Exploring 6G Wireless Networks: Millimeter-Wave Revolution and Mixed-Carrier Communication for Enhanced Spectrum Efficiency

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Abstract. The commercial launch of fifth-generation (5G) wireless cellular networks this year will pave the way for the widespread adoption of millimeter-wave (mm-wave) technology for spectrum access. To completely comprehend the real-world ramifications of offering several services across 6G networks at once, more investigation is required. 6G wireless technology offers improved capacity, latency, speed, and connection over 5G. It makes real-time communication, augmented reality, and the Internet of Things possible. Another objective is low latency, which ensures global coverage and environmental sustainability. In order to achieve high data throughput, 6G technology is experimenting with terahertz frequencies despite challenges such air attenuation and limited propagation ranges. In this work, we use mixed-carrier communication technology to investigate interference control and spectrum efficiency. Mixed-carrier systems are communication systems that transport data using numerous carriers at different frequencies. Numerous communication technologies frequently employ this technique to achieve a range of objectives, such as increased bandwidth efficiency, multiuser support, and improved performance under load. Data transfer is made quick, easy, and interference-free with the use of orthogonal frequency-division multiplexing (MCC) subcarriers. Lastly, several metrics are calculated and compared with the outcomes of lower-order QAM, including SNR, BER, optical power ratio, and interference analysis.

Keywords: 6G network · Mixed carrier communication · Orthogonal frequency-division multiplexing · Interference · Spectrum management

1 Introduction

In wireless communication, the term “mixed carrier communication” usually describes a situation in which several carrier types or communication technologies are combined to create a communication system that is more reliable and adaptable [1, 2]. To increase

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coverage, capacity, or dependability, this may involve using several wireless standards or frequencies concurrently. Millimeter-wave, or mm-wave, technology was used in 5G and provided a broad spectrum with data speeds of up to 1 Gbps and a round-trip latency of 1 ms [3]. 5G introduced a device-centric approach that prioritizes low latency, maximum reliability, and the capacity to connect millions of devices. Studies are being done to influence the direction of wireless communication with sixth-generation (6G) networks by addressing design constraints that may not be addressed by 5G [4]. The mm-waves' poor indoor propagation performance is one of the problems that needs to be fixed for 6G. This may require combining RF spectrum with VLC for performance similar that of a short-range optical Fiber. By enabling a range of services across a large network, 6G aims to increase the heterogeneity of wireless networks to a new level [5].

In digital communication, quadrature amplitude modulation, or QAM, modifies a carrier signal's phase and amplitude in order to transfer data [6]. It is analogous to representing digital information by combining various amplitudes and phase shifts. The number of combinations that can be used to efficiently transmit data over a communication channel depends on the particular scheme [7]. 128-QAM is a high-order digital modulation scheme that can transmit seven bits per symbol for a high data throughput. Because of its sensitivity to noise, it needs a clean and dependable channel for use in applications like digital cable TV and high-speed data transfer [8, 9].

The number of bit errors in digital transmission is the quantity of received bits of a data stream over a communication channel that have been altered due to distortion, noise, interference, or bit synchronization errors [10, 11]. BER is the quantity of bit errors per unit of time. An important concept in many industries, including audio, video, communication systems, and many more, is SNR [12, 13]. It measures how strong a desired signal is in relation to background noise, which may interfere with the signal's ability to be detected or understood [14, 15].

Several methods for enhancing isolation in MIMO antenna systems are covered in the text, with a special emphasis on frequency-tunable decoupling with graphene-based structures [16]. The tunable band stop characteristics offered by these structures improve the isolation between antenna elements [17]. Previous approaches were not frequency tunable; however, graphene-based designs allow for fine tuning of isolation levels. Notwithstanding, certain obstacles persist, such as the necessity of positioning structures perpendicular to the antenna plane, which compromises the system's low-profile characteristic [18]. In a dual-polarized slot ring-based MIMO antenna configuration, the suggested work presents a compact, tunable band stop filter-based decoupling mechanism using graphene, improving isolation by 30.41 dB The study also emphasizes how terahertz (THz) communication is becoming more and more popular because of its high data rate, wide bandwidth, and opportunities for compact system design that reduce radiation [19].

