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RESEARCH ARTICLE

Investigation of multipath compensation efficiency in communication channels using filters with inverse impulse response

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Abstract

Objectives. A key challenge when transmitting data in modern communication systems is the multipath propagation of signals caused by reflections from various obstacles. Various methods have been developed to address this issue including: directional antennas; diversity reception; adaptive filtering; and the choice of effective modulation methods. One promising approach is the use of filters with impulse response (IR) inverse to IR channel. This allows for compensating delayed signals. The effectiveness of such filters depends on the accuracy of their parameter settings. The paper aims to develop guidelines for effectively using filters with inverse IR to compensate for multipath. Additionally, it aims to evaluate the impact of various channel parameters, such as time delays and reflected signal intensities, on the bit error rate (BER) and to determine the energy gain.

Methods. The methods of statistical radio engineering, the theory of optimal signal reception and mathematical modeling were used.

Results. The results of a study on the effectiveness of multipath compensation in communication channels when using filters with inverse IR to that of the channel at the receiving side are presented. A multipath communication channel model was developed in the *Simulink* software environment, consisting of six beams with different time delays and intensities. Discrete information reception was simulated using different modulation methods: 16-QAM (quadrature amplitude modulation), 8-PSK (phase-shift keying), and 8-FSK (frequency-shift keying). The BER value was estimated depending on the signal-to-noise ratio and multipath channel parameters, including time delays and reflected beam intensities. It was shown that the use of filters with inverse IR can significantly reduce BER and improve communication quality. The change in the BER value is estimated for deviations of filter parameters from the ideal ones.

Conclusions. The results demonstrate that the use of compensating filters is effective in combating multipath distortion, especially under strong interference conditions. The data obtained can be used for the design and optimization of modern communication systems operating in complex signal propagation conditions.

Keywords: multipath communication channel, impulse response, filter with inverse impulse response, multi-position modulation, bit error probability, signal-to-noise ratio

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НАУЧНАЯ СТАТЬЯ

Исследование эффективности компенсации многолучевости в каналах связи при использовании фильтров с инверсной импульсной характеристикой

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Резюме

Цели. При передаче данных в современных системах связи одной из ключевых проблем является многолучевое распространение сигналов, вызванное отражениями от различных препятствий. Для борьбы с этим эффектом используются разные методы, такие как направленные антенны, разнесенный прием, адаптивная фильтрация и выбор эффективных методов модуляции. Одним из перспективных подходов является применение фильтров с импульсной характеристикой (ИХ), инверсной ИХ канала, которые позволяют компенсировать задержанные сигналы. Эффективность таких фильтров зависит от точности настройки их параметров. Цель работы состоит в выработке рекомендаций для обеспечения эффективной компенсации многолучевости при использовании фильтров с инверсной ИХ, оценке влияния параметров канала (временных задержек и интенсивностей отраженных сигналов) на вероятность битовой ошибки (bit error rate, BER) и определении энергетического выигрыша.

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

Результаты. Представлены результаты исследования эффективности компенсации многолучевости в каналах связи при использовании на приемной стороне фильтров с ИХ, инверсной ИХ канала. В программной среде *Simulink* разработана модель многолучевого канала связи, включающая шесть лучей с различными временными задержками и интенсивностями. Проведено моделирование приема дискретной информации для разных методов модуляции: 16-КАМ (квадратурной амплитудной), 8-ФМ (многопозиционной фазовой) и 8-ЧМ (многопозиционной частотной) модуляциями. Выполнена оценка вероятности битовой ошибки в зависимости от отношения сигнал/шум и параметров многолучевого канала (временных задержек, интенсивностей отраженных лучей). Показано, что применение фильтров с инверсной ИХ позволяет значительно снизить вероятность битовой ошибки и улучшить качество связи. Оценено изменение величины BER при отклонениях параметров фильтра от идеальных.

Выводы. Результаты демонстрируют, что использование компенсационных фильтров эффективно для борьбы с многолучевыми искажениями, особенно в условиях сильной интерференции. Полученные данные могут быть использованы для проектирования и оптимизации современных систем связи, работающих в сложных условиях распространения сигналов.

Ключевые слова: многолучевой канал связи, импульсная характеристика, фильтр с инверсной импульсной характеристикой, многопозиционная модуляция, вероятность битовой ошибки, отношение сигнал/шум

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INTRODUCTION

Modern communication systems face various challenges, one of which is data transmission in multipath environments. Multipath propagation, caused by signal reflection from various obstacles, can result in interference and degradation of the received signal, significantly reducing the quality of communication. In order to overcome this issue, several methods have been developed, such as: the use of directional antennas [1, 2], diversity reception [3–6], adaptive filtering [7, 8], and the selection of appropriate modulation techniques [9–12]. One key method used to mitigate the negative effects of multipath is through the use of impulse response (IR) filters which are inverse to the channel IR which allows delayed signals to be compensated [13–17]. This paper presents the results of modeling and analysis of the efficacy of these filters in a multipath communication channel when utilizing signals with various modulation techniques, such as: quadrature amplitude modulation (16-QAM, coherent detection); multi-position phase-shift keying (8-PSK, coherent detection); and multi-position frequency-shift keying (8-FSK, noncoherent detection).

