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RESEARCH ARTICLE

Optimization of signal constellations with amplitude-phase shift keying in communication channels with non-fluctuating interference

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Abstract
Objectives. Multi-position amplitude-phase shift keying (APSK) with a ring-shaped signal constellation is one of the most effective ways for transmitting discrete information in satellite systems. The use of APSK is regulated by several standards. The main are DVB-S2 and VSAT which define both the modulation parameters, and the parameters of the signal constellations. The aim of the paper is to determine the best constellations of 16-APSK and 32-APSK, and provide a minimum BER for cases when the communication channel, along with noise, contains non-fluctuating interference.
Methods. Methods of statistical radio engineering, the theory of optimal signal reception, and computer modeling were used.
Results. The optimization of ring-shaped constellations of 16-APSK and 32-APSK signals is attained by changing the distribution of points along the radius and phase for a case in which the communication channel, along with noise, contains non-fluctuating interference: frequency-shift keyed, retransmitted, phase-shift keyed, and harmonic ones. The best constellations of 16-APSK and 32-APSK are determined, and a minimum bit error rate is provided.
Conclusions. In order to improve the quality of communication in information transmission systems in the presence of non-fluctuating interference, the existing constellations 16-APSK (4, 12) and 32-APSK (4, 12, 16) can be used by changing the ratios between the radii of circles 2.5 for 16-APSK and 2.5/3.9 for 32-APSK. Due to the more efficient use of signal power, the use of constellations with a zero-amplitude point for 16-APSK allows reception noise immunity to be increased. For example, when using constellation (1, 5, 10), the energy gain compared to the standard constellation (4, 12) can reach 1 dB.

Keywords: amplitude-phase shift keying, signal constellation, non-fluctuation interference, noise immunity, bit error rate

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НАУЧНАЯ СТАТЬЯ

Оптимизация созвездий сигналов с амплитудно-фазовой манипуляцией в каналах связи с нефлуктуационными помехами

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Резюме
Цели. Многопозиционная амплитудно-фазовая манипуляция (АФМ) с кольцевой формой сигнальных созвездий является одним из наиболее эффективных способов передачи дискретной информации в спутниковых системах. Применение АФМ регламентируется несколькими стандартами, основными из которых являются DVB-S2 и VSAT. Они определяют параметры модуляции, а также параметры сигнальных созвездий. Цель статьи – определение наилучших созвездий 16-АФМ и 32-АФМ, обеспечивающих минимум вероятности битовой ошибки для случаев, когда в канале связи наряду с шумовой присутствуют помехи нефлуктуационного вида.
Методы. Использованы методы статистической радиотехники, теории оптимального приема сигналов и компьютерного моделирования.
Результаты. Рассмотрены способы и проведена оптимизация созвездий кольцевой формы сигналов 16-АФМ и 32-АФМ изменением распределения точек по радиусу и фазе для случая, когда в канале связи наряду с шумовой присутствуют помехи нефлуктуационного вида: частотно-манипулированная, ретранслированная, фазоманипулированная, гармоническая. Определены наилучшие созвездия 16-АФМ и 32-АФМ, обеспечивающие минимум вероятности битовой ошибки.
Выводы. Для улучшения качества связи в системах передачи информации при наличии нефлуктуационных помех можно использовать существующие созвездия 16-АФМ (4, 12) и 32-АФМ (4, 12, 16) с изменением соотношений между радиусами окружностей 2.5 для 16-АФМ и 2.5/3.9 для 32-АФМ. За счет более эффективного использования мощности сигнала применение созвездий с точкой с нулевой амплитудой для 16-АФМ позволяет добиться увеличения помехоустойчивости приема. Например, в случае применения созвездия (1, 5, 10) энергетический выигрыш по сравнению со стандартным созвездием (4, 12) может достигать 1 дБ.

Ключевые слова: амплитудно-фазовая манипуляция, сигнальное созвездие, нефлуктуационные помехи, помехоустойчивость, вероятность битовой ошибки

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INTRODUCTION

Multi-position amplitude and phase-shift keying (APSK) is one of the most effective methods for data transmission in satellite systems with limited and expensive access to the communication channel [1–3]. It allows the capacity of the radio channel to be increased when compared to the binary manipulation. It also provides good noise immunity and thus high efficiency of using the frequency resource.

There are several standards which use APSK modulation for satellite communications including DVB-S2[1] (the second generation of digital satellite television broadcasting) [3, 4] and VSAT (a very-small-aperture terminal) [3, 5]. These standards specify modulation parameters such as the type of signal constellations, signal-to-noise ratio (SNR), data rate, inter alia.

In the light of the growing needs for high-speed data transmission and increased noise immunity of communication systems, optimizing APSK signal constellation formats is quite important since this optimal format allows the radio spectrum efficiency to be increased and data transmission quality to be enhanced. This is particularly important in satellite communications and in communication systems which operate over long distances.

Numerous studies on noise immunity of communication systems with APSK consider signal reception against various noises [6–11] and in channels with non-linearity [12–15].

This paper discusses methods for optimizing 16-APSK and 32-APSK ring-shaped signal constellations by changing the distribution of points over radius and phase for the scenario with non-fluctuating interference present in the communication channel along with noise. The paper aims to determine the best 16-APSK and 32-APSK constellations which ensure minimum bit error rate (BER).

CALCULATION METHODS

The model for APSK signal has the following form:

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

wherein $A = \sqrt{2E_s / T_s}$ is the average amplitude of the signal; $E_s = E_b \log_2 M$ is the average energy of channel symbol; E_b is the average energy per bit of information; ω_0 is carrier frequency; r_i and φ_i are values specifying the amplitude and phase of the signaling element; T_s is the symbol duration time; M is the signal positionality; and t is time.

[1] DVB. https://www.dvb.org/standards/dvb-s2x. Accessed November 11, 2023.