2 Literature Review

In 2023, Abdelaziz Aalili et al. [1] examine the advantages and drawbacks of Massive Multiple-Input Multiple-Output (MIMO) technology in 5G networks, emphasizing its data rates, energy efficiency, and spectral efficiency. It also proposes cell-free MIMO as a viable alternative that would save costs and complexity while enhancing system performance. The article addresses several potential restrictions and difficulties with the Massive MIMO project, including inter-cell interference, modeling energy efficiency, and lowering complexity and costs with cell-free MIMO.

In 2022, Edward J. Oughton et al. [2] discusses a survey that evaluates the technological and financial elements of the fifth generation of cell phones (5G), including a review of the literature, data gathering, analysis, and recommendations. The study creates suggestions for next-generation 6G wireless technologies while identifying trends, obstacles, and opportunities. Subjectivity in recommendations, feedback validation, time sensitivity, communication, industry adoption, evolving technology, heterogeneity of literature, data availability, reliability, interdisciplinary nature, defining metrics, integrating 6G considerations, global variability, and evaluation of quality are some of the challenges that quality assessment faces as it assesses reliability.

In 2021, Silvio Mandelli et al. [3] suggested a unique link adaptation strategy for beyond 5G and 6G networks to shorten inter-site distances. It is easy to deploy without requiring inter-cell coordination, feasible, analytically verified, and maximizes resource use while reducing transmit power. The applicability, robustness, scalability, implementation complexity, and sensitivity to system characteristics of the Link Adaptation scheme are its limits. These may result from sensitivity to system parameters, high implementation complexity in real-world networks, and a lack of comprehensive information.

In 2021, Juan Liu et al. [4] investigate ways to overcome the low peak-to-average power ratio, low PAPR, and non-linearity of power amplifiers in order to increase spectral efficiency in 5G Evolution and 6G communication systems. In order to suppress OOBE and lower SNR loss, a unique non-orthogonal waveform (eNOW) is presented. It must overcome a number of obstacles, including complexity, implementation, performance metrics, compatibility, resource intensiveness, spectrum efficiency, and real-world interference.

In 2020, Ahmed F. Hussein et al. [5] focus on creating and assessing a physical layer (PHY) employing mixed carrier communication (MCC) for visible light communications in 5G and 6G wireless networks. Investigating parameters, encoding techniques, and modulation schemes are all part of the design process. Modeling, simulation, and experimental proof-of-concept are all part of performance evaluation. It presents a unique communication technique called Mixed-Carrier Communication (MCC), addressing performance issues and optimizing physical layer design for concurrent service support while placing a strong emphasis on experimental validation under real-world scenarios.

A novel method is proposed in order to improve the spectral efficiency and interference management for 6g network in terms of SNR, BER, and optical power i.e. Mixed carrier communication. This work investigates the spectral profile and environmental robustness of MCC in OFDM. It employs experimental proof of concept, theoretical models, and Matlab simulations to provide light on the spectral behavior of MCC and its possible consequences for efficient spectrum management in a variety of communication contexts.

3 Methodology

This paper presents a plot of the SNR versus BER. In general, we desire a higher signal power than noise power. The minimum BER is required. We observe that by simulating in MATLAB for modulation schemes such as 8-QAM, 16QAM, 32-QAM, 64-QAM, 128-QAM.

3.1 QAM Block Diagram

An analog channel transmits digital data by a modulation technique named digital communication system represented by a QAM block diagram. The data source, serial-to-parallel converter, symbol mapping, in-phase and quadrature signal generation, the creation, modulation, and summation of carrier signals are all components of the QAM system [5]. The received signal, carrier recovery, amplification, symbol demapping, parallel-to-serial conversion, and output make up the receiver block diagram. To enable the modulation and demodulation of digital data, a QAM communication system's main parts and signal flow are summarized in the Fig. 1 QAM block diagram.