The paper aims to evaluate the impact of multipath channel parameters (delay, reflected signal strength) and the filter on the bit error rate (BER) when receiving discrete signals, as well as to determine the energy gain from employing filters with inverse IR. For analysis, a multipath model was developed in the *Simulink*¹ environment, comprising six beams with distinct delays and intensities (discrete multipath).

MULTIPATH CHANNEL MODEL

An IR communication channel can be defined and its parameters estimated by means of a preliminary probing of the channel with specific form signals such as short δ -pulses, signals with frequency modulation, or signals encoded with specific pseudo-random sequences [18–23]. While this aspect is not detailed in the paper, it is assumed that the parameters of

the IR channel have been determined accurately or with some degree of error. Such information in the model can be obtained by using a short probe pulse, the duration of which determines the lower limit of the range of possible beam delays. For instance, the duration of the probe pulse is chosen to be 1 ns.

A discrete multipath channel model (6 beams, including the direct path $s_{\text{drc}}(t)$) is created using the *MATLAB/Simulink* (trial version) and *Scilab Xcos*² software environments. The delays τ_k of the signals are 0 (for the direct path), 7, 14, 21, 28, and 33 ns, while the relative (relative to the average amplitude of the direct path signal) intensities μ_k of the delayed signals are 0.09, 0.08, 0.07, 0.06, and 0.05, respectively (Fig. 1, left). The values for delays are provided for illustrative purposes only and may be adjusted depending on the specific radio propagation conditions.

Therefore, the output of the multipath channel can be described as follows:

$$s(t) = s_{\text{drc}}(t) + \sum_{k=1}^5 \mu_k s_{\text{drc}}(t - \tau_k) + n(t),$$

wherein $n(t)$ is white Gaussian noise (additive white Gaussian noise channel), t is the time.

The circuit of the filter with inverse IR consists of 6 branches, each with an amplification factor corresponding to the intensity and time delay (Fig. 1, right). In the portion which corresponds to delayed signals, the circuit acts as a mirror (in terms of polarity) of the communication channel mode.

BENCHMARKING FILTER WITH INVERSE IR

The benchmarking of a filter with inverse IR can be clearly seen when passing a single probe pulse through the channel. Figure 2a shows the oscillogram of the signal at the communication channel output showing 1 direct signal and 5 reflections, which corresponds to that of the IR channel.

¹ <https://www.mathworks.com/products/simulink.html>. Accessed February 15, 2025.

² <https://www.scilab.org/software/xcos>. Accessed April 05, 2025.

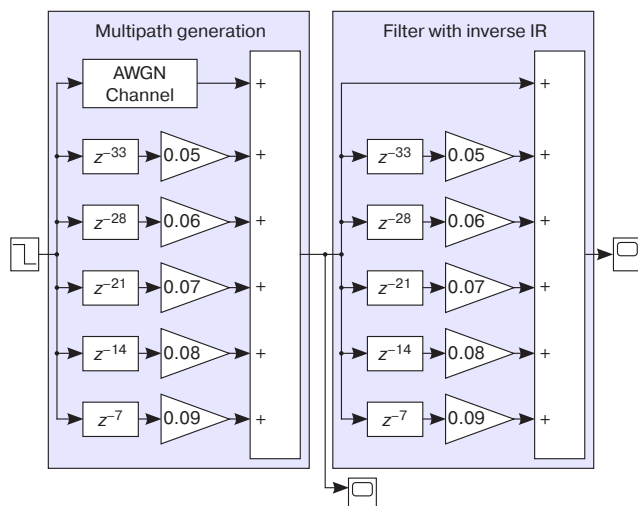


Fig. 1. Multipath signal generation and processing model.
 z^{-1} is delay unit, where “-1” is beam delay time

Figure 2b shows the signal at the output of a filter with inverse IR. This demonstrates that the filter has compensated for delayed beam signals. However, instead of these signals, responses appear at time positions that are twice the time delay. This is easily explained by the characteristics of signal passage through the filter [24].

SIMULATION OF COMMUNICATION CHANNEL USING MULTIPOSITION SIGNALS

Energy gain analysis

The study analyzes the energy gain (in terms of signal-to-noise ratio, SNR) in relation to the relative intensity of a reflected beam for various modulation techniques: 16-QAM, 8-PSK, and 8-FSK. The modeling is conducted with one direct and one reflected beam, with a delay of 7 ns. The intensity of the reflected beam μ varies over a broad range, allowing for an assessment of the impact of both weak and strong reflections on bit error rates. For each modulation technique, the relationships between BER and SNR (E_b/N_0 , where E_b is the energy per bit of information and N_0 is the noise power spectral density) are plotted (Fig. 3) both without the use (dashed lines) and with the use of the inverse IR filter (solid lines).

Figure 4 shows the results of calculating the energy gain for $\text{BER} = 10^{-3}$.

