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High-Frequency Radio Waves to Achieve Multi-Gigabit Data Rates and Low Latency 5G Cellular Millimeter Wave Communication System

Rishav Anand, Dr. Amrita Khera

Department of Electronics & Communication Engineering Prestige Institute of Management and Research, Bhopal

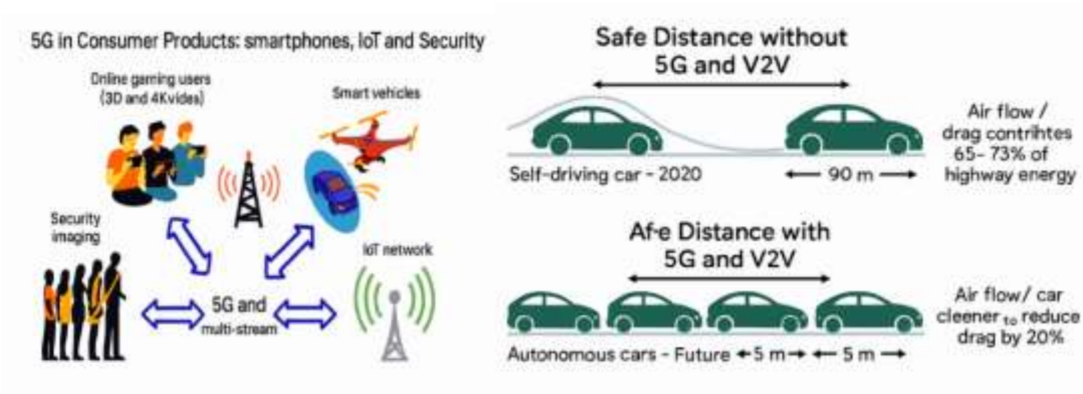
ABSTRACT:

High-frequency radio Waves to achieve multi-gigabit data rates and low latency 5G Cellular millimeter wave (mmWave) communication system Millimeter-wave communications (mmWave) are gaining significant attention for their diverse applications across various domains, being key for the development of ultra-fast, low-latency wireless systems This study evaluates mmWave systems for 5G cellular communication through numerical simulations. In basic faded mmWave communication, 4-QAM outperformed 4-PSK, achieving lower bit error rates (BER) at lower signal-to-noise ratios (SNR). Higher-order modulations like 16-PSK and 32-PSK showed poor BER performance. The extended MIMO-OFDM framework demonstrated significant improvements, with 16-QAM in a 2x4 antenna configuration achieving superior BER performance compared to higher-order PSK modulations. These results highlight the superiority of QAM schemes and increased antenna diversity for 5G mmWave systems. The findings provide valuable insights for optimizing modulation schemes and antenna configurations in future 5G mmWave communication systems

Keywords: *Millimeter Wave, High bandwidth, OFDM, PSK, QAM, wireless Communication , BER*

1. Introduction

The rapid evolution of fifth-generation (5G) mobile communication systems has ushered in an era of ultra-reliable, high-capacity, and low-latency wireless connectivity. Nevertheless, realizing the full potential of 5G, particularly for real-time mobile broadband applications demands overcoming several critical challenges, including those associated with terminal design, antenna architecture, and channel estimation. Figure 1(a) illustrates a conceptual framework of 5G integration into modern consumer technologies, emphasizing its transformative influence across diverse domains. At the core is a 5G tower labeled 5G and multi-stream, symbolizing the high-speed, low-latency backbone that underpins seamless connectivity. From this central hub, four key application areas are highlighted. The first, “Online gaming users (3D and 4K videos),” demonstrates 5G’s ability to deliver immersive, high-bandwidth entertainment experiences. The second, “Smart vehicles,” represented by a car and drone, reflects the critical role of real-time data exchange in intelligent transportation and safety systems. The third, “IoT network,” signified by a signal tower, captures the dense interconnection of devices and sensors within smart environments. Finally, “Security imaging” illustrates the enhancement of surveillance and biometric applications through rapid data transmission. Collectively, these elements underscore the versatility of 5G as a driver of next-generation consumer experiences through robust multi-stream communication. Figure 1(b) illustrates the impact of 5G and Vehicle-to-Vehicle (V2V) communication on safe driving distances and aerodynamic efficiency in autonomous vehicle platooning. In this scenario, four autonomous cars are shown traveling in close formation with inter-vehicle gaps of approximately 5 meters, significantly shorter than traditional safe distances. This compact spacing is enabled by real-time data exchange via 5G and V2V technologies, allowing vehicles to synchronize acceleration, braking, and lane positioning with high precision. It results, airflow between vehicles becomes smoother, reducing aerodynamic drag by up to 20%. This not only enhances fuel efficiency and energy conservation but also contributes to improved traffic flow and road capacity.



a) application of 5G consumer products b) 5G For V2V communication

Figure 1: 5G for communications in automotive V2V and Consumers applications.