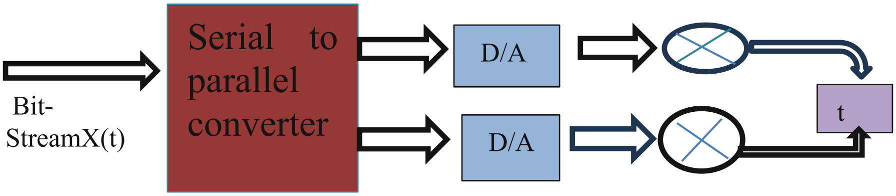

Fig. 1. Block Diagram of QAM

3.2 OFDM Block Diagram

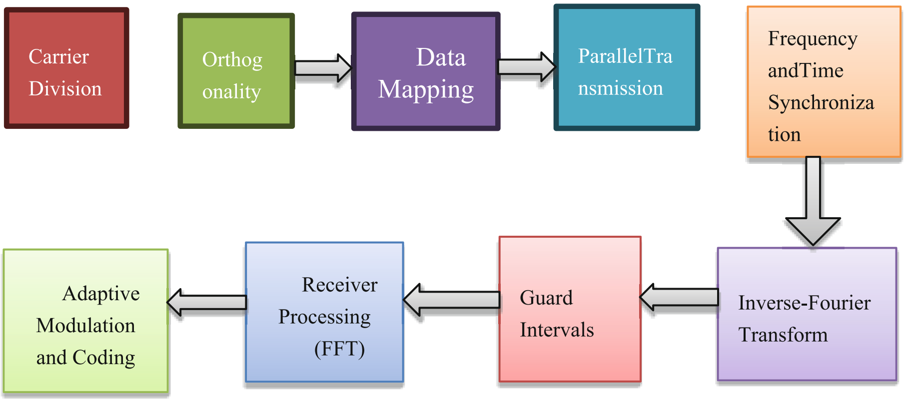

Fig. 2. Block diagram of OFDM

In a digital communication system, random data is generated by creating a series of 0 s and 1 s. The data is then converted to parallel data using a serial-to-parallel converter. Serial-to-parallel converter is then used to transform the data into parallel data. After that, the data is mapped onto a particular modulation scheme, like PSK or QAM. After modulation, the symbols are mapped onto subcarriers using an IFFT operation [6, 9]. After that, the parallel data is formatted for transmission in a serial fashion. To handle synchronization and multipath propagation, a guard interval is added. A channel is used to transmit the signal, which might cause noise and other interference. The received signal is then converted back to parallel for further processing. Following demodulation, the data is transformed back into serial format. Mixed carrier communication is a communication system that combines different types of carriers within the same transmission framework, such as OFDM [11, 13] as shown in the Fig. 2. This approach enhances the performance of OFDM systems by leveraging the strengths of different carrier types. It involves the integration of different subcarrier types, such as QAM, hybrid modulation schemes, adaptive modulation and coding (AMC), spectral efficiency, robustness, non-linear distortion mitigation, improved performance in specific scenarios, and experimental validation. Traditional OFDM systems employ uniformly spaced orthogonal subcarriers, each using the same modulation scheme. Mixed carrier OFDM introduces hybrid modulation schemes, allowing flexibility in adapting to different communication scenarios. It also provides better signal integrity in scenarios with diverse channel conditions, such as cognitive radio systems [17, 18].

4 Simulation Results

Spectral analysis is a crucial tool in digital communication systems, providing insights into the distribution of signal frequency components. It can help determine the signal's bandwidth, which is crucial for data transmission, and guide filter design. Spectral analysis can also reveal spectral regrowth, which increases signal power at frequencies outside the nominal bandwidth. It can also identify interference, which can degrade signal quality and increase BER. Spectral analysis also helps calculate SNR and also reveal the presence of noise and its spectral characteristics, enabling the calculation of noise power and SNR. Spectral analysis can also help improve SNR and reduce BER by focusing on high power regions. The choice of receiver bandwidth is often based on spectral analysis. Spectral efficiency, also known as spectrum efficiency, is the speed at which data or information is transferred over a specific bandwidth in a communication system. Optical power is the amount of energy carried by a light wave, measured in watts or milliwatts. It is crucial in communication systems, particularly fiber optic communication, to quantify the intensity of light signals transmitted through optical Fibers. Optical power is frequently measured in relation to the received signal strength at a photodetector (such as a photodiode) in optical communication systems. The system's performance, including variables like the BER and SNR is influenced by the received optical power. Optimizing optical communication systems' performance and dependability requires varying or managing their optical power. The system performance is taken into consideration when calculating certain parameters such as the BER, SNR, etc. There has been a noticeable drop in the BER as shown below. The ber should be reduced to obtain improved signal transmission (Fig. 3).

