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RESEARCH ARTICLE

Impacts of noise and interference on the bit error rate of the FBMC-OQAM modulation scheme in 5G systems

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Abstract
Objectives. The work sets out to evaluate the noise immunity of the signal modulation method in 5G networks using a filter bank multicarrier with offset quadrature amplitude modulation (FBMC-OQAM) and to analyze the bit error rate (BER).
Methods. In the work, probability theory and mathematical statistics methods are applied according to computer modeling approaches.
Results. An analysis of BER for the signal modulation method in 5G networks, which uses a bank of filters with multiple carriers with offset quadrature amplitude modulation under noise conditions, is presented. The resistance of the method to intra-cell, inter-cell, and inter-beam types of interference in the 5G channel, as well as additive white Gaussian noise, is investigated. The graphical and numerical data obtained through computer modeling demonstrates improved BER in 5G networks using FBMC-OQAM. The presented comparative analysis of error probability in the FBMC-OQAM system under various types of noise and interference emphasizes the impact of these factors on the quality of information transmission.
Conclusions. The FBMC-OQAM method is characterized by the low impact on the error probability of the data transmission system in 5G networks of various types of interference including intra-cell and inter-cell interference, inter-beam interference, and nonlinear distortions. However, it will be necessary to further optimize the method and develop algorithms for enhancing error probability in the FBMC-OQAM system under real conditions in 5G networks. The research results can be used in the development of 5G networks.

Keywords: 5G network, FBMC-OQAM method, white gaussian noise, BER, SNR, inter-cell interference, nonlinear distortion

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НАУЧНАЯ СТАТЬЯ

Влияние шумов и помех на вероятность битовых ошибок в системах 5G, использующих банк фильтров с несколькими несущими со смещенной квадратурной амплитудной модуляцией

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Резюме

Цели. Целью работы являются оценка помехоустойчивости метода модуляции сигналов в сетях 5G с использованием банка фильтров с несколькими несущими со смещенной квадратурной амплитудной модуляцией (FBMC-OQAM) и анализ вероятности битовых ошибок.

Методы. В работе применяются методы теории вероятностей и математической статистики, а также методы компьютерного моделирования.

Результаты. Представлен анализ вероятности битовых ошибок метода модуляции сигналов в сетях 5G с использованием банка фильтров с несколькими несущими со смещенной квадратурной амплитудной модуляцией в условиях шумов и исследована устойчивость метода к различным типам помех, таких как внутрисотовые и межсотовые помехи, межлучевые помехи в канале 5G, а также аддитивный белый гауссов шум. Представлены графические и численные данные, полученные компьютерным моделированием, показывающие улучшение вероятности битовых ошибок в сетях 5G, использующих FBMC-OQAM. Проведен сравнительный анализ вероятности ошибки в системе FBMC-OQAM при различных типах шумов и помех, подчеркивающий влияние этих факторов на качество передачи информации.

Выводы. Метод FBMC-OQAM характеризуется малым влиянием на вероятность ошибки системы передачи данных в сетях 5G таких типов помех, как внутрисотовые и межсотовые помехи, межлучевые помехи и нелинейные искажения. В статье подчеркивается необходимость дальнейшей оптимизации и разработки алгоритмов для улучшения вероятность ошибки в системе FBMC-OQAM в реальных условиях сетей 5G. Результаты исследования могут быть использованы при разработке сетей 5G.