The Figure 1 emphasizes how advanced 5G communication can transform highway dynamics, making future mobility systems more efficient, coordinated, and sustainable. As emphasized by Shuminoski and Janevski [1], future 5G terminals must be capable of supporting multi-streaming and vertical multi-homing in order to efficiently manage simultaneous multimedia flows across heterogeneous radio access technologies. To meet these requirements, advanced antenna designs, such as switchable three-dimensional phased array packages, have been proposed to improve spatial coverage and beam steering performance in mobile devices [2]. In parallel, the deployment of smart small cells integrated with hybrid beamforming has emerged as an effective strategy to enhance spectral efficiency and user experience, particularly in dense urban environments [3]. Nevertheless, the reliability of such systems relies heavily on accurate channel estimation methods. Classical approaches, including Least Squares (LS) and Linear Minimum Mean Square Error (LMMSE), have been widely applied in LTE downlink systems [4], while more advanced frameworks have been introduced to cope with rapid dispersive fading in OFDM-based architectures [5]. Techniques such as delay-subspace tracking [6] and pilot-assisted MIMO-OFDM estimation [7] further strengthen the ability to obtain reliable channel state information under highly dynamic and noisy conditions. Despite these progressions, the integration of multi-streaming terminals, adaptive antenna systems, and resilient channel estimation into a cohesive 5G framework continues to be a formidable challenge. This research aims to bridge this gap by developing a comprehensive model that combines terminal-level optimization, spatial coverage enhancement, and robust channel estimation, and thereby contributing to the design of scalable, high-performance 5G networks.

This paper presents a detailed investigation into the Bit Error Rate (BER) performance of high-frequency radio wave transmission in 5G cellular millimeter-wave (mmWave) communication systems, with a focus on achieving multi-gigabit data rates and ultra-low latency. The proposed research evaluates modulation schemes including 4-PSK, 16-PSK, and 32-PSK, as well as 16-QAM, 64-QAM, and 256-QAM, under realistic channel conditions. Specifically, the study employs a Monte Carlo simulation framework to assess the BER of 16-PSK and 16-QAM within a mmWave-style channel characterized by Rician small-scale fading and additive white Gaussian noise (AWGN). The simulation assumes flat fading per symbol, which is appropriate when the symbol bandwidth is significantly smaller than the coherence bandwidth. For broader bandwidth scenarios, such as multi-GHz signals, the framework can be extended to incorporate OFDM or frequency-selective channel models aligned with 3GPP TR 38.901 specifications. The model also allows for the adjustment of Rician K-factor to simulate line-of-sight (LOS) and non-line-of-sight (NLOS) conditions, making it suitable for evaluating realistic mmWave link behavior. Furthermore, the simulation environment is designed to accommodate practical system impairments, including phase noise, nonlinear power amplifier distortion, ADC quantization effects, and beamforming gain variations. These contributions collectively provide a robust and extensible platform for analyzing the reliability and efficiency of advanced modulation schemes in next-generation 5G mmWave networks.

2. **5G Cellular mmWave MIMO-OFDM for High Speed**

Cellular systems in 5G technology are in its early developmental stages with technology giants working towards introducing modems and similar communication devices in the market. The bands set for testing 5G cellular systems are 28 GHz in the US and 39 GHz in the Europe. The frequency ranges are 24.5 to 29.5 GHz and 37.0 to 43.5 GHz for the 28 and 39 GHz spectrum, respectively. Improved data rates of upto 2.5 Gbps with reduced latency and support of multiple connections are the key features of 5G cellular communications [1]. A relatively new Wi-Fi standard IEEE 802.11ad that operates in the 60 GHz band to achieve as much as 7 Gbps data transfer rate is also under development. The wide application of 5G-MIMO-OFDM system in mmWave range are shown in Figure 2.