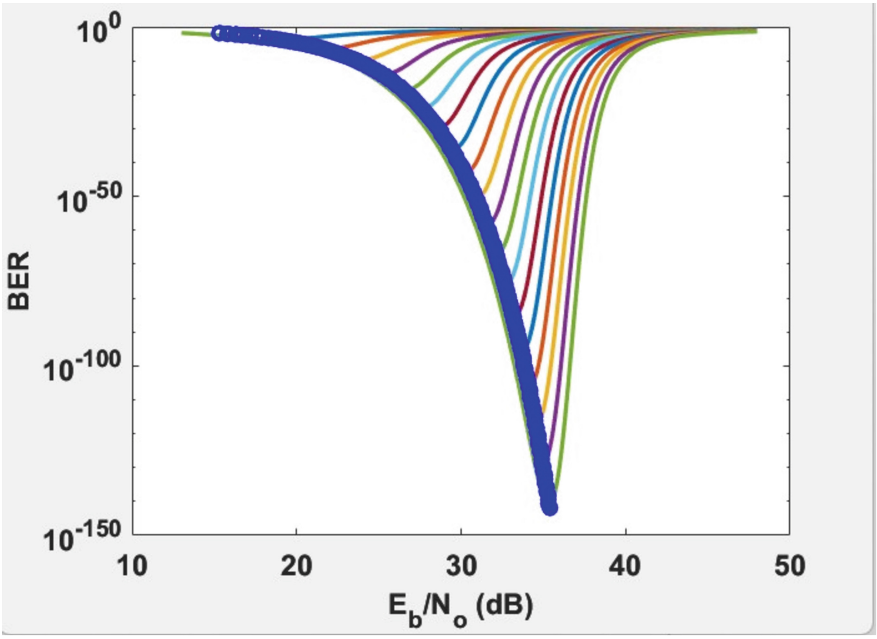

Fig. 3. BER and Signal-to-Noise Analysis in Optical Communication with Clipping Thresholds for 8-QAM.

This graph is meant to show the BER in decibels across a wide range Eb/N0 values, which indicate the energy per bit to noise power spectral density. This graph depicts the overall BER performance at various degrees of noise. This plot is depicted on a log scale to make the variation more visible. The blue dots reflect the BER at the tenth clipping threshold; the BER at other clipping thresholds is not plotted (Fig. 4).

This graph is meant to show the BER in dB across a wide range of Eb/N0 values, which indicate the energy per bit to noise power spectral density. This graph depicts the overall BER performance under various levels of noise. This plot is shown on a log scale to make the differences more obvious. The blue dots represent the BER at each 10th clipping threshold; the BER at other clipping thresholds is not shown (Fig. 5).

This graph is meant to show the BER in decibels over a wide range of Eb/N0 values, which reflect the energy per bit to noise power spectral density. This graph would depict the overall BER performance at various degrees of noise. To make the changes easier to observe, this plot is displayed on a log scale. The blue dots show the BER at the tenth clipping threshold, as the BER at other thresholds is not represented (Fig. 6).

This graph is meant to provide BER in decibels (dB) over a wide range of Eb/N0 values, which indicate the energy per bit to noise power spectral density. This graph would display the overall BER performance under various levels of noise. To better see the contrasts, this plot is given on a log scale. The blue dots reflect the BER at the tenth clipping threshold, while the BER at other clipping thresholds is not shown (Fig. 7).

It has been seen that there has been a noticeable drop in the BER for higher order QAM. The BER should be reduced to obtain improved signal transmission as shown