Ключевые слова: сеть 5G, метод FBMC-OQAM, белый гауссов шум, вероятность битовой ошибки, отношение сигнал/шум, межсотовые помехи, нелинейные искажения

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INTRODUCTION

It is widely anticipated that the fifth generation of wireless communication systems, commonly known as 5G, will revolutionize the ways in which people interact. Promising higher data rates, lower latency, and greater bandwidth, the 5G system has the potential to transform a wide range of industries including healthcare, transportation, and manufacturing. However, the success of 5G depends on its ability to operate reliably in different environments including various types of interference and noise. One of the key technologies used in 5G networks to address these challenges is Filter Bank Multicarrier Modulation Offset Quadrature Amplitude Modulation (FBMC-OQAM) [1]. Offset Quadrature Amplitude Modulation (OQAM) represents an approach according to which the in-phase and quadrature components of the signal are staggered, i.e., offset relative to each other. Such offsetting permits more efficient utilization of the available frequency bandwidth, as well as reducing inter-symbol interference and improving robustness to frequency selective fading. FBMC-OQAM offers several advantages over the traditional orthogonal frequency-division channelization method widely used in 4G networks and earlier wireless communication systems. For example, the higher spectral efficiency of the FBMC-OQAM method increases tolerance to interference and noise. However, the error probability of a system using FBMC-OQAM under different types of interference and noise has yet to be fully investigated. Such research should be urgently conducted in order to inform the design of more efficient 5G networks.

In this connection, the present paper aims to analyze the bit error rate (BER) in 5G systems using the FBMC-OQAM method under different types of interference and noise. The analysis results provide information on the error probability of the FBMC-OQAM system in real communication environments to inform the future development of 5G systems.

1. TYPES OF NOISE AND INTERFERENCE IN THE 5G CELLULAR NETWORK

As compared to previous generations of cellular networks, the fifth-generation New Radio (5GNR)[1] system proposed by the 3rd Generation Partnership Project (3GPP) promises improved spectral efficiency, higher bandwidth, increased data rates, and communication reliability [1]. The spectrum resources used in 5G systems and defined in the 3GPP protocol are divided into two frequency bands (FBs): FB1 < 6 GHz and FB2 > 24 GHz (millimeter band) [2]. The FB1 frequency band, which is almost fully occupied, has limited resources for use in 5G networks, while FB2, representing a portion of the available spectrum where the majority of frequencies are not yet occupied, can be easily applied to future cellular networks [3].

Defined as undesirable impacts on the transmitted signal, interference, which typically results in signal modification or distortion, can arise from a variety of sources including neighboring signals, electromagnetic fields, overlapping signals, and obstacles in the signal propagation path [4]. Noise interference refers to a wideband impact on a signal that acts over an extended period of time. In 5G systems, noise (noise interference) can arise from a variety of sources including electronic components and thermal effects. Interference, which degrades the signal quality to reduce bandwidth and cause errors in data transmission [5], is proving to be a major problem in developing new spectral regions and exploiting the existing spectra in modern 5G systems [6].

In a wireless cellular network based around small cells, multi-level interference, which is determined by the specific characteristics of each low-power node, continuously generates and receives unwanted signals from various nearby sources [7]. The most common kinds of interference associated with wireless networks are self-interference, adjacent channel interference, as well as intra-and inter-cell interference. However, the mobile network is not limited to these interferences only. Each network is susceptible to interference that arises depending on the specific scenario of its deployment.

1.1. Intra-cell and inter-cell interference

Inter-cell interference is a significant cause of network degradation. Such interference occurs when users of two neighboring cells are trying to use the same frequency band simultaneously [8]. Moreover, inter-cell interference has a significant impact on user communication quality at cell edges since the user receives signals both from the macro base station of his cell and from the neighboring cell due to frequency reuse (Fig. 1). Distortions caused by additional equipment within the same cell are called inter-cell interference.

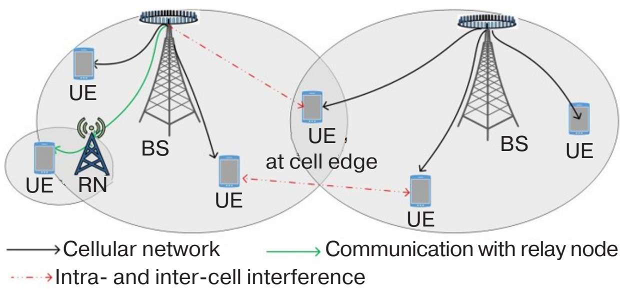

Fig. 1. Intra-cellular and inter-cellular interference. BS is base station, UE is user equipment, RN is relay node

[1] https://www.3gpp.org/technologies/5g-system-overview. Accessed January 20, 2023.