Figures 3 and 4 show that for a reflected beam intensity of $\mu = 0.3$, the gain in the SNR (E_b/N_0), when using a filter with inverse IR, varies between 1 and 10 decibels, depending on the modulation scheme employed. The gain for the 16-QAM signal is approximately twice that of the 8-PSK signal, and more than 10 times that of the 8-FSK signal. This is due to the

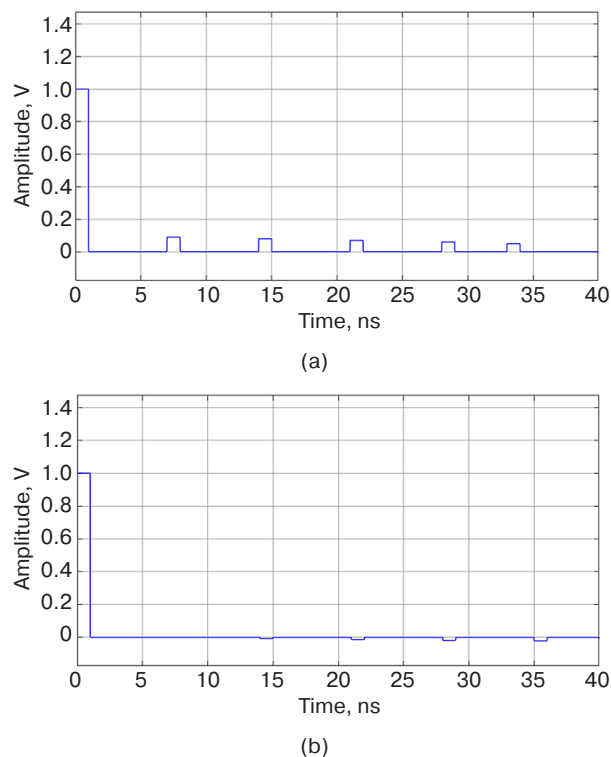


Fig. 2. Oscillograms: (a) IR; (b) signal at the output of the filter with inverse IR

fact that the 8-FSK signal has the highest initial immunity to interference [11]. For example, with the reflected beam intensity of $\mu = 0.3$ and SNR (E_b/N_0) of 9 dB, BER without a filter is approximately 10^{-3} for 8-FSK. It is more than one order of magnitude higher for 8-PSK and twice as high for 16-QAM.

The relationship between BER and SNR

The next stage of the study involves modeling a communication channel with 1 direct beam and 5 reflected beams, each with varying delays (7, 14, 21, 28, and 33 ns) and intensities (for 16-QAM and 8-PSK, $\mu = 0.09, 0.08, 0.07, 0.06$, and 0.05 relative to the average amplitude of the direct signal beam, and for 8-FSK, $\mu = 0.2, 0.3, 0.4, 0.5$, and 0.6). The simulation results are BER as a function of SNR (E_b/N_0) for various numbers of beams (Figs. 5–7), with (solid lines) and without (dashed lines).

Figures 5 and 7 show that for any number of received signals, the filter with inverse IR compensates for multipath interference for all signal types, thus reducing BER. For example, with SNR of 10 dB for 16-QAM and 8-PSK signals with 5 received reflections, BER is reduced approximately by a factor of 7. For 8-FSK signal which has higher noise immunity. More intense reflections are used in the simulations, thus the improvement is less significant than when compared to 16-QAM and 8-PSK signals.

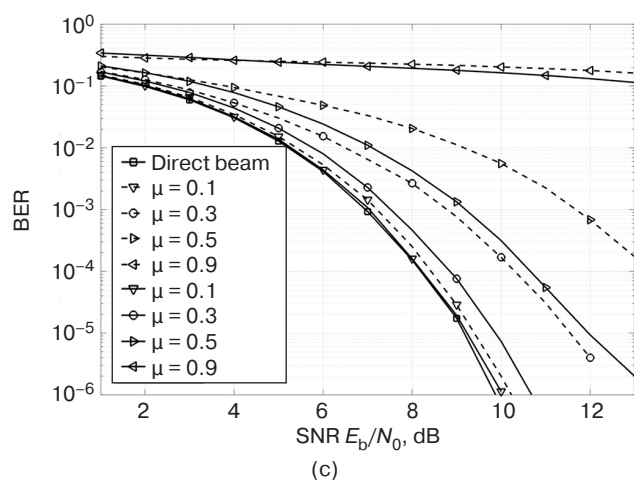
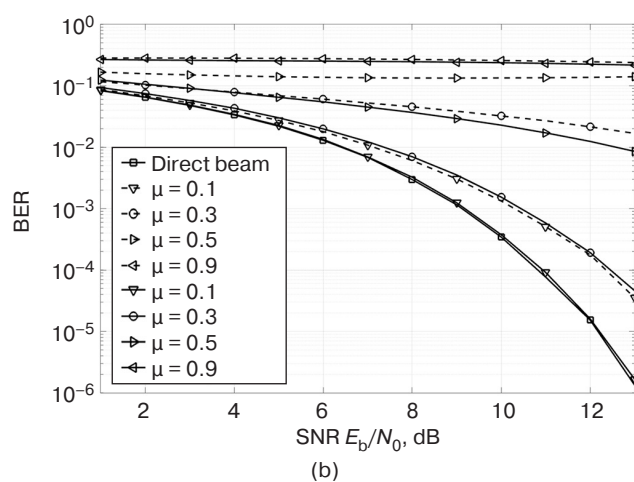
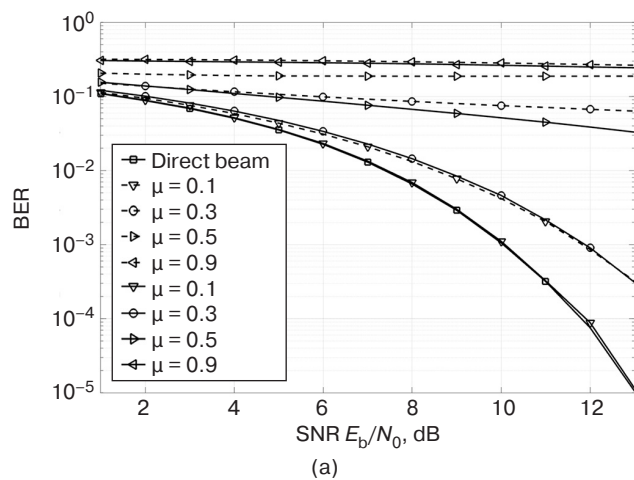