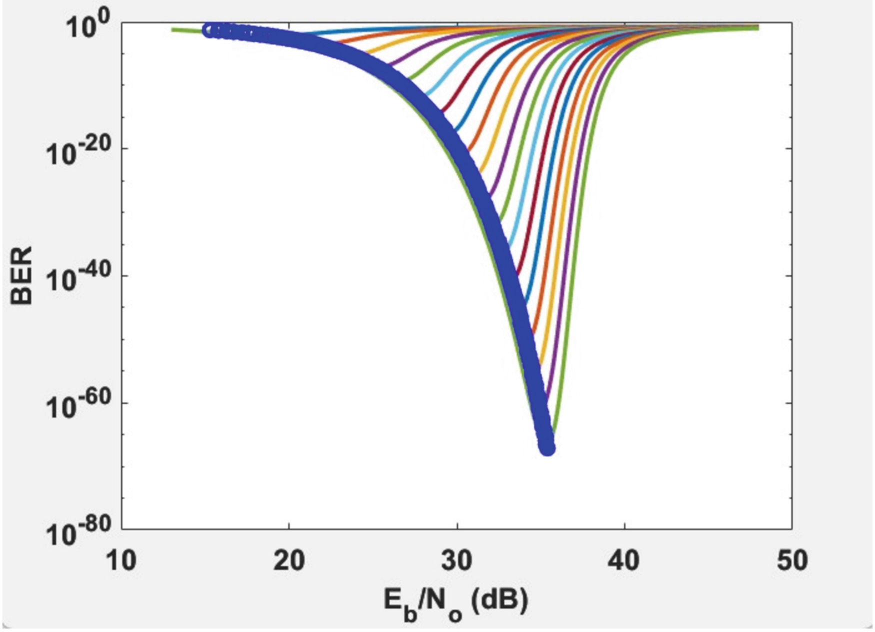

Fig. 4. The graph for 16 QAM illustrates the relationship for BER vs SNR.

in Table 1. The graph also analyzes Bit Error Rate (BER) performance by calculating and comparing BER values for different clipping thresholds which was shown in Fig. 1 to figure e. Finding the right balance between clipping and maximizing signal power is crucial for better performance in optical communication systems.

$$\text{BER} = \frac{4(\sqrt{M}-1)}{\sqrt{M}\log_2(M)}Q(\sqrt{\frac{3\log_2(M)}{M-1}\gamma_{\text{elec}}}) + \frac{4(\sqrt{M}-2)}{\sqrt{M}\log_2(M)}Q(3\sqrt{\frac{3\log_2(M)}{M-1}\gamma_{\text{elec}}}) \tag{1}$$

$$\gamma_{\text{elec}} = \frac{2K^2}{\sigma_{\text{clip}}^2/P_{b(\text{elec})} + (N_o/E_{b(\text{elec})})}, \tag{2}$$

$$\sigma_{\text{clip}}^2 = -2Q^2(\lambda_{\text{top}}) + Q(\lambda_{\text{top}}) + Q(\lambda_{\text{top}})\lambda_{\text{top}}^2 - \phi(\lambda_{\text{top}})\lambda_{\text{top}}, \tag{3}$$

$$K = \frac{1}{2} - Q(\lambda_{\text{top}}), \tag{4}$$

$$\textit{Where } Q(u) = \frac{1}{\sqrt{(2\pi)}}\int_u^\infty \exp(\frac{-u^2}{2})\mathrm{d}u. \tag{5}$$

"Lambda_top" is a parameter that represents the ratio of the upper clipping threshold for optical power to the square root of twice the transmitted electrical power. It plays a critical role in analyzing the BER performance of different modulation orders (e.g., 32-QAM, 64-QAM, 128-QAM) as shown in figure f and figure g. Lambda_top is used to

