Modern radio engineering and telecommunication systems

Современные радиотехнические и телекоммуникационные системы

UDC 621.391.072
https://doi.org/10.32362/2500-316X-2024-12-5-33-41
EDN ELQHEK

RESEARCH ARTICLE

Noise immunity of signal reception with multiple frequency-shift keying against retransmitted interference

Alexandra E. Troitskaya,
Yuriy A. Polevoda @,
Gennady V. Kulikov

MIREA – Russian Technological University, Moscow, 119454 Russia
@ Corresponding author, e-mail: polevoda@mirea.ru

Abstract
Objectives. Radio engineering information transmission systems are widely used in robotic systems employed in various military and civilian services. If such systems are used in a harsh environment, where a large amount of retransmitted interference occurs, for example, if a complex is buried under rubble or is located in reinforced concrete pipes or other utility facilities, communication with the command post may be lost. Thus, the task of maintaining reliable communications under difficult conditions of radio wave propagation is very urgent. In the field of telecommunications, multiposition types of modulation are widely used, which, despite their good spectral characteristics, provide low noise immunity under conditions of nonfluctuating interference, especially in cases of retransmitted interference. Therefore, it is relevant to explore the possibility of using multiple frequency-shift keying (M-FSK) signals in radio systems with complex interference environments. The paper sets out to analyze the noise immunity of coherent reception of M-FSK signals against the background of retransmitted interference.
Methods. Statistical radio engineering and mathematical modeling methods are used according to the theory of optimal signal reception.
Results. A model of the M-FSK signal and retransmitted interference is provided. The statistical parameters of the distributions of random processes occurring in a multichannel coherent receiver of M-FSK signals against retransmitted interference are obtained; based on this, the bit error rate is calculated when receiving M-FSK signals of different positionality M against retransmitted interference with different intensities.
Conclusions. The impact of retransmitted interference is shown to result in a decrease in the noise immunity of M-FSK signal reception, which is greater the higher its intensity. With increasing positionality of M-FSK signals at low intensity of retransmitted interference, the noise immunity of reception is significantly improved; however, high-intensity interference significantly increases the bit error rate. The presence of interference with a relative intensity of 0.5 causes energy losses from 4 to 6 dB depending on the positionality. When $M > 4$, M-FSK signals gain significantly in terms of noise immunity over signals with multiple phase-shift keying, quadrature amplitude modulation, and amplitude and phase-shift keying.

Keywords: multiple frequency-shift keying, retransmitted interference, noise immunity, bit error rate

• **Submitted:** 12.03.2024 • **Revised:** 03.04.2024 • **Accepted:** 12.07.2024

For citation: Troitskaya A.E., Polevoda Yu.A., Kulikov G.V. Noise immunity of signal reception with multiple frequency-shift keying against retransmitted interference. *Russ. Technol. J.* 2024;12(5):33–41. https://doi.org/10.32362/2500-316X-2024-12-5-33-41

Financial disclosure: The authors have no financial or property interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

Помехоустойчивость приема сигналов с многопозиционной частотной манипуляцией на фоне ретранслированной помехи

А.Е. Троицкая,
Ю.А. Полевода @,
Г.В. Куликов

МИРЭА – Российский технологический университет, Москва, 119454 Россия
@ Автор для переписки, e-mail: polevoda@mirea.ru

Резюме

Цели. Радиотехнические системы передачи информации широко применяются в роботизированных комплексах для использования военными и гражданскими службами. При попадании такого комплекса в сложную окружающую среду, в которой возникает большое количество ретранслированных помех, например, при попадании комплекса под завал, в железобетонные трубы или различные коммунальные объекты, связь с командным пунктом может быть потеряна. Задача поддержания надежной связи в сложных условиях распространения радиоволн является весьма актуальной. В области телекоммуникаций широко используются многопозиционные виды модуляции, которые, несмотря на их хорошие спектральные характеристики, обеспечивают невысокую помехоустойчивость в условиях нефлуктуационных помех, особенно в случае ретранслированных помех. Представляется целесообразным исследовать возможность применения сигналов с многопозиционной частотной манипуляцией (М-ЧМ) в радиосистемах со сложной помеховой обстановкой. Целью работы является анализ помехоустойчивости когерентного приема сигналов М-ЧМ на фоне ретранслированной помехи.

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

Результаты. Приведена модель сигнала М-ЧМ и ретранслированной помехи. Получены статистические параметры распределений случайных процессов в многоканальном когерентном приемнике сигналов М-ЧМ на фоне ретранслированной помехи. На этой основе рассчитана вероятность битовой ошибки при приеме сигналов М-ЧМ разной позиционности *M* на фоне ретранслированной помехи с различной интенсивностью.