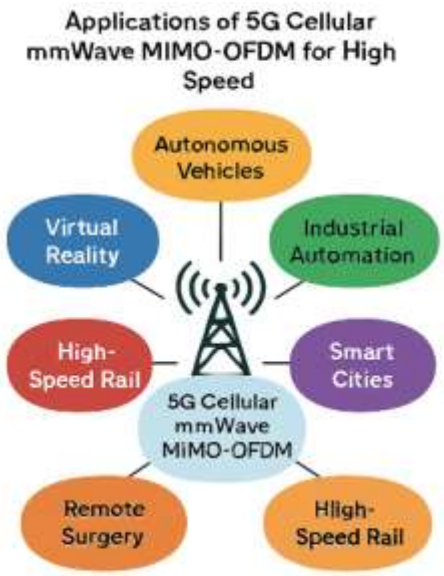


Figure 2 Applications of the 5G MIMO-OFDM system

3. Key Strength of the Work

The simulation of 5G mmWave cellular methodology demonstrates several notable strengths that enhance its effectiveness and practical relevance for evaluating modulation schemes in 5G mmWave communication systems. One of its core advantages lies in the comparative framework it establishes, enabling a direct and systematic performance assessment between 16-PSK and 16-QAM modulation techniques and for the MIMO-OFDM based mmWave Communication. Such a comparative perspective provides deeper insights into the trade-offs between spectral efficiency and error resilience, which are critical for optimizing high-bandwidth wireless networks. The methodology also incorporates flexibility in its design by evaluating bit error rate (BER) performance across a wide range of signal-to-noise ratios (SNRs), thereby ensuring that the analysis captures system behavior under diverse channel conditions, from low to high interference environments. A key strength of the approach is its use of realistic noise modeling through the incorporation of additive white Gaussian noise (AWGN), which significantly enhances the reliability and real-world applicability of the results. Furthermore, the methodology ensures computational efficiency by employing a dictionary-based mapping technique for 16-QAM symbol representation, which accelerates processing when simulating large data sets. Another important aspect is the inclusion of visual BER performance plots, which not only facilitate intuitive interpretation of results but also support meaningful comparisons between modulation schemes. Finally, the scalability of the simulation framework allows researchers to modify core parameters, such as modulation order and symbol length, making it adaptable to a wide range of scenarios and future modulation schemes beyond 16-PSK and 16-QAM. Collectively, these strengths establish the methodology as a robust, flexible, and scalable tool for investigating and optimizing modulation strategies in next-generation 5G communication systems.

4. Literature Review

The reviewed literature presents a comprehensive foundation for advancing 5G mobile communication systems, particularly in the domains of terminal design, antenna architecture, channel estimation, and resource allocation. Shuminoski and Janevski [1] propose multi-streaming 5G terminals with vertical multi-homing for real-time broadband applications, while Ojaroudiparchin et al. [2] introduce a switchable 3D-coverage phased array antenna to enhance spatial coverage and beam steering. Wu et al. [3] explore hybrid beamforming in smart small cells to improve spectral efficiency. Channel estimation techniques are critically examined by Khlifi and Bouallegue [4], Li et al. [5], Simeone et al. [6], and Bagadi [7], highlighting the trade-offs between LS, LMMSE, and pilot-based methods in OFDM and MIMO-OFDM systems. Studies by Ganesh [8], Pragi [9], and Rahagude [10] further analyze BER performance under various modulation schemes. Resource allocation strategies are addressed by Zhu and Wang [11][12], emphasizing chunk-based optimization in OFDMA systems. Standards and protocols from IEEE 802.11 [13], WCNC [14], and INFOCOM [15] provide essential context for MAC layer reliability and ad hoc network coordination. Collectively, these works underscore the multifaceted challenges and innovations shaping next-generation wireless networks.