As shown in Fig. 2, inter-channel interference occurs when signals from two or more separate channels interfere with each other (the horizontal axis shows frequency *f* (Hz), while the vertical axis represents signal strength (dB); f_1 is the center frequency of channel 1; f_2 is the center frequency of channel 2) due to multiple wireless communication devices operating at close range. As a consequence, the stronger signal transmitter interferes with the weaker signal receiver.

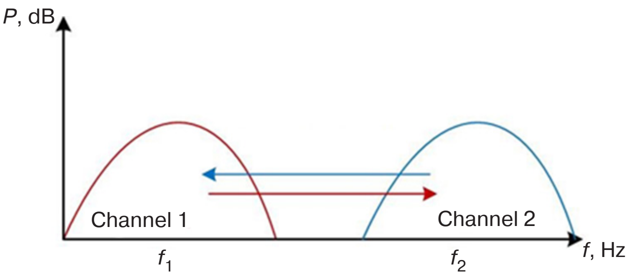

Fig. 2. Inter-channel interference

1.2. Inter-beam interference

Representing a novel technology used in modern cellular communications systems, beamforming defines the best route for providing optimal bandwidth to a certain user in a particular direction. This approach is necessary to compensate for attenuation losses in signal transmission, especially in millimeter wave communications. The base station (BS) generates multiple narrow beams of radio frequency (RF) signals in all directions of the coverage area. The BS and/or mobile terminal antennas are tuned to focus the transmitted signal in a particular direction, forming the so-called "beam" or directional signal [9]. However, the spatial separation of multiple beams results in inter-beam interference [10]. As shown in Fig. 3, this is caused by neighboring BS beams of the same or neighboring cell.

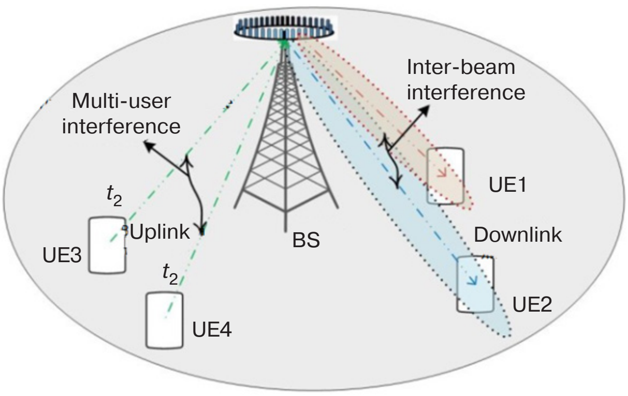

Fig. 3. Inter-beam and multi-user interference; t_2 is data transmission path

1.3. Nonlinear distortion in 5G networks

A common problem in wireless communication systems, including 5G networks, Nonlinear distortion occurs when the transmitted signal is significantly amplified and its power becomes too high, resulting in the amplifier going into nonlinear mode [11]. In this case, the signal is distorted, and information is incorrectly decoded in the receiver.

In 5G networks, nonlinear distortion can occur in transmitter or receiver circuits as a result of multiple factors to affect the characteristics of the transmitted signal [12]. In the frame of FBMC, nonlinear distortion can cause intermodulation distortion. This occurs when transmitted signals mix with each other to generate additional undesired frequencies, resulting in increased interference between subcarriers and leading to increased bit error rates and reduced data transmission efficiency.

The output signal $y(t)$ passed through the nonlinear distortion amplifier can be represented using the Taylor expansion:

$$y(t) = a_0 x(t) + a_1 x^2(t) + a_2 x^3(t), \quad (1)$$

where $x(t)$ is the input signal; a_0 is the linear gain of the power amplifier; a_1 and a_2 are coefficients at the nonlinear terms of the expansion.

