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RESEARCH ARTICLE

Non-fluctuation interference rejection using an adaptive filter based on spectrum envelope analysis

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Abstract
Objectives. The rapid advancement of wireless technologies, including IoT and 5G/6G, is accompanied by an increase in the overall level of electromagnetic interference. This sets engineers the task of developing effective methods to suppress such interference, including especially challenging non-fluctuating interference of various kinds. The study aims to implement and analyze the effectiveness of a non-fluctuation interference rejection method using an adaptive filter based on spectrum envelope analysis.
Methods. Mathematical modeling, spectral analysis, and adaptive filtering methods are used in the work. The described approach is based on spectrum envelope extraction for identification and subsequent suppression of non-fluctuation interference.
Results. The effectiveness of an adaptive algorithm for suppressing non-fluctuation interference based on the analysis of the spectrum envelope has been demonstrate. This algorithm can be used as a means for isolating the envelope of the interference spectrum to enable the formation of the amplitude-frequency response of the notch filter in real time. Processing methods for three types of non-fluctuation interference were implemented and tested: harmonic, frequency-shift keying (FSK), and phase-shift keying (PSK). A signal with quadrature amplitude modulation forms a useful signal for the purposes of the study. The experimental results demonstrate the good efficiency of the proposed method. The developed adaptive notch filter based on spectrum envelope analysis is highly effective in combating harmonic interference to achieve energy gains of 8–9 dB depending on the relative intensity of interference. Notably, even as interference intensifies, the filter effectiveness persists, albeit with a slight reduction. The algorithm functions effectively under exposure to narrowband FSK and PSK interference.
Conclusions. The proposed adaptive algorithm for suppressing fluctuation interference based on spectrum envelope analysis is optimally effective in the presence of harmonic interference within the communication channel, but less effective in the presence of more broadband interference. The study is of practical importance for digital communication systems, where high noise immunity is required in a complex electromagnetic environment.

Keywords: quadrature amplitude modulation, non-fluctuation interference, spectrum envelope, adaptive filtering, rejection, bit error rate, noise immunity

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НАУЧНАЯ СТАТЬЯ

Режекция нефлуктационных помех с помощью адаптивного фильтра на основе анализа огибающей спектра

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Резюме

Цели. Активное развитие беспроводных технологий, включая IoT (Internet of Things, интернет вещей) и 5G/6G, сопровождается ростом уровня электромагнитных помех, что ставит перед инженерами задачу разработки эффективных методов их подавления. Особую сложность представляют нефлуктуационные помехи разного рода. Цель данного исследования заключается в реализации и анализе эффективности метода режекции нефлуктуационных помех с использованием адаптивного фильтра, основанного на анализе огибающей спектра.

Методы. В работе использованы методы математического моделирования, спектрального анализа и адаптивной фильтрации. Предложен подход, основанный на выделении огибающей спектра для идентификации и последующего подавления нефлуктуационных помех.

Результаты. Проведено исследование эффективности адаптивного алгоритма подавления нефлуктуационных помех на основе анализа огибающей спектра, который позволяет выделять огибающую спектра помехи, что обеспечивает формирование амплитудно-частотной характеристики режекторного фильтра в реальном времени. В ходе исследования реализованы и протестированы методы обработки для 3 типов нефлуктуационных помех: гармонической, частотно-манипулированной (ЧМ) и фазоманипулированной (ФМ). В качестве полезного сигнала использован сигнал с квадратурной амплитудной модуляцией. Экспериментальные результаты демонстрируют хорошую эффективность предложенного метода, Разработанный адаптивный режекторный фильтр на основе анализа огибающей спектра обладает высокой эффективностью при борьбе с гармонической помехой: энергетический выигрыш в зависимости от относительной интенсивности помехи может составлять до 8–9 дБ. При увеличении количества помех эффективность фильтра сохраняется, хотя и несколько снижается. Алгоритм при определенных условиях работоспособен в условиях воздействия узкополосных ЧМ- и ФМ-помех.

Выводы. Предложенный адаптивный алгоритм подавления нефлуктуационных помех на основе анализа огибающей спектра наиболее эффективен при наличии в канале связи гармонических помех и менее эффективен при наличии более широкополосных помех. Работа имеет практическую значимость для систем цифровой связи, где требуется высокая помехоустойчивость в условиях сложной электромагнитной обстановки.

Ключевые слова: квадратурная амплитудная модуляция, нефлуктуационные помехи, огибающая спектра, адаптивная фильтрация, режекция, вероятность битовой ошибки, помехоустойчивость

Для цитирования: Коняшкин Г.В., Куликов Г.В. Режекция нефлуктационных помех с помощью адаптивного фильтра на основе анализа огибающей спектра. *Russian Technological Journal*. 2025;13(5):63–74. https://doi.org/10.32362/2500-316X-2025-13-5-63-74, https://www.elibrary.ru/QHZTAK

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Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

The rapid advancement of wireless technologies, such as the Internet of Things (IoT) and 5G/6G, is accompanied by an increase in the overall level of electromagnetic interference. This poses a challenge to engineers in terms of developing effective methods for their suppression. The suppression of non-fluctuating interference turns out to be particularly challenging. Such interference includes harmonic signals, as well as frequency and phase modulation signals, which may be caused by either accidental technical violations of radio regulations or intentional actions. Such interference significantly reduces signal-to-interference-plus-noise ratio (SINR), hindering information decoding and elevating the probability of errors within communication systems [1–7].