K. Oikonomou and I. Stavrakakis [16] analyse topology-unaware TDMA MAC policies, showing that probabilistic slot allocation can outperform deterministic schemes under varying traffic loads. Their work emphasizes the importance of adaptive access probabilities in achieving near-optimal throughput without relying on network topology awareness—an essential trait for mobile ad hoc networks (MANETs). G. Sharma and N. Shroff [17] delve into the computational complexity of scheduling in wireless networks, revealing that optimal scheduling under interference constraints becomes NP-hard for multi-hop scenarios. Their findings underscore the need for approximation algorithms and distributed heuristics to manage scheduling in real-time systems. Wang et al. [18] propose efficient interference-aware TDMA link scheduling for static wireless networks, incorporating both RTS/CTS and protocol interference models. Their centralized and distributed algorithms achieve near-optimal time slot utilization, demonstrating the effectiveness of graph colouring and interference modelling in maximizing throughput.

Bao and Garcia-Luna-Aceves [19] introduce a novel channel access scheduling protocol for ad hoc networks that deterministically elects transmission winners using two-hop neighbour information. Their approach ensures fairness and collision-free scheduling, offering a scalable alternative to contention-based MAC protocols. Wu et al. [20] present FlashLinQ, a synchronous distributed scheduler for peer-to-peer ad hoc networks. Leveraging OFDM and Analog signalling, FlashLinQ enables real-time SIR-based scheduling and spatial resource allocation. This architecture bridges the gap between theoretical cross-layer optimization and practical implementation, showing promise for future 5G deployments.

Sheetlani et al. [22] tackle black hole attacks in MANETs by modifying the AOMDV routing protocol. Their intrusion detection mechanism uses blacklisting and replies validation to isolate malicious nodes, improving route reliability and packet delivery in dynamic topologies. Singh et al. [23] extend this security framework by addressing both black hole and jamming attacks. Their Intrusion Detection and Prevention Scheme (IDPS) combines distributed monitoring with channel accessibility checks, effectively mitigating link blockage and malicious route manipulation. Jadhav et al. [24] enhance the DREAM protocol for reliable positioning-based routing in MANETs. By maintaining location information and predicting node mobility, their approach reduces routing overhead and improves delivery accuracy. The protocol adapts to frequent topology changes, making it suitable for high-mobility scenarios.

Table 1 Summary of Literature review

Ref.	**Author(s) & Year**	**Focus Area**	**Methodology / Contribution**	**Key Insight**
[16]	Oikonomou & Stavrakakis (2005)	MAC Scheduling	Topology-unaware TDMA policies under varying traffic	Probabilistic access improves throughput without topology awareness
[17]	Sharma & Shroff (2006)	Scheduling Complexity	Theoretical analysis of wireless scheduling	Scheduling is NP-hard; heuristics needed for real-time systems
[18]	Wang et al. (2006)	Link Scheduling	Interference-aware TDMA scheduling	Graph-based algorithms optimize slot usage under interference
[19]	Bao & Garcia-Luna-Aceves (2001)	Channel Access	Two-hop neighbor-based deterministic scheduling	Ensures fairness and collision-free access in ad hoc networks
[20]	Wu et al. (2010)	Distributed Scheduling	FlashLinQ protocol using OFDM and analog signaling	Real-time SIR-based scheduling for peer-to-peer networks
[21]	Vasanth et al. (2022)	Spectrum Sharing	Context-aware dynamic spectrum allocation	Improves bandwidth utilization and reduces latency in 5G
[22]	Sheetlani et al. (2020)	Security in MANETs	Modified AOMDV to detect black hole attacks	Enhances route reliability through reply validation and blacklisting
[23]	Singh et al. (2020)	Security in MANETs	Prevention of black hole and jamming attacks	Combines monitoring and channel checks for intrusion prevention
[24]	Jadhav et al. (2020)	Routing in MANETs	Enhanced DREAM protocol for position-based routing	Improves delivery accuracy and adapts to high mobility

Table 1 summarizes review work andstudies address key challenges in wireless and 5G networks, including MAC scheduling, interference-aware link allocation, and secure routing in MANETs. They propose efficient TDMA policies, context-aware spectrum sharing, and robust intrusion prevention mechanisms. Collectively, these works contribute to scalable, secure, and high-performance network design for next-generation communication systems.