1.4. Noise interference

The error probability in the communication channel depends on the noise level. Additive white Gaussian noise (AWGN) comes from many natural sources ranging from the motion of atoms in a conductor to radiation emitted by the earth and space objects. The linear and time independent AWGN channel, which is well suited for wireless communication, allows modulated signals to pass through it without any amplitude loss or phase distortion [13]. The output signal of the channel may be defined as follows:

$$y(t) = x(t) + n(t), \quad (2)$$

where summand $n(t)$ is the noise having the Gaussian distribution with zero mean and variance as the noise power; $x(t)$ is the transmitted signal.

The AWGN channel can be used by designers to evaluate the impact of various factors on the error probability in the system, in particular, to evaluate the impact of modulation schemes, channel coding techniques, and error correction algorithms [14], as well as physical layer parameters such as carrier frequency, bandwidth, and transmitted power.

2. BER AND SIGNAL-TO-NOISE RATIO

Representing the accuracy of digital data transmission in a communication system, the bit error rate is defined as the ratio of the number of bits received with an error to the total number of bits transmitted over the communication channel. It can be expressed as a percentage or decimal. Meanwhile, the bit error rate defines the probability that a bit in the transmitted signal will be received with an error. The BER value can be affected by various factors such as noise, interference, modulation scheme, and transmission range.

An important parameter determining the performance of a communication system is the signal-to-noise ratio (SNR), typically expressed in decibels, as follows:

$$\mathrm{SNR} = 10\lg\frac{P_\mathrm{s}}{P_\mathrm{n}}, \quad (3)$$

where P_s is the signal power; P_n is the noise power.

In practical terms, a high SNR value is preferable for any communication system due to providing higher accuracy and reliability of information transmission. On the other hand, a low SNR value may cause errors in the transmitted data, thus resulting in the reduced quality of the communication system.

3. SIMULATION AND ANALYSIS RESULTS

The present paper continues analysis of the model presented in previously published research [15, 16].

The model consists of a transmitter and a receiver of FBMC-OQAM signal, according to which the signal itself is simulated along with various perturbances: white Gaussian noise, spurious components of adjacent channels, intra-cell and inter-cell interference, inter-beam interference, and nonlinear distortion. By simulating the division of the signal into multiple subcarriers, each with its own narrowband filter, the model promotes efficient frequency utilization and high spectral efficiency. The offset quadrature modulation is used, where each subcarrier is split into two parallel streams: in-phase (I) and quadrature (Q). This permits a reduction in the inter-symbol interference caused by overlapping neighboring subcarriers. Using this model, numerical estimates for BER as a function of SNR can be obtained for different conditions.

New results obtained using the described model and its further analysis—in particular, investigating the impact of different noise and interference in 5G networks—are hereby presented.

The system is capable of processing I-data and Q-data of different sizes and different lengths of Fast Fourier Transform (FFT). Experiments are conducted using different combinations of parameters to demonstrate the adaptability of the system to different conditions.

For model verification, the experimentally obtained BER are compared with the known BER derived theoretically under identical AWGN channel conditions. The BER dependence on SNR for FBMC-OQAM system, obtained via a simulation for verifying the model's efficiency, is shown in Fig. 4 [17].

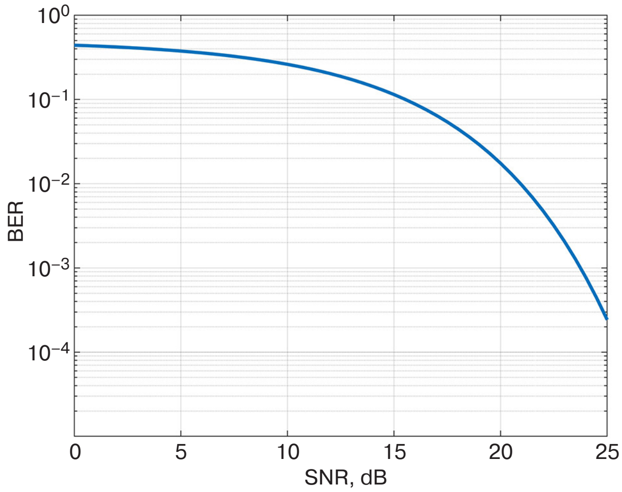

Fig. 4. BER on SNR dependence obtained through simulation

Simulation results are obtained at parameters given in the Table below.