Выводы. Показано, что воздействие ретранслированной помехи приводит к снижению помехоустойчивости приема сигналов М-ЧМ, которое тем больше, чем выше интенсивность помехи. С возрастанием позиционности сигналов М-ЧМ при небольшой интенсивности ретранслированной помехи помехоустойчивость приема значительно улучшается, но помеха большой интенсивности сильно увеличивает вероятность битовой ошибки. Наличие помехи с относительной интенсивностью 0.5 вызывает энергетические потери от 4 до 6 дБ в зависимости от позиционности. При $M > 4$ сигналы М-ЧМ значительно выигрывают в помехоустойчивости у сигналов с многопозиционной фазовой, квадратурной амплитудной и амплитудно-фазовой манипуляцией.

Ключевые слова: многопозиционная частотная манипуляция, ретранслированная помеха, помехоустойчивость, вероятность битовой ошибки

• **Поступила:** 12.03.2024 • **Доработана:** 03.04.2024 • **Принята к опубликованию:** 12.07.2024

Для цитирования: Троицкая А.Е., Полевода Ю.А., Куликов Г.В. Помехоустойчивость приема сигналов с многопозиционной частотной манипуляцией на фоне ретранслированной помехи. *Russ. Technol. J.* 2024;12(5):33–41. https://doi.org/10.32362/2500-316X-2024-12-5-33-41

Прозрачность финансовой деятельности: Авторы не имеют финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

Radio engineering information transmission systems are widely used in robotic complexes for military and civilian applications such as civil defense, emergencies and disaster relief[1] [1–4]. In a harsh environment involving a large amount of retransmitted interference[2] [5–7], e.g., when the complex gets under rubble, reinforced concrete pipes, or various utilities, communication with the command center may be lost. Therefore, maintaining reliable communication with such robotic complexes under complex conditions of radio wave propagation is highly relevant.

Currently, multiposition modulation types are widely used in telecommunications. It is known that signals with multiple phase-shift keying (M-PSK), quadrature amplitude manipulation (QAM), and amplitude and phase-shift keying (APSK), despite their good spectral characteristics, have low noise immunity under conditions of nonfluctuating interference, especially in cases of retransmitted interference [8–12]. Therefore, it makes sense to investigate the possibility of using M-FSK signals [13–15] in radio systems operating in a complex interference environment. The paper aims to analyze the noise immunity of the coherent reception of M-FSK signals against retransmitted interference.

MODELING M-FSK SIGNAL AND RETRANSMITTED INTERFERENCE

Multiple frequency-shift keying is a method for transmitting digital information using multiple frequencies. In communication technology, M-FSK signals of different M positionality (ranging from 4 to 64) are used, which have different bandwidths at a given rate of information transmission.

For an M-FSK signal, the ith version of sending a channel symbol with duration T_s, carrying information about $k = \log_2 M$ information bits, can be written as follows:

$$s_i(t) = A_0 \cos\left[\left(\omega_0 + \left(i - \frac{M+1}{2}\right)\right)\Delta\omega t\right], \quad i = \overline{1, M},\ t \in (0, T_s], \tag{1}$$

where $A_0 = \sqrt{2E_s / T_s}$ is the signal nominal amplitude, $E_s = kE_b$ is channel symbol energy, E_b is the energy per one bit of information; ω_0 is the center frequency of the signal spectrum (carrier frequency); $\Delta\omega = 2\Delta\omega_d$, $\Delta\omega_d$ is frequency deviation (the minimum deviation that fulfills the orthogonality condition is equal to $\pi/2T_s$); and t is time.

By introducing the notations of shift keying index $h = \Delta\omega_d T_s/\pi$ and multiposition channel symbol $C_i = \pm 1, \pm 3, ..., \pm(M-1)$, expression (1) can be represented in the following form [15]:

$$s_i(t) = A_0 \cos\left(\omega_0 t + C_i h \frac{\pi}{T_s} t\right).$$

An example of frequency distribution for 8-FSK signal is shown in Fig. 1. The signal points and their corresponding channel symbols are arranged according to the Gray code.

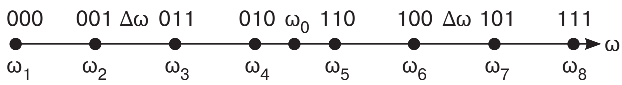

Fig. 1. Example of frequency arrangement for 8-FSK signal

[1] Order No. 633 dated December 26, 2018. On Approval and Enactment of the Radio Communications Manual of the Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters. https://base.garant.ru/72152196/ (in Russ.). Accessed November 25, 2023.