The constellation format may be optimized by estimating the probability of incorrect signal reception, i.e., by searching for the minimum of the function describing the dependence of the BER P_{eb} on constellation parameters. The methodology required for calculating BER is given in [16], while [16–19] offer details of the calculations of statistical characteristics of random process distributions in the optimal receiver solver, such as mathematical expectations, m_{mi}, and variances, D_{mi}, for different combinations of symbols in the presence of different types of non-fluctuating interference and noise interference at power spectral density N_0. These characteristics depend on various parameters of signals and interference. In particular, these include:

- exposure to phase-shift keyed interference [17]:

$$s_{int}(t) = \mu A a_j \cos[(\omega_0 t + \Delta\omega_{int})t + \varphi_{int}],$$
$$t \in ((j-1)T_{int}, jT_{int}],\ j = \overline{1, N_{int}},$$

  wherein μ is relative (in amplitude) interference intensity, $a_j = \pm 1$ is random symbol of interference, φ_{int} is its random initial phase, N_{int} is relative channel velocity of interference, and $T_{int} = T_s/N_{int}$, $\Delta\omega_{int}$ is interference detuning,

$$m_{mi} = \frac{E_s}{N_0}\left\{2r_m[r_m - r_i\cos(\varphi_m - \varphi_i)] + \frac{\mu}{N_{int}} \times \right.$$
$$\times 2S(y)[r_m \sum_{j=0}^{N_{int}-1} a_j \cos(y(2j+1) + \varphi_{int} - \varphi_m)] -$$
$$\left. - r_i \sum_{j=0}^{N_{int}-1} a_j \cos(y(2j+1) + \varphi_{int} - \varphi_i)\right\}, \quad (2)$$
$$y = \frac{\Delta\omega_{int} T_s}{N_{int}},\ S(y) = \frac{\sin y}{y};$$

- exposure to the frequency-shift keyed interference [18]:

$$s_{int}(t) = \mu A \cos[(\omega_0 + a_j \Delta\omega_d + \Delta\omega_{int})t + \varphi_{int}],$$
$$t \in ((j-1)T_{int}, jT_{int}],\ j = \overline{1, N_{int}},$$

  wherein $\Delta\omega_d$ is interference deviation,

$$m_{mi} = \frac{E_s}{N_0}(r_m^2 + r_i^2 - 2r_m r_i \cos(\varphi_m - \varphi_i)) + \frac{2E_s}{N_0} \times$$
$$\times \frac{\mu}{N_{int}} \sum_{j=1}^{N_{int}} \frac{\sin y}{y}[r_m \cos(x(2j-1) + \varphi_{int} - \varphi_m)] -$$
$$-r_i \cos(x(2j-1) + \varphi_{int} - \varphi_i)], \quad (3)$$
$$y = \frac{(a_j \Delta\omega_d + \Delta\omega_{int})T_s}{2N_{int}};$$

- exposure to the retransmitted interference [19]:

$$s_{\text{int}}(t)=\begin{cases}\mu A r_\tau \cos(\omega_0(t-\tau)+\varphi_\tau+\varphi_{\text{int}}),\ 0<t\le\tau,\\ \mu A r_i \cos(\omega_0(t-\tau)+\varphi_i+\varphi_{\text{int}}),\ \tau<t\le T_s,\end{cases}$$

wherein τ is the interference delay,

$$m_{mi}=\frac{E_s}{N_0}[(r_m^2+r_i^2-2r_m r_i\cos(\varphi_m-\varphi_i)]+\frac{2E_s}{N_0}\mu r_\tau\times$$
$$\times\frac{\tau}{T_s}[r_m\cos(\varphi_{\text{int}}+\varphi_\tau-\varphi_m)-r_i\cos(\varphi_{\text{int}}+\varphi_\tau-\varphi_i)]+ \quad (4)$$
$$+\frac{2E_s}{N_0}\mu r_m\cdot\left(1-\frac{\tau}{T_s}\right)[r_m\cos\varphi_{\text{int}}-r_i\cos(\varphi_{\text{int}}+\varphi_\tau-\varphi_i)];$$

- exposure to harmonic interference [16]:

$$s_{\text{int}}(t)=\mu A\cos[(\omega_0+\Delta\omega_{\text{int}})t+\varphi_{\text{int}}],$$
$$m_{mi}=\frac{E_s}{N_0}[0.5(r_m^2+r_i^2-2r_m r_i\cos(\varphi_m-\varphi_i))+$$
$$+\mu\frac{\sin(\Delta\omega_{\text{int}}T_s/2)}{\Delta\omega_{\text{int}}T_s/2}(\cos\eta(r_m\cos\varphi_m-r_i\cos\varphi_i)- \quad (5)$$
$$-\sin\eta(r_m\sin\varphi_m-r_i\sin\varphi_i))],$$
$$\eta=\Delta\omega_{\text{int}}T_s/2+\varphi_{\text{int}}.$$

For all interference types, the variances of all random processes being studied herein are determined by the following equation:

$$D_{mi}=\frac{2E_s}{N_0}[r_m^2+r_i^2-2r_m r_i\cos(\varphi_m-\varphi_i)]. \quad (6)$$

The following parameters are assumed for the example calculations: SNR is E_b/N_0 = 13 dB, relative (in amplitude) interference intensity is $0.1\le\mu\le0.3$, interference detuning is $\Delta\omega_{\text{int}}=0$, while phase-shift keyed and frequency-shift keyed interferences have a relative channel velocity $N_{\text{int}}=2$; for frequency-shift keyed interference, the reduced deviation is $\Delta\omega_d T_s=6$ and relative delay of retransmitted interference is $\tau/T_s=0.5$.