Table. Model parameters

Number of subcarriers	2048
I/Q data size	$N = 64, 32, 16$
Data frame length	1
FFT size	8192, 4096, 2048, 512
Filter type	Prototype filter used in FBMC-OQAM
Overlap coefficient	$K = 4$
Channel model	Randomized initial sequence
Noise type	AWGN
Interference type	Interference from other cellular communication systems, nonlinear distortion, inter-cell interference
SNR range	From −10 dB to 30 dB

The error probability of the system is studied for a 512-point, 2048-point, 4096-point, and 8192-point FFT. The system uses matched filtering with overlapping coefficient K representing the number of multicarrier symbols overlapped on the time interval. The impact of changing the symbol length is analyzed for a 512-point, 1024-point, and 2048-point FFT. The results show that changing the symbol length has almost no impact on the error probability in FBMC-OQAM system.

From the results (Fig. 5) for $N = 64$, it can be seen that when the FFT length is reduced, the SNR required to achieve BER value equal to 10^{-6} increases. In particular, for an 8192-point FFT, SNR = 6 dB is required to achieve the desired BER value, while for 4096-point, 2048-point, and 512-point FFTs, the required SNR values are 7.8, 12, and 20 dB, respectively. This means that longer FFT length provides better BER at lower SNR values. Thus, increasing FFT length may be a useful strategy for reducing error probability.

Simulation results for $N = 32$ with different FFT lengths are shown in Fig. 6. It can be seen that, upon reduction of FFT length, the SNR required to achieve a BER value equal to 10^{-6} increases. In particular, for an 8192-point FFT, SNR = 1.5 dB is required for the system to achieve the desired BER value, while for 4096-point,