Fig. 3. BER dependency on SNR when receiving signals with one direct and one reflected beam:
(a) 16-QAM;
(b) 8-PSK;
and (c) 8-FSK

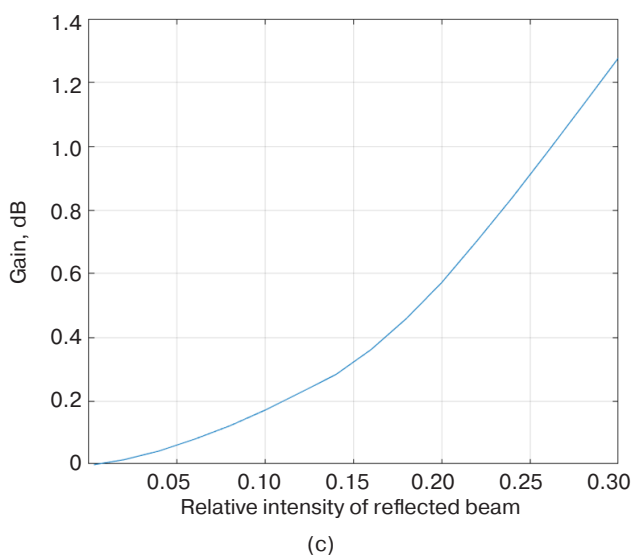
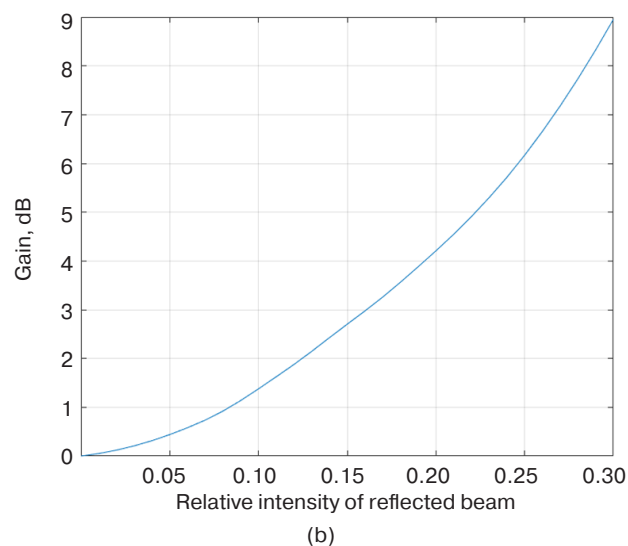
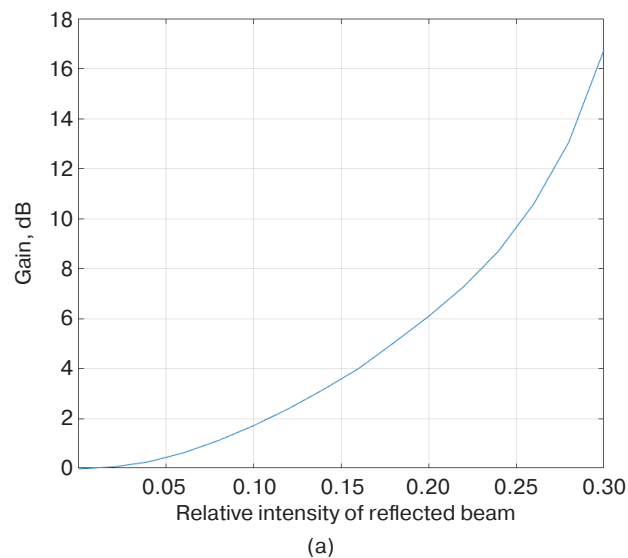


Fig. 4. Results of calculating the energy gain for:
(a) 16-QAM;
(b) 8-PSK;
and (c) 8-FSK