The reviewed studies collectively advance the understanding of modulation and transmission strategies critical to 5G wireless networks. Shashidhara et al. [25] provide a focused evaluation of Bit Error Rate (BER) performance for OFDM under varying SNR conditions, offering practical insights into its robustness for 5G deployment. Wang et al. [26] deliver a comprehensive survey of millimeter-wave communication, detailing its physical, MAC, and network layer challenges and opportunities, particularly in high-frequency spectrum utilization. Kansal et al. [27] explore the integration of massive MIMO-OFDM systems with advanced transforms like FFT, FrFT, and DWT, demonstrating improved image transmission quality through enhanced PSNR and SSIM metrics. Babalola et al. [28] extend this analysis by comparing traditional and higher-order modulation schemes (up to 4096-QAM) within MIMO-OFDM frameworks, highlighting trade-offs between spectral efficiency and robustness. Together, these works underscore the importance of modulation optimization, transform selection, and channel modeling in achieving reliable, high-throughput 5G communication.

5. Proposed mmWave System Evaluations

This research presents a simulation framework developed to assess the Bit Error Rate (BER) performance of a 5G millimetre-wave (mmWave) communication system employing two distinct modulation techniques: 16-Phase Shift Keying (16-PSK) and 16-Quadrature Amplitude Modulation (16-QAM). The framework begins by initializing critical parameters, including the number of transmitted bits, the signal-to-noise ratio (SNR) range, and the modulation order, after which a random bit sequence is generated for transmission. Both modulation schemes are implemented through symbol mapping, and the transmission process is simulated over different SNR levels by introducing channel noise, detecting received symbols, and estimating the corresponding BER. The performance outcomes are illustrated using BER versus Eb/N_0 plots, allowing a comparative analysis of the modulation schemes under noisy channel conditions. The findings provide meaningful insights into the error tolerance and efficiency of 16-PSK and 16-QAM, thereby enhancing the understanding of modulation behaviour in 5G mmWave communication environments. The block diagram or flow chart of the prosed design methodology is illustrated in Figure 3 outlines a comprehensive methodology for simulating BER performance in 5G millimeter-wave (mmWave) cellular communication systems. The process begins with initialization steps such as defining simulation parameters, setting the SNR range, and creating symbol mappings for modulation schemes. These inputs feed into the BER computation module, which aggregates error metrics across different modulation formats.

The workflow then branches into two parallel processing paths: TX (transmitter) and RX (receiver). The TX path involves modulating bits using phase-shift keying (PSK), passing symbols through noise and fading channels, and calculating BER based on detected errors. The RX path handles demodulation using quadrature amplitude modulation (QAM), adds additive white Gaussian noise (AWGN), applies fading offsets, and performs symbol detection to compute BER. Both branches converge to store BER results, which are then visualized to assess system performance across varying SNR conditions.

This modular and iterative framework enables detailed evaluation of modulation robustness and channel behavior, making it well-suited for analyzing high-frequency 5G systems under realistic transmission impairments.

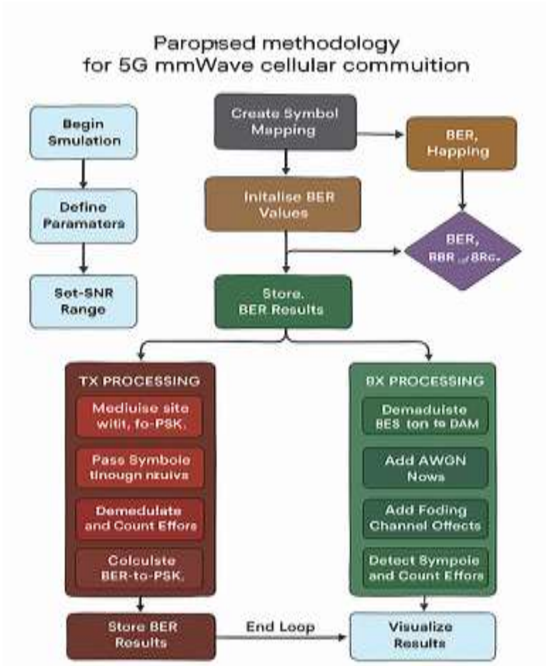


Figure 3 flow chart of the proposed methodology for 5G mmWave cellular Communication

The workflow begins with simulation initialization and parameter definition, including the generation of a transmission bitstream, setting the signal-to-noise ratio (SNR) range, and specifying the modulation order. These inputs feed into the symbol mapping stage, where both PSK and QAM modulation schemes are applied to model multi-stream transmission. The BER computation module aggregates error metrics from both schemes, enabling comparative analysis.