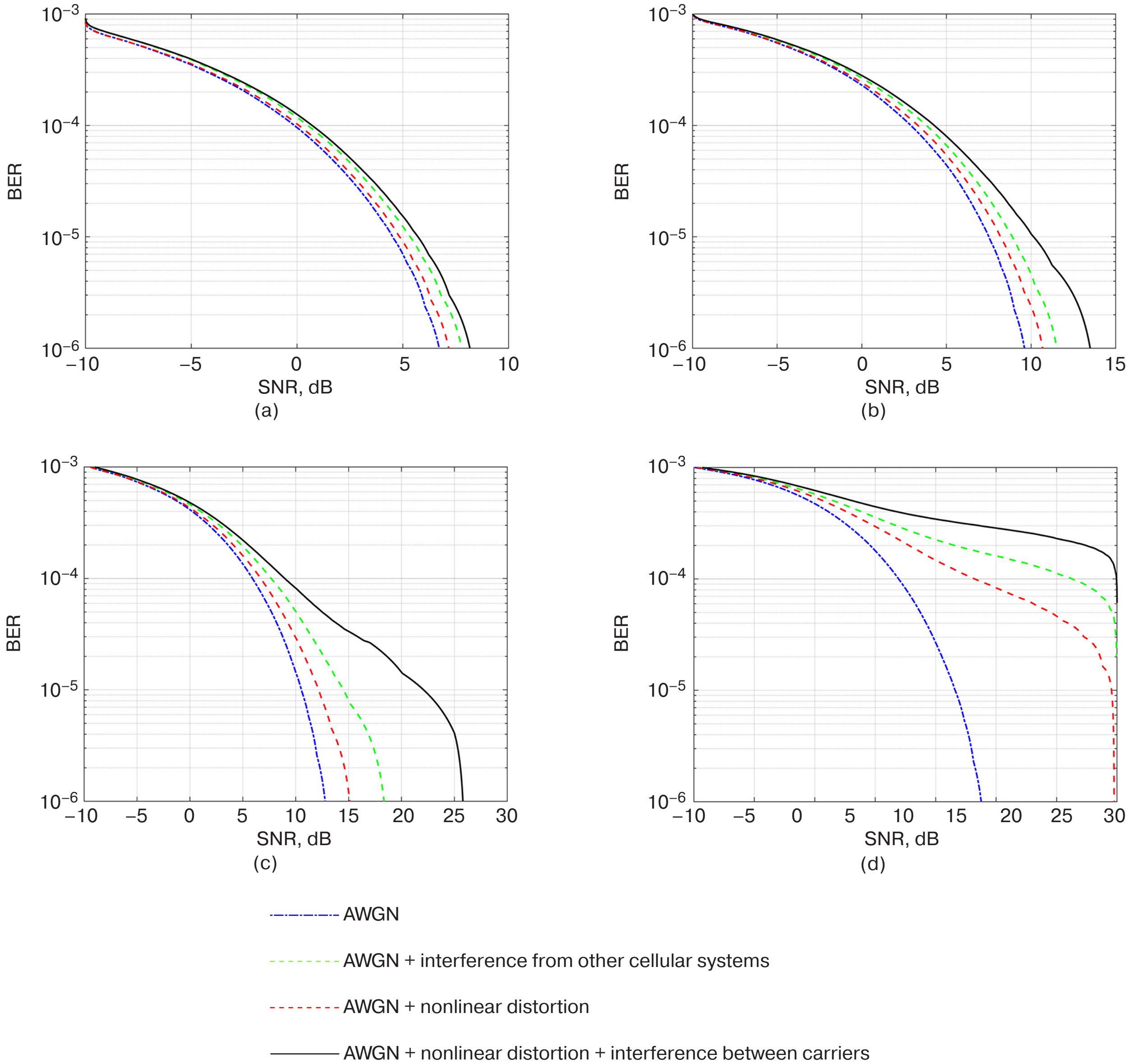

Fig. 5. Simulation results for $N = 64$ and FFT length:
(a) 8192,
(b) 4096,
(c) 2048,
and (d) 512