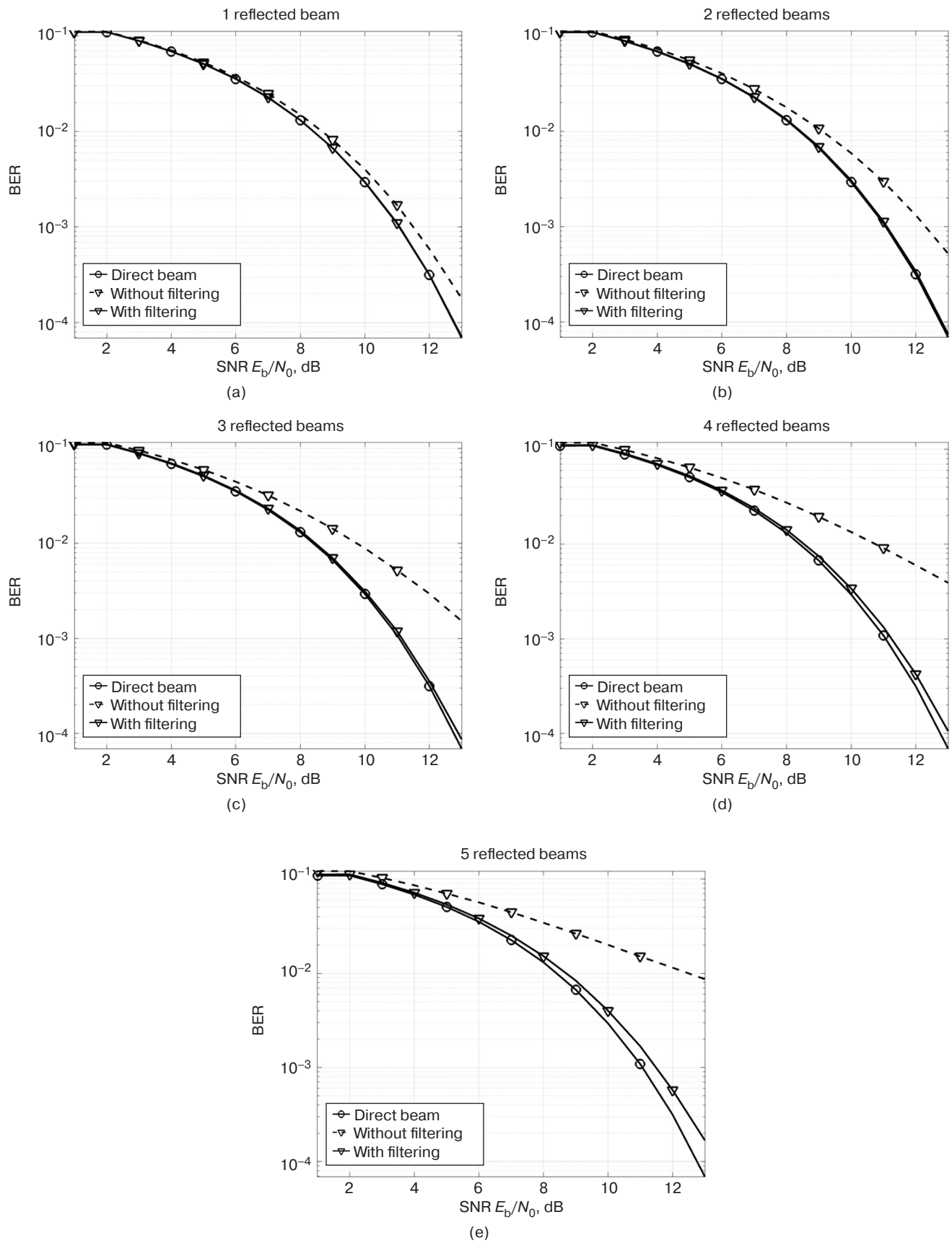


Fig. 5. BER dependence on SNR at different number of beams for 16-QAM

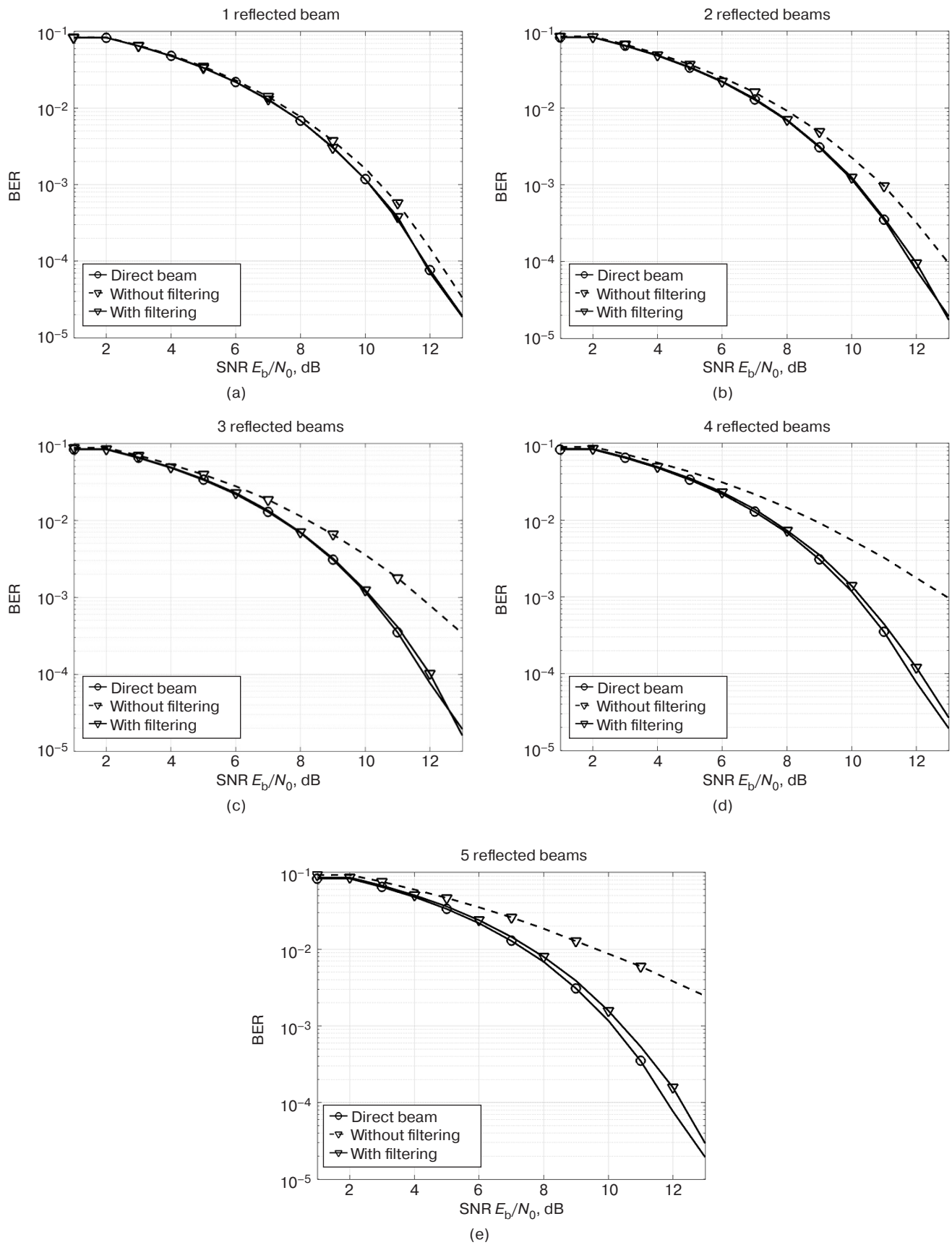


Fig. 6. BER dependence on SNR at different number of beams for 8-PSK

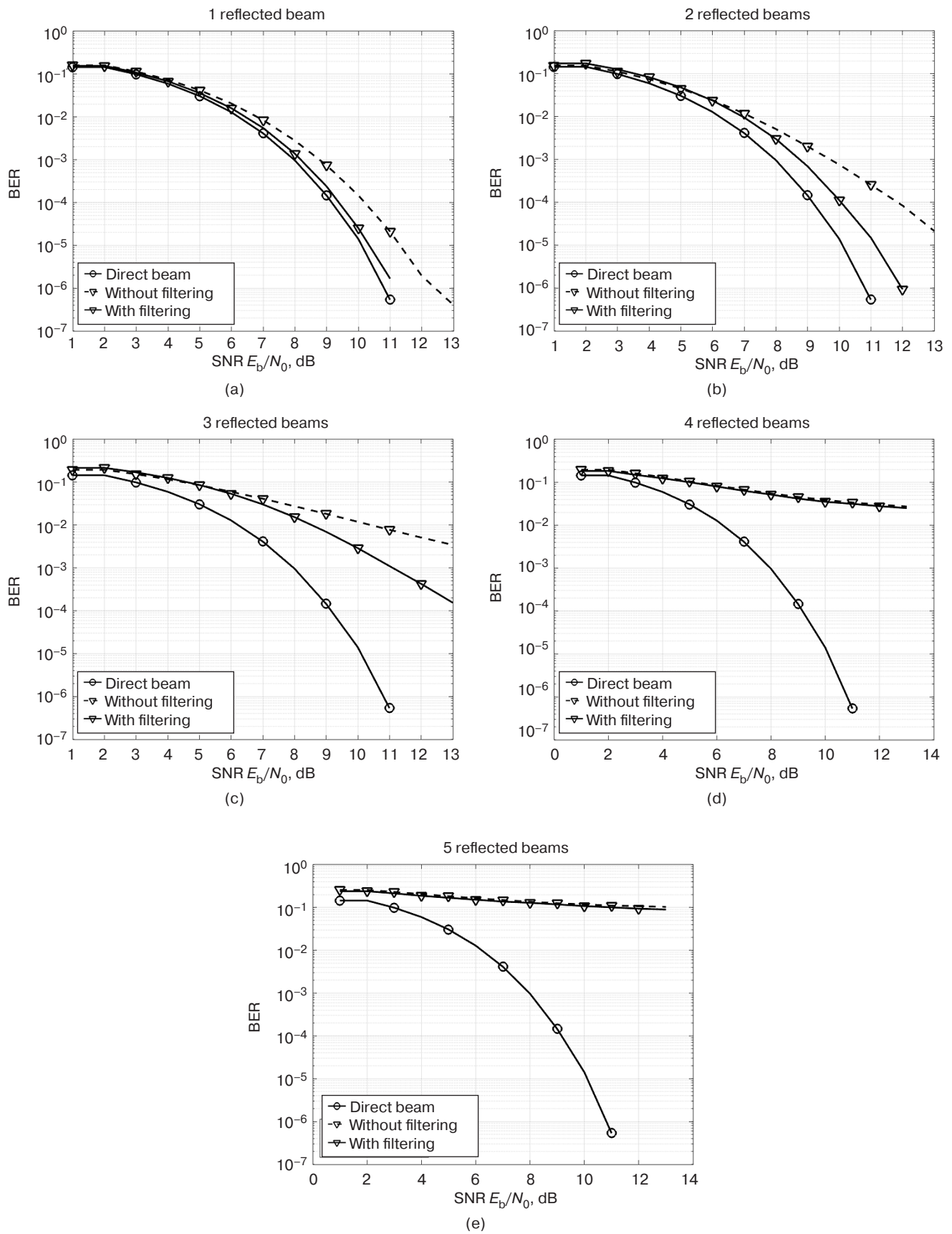


Fig. 7. BER dependence on SNR at different number of beams for 8-FSK

The impact of parameter inaccuracy in the filter with inverse IR

The performance of the filter with inverse IR depends on the precision of its parameter settings, including gain coefficients and time delays within the branches. Under real-world conditions, these parameters can deviate from their calculated values due to variations in the signal transmission environment, inaccuracies in channel estimation, or errors in adaptive algorithms. Therefore, it is essential to assess how parameter deviations in the filter with inverse IR affect communication quality and BER.