OPTIMIZING THE CONSTELLATION FORMAT FOR 16-APSK

The 16-APSK signal constellation (4, 12). The 16-APSK signal constellation (4, 12) has two levels of signaling element amplitudes (Fig. 1): $A_1=r_1A$, and $A_2=r_2A$. The relation is expressed through coefficient k: $A_1=kA_2$, and two energy levels E_1 and E_2, respectively. Since constellation symbols have on average the same frequency of occurrence when transmitting information, the average symbol energy can be determined by averaging over the signaling constellation, as follows:

$$E_s=\frac{A^2}{2}T_s=\frac{1}{16}(4E_1+12E_2)=$$
$$=\frac{1}{16}\cdot\frac{A_1^2}{2}T_s(4+12k^2)=\frac{1}{8}A_1^2T_s(1+3k^2).$$

Hence,

$$A_1=\frac{2}{\sqrt{1+3k^2}}A,\ A_2=\frac{2k}{\sqrt{1+3k^2}}A. \quad (7)$$

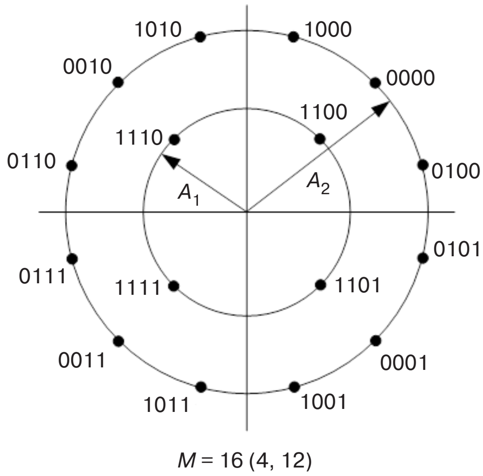


Fig. 1. 16-APSK signal constellation (4, 12)

Substituting (7) into (2)–(6) with allowance for (1) and methodology [16], BER dependencies on coefficient k can be obtained (Fig. 2).

The graphs show that in the presence of noise interference alone, BER minimum for the constellation format (4, 12) can be observed at k = 2.5. It shifts to a higher k value in the presence of non-fluctuating interference with high intensity in the radio channel.

Conventional 16-APSK constellations, such as (4, 12) in DVB-S2 and VSAT systems or (8, 8) in some other systems, have non-uniform energy distribution between points of different levels. The use of a zero-amplitude point in the center of the constellation can reduce this energy difference. The more uniform the energy distribution among points, the more efficiently the bandwidth can be utilized. In this case, the number of transmitted points in the constellation is reduced rather than the number of symbols, i.e., the information transmission rate is not reduced.

16-APSK signal constellations (1, 4, 11) and (1, 5, 10). We consider two types of 16-APSK constellation format: (1, 4, 11) and (1, 5, 10). In the

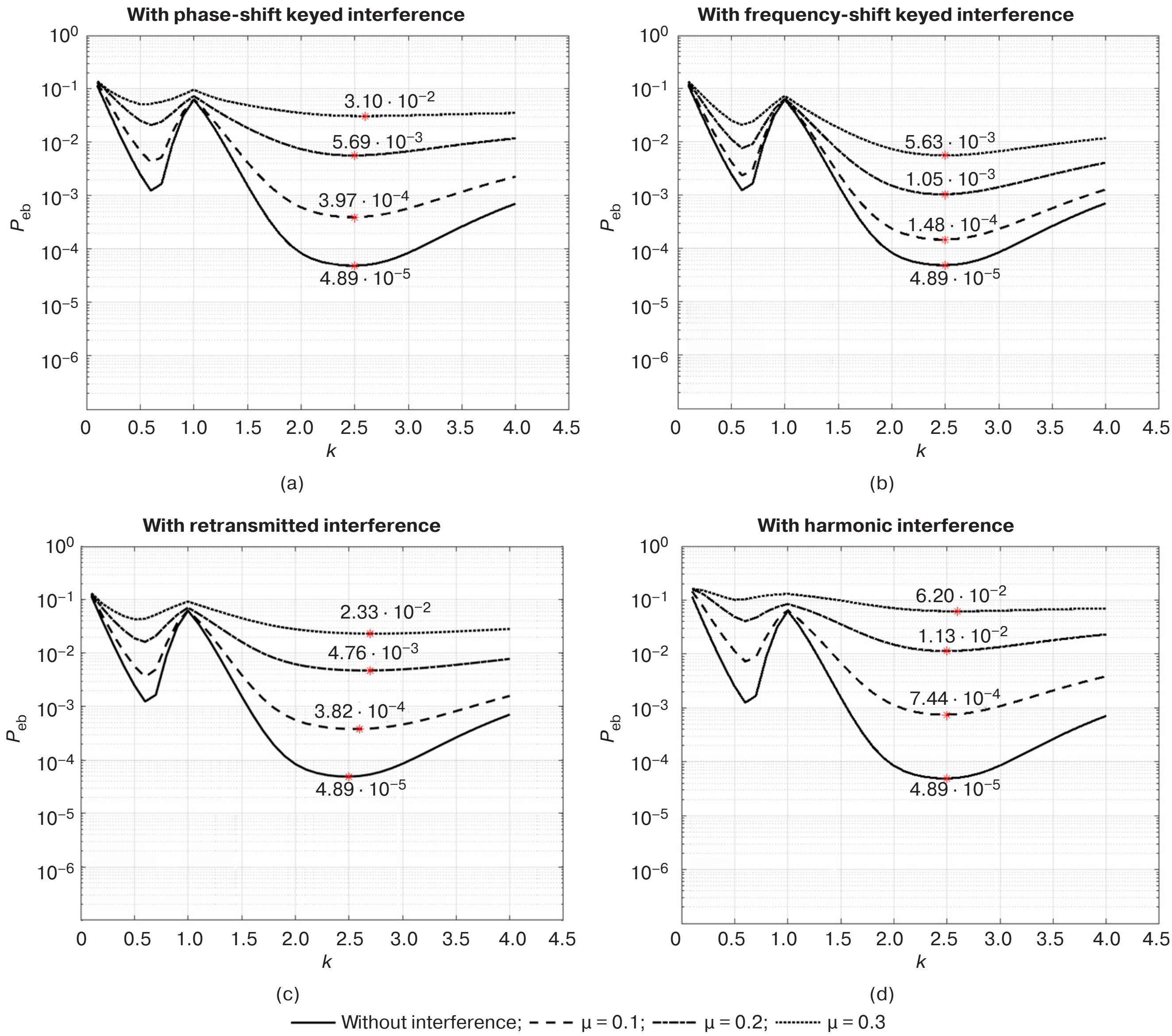


Fig. 2. Dependencies of BER on coefficient k for the 16-APSK constellation format (4, 12) at different types of interference