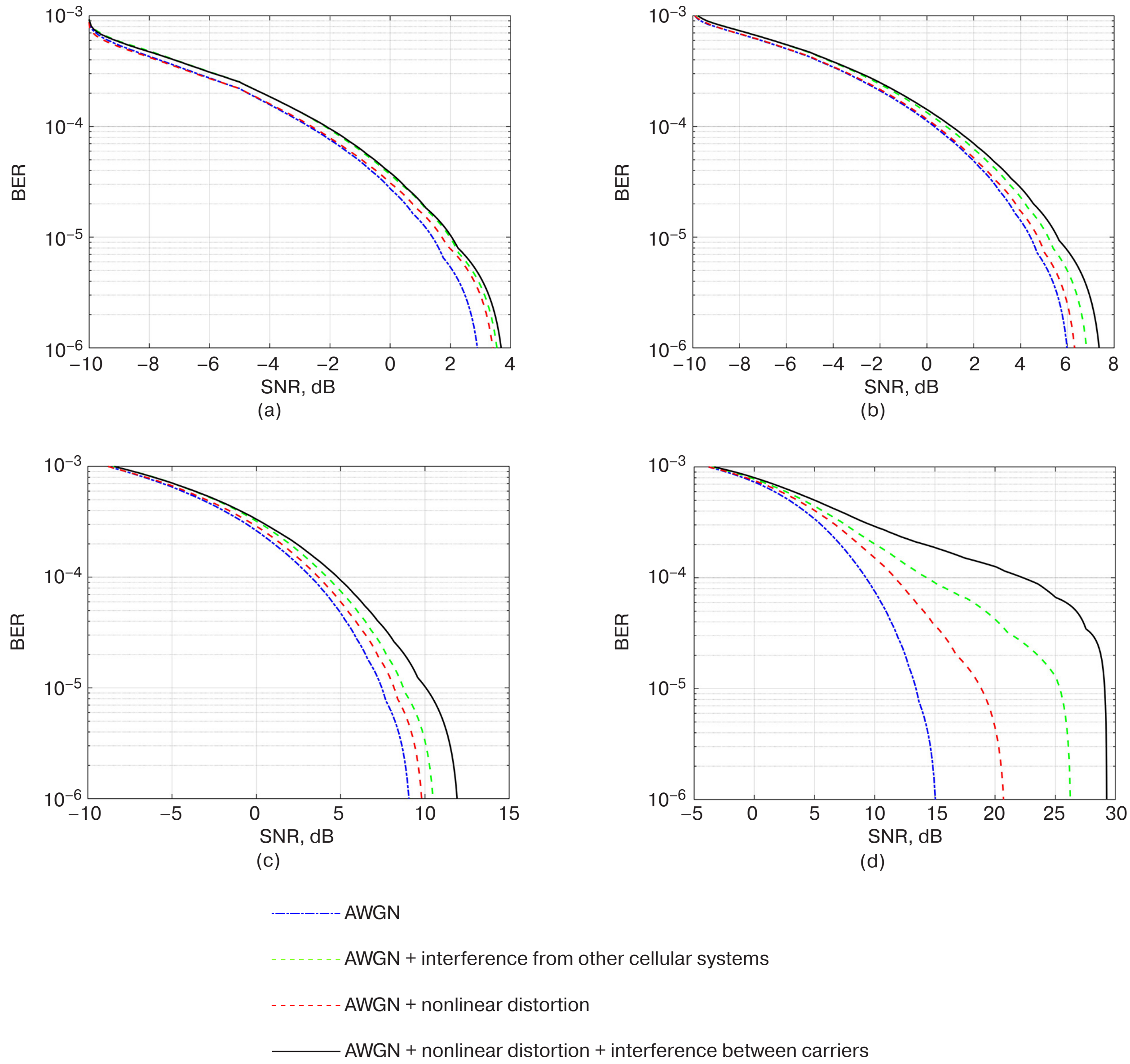

Fig. 6. Simulation results for N = 32 and FFT length:
(a) 8192,
(b) 4096,
(c) 2048,
and (d) 512

2048-point, and 512-point FFTs, the required SNR values are 5, 8, and 14 dB, respectively. Hence, even in this case, increasing the FFT length may be a useful strategy for reducing error probability.

It can be observed from Fig. 7 that the trend of increasing the required SNR to achieve the same BER level for $N = 16$ becomes even more noticeable as the FFT length decreases. The same dependence can be observed in Figs. 5 and 6. Here, it can be seen that BER decreases with SNR increasing for all FFT lengths. In addition, the system with the longest FFT length equal to 8192 has a low BER, requiring the highest SNR to achieve BER equal to 10^{-6}. On the other hand, the system with the minimal FFT length of 512 has the best BER, requiring the lowest SNR to achieve the same BER value. Systems with FFT lengths of 4096 and 2048 have similar error probabilities, the former requiring a slightly higher SNR to achieve the same BER. Hence, it can be concluded from these results that, for a system with fixed $N = 16$, smaller FFT lengths result in better BER at higher SNR levels, while greater FFT lengths require a higher SNR to achieve the same BER. This emphasizes the importance of selecting the appropriate FFT length in the system.