Conventional suppression methods, including adaptive filters utilizing LMS[1]/NLMS[2] algorithms or fast Fourier transform (FFT) approaches, are often ineffective [8–12]. This insufficiency stems from their restricted capacity to adapt to transient interference and high processing computational costs. Furthermore, methods relying on initial spectrum analysis necessitate precise knowledge of the interference frequency response, which represents a particular challenge when faced with dynamically changing interference.

The present work introduces a novel method for leveraging a priori information on the spectral envelope of the useful signal. After extracting a spectral interference mask, a notch filter for eliminating the identified frequency components is synthesized [13]. A significant benefit of this algorithm is its adaptability, which allows it to be operated in the absence of a priori information on interference characteristics and in real-time. To evaluate its versatility, the algorithm is subjected to tests involving three distinct categories of non-fluctuation interference. The experimental results demonstrate that the developed adaptive filter effectively minimizes interference levels while maintaining a minimal effect on the useful signal.

This study is relevant due to the growing requirements for noise immunity of modern radio systems, especially those arising in the context of the rise of IoT technologies and autonomous devices, where reliable communication is crucial for both safety and proper function. The findings of this study can be applied to improve the performance of telecommunications equipment, military communication networks, and industrial automation systems, enabling them to operate effectively in challenging electromagnetic environments.

INTERFERENCE REJECTION METHOD

The adaptive filter implemented during the study, which is designed based on spectrum envelope analysis, functions as follows:

1. Spectral processing. The received signal-interference mixture is subjected to FFT spectral analysis. The conversion of the signal from the time domain to the frequency domain provides a basis for obtaining a spectral picture for further analysis.
2. Spectrum envelope extraction. The spectrum envelope of the received mixture is calculated by extrapolating values of local maximums of the spectrum over a given range of points. This enables the clear identification and isolation of individual frequency components within a mixture of signals and interference.
3. Spectrum envelope analysis. To identify the frequency components that require filtering, the spectrum envelope of the received signal is examined. For this, the a priori known (since the receiving side knows the main parameters of the signal – in particular, the modulation method and the information transmission rate) spectrum reference envelope of the useful signal is subtracted from the spectrum envelope of the received mixture. This allows extraction of the interference spectrum envelope, whose parameters can then be utilized in configuring the filtering system.

[1] The Least Mean Squares (LMS) algorithm is an adaptive filtering technique used to adjust the filter coefficients so as to minimize the mean square error between the filter output and the desired signal.

[2] The Normalized Least Mean Squares (NLMS) algorithm is an adaptive filtering method used to optimize filter parameters in real time. It extends the basic LMS algorithm by normalizing the adaptation step, which increases its stability and efficiency when working with time-varying signals.

4. Synthesis of the notch filter. The derived interference spectrum envelope can be used for the real-time generation of an amplitude-frequency response for a customizable notch filter, which filters the mixture of signal and interference. This adaptable notch filter can be designed as a multi-band system with customizable gain levels across different frequency bands [13], or as a filter utilizing a synthesized amplitude-frequency response, the latter approach being implemented in this study.

A functional diagram of the adaptive filter implementing this algorithm is shown in Fig. 1.

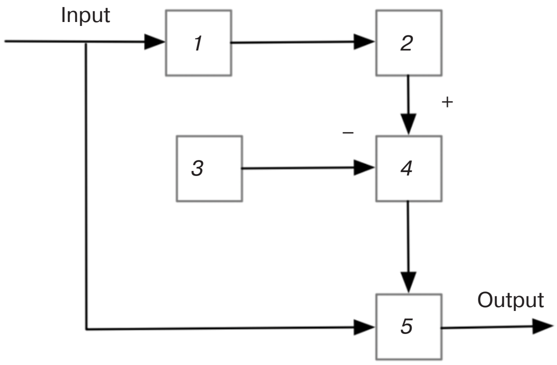


Fig. 1. Functional diagram of the adaptive filter based on the spectrum envelope analysis: *1* is a Fourier converter; *2* is a spectrum envelope detector; *3* is a reference spectrum envelope of the useful signal; *4* is an adder; and *5* is a notch filter with synthesized amplitude-frequency response

ADAPTIVE FILTERING COMPUTER SIMULATION

An adaptive filter based on spectrum envelope analysis is simulated in *MATLAB/Simulink* (trial version) and *Scilab/Xcos* for a 16-Quadrature Amplitude Modulation (16-QAM) signal (Fig. 2). The results of the study can be easily adapted to other signals with stationary spectrum.

Within the "M QAM Modulation" section, a useful signal of a given dimension is generated, after which an additive white Gaussian noise is superimposed in the channel and added to the selected type of non-fluctuation interference generated in the "Generation of various types of non-fluctuation interference" section. Then, if necessary, transfer to the carrier frequency is performed, after which the resulting mixture of signal and interference is branched into 2 sections of demodulation and BER calculation for processing with and without an adaptive filter. This also falls into the subsystem for isolating the envelope of the interference spectrum detailed in Fig. 3.