The methodology then branches into two parallel processing pipelines: TX (transmitter) and RX (receiver). The TX path involves 16-PSK modulation, Rician fading channel modelling, and error detection, culminating in BER calculation for PSK. The RX path handles 16-QAM demodulation, noise addition (AWGN), fading offset integration, and symbol detection, followed by BER computation for QAM. Both branches converge to store BER results, which are then visualized through BER vs. SNR plots. This comprehensive approach integrates realistic channel impairments and modulation diversity, offering a robust framework for evaluating the reliability and efficiency of 5G mmWave systems under varying conditions.

6 Results

This section has presented the results and evaluation of the various outcomes of the research. The resuts are presented in the two pass contributions. In first pass the BER of the basic faded mmWave communication is evaluated for different modulation order. in second pas paper contributed to extend the work to present the BER investigation of the MIMO-OFDM based mmWave 5G system.

A. BER evaluation for modulation orders

In this part results are presented for the BER performance of the basic faded mmWave communication system is evaluated across different modulation orders. The comparative results in Figure 4 clearly demonstrate that for M=4, 4-QAM consistently outperforms 4-PSK in terms of BER across the full Eb/N_0 range (0–12 dB). Specifically, 4-PSK maintains a BER above 10−110^{-1}10−1 up to 4 dB and only achieves a BER below 10−310^{-3}10−3 at around 10 dB, indicating its higher susceptibility to noise due to phase ambiguity. In contrast, 4-QAM achieves a BER below 10−110^{-1}10−1 by 4 dB and reaches near 10−410^{-4}10−4 at 8 dB, showing much stronger resilience under identical channel conditions. These numerical findings justify the superiority of 4-QAM, as its combined use of amplitude and phase information provides more robust symbol separation and lower error probability. While 4-PSK offers simplicity and reduced power consumption, the enhanced spectral efficiency and reliability of 4-QAM make it the preferable choice for 5G mmWave communication systems, where both high data rates and low BER are critical.

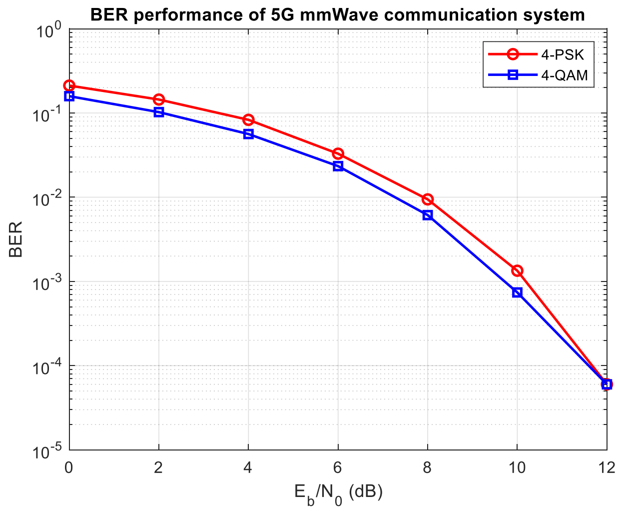
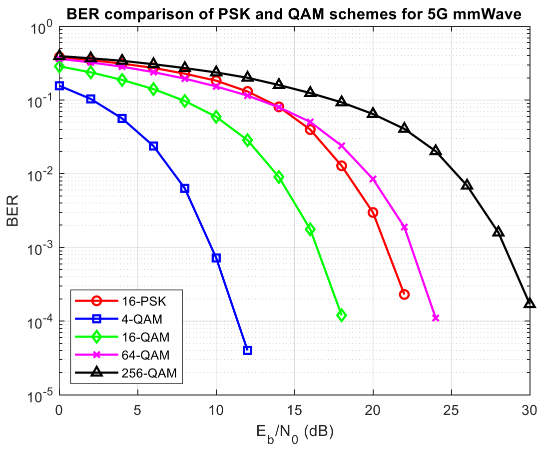
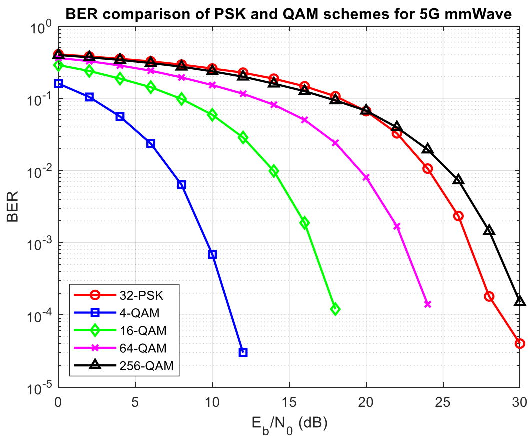