[2] ITU-R Recommendation P.1238-6 (10/2009). *Radio wave propagation data and prediction methods for planning indoor radio communication systems and local area radio networks in the frequency range 900 MHz to 100 GHz*. Series R. Radio wave propagation (in Russ.).

We use signal (1) with time delay $\tau \le T_s$ and random phase φ_{int} as the retransmitted interference arising due to M-FSK signal reflecting from some obstacle:

$$s_{int}(t) = \begin{cases} \mu A_0 \cos\left[\left(\omega_0 + \left(j - \frac{M+1}{2}\right)\Delta\omega\right)(t-\tau) + \varphi_{int}\right], \\ 0 < t \le \tau, \\ \mu A_0 \cos\left[\left(\omega_0 + \left(i - \frac{M+1}{2}\right)\Delta\omega\right)(t-\tau) + \varphi_{int}\right], \\ \tau < t \le T_s, \end{cases} \quad (2)$$

where μ is the relative intensity of the retransmitted interference, i and j are running signal numbers in the transmitted sequence.

The temporal relationship between the useful radio signal and retransmitted interference is shown in Fig. 2.

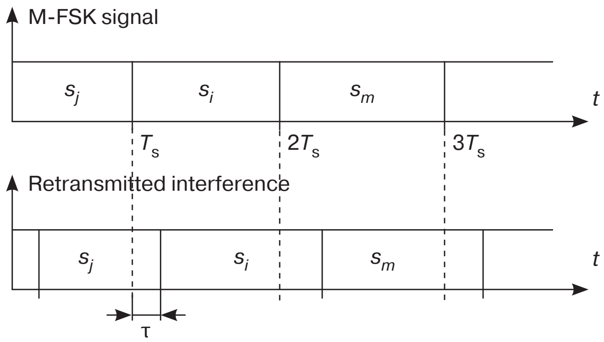

Fig. 2. Temporal relations between useful signal and retransmitted interference

We consider the presence of white Gaussian noise $n(t)$ with single-sided spectral density N_0 and δ correlation function at the receiver input of the information transmission system which are additional to the useful signal and retransmitted interference:

$$R(\tau) = \frac{N_0}{2}\delta(\tau).$$

CALCULATING THE BIT ERROR RATE

We consider a multichannel coherent demodulator [14, 15] as a receiver of M-FSK signals. In the presence of white Gaussian noise, the demodulator computes M integrals of convolution I_i of the received oscillation and M reference signals, as well as making a maximum likelihood decision on the channel symbol.

The bit error rate (BER) is calculated using the method described in [10–12]. For this, random parameters of retransmitted interference (2), such as intensity μ, phase φ_{int}, delay τ, and information symbol in the delayed copy, are assumed as initially fixed. This allows the probability of erroneous reception of a channel symbol conditioned on them to be determined:

$$P_{es}^{*} = 1 - \prod_{i=1}^{M} p_i(I_m > I_i)\Big|_m, \ m \ne i. \quad (3)$$

Given this condition, and assuming the presence of white Gaussian noise at the receiver input, the distributions of random processes being convolution integrals in the receiver channels and their linear combinations "mi" can be considered as normal. To obtain probabilities $p_i(I_m > I_i)$ included in (3) and defined through the standard probability integral (error function), it would be sufficient to calculate their conditional statistical characteristics:

- mathematical expectation

$$m_{mi}^{*} = \frac{2E_s}{N_0}\left\{1 + \mu\frac{\sin x}{x} \times \right.$$
$$\times \frac{\tau}{T_s}\cos\left[\left(\frac{M+1}{2} - \frac{j+m}{2}\right)\Delta\omega T_s\frac{\tau}{T_s} + \eta\right] +$$
$$+ \mu\left(1 - \frac{\tau}{T_s}\right)\cos\left[\left(\frac{M+1}{2} - m\right)\Delta\omega T_s\frac{\tau}{T_s} + \eta\right] - \frac{\sin y}{y} -$$
$$- \mu\frac{\tau}{T_s}\cdot\frac{\sin z}{z}\cos\left[\left(\frac{M+1}{2} - \frac{(j+i)}{2}\right)\Delta\omega T_s\frac{\tau}{T_s} + \eta\right] -$$
$$- \left(1 - \frac{\tau}{T_s}\right)\mu\frac{\sin g}{g}\cos\left[\frac{(m-i)\Delta\omega T_s}{2} - \right.$$
$$\left.\left. - \left(\frac{m+i}{2} + \frac{M+1}{2}\right)\Delta\omega T_s\frac{\tau}{T_s} + \eta\right]\right\},$$

