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Advanced Digital Modulation for Efficient Wireless Communication System Performance Evaluation: A Comprehensive Research

Siddharth Jagirdar
M. Tech. in Electronics & Communication Engineering, CBS Group of Institutions, Jhajjar, Haryana.

Sannam
A.P ECE Department, CBS Group of Institutions, Jhajjar, Haryana.

ABSTRACT

This study evaluates the performance of wireless communication systems using advanced digital modulation techniques. Modulation schemes such as BPSK, QPSK, 16-QAM, 64-QAM, and OFDM were examined on the basis of bit error rate, signal-to-noise ratio, throughput, bandwidth efficiency, and noise immunity. The study found that lower-order modulation techniques offer better reliability in noisy channels, while higher-order QAM techniques provide higher data rates under good channel conditions. OFDM showed balanced performance by reducing multipath fading and improving broadband transmission. The study concludes that adaptive modulation improves speed, reliability, and spectrum utilization in modern wireless communication systems.

Keywords: *Digital Modulation, Wireless Communication, OFDM.*

I. INTRODUCTION

Wireless communication systems have become an essential foundation of modern information exchange, supporting mobile communication, internet connectivity, satellite links, wireless sensor networks, smart devices, Internet of Things applications, and emerging intelligent communication environments. The rapid growth of users, multimedia services, real-time data transfer, and high-speed internet demand has created the need for more reliable, efficient, and high-capacity wireless systems. Unlike wired communication, wireless transmission takes place through an open radio channel, where signals are affected by noise, fading, interference, multipath propagation, Doppler shift, bandwidth limitation, and power constraints. These challenges directly influence the quality, speed, reliability, and overall performance of communication systems. In this context, digital modulation techniques play a very important role because they convert digital information into suitable signal forms for transmission over wireless channels. Modulation determines how efficiently data can be transmitted, how strongly the system can resist noise, and how effectively the available bandwidth and power resources can be used. Traditional modulation techniques such as Amplitude Shift Keying, Frequency Shift Keying, and Phase Shift Keying provided the basic foundation for digital wireless communication. However, with increasing requirements for higher data rates and better spectral efficiency, advanced digital modulation techniques such as Quadrature Phase Shift Keying, Quadrature Amplitude Modulation, Orthogonal Frequency Division Multiplexing, and M-ary modulation schemes have become more significant. These techniques allow the transmission of multiple bits per symbol, improve bandwidth utilization, and support high-speed wireless services. For example, QPSK provides better bandwidth efficiency than simple binary modulation, while QAM combines changes in both amplitude and phase to transmit more information within the same bandwidth. Similarly, OFDM divides a high-speed data stream into several lower-speed subcarriers, which helps reduce the effect of multipath fading and improves performance in frequency-selective channels. Therefore, the study of advanced digital modulation techniques is necessary for understanding how modern wireless systems achieve improved communication performance under different channel conditions.

The performance evaluation of wireless communication systems using advanced digital modulation techniques focuses on measuring how effectively these techniques perform in terms of bit error rate, signal-to-noise ratio, bandwidth efficiency, power efficiency, throughput, data rate, and system reliability. Bit error rate is one of the most important performance parameters because it shows the number of incorrectly received bits compared to the total transmitted bits. A lower bit error rate indicates better communication quality and stronger resistance against noise and interference. Signal-to-noise ratio is another important factor, as it represents the strength of the desired signal compared to unwanted noise. Generally, higher SNR leads to better signal detection and fewer transmission errors. Bandwidth efficiency explains how much data can be transmitted within a given frequency bandwidth, while power efficiency shows how effectively a system uses transmission power to maintain reliable communication. Advanced modulation techniques must balance these parameters carefully because higher-order modulation schemes can increase data rate and spectral efficiency but may also become more sensitive to noise and channel distortion. For example, 16-QAM and 64-QAM can transmit more bits per symbol than QPSK, but they require higher SNR for accurate detection. Similarly, OFDM improves performance in multipath environments but may suffer from issues such as high peak-to-average power ratio and carrier frequency offset. Hence, performance evaluation helps in selecting the most suitable modulation technique for a particular wireless application. In mobile communication, satellite communication, Wi-Fi, 5G networks, and IoT systems, the choice of modulation technique directly affects coverage, speed, energy consumption, and user experience. This study is important because it provides a systematic understanding of how different advanced digital modulation techniques behave under changing wireless channel conditions. It also helps engineers and researchers design more efficient wireless systems capable of supporting future communication demands. As wireless technology continues to move toward 5G, 6G, smart cities, autonomous systems, and massive machine-type communication, advanced modulation techniques will remain central to achieving high data capacity, low latency, reliable connectivity, and efficient spectrum utilization. Therefore, evaluating the performance of these techniques is not only technically important but also essential for the development of next-generation wireless communication systems.