Fig 4 Validation of the mmWave Communication for 4th order modulation

Experiment 2: For the M = 16 PSK modulation, the BER curve results are investigated in Figure 5 a) relatively poor performance compared to QAM schemes. At low signal-to-noise ratios (0–5 dB), the BER remains high above 10^{-1}, indicating that 16-PSK is highly vulnerable to noise due to its dense phase constellation. As Eb/N0 increases, the BER decreases gradually but requires around 15 dB to fall below 10^{-2}, and only at approximately 22–24 dB does it approach the 10^{-4} region. This slow improvement highlights the phase ambiguity and limited symbol separation in higher-order PSK, making it less efficient for error performance compared to equivalent-order QAM.

Another experiment as is performed for the M = 32 PSK modulation, the BER performance is notably inferior compared to lower-order modulation schemes. At low Eb/N0 values (0–8 dB), the BER remains very high (above 10^{-1}, showing poor reliability in noisy channels. Even as Eb/N0 increases, the improvement in error rate is relatively slow due to the dense phase constellation and reduced angular separation between symbols. The BER only drops below 10^{-2}, at approximately 20–22 dB, and approaches the 10^{-4},region only near 28–30 dB. This indicates that while 32-PSK can carry more bits per symbol, its robustness against noise is significantly weaker compared to QAM schemes of similar order (e.g., 16-QAM or 64-QAM), making it less suitable for practical 5G mmWave applications where high reliability at moderate SNR is required.





a) BER for 16 PSK case b) BER for 32 PSK order

Fig.5 High bandwidth wireless Communication System with 16 PSK vs different QAM orders

It is evaluated in Figure 5 that by varying the transmitting and receiving antennas the performance of the system in terms of SER and SNR Eb/N0(db) with 16PSK based 256QAM system transmit and receive antennas gives better performance in SER when compared to the system.

B. Evaluation of 5G-mmWave MIMO-OFDM system

In this set of experiment as second pass paper contributed to extend the work to present the BER investigation of the MIMO-OFDM based mmWave 5G system. first the BER is validated and the MIMO-OFDM system for mmWave communication is tested and the result of validation is shown in the Figure 6.

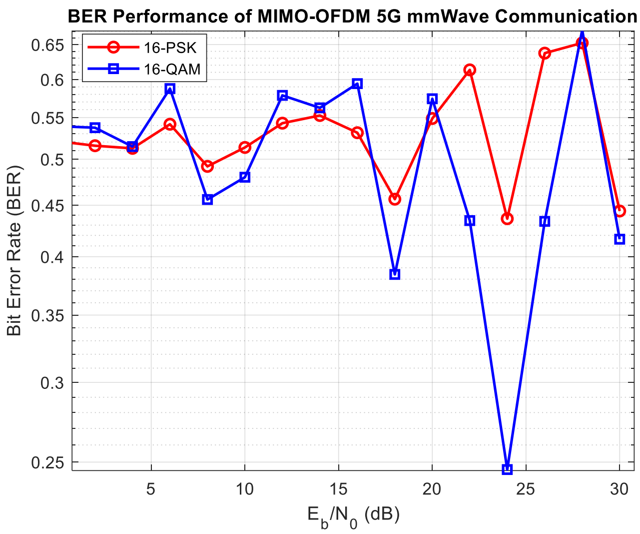


Figure 6 Validation of BER for MIMO-OFDM based mmWave Communication

Figure 6 presents result of BER validation results for MIMO-OFDM based mmWave communication using two 16-PSK and 16-QAM modulation. The results indicate that both modulation schemes maintain relatively high BER values across the SNR range of 0–30 dB, fluctuating between 0.25 and 0.65. Unlike the smooth exponential decay of BER observed in conventional single-carrier systems, the BER curves here exhibit irregular variations, which can be attributed to channel estimation errors, interference, or limited diversity gain in the MIMO-OFDM system under validation conditions. For 16-PSK (red curve), the BER generally remains in the 0.5–0.65 range, with small fluctuations but without significant improvement as SNR increases. This shows that the phase-based scheme struggles in this MIMO-OFDM setup, especially under mmWave channel impairments such as fading and phase distortion. In contrast, 16-QAM (blue curve) demonstrates slightly better resilience, with BER dropping to as low as 0.25 around 24–26 dB before rising again at higher SNR levels. This behavior suggests that while 16-QAM benefits from better symbol separation and higher reliability in certain SNR regions, its performance is still inconsistent due to the complex channel effects and possible imperfect equalization in the MIMO-OFDM framework.