- variance

$$D_{mi}^{*} = \frac{4E_s}{N_0}\left(1 - \frac{\sin y}{y}\right),$$

where

$$\eta = \varphi_{int} - \omega_0\tau, \ x = (j-m)\frac{\Delta\omega T_s}{2}\cdot\frac{\tau}{T_s},$$
$$y = (m-i)\Delta\omega T_s, \ z = (j-i)\frac{\Delta\omega T_s}{2}\cdot\frac{\tau}{T_s},$$

$$g = (m-i)\frac{\Delta\omega T_s\left(1 - \frac{\tau}{T_s}\right)}{2}.$$

For obtaining the unconditional error probability P_{es}, the averaging of conditional probability P_{es}^{*} for random interference parameters, such as the random phase φ_{int}, is carried out using a numerical method. Parameters μ and τ are assumed to be fixed. At the same time, the calculations are performed with an enumeration of all possible combinations of channel symbols. When calculating the BER P_{eb}, recommendation [14] describing the relationship between its value and the error probability when receiving channel symbol P_{es} for multiposition orthogonal signals is taken into account:

$$P_{eb} = P_{es}/((M-1)/(M/2)).$$

CALCULATION RESULTS

Based on the derived formulas, the noise immunity of the M-FSK signal reception with positionalities M = 2, 4, 8, 16, 32 is calculated. During the study, the following radio channel parameters vary: signal-to-noise ratio (SNR) E_b/N_0 lies within the range from 1 to 13 dB; the relative intensity of retransmitted interference μ lies in the range [0; 1]; the relative interference delay τ/T_s = 0.5. The calculation results are presented in Figs. 3 and 4.

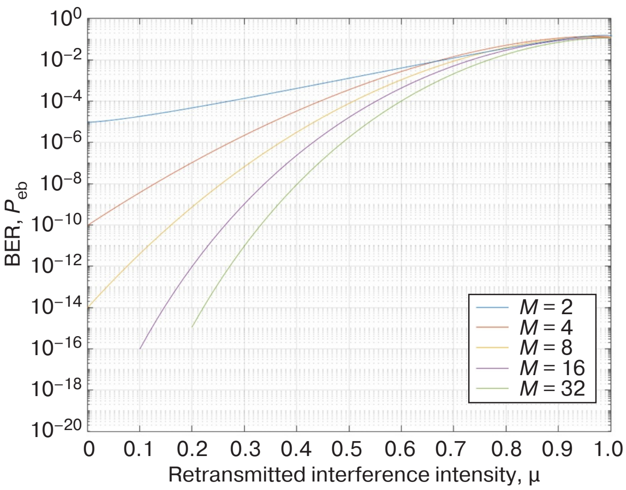

Fig. 3. Dependencies of BER P_{eb} on the relative intensity of the retransmitted interference μ at E_b/N_0 = 13 dB

The exposure to retransmitted interference results in reduced noise immunity: the higher the interference intensity, the greater the reduction. From this perspective, signals with higher positionality ($M \geq 8$) are preferable; at low relative interference intensity ($\mu < 0.3$), these provide a BER several orders of magnitude lower than low-position 2-FSK and 4-FSK signals.

Even at high relative intensity of retransmitted interference ($\mu \in [0.4; 0.5]$), the use of signals with multiple frequency-shift keying allows a fairly low bit error rate (10^{-5}–10^{-4}) to be maintained, which is not available when using other types of QAM [10], M-PSK [11], and APSK [12] signals at the same positionality.

The energy losses due to the impact of retransmitted interference during reception of M-FSK signals can be estimated by plotting the dependence of BER P_{eb} on SNR E_b/N_0 at different relative interference intensities μ (Fig. 4).

From the graphs, it can be seen that increasing the M-FSK signal positionality from 2 to 32 significantly improves the reception noise immunity. For example, at a low intensity of retransmitted interference ($\mu \leq 0.1$) and SNR (E_b/N_0 = 10 dB), the BER is seven times lower.

The presence of interference with relative intensity μ = 0.5 at $P_{eb} = 10^{-4}$ causes an energy loss of 5 to 6 dB depending on positionality. Nevertheless, the reception noise immunity of M-FSK signals of high positionality remains generally high.