The spectrograms obtained as a result of the circuit operation clearly reveal the principle of operation and validate the functionality of the algorithm illustrated in Fig. 4.

The three distinct interference generators created for research purposes encompass harmonic interference (ranging from 1 to 4 harmonics), frequency-shift keying (FSK), and phase-shift keying (PSK) types. The diagram's upper section illustrates an algorithm designed to isolate the interference spectrum envelope in adherence to the principles outlined in Fig. 1. Data from the analyzed envelope of the interference spectrum is processed with the Yule–Walker function[3] to create IIR filters that possess a predetermined frequency response. This design process, which relies on the Yule–Walker equations [14–16], results in a filter with a specific transfer function:

$$H(z)=\frac{B(z)}{A(z)}=\frac{b_0+b_1z^{-1}+\ldots+b_{n_b}z^{-n_b}}{1+a_1z^{-1}+\ldots+a_{n_a}z^{-n_a}},$$

where n_a and n_b are the degrees of the denominator and numerator, respectively, while z is a complex variable of the Z-transform $(z=\mathrm{e}^{j\omega_n})$ that bridges the filter's difference equation and its transfer function; $\omega=\frac{2\pi n}{N}$.

Through an iterative process, the interference spectrum envelope algorithm aims to minimize the mean square error between the desired and actual frequency response.

The main stages of the algorithm are the following:

1. Defining the desired frequency response. The user defines the vectors of frequency *f* and corresponding amplitudes *m*, specifying the desired characteristic. Frequencies are normalized relative to the Nyquist frequency $(0 \le f \le 1)$.
2. Calculating the autocorrelation function. The autocorrelation function $r(k)$ describes how the signal correlates with itself at various time delays *k*. The desired frequency response is transformed into an autocorrelation function using the inverse Fourier transform as expressed by:

$$r(k)=\frac{1}{N}\sum_{n=0}^{N-1}|H_\mathrm{d}(\mathrm{e}^{j\omega_n})|^2\,\mathrm{e}^{j2\pi kn/N},$$

where $|H_\mathrm{d}(\mathrm{e}^{j\omega_n})|^2$ is the squared amplitude of the desired characteristic, *N* is the number of sampling points, and *k* is the delay index.

[3] *Signal Processing Toolbox User's Guide*. Copyright 1988–2002 by The MathWorks, Inc.

