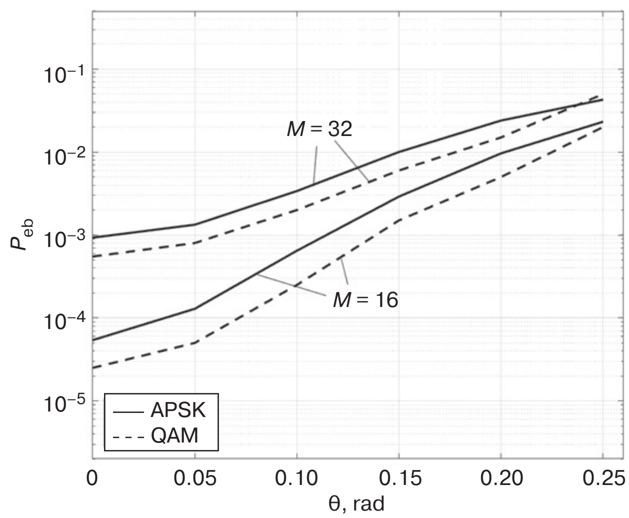



**Fig. 9.** Dependencies of the bit error probability on phase imbalance of quadrature channels for APSK and QAM signals ($E_b/N_0$ = 13 dB)

## CONCLUSIONS

Thus, the results allow the following conclusions to be drawn:

1. The amplitude and phase imbalance of quadrature reference oscillations when receiving APSK signals, as well as QAM signals, may result in the significant decrease in noise immunity.
2. The acceptable value of amplitude imbalance for APSK receiver may be considered as ±10%.
3. The acceptable value of phase imbalance for APSK receiver may be considered as 2°–3°.
4. The amplitude imbalance of quadrature reference oscillations when receiving QAM signals affects more than that while receiving APSK signals. Phase imbalances are nearly the same.

**Authors' contributions**

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

**X.Kh. Dang**—making calculations, processing of results.

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