COMPARING RECEPTION NOISE IMMUNITY OF M-FSK SIGNALS WITH OTHER TYPES OF MULTIPOSITION MODULATION

For comparison, the graphs of BER dependence on the relative intensity of retransmitted interference while receiving M-FSK and QAM signals [10] of the same positionality 4, 16, and 32 are shown in Fig. 5.

It can be seen that, at positionality M = 4, the reception noise immunity of these signals is approximately the same; however, with an increasing value of M, signals with M-FSK improve significantly (by several times for BER) over QAM signals across a wide range of retransmitted interference intensities ($\mu \in [0; 0.6]$). A similar conclusion can be made with respect to APSK signals [12], whose reception immunity approximately corresponds to QAM and, even more so, with respect to M-PSK signals [11] being lost to QAM. However, when mentioning the advantages of M-FSK signals, their spectral characteristics, according to which significant losses to other signals may occur, should be taken into account [13, 15].

CONCLUSIONS

In the present work, the reception noise immunity of signals with multiple frequency-shift keying of M positionality from 2 to 32 is analyzed in the presence of retransmitted interference in the communication channel for different SNR and relative interference intensity values. The research allows the following conclusions to be drawn:

1. Increasing positionality improves noise immunity of M-FSK signal reception while decreasing BER by several orders of magnitude at a low intensity of retransmitted interference.