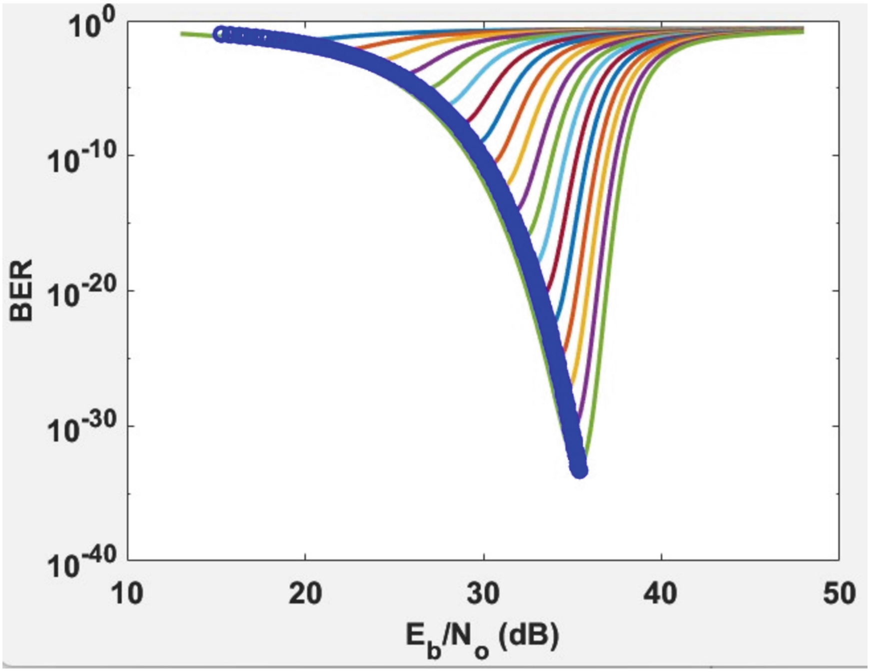

Fig. 5. The graph for 32 QAM illustrates the relationship for BER vs SNR.

evaluate how changes in power levels and clipping thresholds affect BER and to find the optimal Lambda_top for minimizing BER. It quantifies the relationship between optical and electrical aspects of the communication system and influences signal clipping and distortion. The term "Lambda_top_elec" could potentially represent a parameter related to electrical aspects of the system, possibly referring to the proportion of an electrical property to twice the transmitted electrical power squared (Fig. 8).

$$\lambda_{\text{top-elec}} = \frac{\eta_{\text{elec}}}{P_{\text{elec}}} = \lambda_{\text{top}}\sqrt{2\pi}. \tag{6}$$

There has been a noticeable drop in the BER and increased values of λtop. Pb(elec) and Eb(elec) stand for energy and electric power per bit in above graph, and no denotes noise spectral density. Figure investigates BER across QAM modulations in order to maximize spectral efficiency and minimize BER. BER improves with increasing SNR; however, excessive signal power introduces clipping noise, especially at higher modulation orders (Fig. 9).

There has been a noticeable drop in the BER and increased values of Eb/N0. Figure g illustrates the relationship for different modulations between the ideal SNR and target BER, and Figure f displays the ideal λtop for the desired BER. For example, Table lists the suggested SNR and λtop values for a target BER. Using the PWM-like frame power, the ideal electrical power clipping threshold (ηelec) is found by converting λtop into electric power. This reduces BER and reduces clipping noise (Fig. 10).

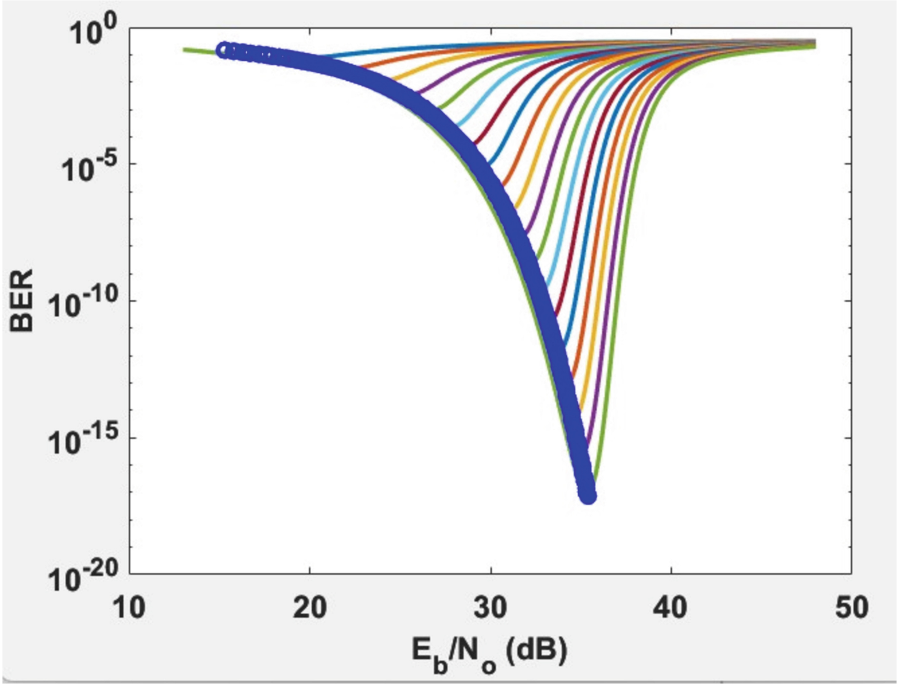

Fig. 6. The graph for 64-QAM illustrates the relationship for BER vs SNR.