(1, 4, 11) configuration, there is 1 point with zero amplitude $A_1 = 0$ in the center of the constellation, 4 points with amplitude A_2 in the first (small) circle, and 11 points with amplitude $A_3 = kA_2$ in the large circle (Fig. 3a). Similar to (7), we determine the relations for A_2 and A_3:

$$E_s = \frac{A^2}{2} T_s = \frac{1}{16}(E_1 + 4E_2 + 11E_3) =$$

$$= 0 + \frac{1}{16} \cdot \frac{A_2^2}{2} T_s (4 + 11k^2) = \frac{A_2^2}{32} T_s (4 + 11k^2).$$

Hence,

$$A_1 = 0, A_2 = \frac{4A}{\sqrt{4 + 11k^2}}, A_3 = \frac{4kA}{\sqrt{4 + 11k^2}}.$$

Thus, for configuration (1, 5, 10) (Fig. 3b), the following may be obtained:

$$E_s = \frac{A^2}{2} T_s = \frac{1}{16}(E_1 + 5E_2 + 10E_3) =$$

$$= 0 + \frac{1}{16} \cdot \frac{A_2^2}{2} T_s (5 + 10k^2) = \frac{A_2^2}{32} T_s (5 + 10k^2),$$

$$A_1 = 0, A_2 = \frac{4A}{\sqrt{5 + 10k^2}}, A_3 = \frac{4kA}{\sqrt{5 + 10k^2}}.$$

Figure 4 shows dependencies of BER on coefficient k while receiving 16-APSK signals when applying the constellation format (1, 4, 11) for different types of interference.

Figure 5 shows similar results for the 16-APSK format (1, 5, 10).

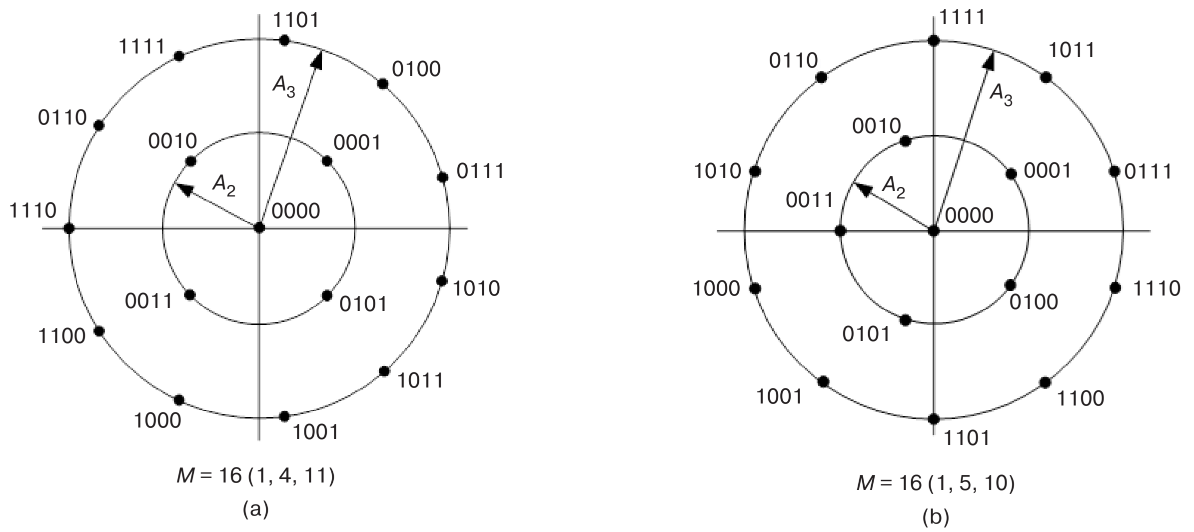


Fig. 3. 16-APSK signal constellations (1, 4, 11) and (1, 5, 10)