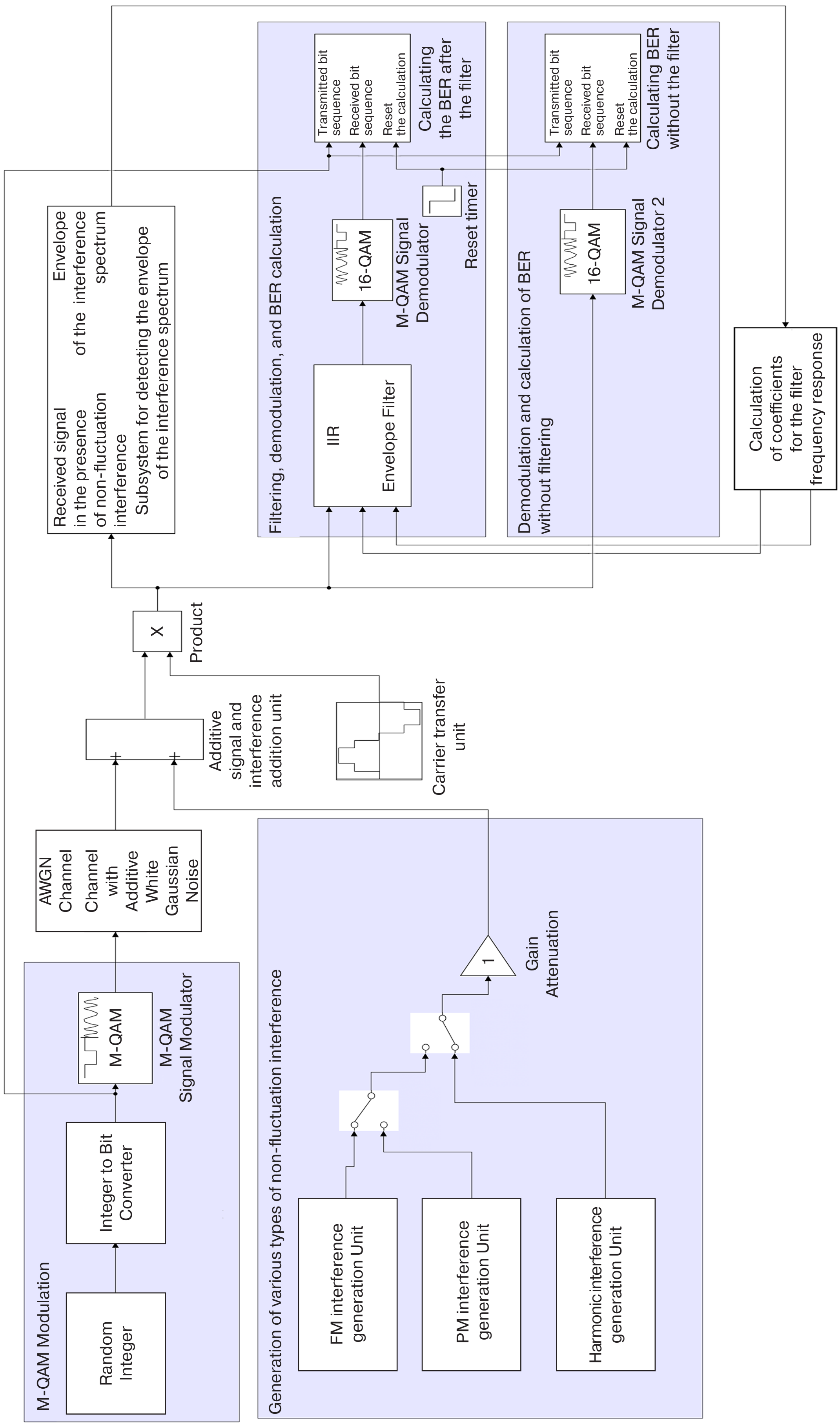


Fig. 2. Functional diagram for investigating the influence of different types of non-fluctuation interference. IIR is infinite impulse response and BER is bit error rate