In order to evaluate this, a scenario is selected with a channel comprising a direct and delayed signal, with a relative power of 0.2 and a time delay of 21 ns at SNR of 10 dB.

Figure 8 presents graphs of the relationship between BER and deviation of the gain in the filter branch, normalized to a nominal value of 0.2, for 16-QAM, 8-PSK, and 8-FSK signals.

From the results obtained, it can be concluded that the correct operation of the filter is maintained within a fairly broad range of gain variations in the filter section. Therefore, even if the gain deviates by 1.5 times the nominal value specified by the reflected beam level, BER will increase approximately twofold. If the gain deviates two times, BER will increase by an order of magnitude for all signals under consideration.

Figure 9 shows graphs of the relationship between BER and the deviation of the delay in the filter branch, normalized to a nominal value of 21 ns, for 16-QAM, 8-PSK (at the reflected beam intensity of $\mu = 0.2$), and 8-FSK (at the reflected beam intensity of $\mu = 0.5$).

The graphs in Figs. 9a and 9b (for 16-QAM and 8-PSK, respectively) have a characteristic appearance which can be explained by the use of a complex envelope in the signal representation model. This results in a lower “plateau” along the normalized delay time axis, with a duration determined by the channel symbol duration, during which the information component of the signal phase remains constant. When the delay deviates beyond the boundaries of this “plateau,” BER sharply increases. For the 8-FSK model, BER cannot be accurately estimated when the delay deviates from the nominal value by less than 5% due to certain software limitations. Nevertheless, the results indicate that the filter is operating correctly within a very narrow range around the nominal delay value. It can be said that an accuracy of approximately 1% is required for proper operation.

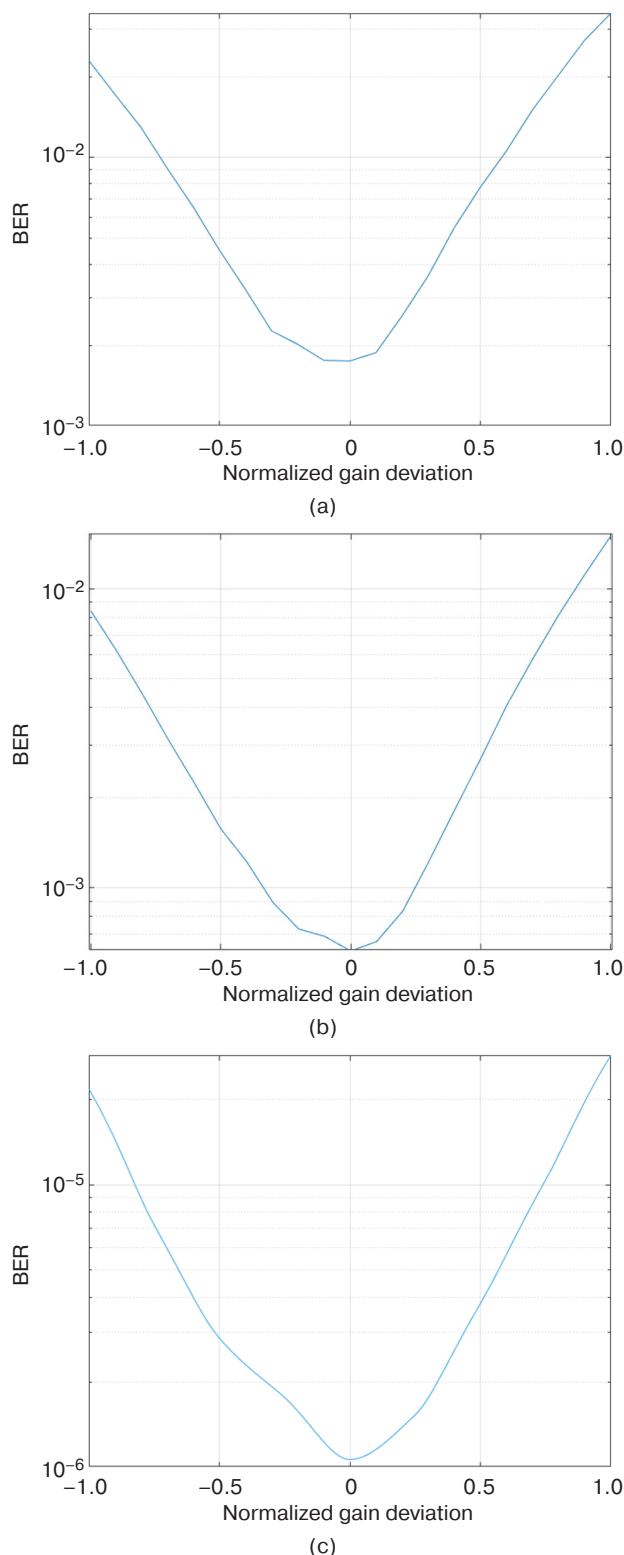


Fig. 8. BER dependence on the normalized gain deviation in the filter branch for signals:
(a) 16-QAM;
(b) 8-PSK;
and (c) 8-FSK