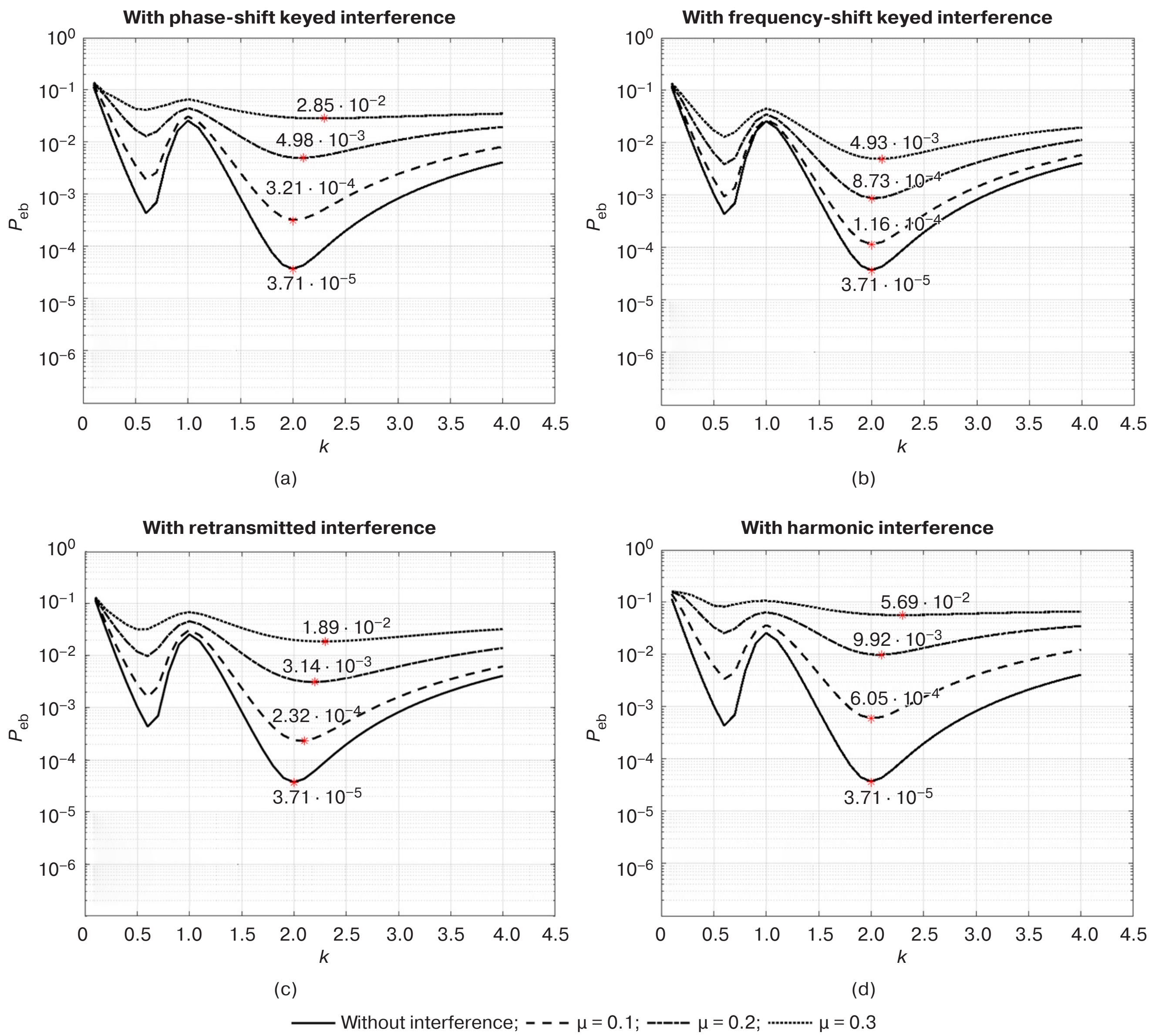


Fig. 4. Dependencies of BER on coefficient k for the 16-APSK constellation format (1, 4, 11) at different types of interference

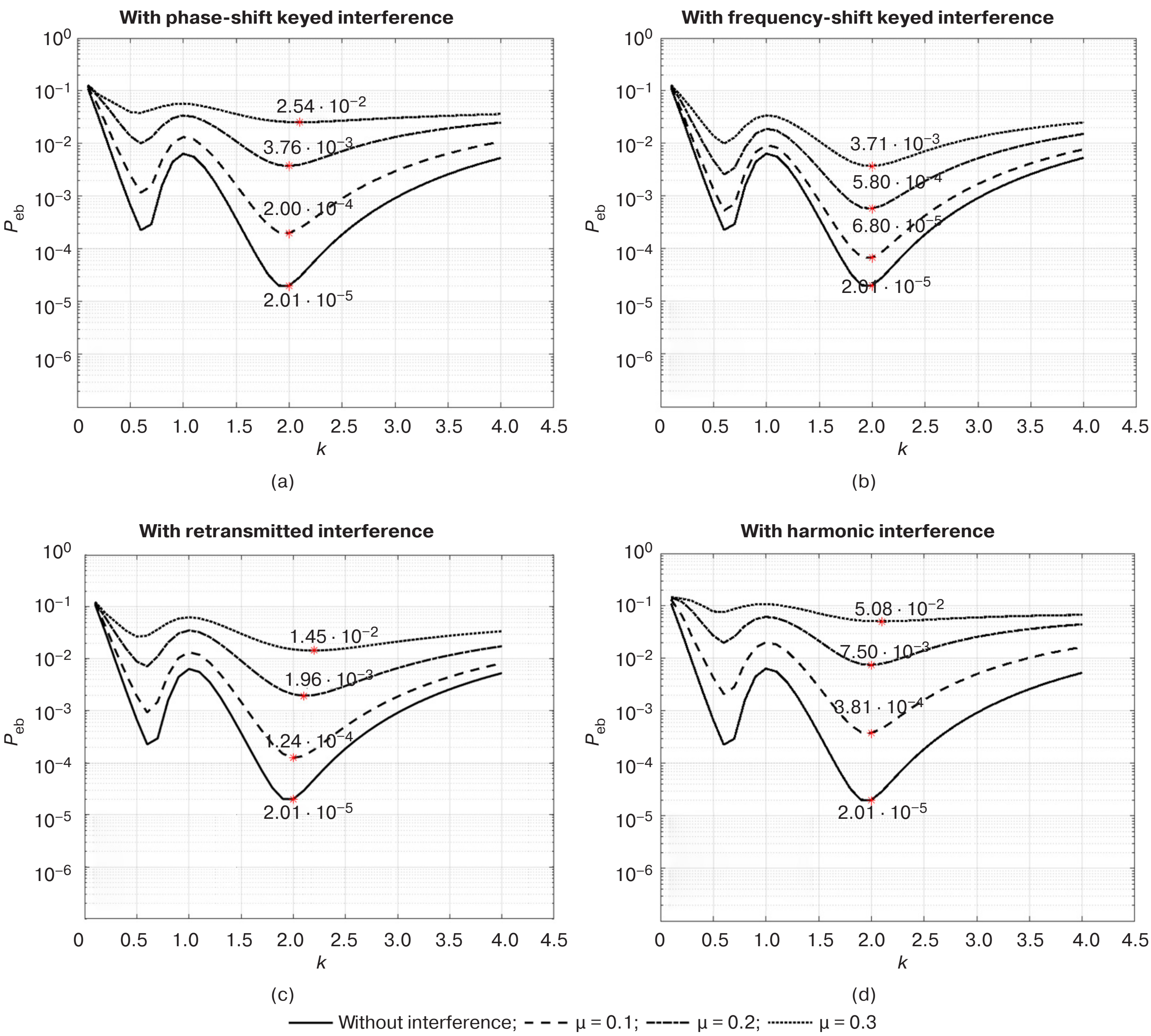


Fig. 5. Dependencies of BER on coefficient *k* for the 16-APSK constellation format (1, 5, 10) at different types of interference

The graphs show that the use of 16-APSK formats (1, 4, 11) and (1, 5, 10) yields some increase in noise immunity at the optimal value of coefficient *k* compared to format (4, 12). It can also be noted that with increasing relative interference intensity μ, the optimal value of *k* shifts to a higher value.