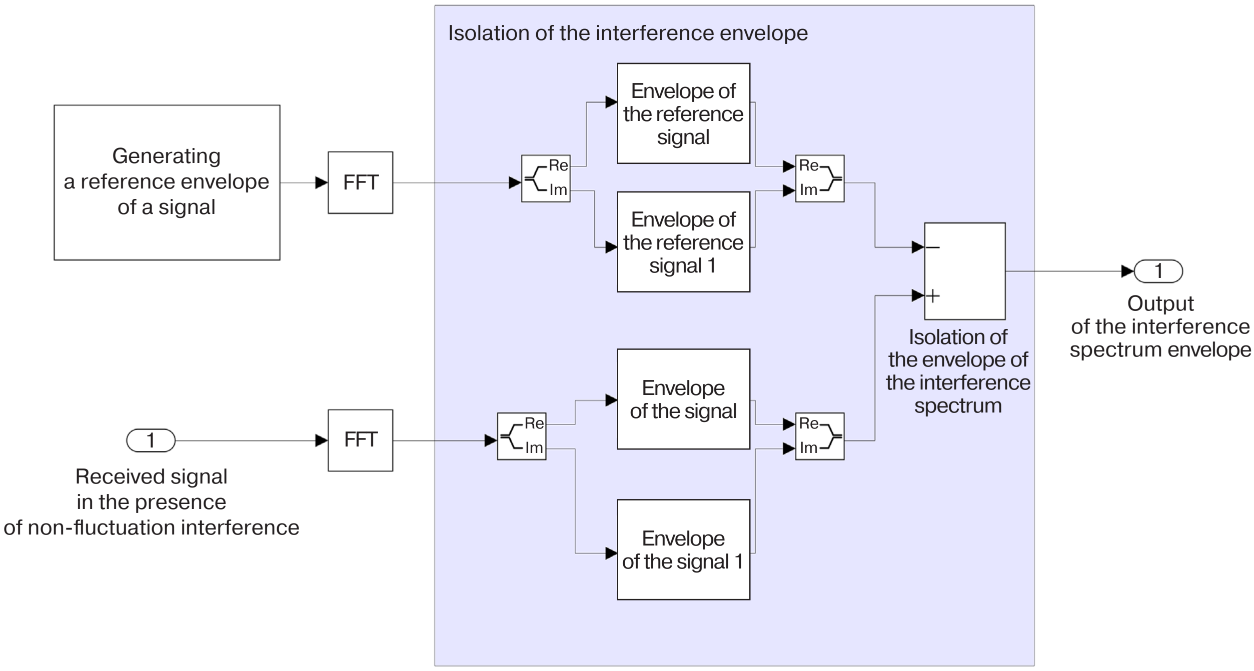


Fig. 3. Subsystem for isolating the envelope of the interference spectrum

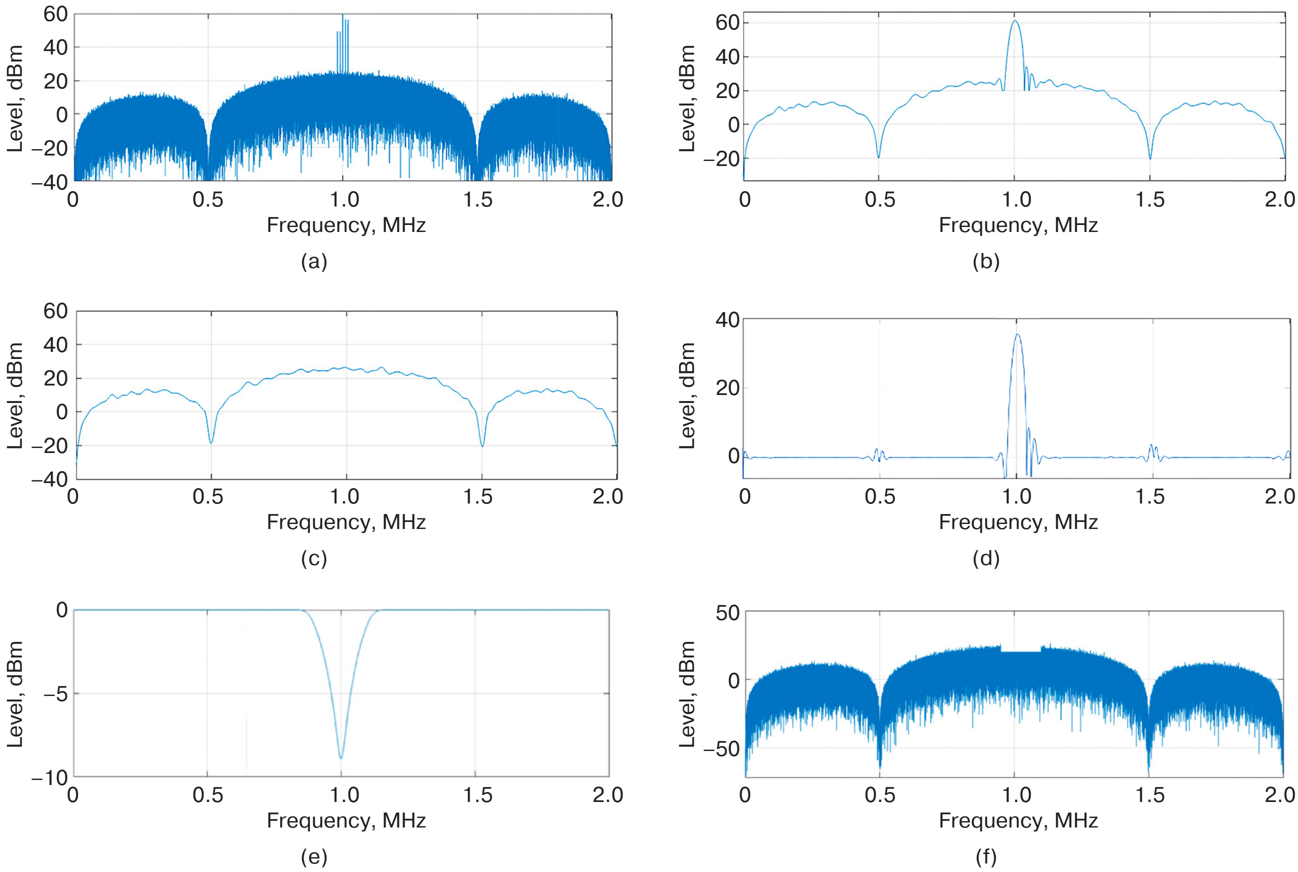


Fig. 4. Spectrograms illustrating the principle of the algorithm:
(a) the spectrum of the received signal with interference; (b) envelope of spectrum of received signal with interference; (c) signal envelope reference; (d) difference of envelopes of received signal with interference and reference envelope of signal spectrum; (e) synthesized frequency response of the notch filter; and (f) a spectrum of the filtered signal. The level in this case is the relative unit of signal power, expressed in decibels with respect to 1 mW

3. Solving the Yule–Walker equations for the denominator $A(z)$ of the transfer function. The $n \times n$ autocorrelation matrix $\mathbf{R}$ is formed, depending on the required filter order. Given a filter order of n, the denominator coefficients $\mathbf{a} = [a_1, a_2, \ldots, a_n]^{\mathrm{T}}$ are derived from the following system:

$$\mathbf{R} \cdot \mathbf{a} = -r,$$

where $R_{ij} = r(|i - j|)$ are elements of the autocorrelation matrix; $r = [r(1), r(2), \ldots, r(n)]^{\mathrm{T}}$. Next, the denominator is calculated in the form of $A(z) = 1 + a_1 z^{-1} + \ldots a_n z^{-n}$.
4. Calculating the coefficients of the numerator $B(z)$ of the transfer function. After committing $A(z)$, the coefficients of the numerator $B(z)$ are determined by the least-squares method, minimizing the error, as follows:

$$\sum_{i=0}^{L-1} \left| H_{\mathrm{d}}(\mathrm{e}^{j\omega_n}) - \frac{B(\mathrm{e}^{j\omega_i})}{A(\mathrm{e}^{j\omega_i})} \right|^2,$$

where $A(z)$ is the denominator already found and L is the number of frequency points.

Then, for simplicity, a transition to a linear form is performed when calculating the numerator $B(z)$, as follows:

$$B(z) \approx H_{\mathrm{d}}(\mathrm{e}^{j\omega_i}) A(z).$$

5. Iterative refinement. At this point, the algorithm may re-adjust $A(z)$ and $B(z)$ to enhance the alignment with the desired frequency response.