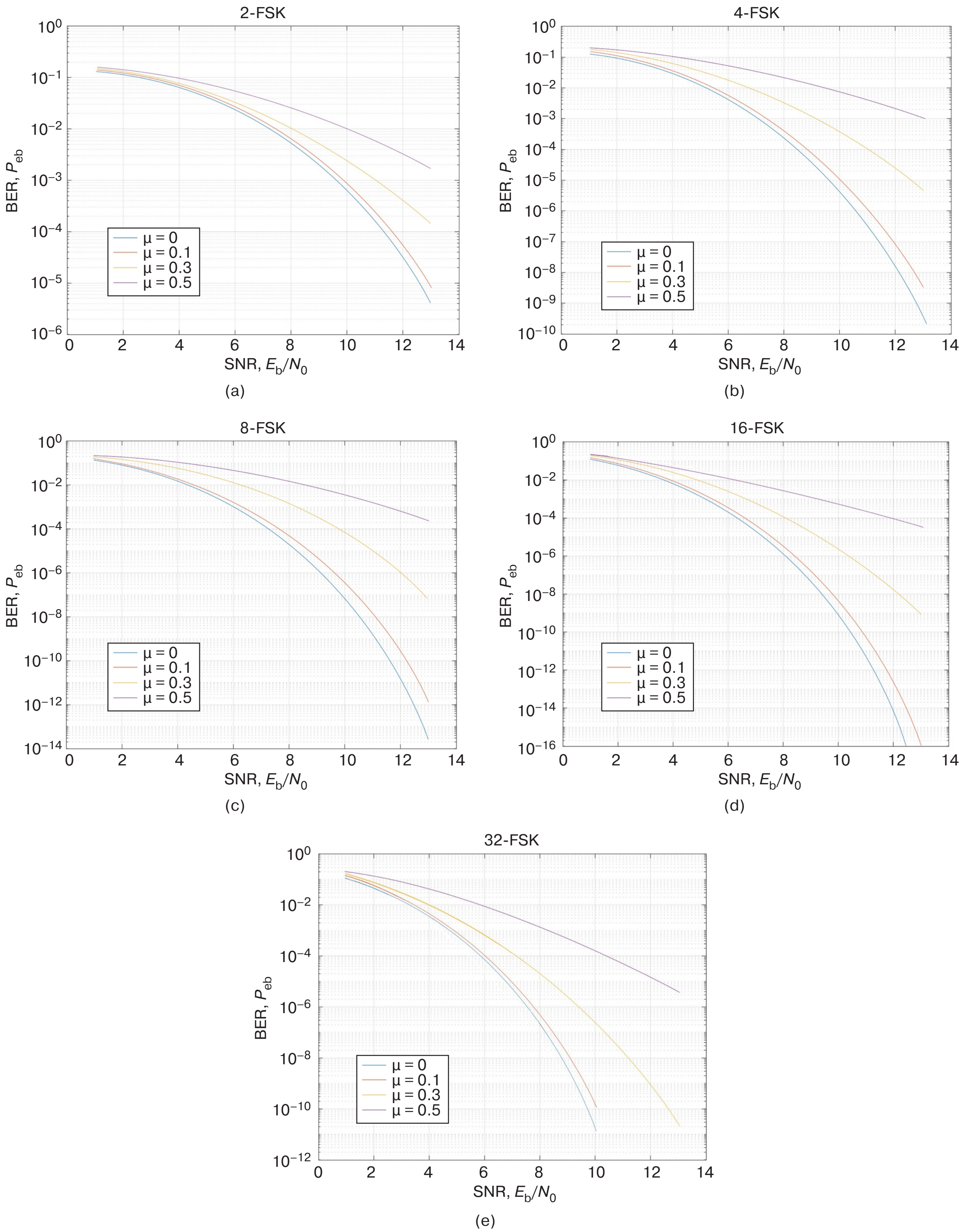

Fig. 4. Dependencies of BER P_{eb} on SNR E_b/N_0 under the influence of retransmitted interference for signals:
(a) 2-FSK,
(b) 4-FSK,
(c) 8-FSK,
(d) 16-FSK,
(e) 32-FSK

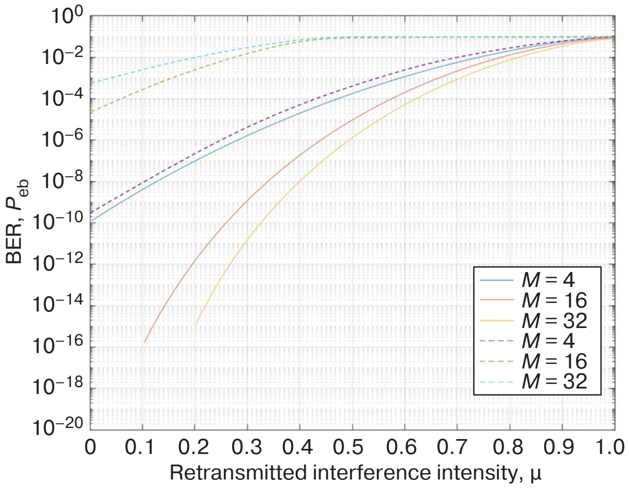

Fig. 5. Dependencies of BER P_{eb} on the relative intensity μ of retransmitted interference while receiving M-FSK (solid lines) and QAM (dashed lines) signals of the same positionality

2. The impact of retransmitted interference reduces M-FSK signal reception noise immunity, which is greater the higher its intensity. For example, the presence of interference with a relative intensity $\mu = 0.5$ at $P_{eb} = 10^{-4}$ causes energy losses from 4 to 6 dB depending on the M-FSK signal positionality.
3. At $M > 4$, M-FSK signals significantly gain in noise immunity over M-PSK, QAM, and APSK signals across a wide range of retransmitted interference intensities.
4. The use of M-FSK signals with such high energy characteristics is justified in radio channels without significant frequency limitations.

Authors' contributions

A.E. Troitskaya—conducting computer calculations.

Yu.A. Polevoda—processing the results.