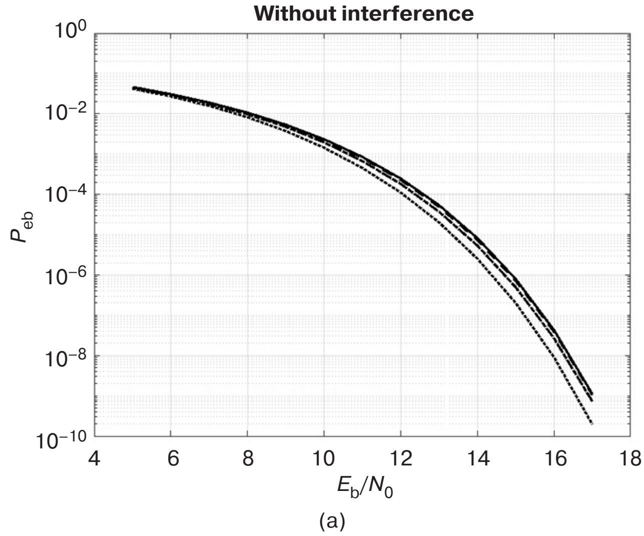
For comparison, Table 1 summarizes the optimal values of coefficients *k* for different formats, at which the BER is minimized.

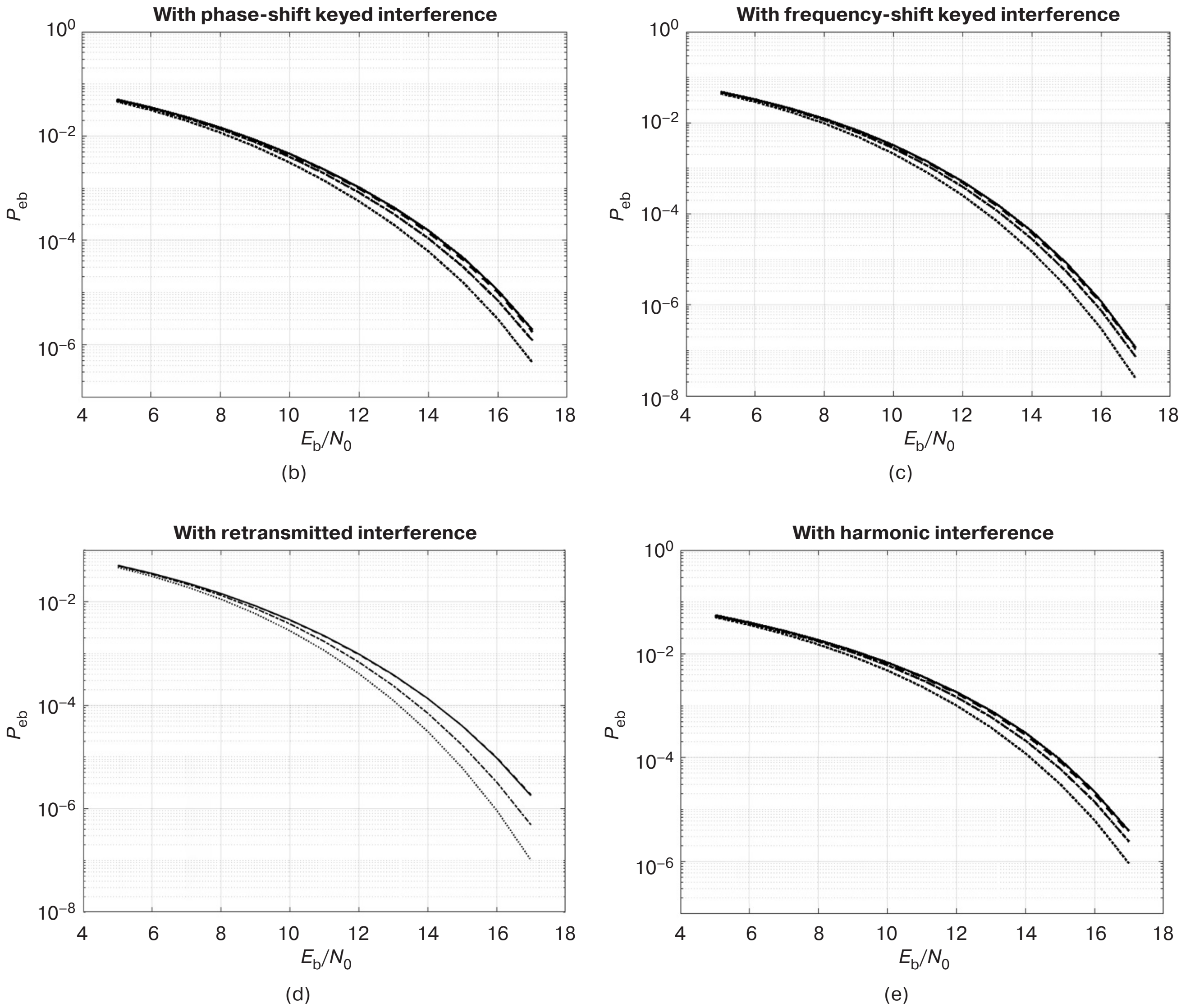
Figure 6 shows the calculation results for the reception noise immunity of 16-APSK signals with formats (1, 4, 11) and (1, 5, 10). It also shows the optimized constellation (4, 12) (at $A_2 = 2.5A_1$) compared to the standard version (4, 12) (at $A_2 = 2.7A_1$) used in the DVB-S2 standard, when received against different types of interference with relative intensity $\mu = 0.16$. The average energies for all formats are assumed to be similar.

The advantage of format (1, 5, 10) over other types of constellations is evident. The energy gain in this case reaches 1 dB. When using format (1, 4, 11), some increase in noise immunity is also observed when compared to the optimal constellation (4, 12). However, it is small.