SIMULATION RESULTS

Harmonic interference

For harmonic interference, rejection efficiency is studied taking into account the amount of interference simultaneously present in the communication channel, the relative amplitude of μ interference (interference amplitude divided by the average amplitude of the useful signal), and the signal-to-noise ratio (SNR). The resulting BER is then employed to gauge the rejection efficiency.

The results of the study into the impact of harmonic interference levels on filter efficiency are presented in Table.

The obtained values plotted in Fig. 5 illustrate the filtering efficiency depending on the amount of harmonic interference.

The graph demonstrates that the adaptive filtering method, which is most efficient when dealing with a small amount of harmonic interference, maintains its effectiveness even as the interference increases.

The BER vs. SNR relationships at different relative intensities of one harmonic interference μ for two cases, without filtering and using the developed adaptive notch filter, are shown in Fig. 6.

Table. Study results depending on the amount of harmonic interference at SNR = 13 dB, μ = 1

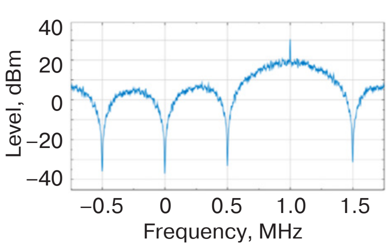
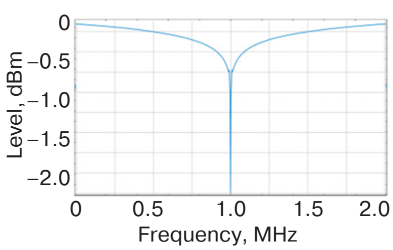
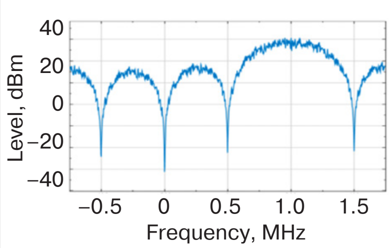
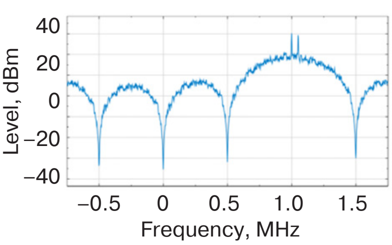
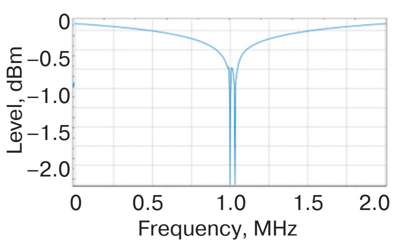
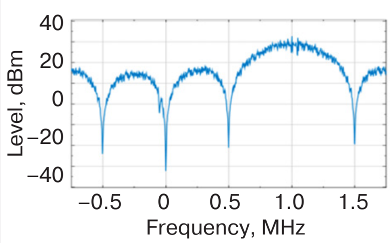
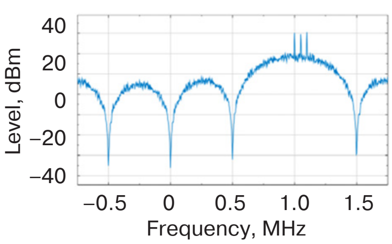
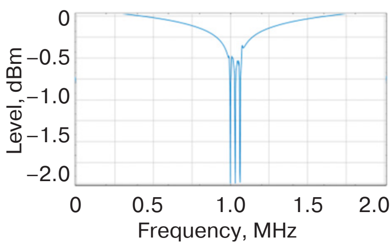
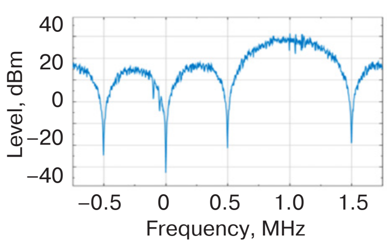
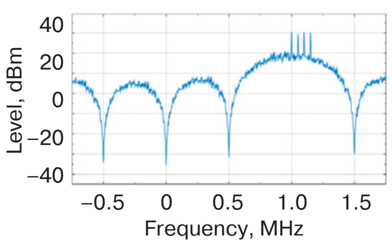
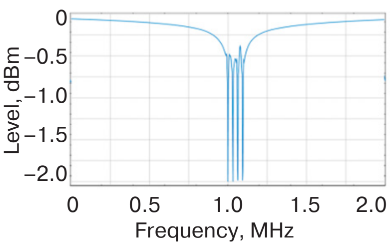
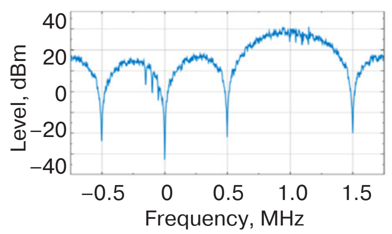
Spectrum before filtration	Filter frequency response	Spectrum after filtration	BER with/without filtration
			0.01059 0.09377
			0.01294 0.04491

Table. Continued

Spectrum before filtration	Filter frequency response	Spectrum after filtration	BER with/without filtration
			0.06486 0.14781
			0.08102 0.13731