CONCLUSIONS

Simulation results verify high resistance of FBMC-OQAM modulation method in 5G networks

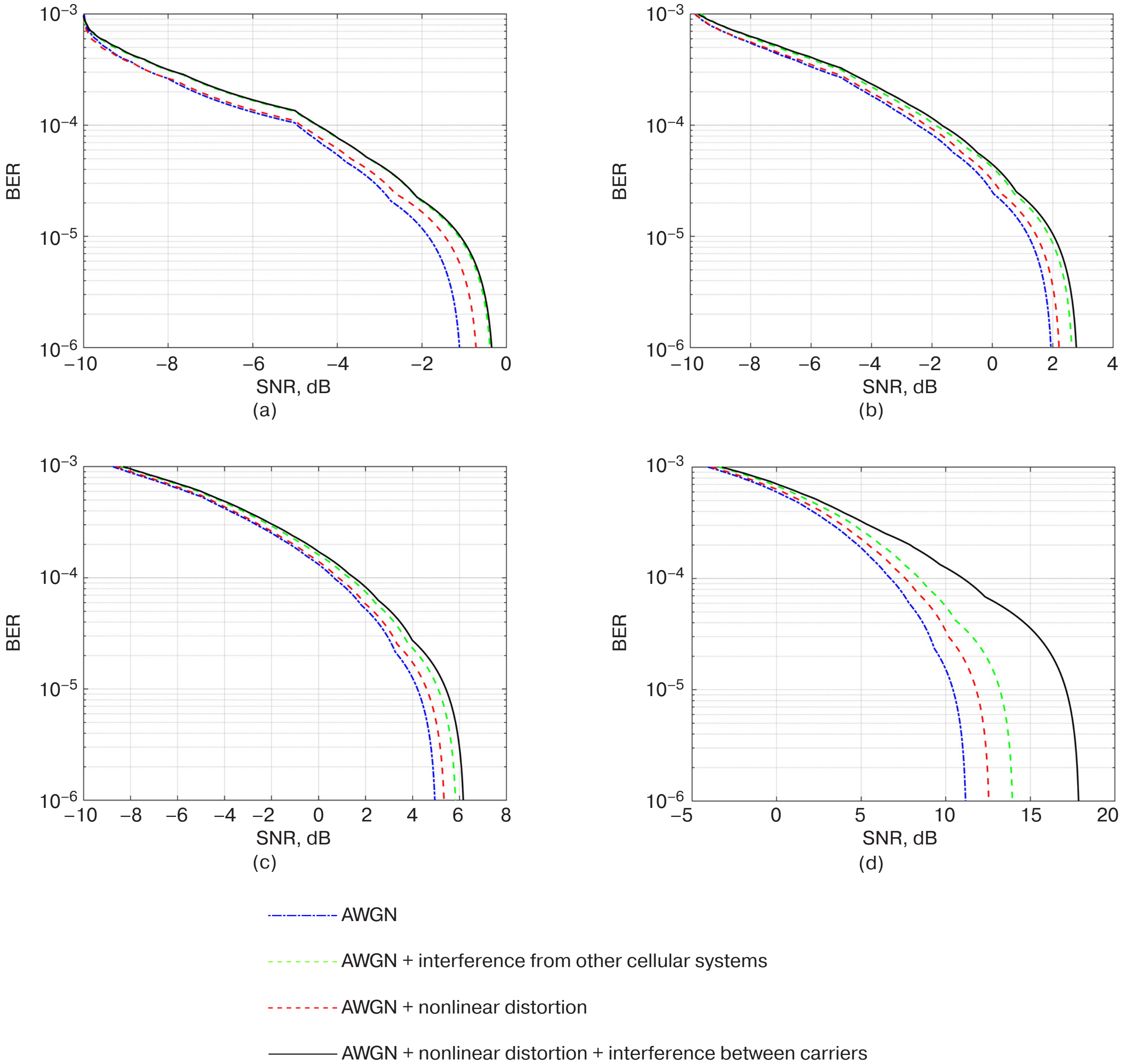

Fig. 7. Simulation results for N = 16 and FFT length:
(a) 8192,
(b) 4096,
(c) 2048,
and (d) 512

to various types of interference, thus significantly improving communication quality. Increasing the FFT length effectively reduces the probability of data transmission errors, while the optimal choice of the FFT length depends on specific conditions of 5G networks.

Authors' contribution. All authors equally contributed to the research work.

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