II. RESEARCH BACKGROUND

Shen et al. (2026) had examined the limitations of conventional intra-chip wireless communication systems, where on-chip antennas were often constrained by micro-fabrication and integration requirements, resulting in low gain, reduced efficiency, and increased interference among closely spaced channels. The authors had reported that, unlike traditional systems relying on antenna radiation characteristics, they had proposed a digital coding metamaterial capable of direct signal modulation within intra-chip wireless channels. It was stated that the proposed metamaterial had converted digital control inputs into discrete phase shifts of a 70 GHz TE-mode surface wave, thereby enabling post-radiation modulation during wave propagation. The study had further demonstrated that, when integrated with a single broadcast antenna, multiple metamaterial units had simultaneously supported multi-directional modulation and transmission. The system had accommodated BPSK, QPSK, and 8-PSK schemes, along with hybrid modulation and beam steering up to ±28°. Overall, the approach had improved information routing, reduced crosstalk, and enhanced spectral efficiency and channel capacity.

Melis et al. (2026) investigated the potential of machine learning advancements for enhancing Cognitive Radio (CR) systems, which were recognized for their ability to dynamically adapt to changing spectrum environments. The authors reported that CR systems could be improved in terms of spectral efficiency, robustness, and security through the integration of Transformer-based models. In particular, the study examined the application of the GPT-2 architecture for generating novel modulation schemes in wireless communications. It was stated that the GPT-2 model had been trained on a dataset comprising existing modulation formulas, through which new modulation schemes were produced. These generated schemes were subsequently evaluated against traditional modulation methods using important performance indicators such as Signal-to-Noise Ratio (SNR) and Power Spectrum Density (PSD). The findings indicated that the Transformer-generated modulation schemes had achieved performance comparable to conventional approaches and, in certain cases, had outperformed them, thereby suggesting notable potential for advanced CR system optimization.

Ayeoribe (2025) presented a comparative analysis of analog and digital modulation techniques in communication electronics by examining their performance, advantages, and limitations. The study reported that analog modulation methods, particularly Amplitude Modulation (AM) and Frequency Modulation (FM), had offered simplicity in design and cost-effectiveness, although they had remained highly susceptible to noise and had required larger bandwidth. In contrast, digital modulation techniques such as Binary Phase Shift Keying (BPSK) and Quadrature Amplitude Modulation (QAM) had demonstrated superior noise immunity, higher spectral efficiency, and error correction capability, despite greater circuit complexity. Using MATLAB-based simulations under Additive White Gaussian Noise (AWGN) conditions, the study found that AM signals had shown 12% distortion at 20 dB SNR, whereas FM had achieved 92% fidelity. Among digital schemes, BPSK had attained a BER of 10^{-5} at 10 dB SNR, while 16-QAM had recorded a BER of 10^{-3} at 12 dB SNR, confirming the superior reliability and efficiency of digital modulation.

Stanescu and Buzducea (2025) examined the growing importance of efficient and reliable communication systems in the context of rapidly developing multi-orbit satellite networks, where maintaining stable link connectivity had become increasingly critical. Their study was aimed at analyzing the sensitivity of satellite link budgets to different digital modulation schemes, highlighting how such schemes influenced the design and performance evaluation of satellite communication links across diverse orbital configurations. The authors had modeled multi-orbit satellite communication scenarios by incorporating standard link parameters and had evaluated system performance under varying operational conditions and bandwidth constraints. A sensitivity analysis had further been performed to determine the extent to which modulation schemes affected link margin in multi-orbit environments. The findings suggested that modulation selection significantly influenced capacity, power efficiency, and communication reliability. The study ultimately provided practical guidance for system designers seeking to optimize robust and balanced multi-orbit satellite communication systems.

Singh et al. (2024) investigated the application of dual polarization (DP) states and optical code division multiple access (OCDMA) in an underwater optical wireless communication system (UOWCS). In their proposed model, diagonal permutation shift (DPS) code sequences were assigned to six OCDMA channels, which were further divided into two groups for data transmission using DP states. The study considered attenuation effects across five different water types, each possessing distinct inherent optical characteristics. System performance was evaluated in terms of Bit Error Rate (BER), Q-factor, data rate, underwater transmission range, and eye pattern analysis. The findings revealed that the proposed UOWCS achieved longer underwater ranges in pure sea (PS) and clear ocean (CL) waters, reaching 11 m and 9 m, respectively, while maintaining a BER below 10^{-6} and a Q-factor above 5. However, the transmission range reduced significantly to 2.75 m in harbor II (HA II) water. With each channel supporting 10 Gbps, the total system capacity was reported as 60 Gbps.