U-OFDM is a variation of traditional OFDM in wireless communication systems, where subcarriers are intentionally designed to partially overlap, allowing for more efficient use of the available frequency spectrum. Key characteristics of U-OFDM include higher spectral efficiency, interference management, and increased data rate. The simulation in MATLAB evaluates the Bit Error Rate (BER) performance of a U-OFDM system under different interference scenarios, including variations in Pulse Width Modulation (PWM) duty cycle and harmonic distortions. The goal is to assess the system's performance and compare BER under different conditions. The system uses 128-QAM modulation and includes interference from various sources. The simulation loop in matlab generates a random bit stream, applies QAM modulation, performs Inverse Fast Fourier Transform (IFFT), introduces interference, noise, and distortion, calculates the received signal, and computes the BER for each SNR value. The code calculates and plots the BER against the Signal-to-Interference-plus-Noise Ratio (SINR) and calculates the difference between SINR and predefined SINR values as tabulated in Table1.

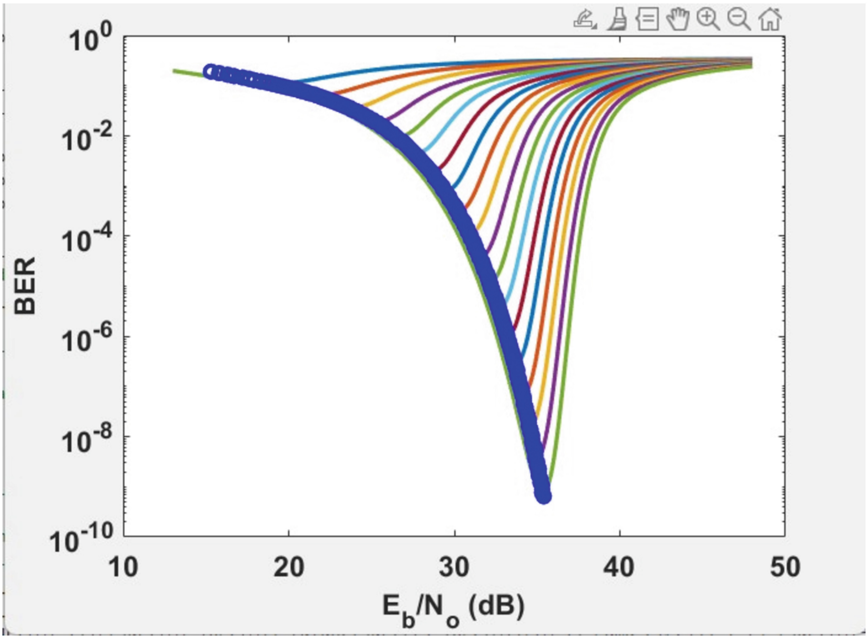

Fig. 7. The graph for 128 QAM illustrates the relationship for BER vs SNR.

Table 1. Shows the ideal SNR, λtop, and λtop − elec values to BER threshold.

QAM	SNR	λtop	λtop_elec
8-QAM	16.7	1.899	4.76
16-QAM	19.6	2.1964	5.5056
32-QAM	27.5	2.75	6.893
64-QAM	30.2	3.145	7.883
128-QAM	33.4	3.342	8.3771