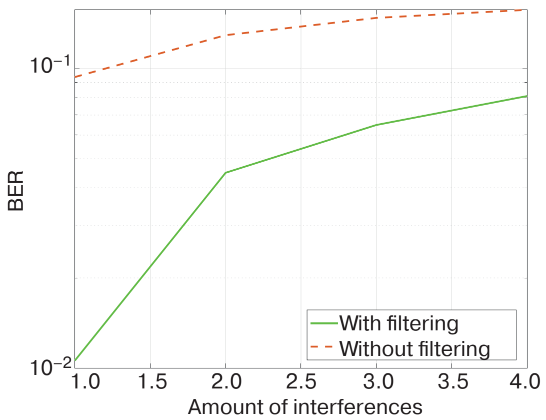


Fig. 5. BER vs. the amount of interference

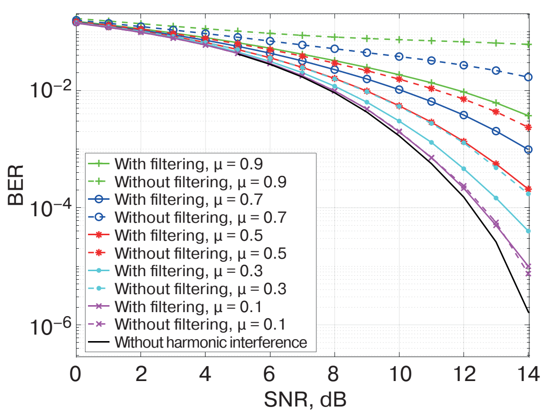


Fig. 6. BER vs. SNR using a notch filter based on the spectrum envelope analysis and without a filter when receiving 16-QAM signals against harmonic interference with different relative intensity μ

It can be concluded from the graphs that the use of the developed filter is efficient at any relative amplitude of interference. For $\mu = 0.9$, the energy gain is on the order of 8–9 dB at BER = 10^{-2} and for $\mu = 0.5$, it is 3 dB at BER = 10^{-3}.

FSK interference

The width of the FSK interference spectrum depends on its transmission rate (keying frequency) V_{inter} and frequency deviation F_{dev}. Therefore, the BER dependence on different deviation $F_{dev\ rel}$ normalized relative to the channel signal rate V_s is studied. The interference-to-signal transmission rate ratio is selected from the condition $V_{inter} << V_s$. In this case, the interference effect is concentrated on the main lobe of the QAM signal.

The BER vs. SNR relationships at different deviation $F_{dev\ rel}$ of the FSK interference for two cases, without filtering and using the developed adaptive notch filter, are shown in Fig. 7.

The graph indicates that this adaptive filter is more successful at mitigating harmonic interference as compared to FSK interference. However, it can also be used to partially reduce interference with a low frequency deviation $F_{dev\ rel} \leq 0.01$. For higher deviations, the filter proves ineffective.

This study investigates the impact of FSK interference with varying relative intensity μ at $F_{dev\ rel} = 0.01$, both in the absence of filtration and with the implementation of a synthesized notch filter. The findings are illustrated in Fig. 8.

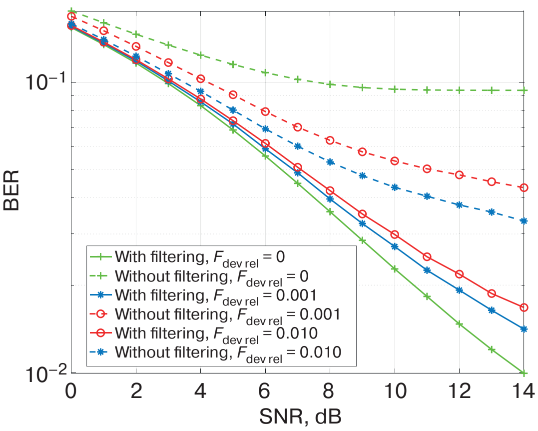


Fig. 7. BER vs. SNR using a notch filter based on the spectrum envelope analysis and without a filter when receiving 16-QAM signals against a background of FSK interference with different relative deviation at μ = 1

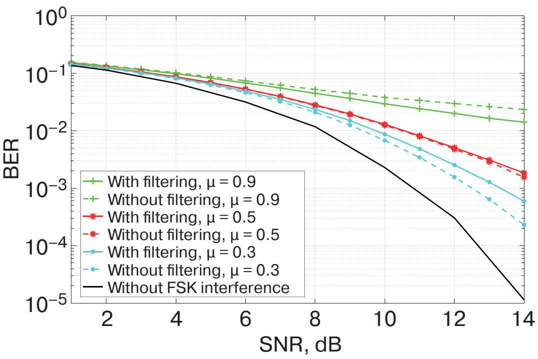


Fig. 8. BER vs. SNR using a notch filter based on spectrum envelope analysis and without a filter when receiving 16-QAM signals against FSK interference with varying relative intensity μ

It can be concluded from the graphs that the use of the developed filter is efficient at a relative interference intensity of μ > 0.9 only. In other cases, the useful signal is rejected. However, under favorable conditions, the energy gain is on the order of 2–4 dB at BER = 10^{-2}.