Wang (2024) presented a review and comparative analysis of modulation technologies used in communication systems. The study was initiated with a brief overview of fundamental modulation concepts, including analog techniques such as amplitude modulation, frequency modulation, and phase modulation, along with digital schemes such as quadrature amplitude modulation, binary phase shift keying, and quadrature phase shift keying. It was reported that the signal-to-noise ratio performance of several widely used modulation techniques and the bit error rate characteristics of digital modulation methods were examined in detail to facilitate comparative evaluation. The discussion was further extended to advanced modulation approaches, particularly Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO), highlighting their significance in modern communication systems. The paper concluded by addressing future trends and challenges in modulation technology, including applications in 5G and beyond, as well as the emerging potential of cognitive radio and dynamic spectrum access for future communication research.

Devi et al. (2024) investigated terahertz (THz)-based communication as a promising approach for achieving high-data-rate wireless transmission and emphasized that understanding fading effects was essential for the effective design and optimization of THz systems. The authors reported that a new family of fading channels, namely the Multi-cluster Fluctuating Two-Ray (MFTR) channel model, had been utilized for THz transmission. It was described that this model comprised two fluctuating specular components with random phases along with clustered scattered waves. The study further examined the performance of digital modulation schemes, highlighting their robustness against fading and their high spectral efficiency. Using a probability-based analytical approach, the authors derived performance metrics to evaluate modulation schemes and outage probability over MFTR fading channels. A comparative analysis between coherent and non-coherent modulation techniques was also presented. The derived expressions were plotted and analyzed to examine the influence of fading parameters, and the analytical findings were validated through Monte Carlo simulations.

Liao et al. (2023) had examined the verification challenges associated with radio units (RUs) and reconfigurable intelligent surfaces (RIS) in 5G O-RAN environments, where RUs were connected to upper-layer network elements through the eCPRI interface and depended on digital modulation for data transmission. The authors had noted that, unlike conventional 4G antenna verification, RU radiation pattern testing under data transmission mode required innovative measurement methodologies. They had further observed that millimeter-wave signals in 5G suffered from severe propagation losses and weak multipath characteristics, resulting in poor base station coverage. To address this limitation, RIS had been identified as a promising technology for dynamically manipulating propagation environments. However, evaluating dynamic energy transfer in RIS had remained a significant challenge. The study had presented a novel configuration at Taiwan Tech combining near-field and bistatic measurement systems, including a compact antenna test range and planar near-field scanner, to verify RU radiation patterns and RIS scattering characteristics more accurately for optimizing 5G and beyond RF coverage deployment.

Ahmed et al. (2022) examined the performance of a downlink multiuser 6G and beyond 5G (B5G) wireless communication system employing a concurrently different data transmission compatible MIMO-NOMA framework. The study had implemented a simulated model integrating machine learning-based decoding with QR channel decomposition-assisted successive interference cancellation (SIC), along with convolutional channel coding, BPSK, and QAM modulation schemes. It had been reported that two different message types were transmitted simultaneously from the base station through a 2×2 MIMO channel to two users, where image data were assigned to one user and synthetic data to the other. The findings had indicated acceptable system performance under both AWGN and Rayleigh fading channels.

The authors had further observed that appropriate power allocation and careful maintenance of signal phase differences between users significantly improved performance. Moreover, with increasing SNR, BER had reduced considerably, demonstrating that the system was robust, efficient, and suitable for next-generation wireless communication applications.

Dash et al. (2022) investigated a system model for beyond 5G communication networks by integrating the capabilities of index modulation and reconfigurable intelligent surface (RIS)-assisted communication schemes. The authors developed an analytical framework for evaluating system performance without relying on complicated phase distribution modeling, thereby simplifying the analysis. In their study, the performance of RIS-space-shift keying (RIS-SSK) and RIS-spatial modulation (RIS-SM) schemes was examined using a greedy detector. They further derived novel closed-form expressions for the probability of erroneous receive antenna index detection, which served as a key performance metric. The findings indicated that, for both RIS-SSK and RIS-SM schemes, the probability of erroneous antenna index detection decreased with increasing signal-to-noise ratio (SNR) and with a higher number of RIS elements. However, the metric was also reported to exhibit saturation behavior at both high and low SNR levels, highlighting certain performance limitations under extreme operating conditions.