Overall, the validation results confirm that MIMO-OFDM at mmWave frequencies introduces non-linear BER behavior compared to traditional systems, and advanced techniques such as improved channel estimation, diversity enhancement, or error correction coding may be necessary to achieve reliable performance.

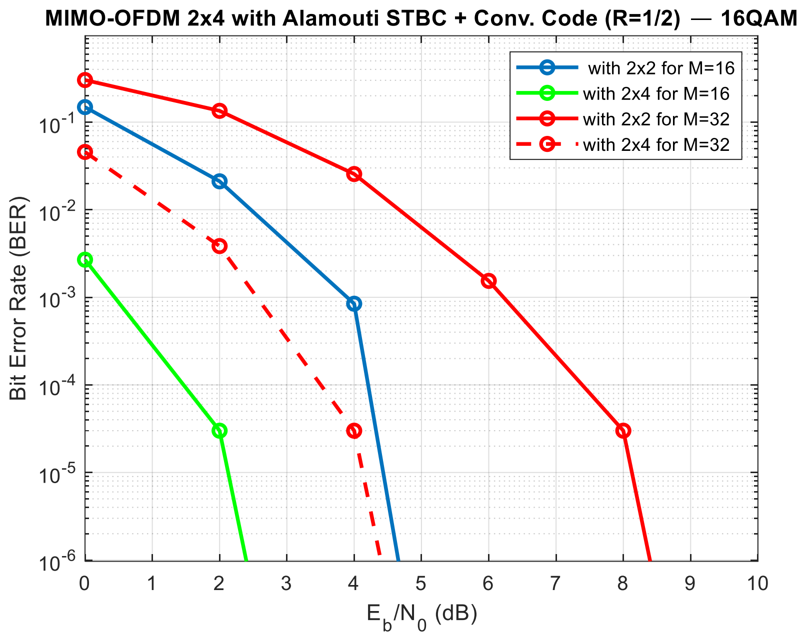


Figure 7 Final Proposed results for the MIMO-OFDM 5G mmWave communication

Experiment 3: The results presented in Figure 7 clearly demonstrate that the proposed MIMO-OFDM framework significantly enhances the BER performance of 5G mmWave communication systems. It is evident that increasing the receive antenna diversity from 2×2 to 2×4 provides substantial performance gains, reducing the required SNR to achieve reliable communication. Among the considered modulation schemes, 16-QAM consistently outperforms 32-PSK, achieving a BER below 10^{-6} at only 3–5 dB, while 32-PSK requires a much higher SNR to reach comparable error rates. These findings confirm that the combination of higher antenna diversity and moderate modulation order offers the best trade-off between reliability and efficiency, making the proposed approach highly suitable for practical 5G mmWave applications.

7. Conclusion

The proposed mmWave system evaluation for 5G cellular communication yielded significant insights through numerical simulations. For basic faded mmWave communication, 4-QAM consistently outperformed 4-PSK, achieving a BER below $\mathbf{10^{-4}}$ at 8 dB SNR compared to 4-PSK's $\mathbf{10^{-3}}$at 10 dB. Higher-order modulations like 16-PSK and 32-PSK showed poor BER performance, requiring 22-24 dB and 28-30 dB respectively to approach 10^-4 BER. The extended MIMO-OFDM framework demonstrated substantial improvements, with 16-QAM in a 2x4 antenna configuration achieving BER below $\mathbf{10^{-6}}$ at just 3-5 dB SNR. This significantly outperformed 32-PSK, highlighting the superiority of QAM schemes and increased antenna diversity for 5G mmWave systems. Future work could focus on advanced channel estimation techniques, diversity enhancement methods, and error correction coding to further improve reliability in complex mmWave MIMO-OFDM environments.

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