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

REFERENCES

1. Askhadeev A.I., Pavlov E.V., Barannik A.Y., Lagutina A.V., Kozlov V.I., Penkov I.A., Chirko O.V. Emercom of Russia Robotics System. State and Prospects of Development. *Tekhnologii grazhdanskoi bezopasnosti = Civil Security Technologies*. 2022;19(2–72):41–47 (in Russ.). Available from URL: https://www.vniigochs.ru/upload/medialibrary/6b3/ufktj81owcrv39y864piuh8dtzmw0njo/p_8_Emercom_Russia_Robotics_System_tgb_2_2022.pdf
2. Antokhin E.A., Panasenko N.N., Chernova A.D. Main requirements to wireless communication channels of military ground robotic complexes. *Robototekhnika i tekhnicheskaya kibernetika = Robotics and Technical Cybernetics*. 2017;4(17):10–14 (in Russ.).
3. Andreev V.P. Ensuring the safety of the work of film and TV journalists by means of extreme robotics. In: *Proceedings of the International Scientific and Technological Conference EXTREME ROBOTICS*. 2022;1(1):25–34 (in Russ.). Available from URL: https://er.rtc.ru/images/docs/2022/Proceedings_ER-2022.pdf
4. Manko S.V., Lokhin V.M., Diane S.K. Prototype multi-agent robotic debris removal system: principles of development and experimental studies. *Russ. Technol. J.* 2022;10(6):28–41 (in Russ.). https://doi.org/10.32362/2500-316X-2022-10-6-28-41
5. Gureev A.V., Gureev I.A., Pavlyuk Y.M., Thurain T. The effect of multipath propagation on characteristics of indoor broadband wireless systems. *Elektronnye informatsionnye sistemy = Electronic Information Systems*. 2017;4(15):17–23 (in Russ.).
6. Gureev A.V. Energetic characteristics of indoor wave propagation. *Izvestiya vysshikh uchebnykh zavedenii. Elektronika = Proceedings of Universities. Electronics*. 2015;20(4):421–430 (in Russ.).
7. Gureev A.V., Gureev I.A., Pavlyuk Y.M., Zhmylev V.A., Kachurenko D.S. Investigation of characteristics of electromagnetic waves propagation in buildings. *Elektronnye informatsionnye sistemy = Electronic Information Systems*. 2019;4(23):95–101 (in Russ.).
8. Bashkirov A.V., Krisilov A.V., Mashin V.V., Muratov A.V., Khoroshailova M.V. Analysis of symbol error rate for 16-QAM signals in the presence of QPSK signals and 16-QAM signals. *Radiotekhnika = Radioengineering*. 2020;84(6–12):5–9 (in Russ.). https://doi.org/10.18127/j00338486-202006(12)-01
9. Sidelnikov G.M. Comparative analysis of efficiency of spaced reception of signals with quadrature amplitude and with phase modulation in a channel with discrete multipath. *Vestnik Povolzhskogo gosudarstvennogo tekhnologicheskogo universiteta. Seriya: Radiotekhnicheskie i infokommunikatsionnye sistemy = Vestnik of Volga State University of Technology. Series: Radio Engineering and Infocommunication Systems*. 2020;2(46):18–30 (in Russ.). https://doi.org/10.25686/2306-2819.2020.2.18
10. Kulikov G.V., Lelyukh A.A., Grachenko E.N. Noise immunity of coherent signal receiver with quadrature amplitude modulation in the presence of relayed interference. *J. Commun. Technol. Electron*. 2020;65(8):934–938. https://doi.org/10.1134/S1064226920070074
[Original Russian Text: Kulikov G.V., Lelyukh A.A., Grachenko E.N. Noise immunity of coherent signal receiver with quadrature amplitude modulation in the presence of relayed interference. *Radiotekhnika i Elektronika*. 2020;65(8):804–808 (in Russ.). https://doi.org/10.31857/S0033849420070074]
11. Nguyen V.D. Noise immunity of correlation receiver of signal with multi-position phase shift keying in the presence of retransmitted interference. *Zhurnal radioelektroniki = J. Radio Electronics*. 2019;3 (in Russ.). https://doi.org/10.30898/1684-1719.2019.3.4

12. Kulikov G.V., Dang X.Kh. Noise immunity of reception of signal with amplitude-phase shift keying in a two-path communication channel. *Voprosy radioelektroniki. Seriya: Tekhnika televideniya = Questions of Radio Electronics. Series: TV Technique*. 2022;2:43–49 (in Russ.).
13. Haykin S. *Communication Systems*. John Wiley & Sons. Inc.; 2001. 816 p.
14. Proakis J. *Tsifrovaya svyaz'* (*Digital Communication*): transl. from Engl. Moscow: Radio i svyaz'; 2000. 800 p. (in Russ.). [Proakis J. *Digital Communications.* N.Y.: McGraw-Hill; 1995. 928 p.]
15. Xiong F. *Digital Modulation Techniques.* 2nd ed. Boston, London: Artech House, Inc.; 2006. 1039 p.