CONCLUSIONS

The paper presents the results of an investigation into the efficiency of the filter with inverse IR to that of the communication channel with a discrete multipath at the reception of signals with multi-position types of modulation, such as 16-QAM, 8-PSK, and 8-FSK. Based on mathematical modeling in the *Simulink* environment, the impact of channel parameters and filter parameters on BER is explored.

The use of such compensation filters offers a substantial energy advantage in terms of SNR, which varies depending on the modulation type from units to tens of decibels, making them particularly promising for high-speed communication systems. It was ascertained that the filter continues to function with deviations in the branch gains up to 1.5 times the nominal value, although it is highly sensitive to the accuracy of time delays, with a permissible deviation of 1%.

The efficiency of the filter is also dependent on the number and intensity of beams. Therefore, the upper limit of applicability can be considered to be the value of μ , which is slightly greater than 0.5. When $\mu \rightarrow 0.9$, the filter becomes ineffective due to the high level of response at time positions that are twice the time delay (Fig. 2).

Therefore, the use of filters with inverse IR to that of the communication channel is an effective method for combating multipath distortion, significantly improving communication quality and gain. The results obtained confirm the potential of this approach in increasing the reliability and capacity of modern telecommunication systems.

Future research will focus on developing adaptive algorithms aimed at determining the IR of the communication channel and automatically determining parameters for a filter with inverse IR.

Authors' contribution

All authors contributed equally to the research work.

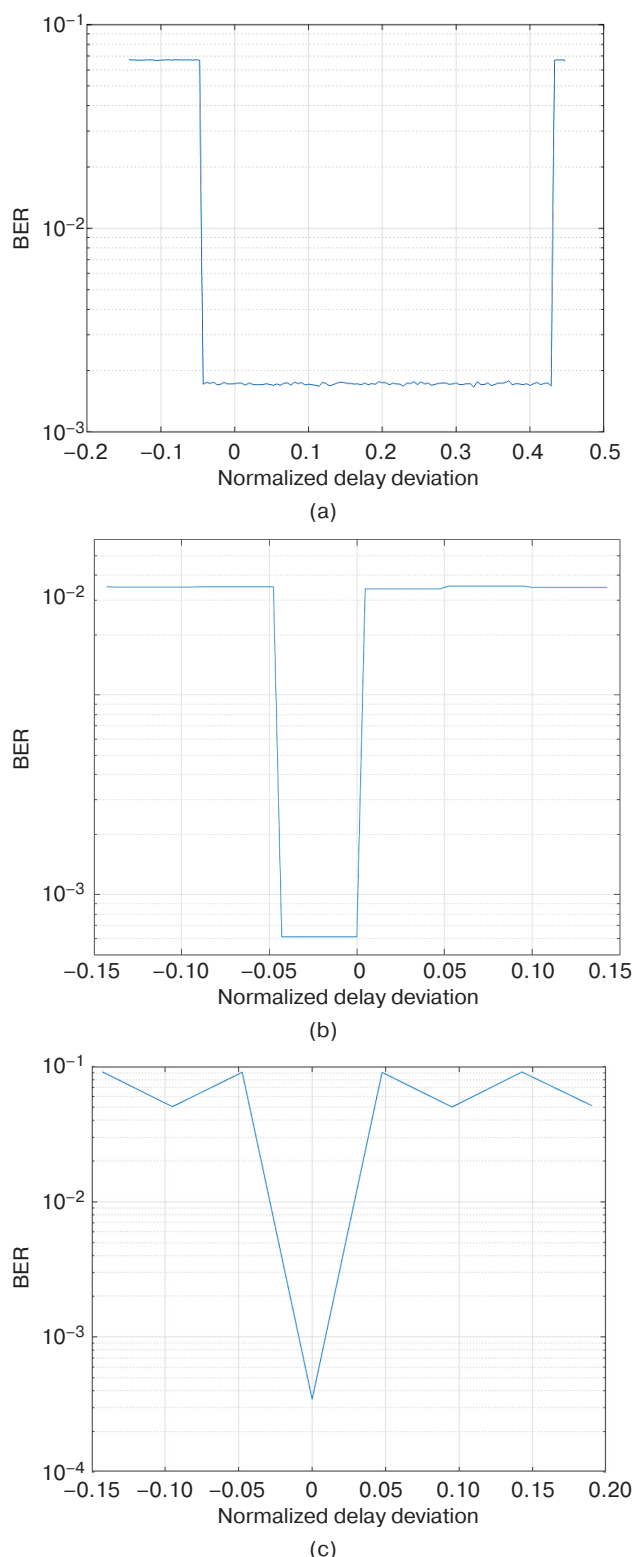


Fig. 9. BER dependence on the normalized delay deviation in filter branch for signals:
(a) 16-QAM;
(b) 8-PSK;
and (c) 8-FSK

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