Table 1. Optimal values of coefficients *k*

Format		*M* = 16				
		μ	0	0.1	0.2	0.3
1, 4, 11	*k*	Frequency-shift keyed	2	2	2	2.1
		Retransmitted	2	2	2.1	2.2
		Phase-shift keyed	2	2	2.1	2.3
		Harmonic	2	2	2.1	2.3
1, 5, 10	*k*	Frequency-shift keyed	2	2	2	2
		Retransmitted	2	2	2	2.1
		Phase-shift keyed	2	2	2	2.1
		Harmonic	2	2	2	2.1
4, 12	*k*	Frequency-shift keyed	2.5	2.5	2.5	2.5
		Retransmitted	2.5	2.6	2.7	2.9
		Phase-shift keyed	2.5	2.5	2.5	2.6
		Harmonic	2.5	2.5	2.5	2.6





$M16 = 1, 4, 11$; $A_2 = 2A_1$; $M16 = 1, 5, 10$; $A_2 = 2A_1$; $M16 = 4, 12$; $A_2 = 2.5A_1$; $M16 = 4, 12$; $A_2 = 2.7A_1$

Fig. 6. Dependencies of BER on SNR for different constellation formats under different types of interference

OPTIMIZING THE CONSTELLATION FORMAT FOR 32-APSK

The 32-APSK (4, 12, 16) signal constellation (Fig. 7) has 3 circles with amplitude ratios $A_2 = k_2A_1$ and $A_3 = k_3A_1$ and three energy levels E_1, E_2, and E_3, respectively. The amplitude ratios can be calculated in a similar way to that of $M = 16$. The average symbol energy may be written, as follows:

$$E_s = \frac{A^2}{2}T_s = \frac{1}{32}(4E_1 + 12E_2 + 16E_3) = \\ = \frac{A_1^2}{16}T_s(1 + 3k_2^2 + 4k_3^2).$$

Hence,

$$A_1 = \frac{2\sqrt{2}A}{\sqrt{1+3k_2^2+4k_3^2}},\ A_2 = \frac{2\sqrt{2}k_2A}{\sqrt{1+3k_2^2+4k_3^2}}, \\ A_3 = \frac{2\sqrt{2}k_3A}{\sqrt{1+3k_2^2+4k_3^2}}.$$

The dependence of BER on coefficients k_2 and k_3 appears as a surface in the three-dimensional coordinate system. Figure 8 shows an example at SNR E_b/N_0 = 13 dB and the absence of interference. In this case, minimum P_{eb} value is achieved for $k_2 = 2.5$ and $k_3 = 3.9$.

The optimal values of coefficients k_2 and k_3 at which the BER is minimal in the presence of different types of interference are given in Table 2.

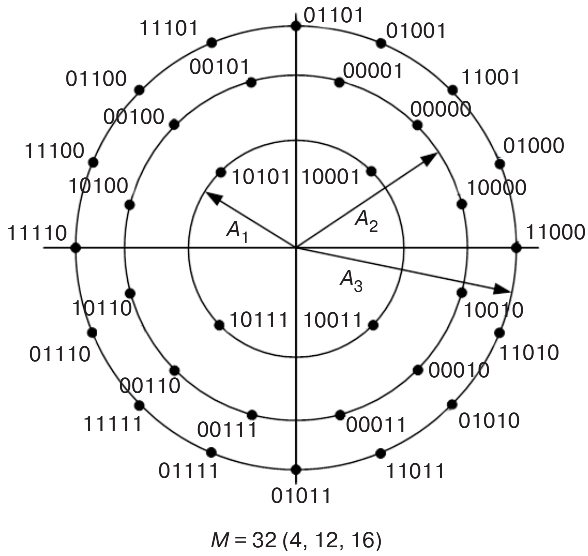


Fig. 7. 32-APSK signal constellation (4, 12, 16)

It follows from Table 2 that the optimal values of these ratios increase with increasing interference intensity. Thus, if in the presence of noise interference only ($\mu = 0$), the optimal ratios are $A_2 = 2.5A_1$ and $A_3 = 3.9A_1$, then for $\mu = 0.3$, average ratios $A_2 = 2.65A_1$ and $A_3 = 5.2A_1$ are recommended.

Figure 9 shows the results of noise immunity calculation for 32-APSK format ($A_2 = 2.5A_1$ and $A_3 = 3.9A_1$) when compared to the format used in DVB-S2 standard ($A_2 = 2.64A_1$ and $A_3 = 4.64A_1$) under different types of interference. The average energies for both formats are assumed to be similar. It can be observed that BER is slightly reduced in all cases, and the energy gain at $10^{-5} \le P_{eb} \le 10^{-4}$ is about 1 dB.

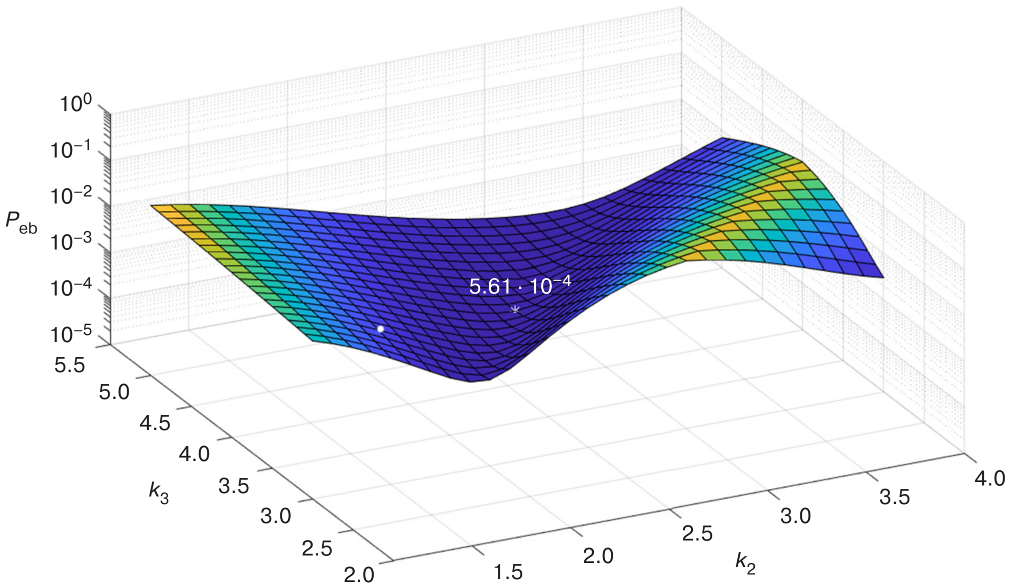
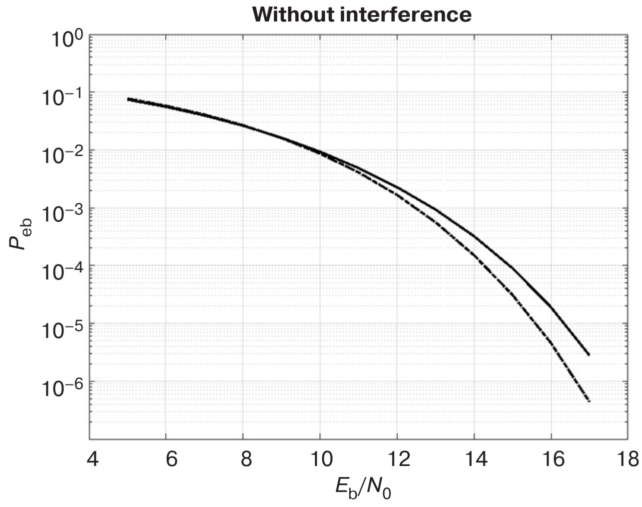