СПИСОК ЛИТЕРАТУРЫ

1. Асхадеев А.И., Павлов Е.В., Баранник А.Ю., Лагутина А.В., Козлов В.И., Пеньков И.А., Чирко О.В. Система робототехники МЧС России. Состояние и перспективы развития. *Технологии гражданской безопасности.* 2022;19(2–72): 41–47. URL: https://www.vniigochs.ru/upload/medialibrary/6b3/ufktj81owcrv39y864piuh8dtzmw0njo/p_8_Emercom_Russia_Robotics_System_tgb_2_2022.pdf
2. Антохин Е.А., Панасенко Н.Н., Чернова А.Д. Основные требования к беспроводным каналам связи наземных робототехнических комплексов военного назначения. *Робототехника и техническая кибернетика*. 2017;4(17):10–14.
3. Андреев В.П. Обеспечение безопасности работы кино- и тележурналистов средствами экстремальной робототехники. *Экстремальная робототехника*. *Труды 33-й Международной научно-технической конференции*. 2022;1(1):25–34. URL: https://er.rtc.ru/images/docs/2022/Proceedings_ER-2022.pdf
4. Манько С.В., Лохин В.М., Диане С.К. Принципы построения и экспериментальные исследования прототипного образца многоагентной робототехнической системы для разбора завалов. *Russian Technological Journal*. 2022;10(6): 28–41. https://doi.org/10.32362/2500-316X-2022-10-6-28-41
5. Гуреев А.В., Гуреев И.А., Павлюк Ю.М., Тхурайн Т. Влияние многолучевости распространения радиоволн на характеристики широкополосных беспроводных систем внутри зданий. *Электронные информационные системы*. 2017;4(15):17–23.
6. Гуреев А.В. Энергетические характеристики распространения электромагнитных волн внутри зданий. *Известия высших учебных заведений. Электроника*. 2015;20(4):421–430.
7. Гуреев А.В., Гуреев И.А., Павлюк Ю.М., Жмылев В.А., Качуренко Д.С. Исследование характеристик распространения электромагниных волн внутри зданий. *Электронные информационные системы*. 2019;4(23):95–101.
8. Башкиров А.В., Крисилов А.В., Машин В.В., Муратов А.В., Хорошайлова М.В. Анализ вероятностей символьных ошибок для 16-QAM-сигналов в присутствии QPSK-сигналов и 16-QAM-сигналов. *Радиотехника*. 2020;84(6–12): 5–9. https://doi.org/10.18127/j00338486-202006(12)-01
9. Сидельников Г.М. Сравнительный анализ эффективности разнесенного приема сигналов с квадратурной амплитудной и с фазовой модуляцией в канале с дискретной многолучевостью. *Вестник Поволжского государственного технологического университета. Серия: Радиотехнические и инфокоммуникационные системы*. 2020;2(46):18–30. https://doi.org/10.25686/2306-2819.2020.2.18
10. Куликов Г.В., Лелюх А.А., Грачeнко Е.Н. Помехоустойчивость когерентного приемника сигналов с квадратурной амплитудной манипуляцией при наличии ретранслированной помехи. *Радиотехника и электроника*. 2020;65(8): 804–808. https://doi.org/10.31857/S0033849420070074
11. Нгуен В.З. Помехоустойчивость корреляционного приемника сигналов с многопозиционной фазовой манипуляцией при наличии ретранслированной помехи. *Журнал радиоэлектроники.* 2019;3. https://doi.org/10.30898/1684-1719.2019.3.4
12. Куликов Г.В., Данг С.Х. Помехоустойчивость приема сигналов с амплитудно-фазовой манипуляцией в двухлучевом канале связи. *Вопросы радиоэлектроники. Серия: Техника телевидения*. 2022;2:43–49.
13. Haykin S. *Communication Systems*. John Wiley & Sons. Inc.; 2001. 816 p.
14. Прокис Дж. *Цифровая связь*: пер. с англ.; под ред. Д.Д. Кловского. М.: Радио и связь; 2000. 800 с.
15. Xiong F. *Digital Modulation Techniques.* 2nd ed. Boston, London: Artech House, Inc.; 2006. 1039 p.

About the authors

Alexandra E. Troitskaya, Student, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: troitskaya.a.e@mirea.ru. https://orcid.org/0009-0002-9315-8829

Yuriy A. Polevoda, Postgraduate Student, Department of Radio Electronic Systems and Complexes, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: polevoda@mirea.ru. https://orcid.org/0009-0007-6327-9685

Gennady V. Kulikov, Dr. Sci. (Eng.), Professor, Department of Radio Electronic Systems and Complexes, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: kulikov@mirea.ru. Scopus Author ID 36930533000, RSCI SPIN-code 2844-8073, http://orcid.org/0000-0001-7964-6653

Об авторах

Троицкая Александра Евгеньевна, студент, Институт радиоэлектроники и информатики, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: troitskaya.a.e@mirea.ru. https://orcid.org/0009-0002-9315-8829

Полевода Юрий Александрович, аспирант, кафедра радиоэлектронных систем и комплексов, Институт радиоэлектроники и информатики, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: polevoda@mirea.ru. https://orcid.org/0009-0007-6327-9685

Куликов Геннадий Валентинович, д.т.н., профессор, кафедра радиоэлектронных систем и комплексов, Институт радиоэлектроники и информатики, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: kulikov@mirea.ru. Scopus Author ID 36930533000, SPIN-код РИНЦ 2844-8073, http://orcid.org/0000-0001-7964-6653

Translated from Russian into English by K. Nazarov
Edited for English language and spelling by Dr. David Mossop