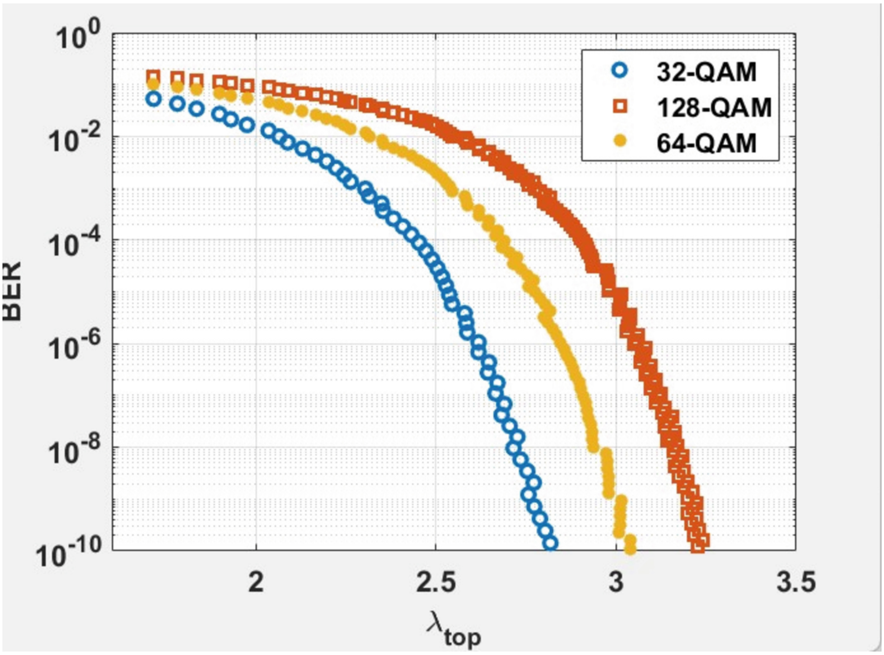

Fig. 8. The graph illustrates the relationship between BER and λtop from.

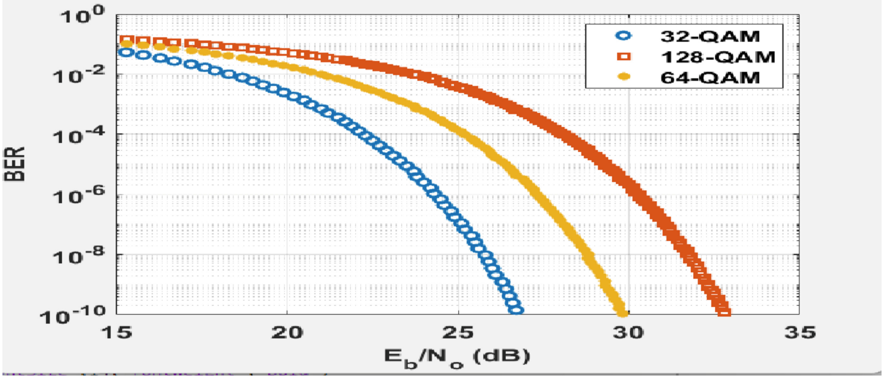

Fig. 9. The graph illustrates the relationship between BER and Eb/N0.

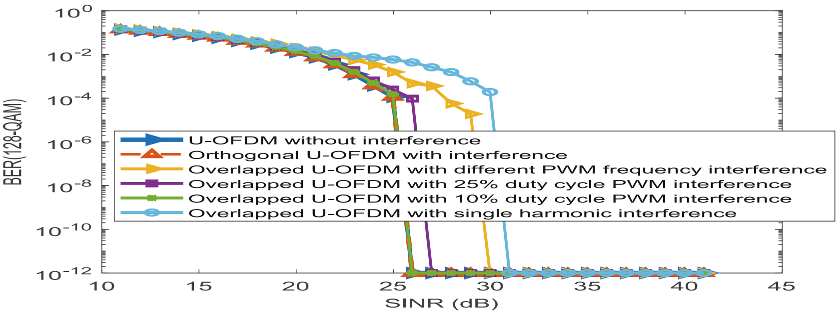

Fig. 10. Bit Error Rate (BER) for 128-QAM of an Underlapped-Orthogonal Frequency Division Multiplexing (U-OFDM) communication system under different interference scenarios.

5 Conclusion

MCC is a new wireless technology for 6G that can provide multiple services, such as broadband access, IoT connectivity, sensing, and localization. In order to prevent performance degradation, this work discusses the design of MCC and suggests SNR thresholds for various modulation techniques. Good BER performance can be achieved even in the presence of interference with a properly managed spectrum, according to a study on interference management and spectrum analysis. The performance evaluation of 6G based system parameters using MCC was simulated and measured SNR, BER and spectral efficiency throughput with different higher QAM.

6 Future Scope

The future scope for the next QAM technologies involves higher-order QAM schemes (e.g., 256-QAM, 512-QAM) to increase data rates, along with advanced error correction, signal processing, and MIMO systems, all aimed at optimizing performance and integration into communication standards.

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