PSK interference

Since the width of the PSK interference spectrum depends on its transmission rate (keying frequency) V_{inter}, it is the BER dependence on different transmission rate $V_{inter\ rel}$ normalized to the channel signal rate V_s that is investigated.

The dependence of BER on SNR when receiving a 16-QAM signal against PSK interference with a relative amplitude of μ = 1 and a different relative transmission rate $V_{inter\ rel}$ for the case without filtering and that using the developed adaptive notch filter is shown in Fig. 9.

An examination of the generated graphs reveals that the implemented filter is more successful in mitigating harmonic interference as compared to PSK interference. Nevertheless, it also demonstrates the ability to partially suppress interference having a low relative transmission rate $V_{inter\ rel} \leq 0.01$. At higher relative transmission rates, the filter is ineffective.

The simulation results of the investigation into the effect of the PSK interference with varying relative intensity μ at $V_{inter\ rel}$ = 0.01 are shown in Fig. 10.

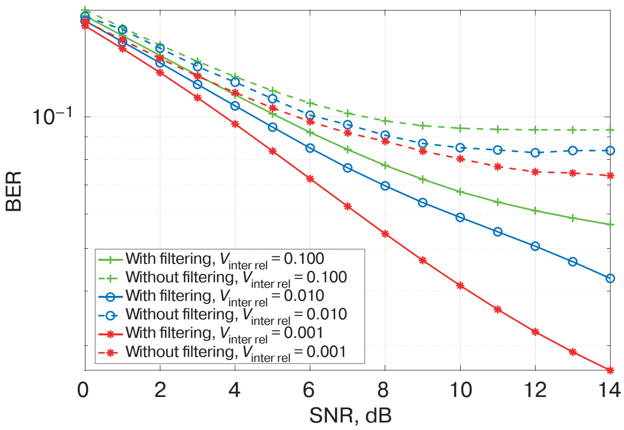


Fig. 9. BER vs. SNR using a notch filter based on spectrum envelope analysis and without filter when receiving 16-QAM signals against PSK interference at different relative transmission rates

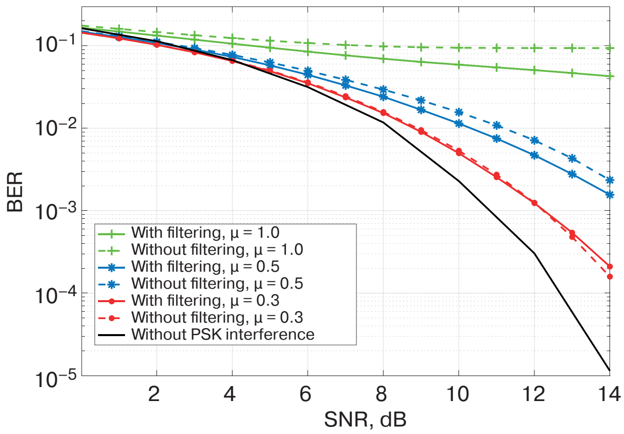


Fig. 10. BER vs. SNR using a notch filter based on the spectrum envelope and without filtering when receiving 16-QAM signals against PSK interference at $V_{inter\ rel}$ = 0.01 and different relative intensity μ

It can be seen that the developed filter, as in the case of FSK-interference, is efficient at high μ = 1, thus providing an energy gain of several decibels. In addition, it provides a small energy gain at average values of μ = 0.5. However, the situation is exacerbated at low μ < 0.3. This is due to the fact that the components of the useful signal are also rejected, which is more noticeable in the latter case. However, for μ > 0.5, there is an energy gain on the order of 2–4 dB and BER = 10^{-2}.

CONCLUSIONS

Based on the study results, the following can be concluded:

1. The developed adaptive notch filter based on spectrum envelope analysis is highly efficient in combating harmonic interference. It can achieve an energy gain of 8–9 dB depending on the interference intensity. With an increase in the amount of interference, the filter efficiency is maintained although at a slightly reduced rate.
2. Initially designed to address harmonic interference, the rejection algorithm demonstrates effectiveness in managing narrowband FSK and PSK interference in specific scenarios.
3. For the FSK interference rejection, the effectiveness of the filter is highly influenced by both the deviation of the interference frequency and its intensity. The filter performs best when dealing with narrowband FSK interference; however, its effectiveness diminishes as the frequency deviation increases. At low frequency deviation ($F_{\text{dev rel}}$ = 0.01) and high interference intensity ($\mu > 0.5$), employing the filter can yield an energy gain of 2–4 dB.
4. For PSK interference rejection, the effectiveness of the notch filter is heavily influenced by both the interference rate and its intensity, showing a decline in efficiency as the interference rate rises. However, employing the filter can still yield an energy gain of 2–4 dB at $\mu > 0.5$.
5. The effectiveness of the developed notch filter improves as the relative intensity of FSK and PSK interference increases. However, when the relative intensity is below 0.5, filtering is ineffective due to significant rejection of the useful signal.
6. The effectiveness of the filter hinges on the non-fluctuation interference maintaining a consistent state, which is directly influenced by the iterative synthesis algorithm speed for achieving the desired frequency response.

Authors' contribution

All authors equally contributed to the research work.

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