Fig. 8. Dependence of BER on k_2 and k_3 coefficients

Table 2. Optimal values of coefficients k_2 and k_3

Format			$M = 32$			
	μ		0	0.1	0.2	0.3
4, 12, 16	k_2/k_3	Frequency-shift keyed	2.5/3.9	2.5/3.9	2.5/4.0	2.6/4.4
		Retransmitted	2.5/3.9	2.5/3.9	2.6/4.5	2.6/4.8
		Phase-shift keyed	2.5/3.9	2.5/3.9	2.6/4.4	2.5/6.0
		Harmonic	2.5/3.9	2.5/4.0	2.6/4.4	3/6.0



(a)

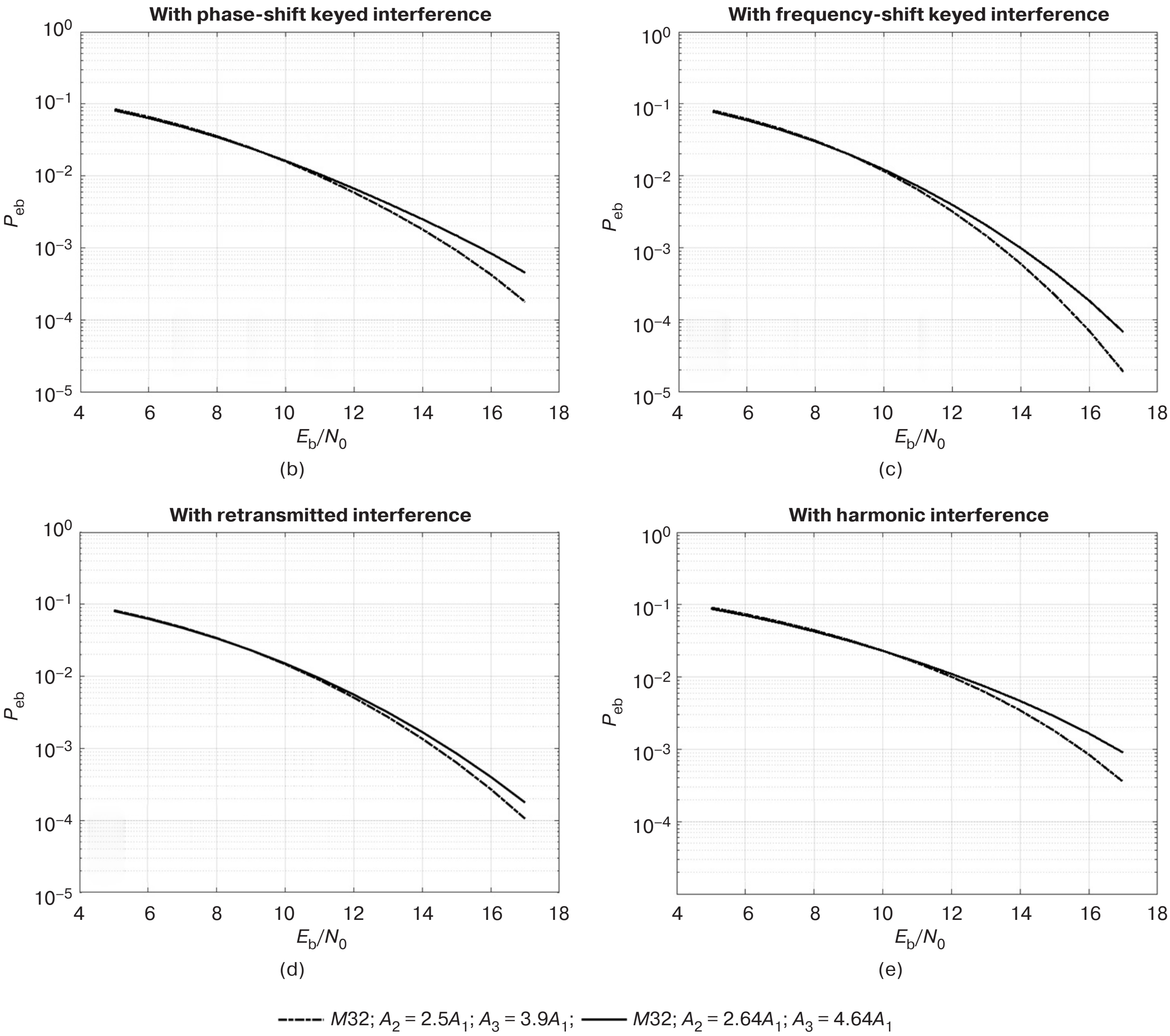


Fig. 9. Dependencies of BER on SNR for suggested amplitude ratios and standard ratios of DVB-S2 standard at different interference types

CONCLUSIONS

The following conclusions can be drawn as a result of this study:

1. The quality of communication in information transmission systems in the presence of non-fluctuating interference of low intensity can be improved by using the existing constellations of 16-APSK (4, 12) and 32-APSK (4, 12, 16), with a change in amplitude ratios ($A_2 = 2.5A_1$) for 16-APSK and ($A_2 = 2.5A_1$ and $A_3 = 3.9A_1$) for 32-APSK.
2. Due to the more efficient use of the signal power, applying constellations with a zero-amplitude point to 16-APSK allows reception noise immunity to be increased. For example, using constellation (1, 5, 10) with a ratio of $A_2 = 2A_1$, the power gain over standard constellation (4, 12) can be up to 1 dB.

Authors' contributions

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

X.Kh. Dang—conducting computer calculations.

A.A. Lelyukh—processing the results.

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