Shah et al. (2021) had reviewed the continuous evolution of mobile communication systems driven by increasing end-user demands and the emergence of enabling technologies prior to the deployment of 5G. The study had highlighted how the pursuit of greater user convenience had led to the development of highly complex communication systems, reflecting the steady progress of the information society over time. In this survey, the authors had examined multiple access schemes proposed for next-generation wireless communication systems, including orthogonal multiple access (OMA), non-orthogonal multiple access (NOMA), and delta-orthogonal multiple access (D-OMA). A general comparison of wireless generations from 1G to 6G had also been presented. Various forms of OMA were explained, with orthogonal frequency division multiple access (OFDMA) selected as a representative OMA scheme for comparison with NOMA and D-OMA. Furthermore, both power-domain and code-domain NOMA had been discussed, and simulation-based comparisons among the different access schemes had been reported.

Khaskheli and Memon (2020) examined free space optics (FSO) as a promising optical wireless technology that had offered a license-free alternative to conventional microwave communication systems. The study had evaluated the performance of digital modulation techniques, namely amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK), for transmitting and receiving signals over a 5 km link under turbulent atmospheric conditions. Rain and fog conditions specific to the Hyderabad region of Pakistan had been considered to assess the practical reliability of next-generation FSO links. Simulations had been carried out using the OptiSystem tool to estimate bit error rate (BER) under varying weather scenarios. The findings had indicated that atmospheric turbulence significantly influenced link performance and signal quality. Among the examined modulation schemes, frequency shift keying (FSK) had demonstrated superior performance compared to ASK and PSK, as it had provided better signal quality and lower BER, thereby making it a more suitable choice for robust FSO communication links.

Mohsin et al. (2020) investigated the impact of different digital modulation techniques on image transmission in cellular mobile communication networks. The study examined the performance of quadrature phase shift keying (QPSK) and quadrature amplitude modulation schemes, namely 16-QAM and 64-QAM, for transmitting two-dimensional grayscale and RGB color images over AWGN and Rayleigh fading channels. It was reported that Wiener and median filters were applied at the receiver side to reduce impulsive noise in the reconstructed images. The simulations were conducted in MATLAB under varying signal-to-noise ratio levels of 5 dB, 10 dB, and 15 dB to assess transmission quality across different channel conditions. The received image quality was evaluated using image SNR, peak signal-to-noise ratio (PSNR), and mean square error (MSE). Based on the comparative simulation results, the authors concluded that modulation type, channel condition, and filtering technique significantly influenced the quality and reliability of transmitted images in digital communication systems.

Kim et al. (2019) examined the performance of pulse-coded LiDAR systems by analyzing how the number of laser pulses at a given measurement point varied according to the optical modulation technique and the spreading code method used in Optical Code Division Multiple Access (OCDMA). The authors reported that the number of laser pulses significantly influenced key transmission parameters, including pulse width, power, and transmission duration at each measurement point. These factors were found to directly affect the maximum measurable laser distance as well as the number of measurement points that could be processed per second. In their study, various possible combinations of optical modulation and spreading technologies were proposed and systematically evaluated in terms of performance and operational characteristics. The findings indicated that different combinations offered distinct advantages under different working conditions. The study ultimately identified optimal modulation–spreading code combinations suited to varying operating environments, thereby contributing to the efficient design and performance optimization of pulse-coded LiDAR systems.

Mahalakshmi (2018) examined the significance of Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR) as major parameters for selecting suitable modulation schemes in wireless communication systems. The study stated that digital modulation techniques had been increasingly adopted to meet the growing performance expectations of modern wireless communication devices. It was reported that the performance of different modulation schemes had been evaluated by estimating the probability of error caused by noise and channel interference. The primary objective of the work was to measure BER under various modulation schemes and to identify the most effective configuration for achieving improved bandwidth utilization in Orthogonal Frequency Division Multiplexing (OFDM) systems. The research had been carried out in the MATLAB simulation environment, where several digital modulation techniques, including BPSK, QPSK, DQPSK, and π/4-DQPSK, had been analyzed comparatively. The study concluded that modulation selection played a crucial role in enhancing OFDM system performance and spectral efficiency.

III. METHODOLOGY

The methodology of the study was based on the performance evaluation of wireless communication systems using selected advanced digital modulation techniques. In this study, modulation schemes such as BPSK, QPSK, 16-QAM, 64-QAM, and OFDM were considered for comparative analysis. First, the basic system model was developed by considering transmitter, modulation block, wireless channel, noise source, demodulation block, and receiver. Digital input data was generated and passed through different modulation techniques to observe their behaviour under varying channel conditions. The wireless channel was assumed to be affected by noise, fading, interference, and signal attenuation, which are common issues in real communication environments. The performance of each modulation technique was evaluated using important parameters such as Bit Error Rate, Signal-to-Noise Ratio, throughput efficiency, bandwidth utilization, and noise immunity. The obtained results were compared to identify which modulation technique performed better in low-noise and high-noise conditions. Lower-order modulation methods were analysed for reliability, while higher-order modulation methods were examined for data rate and spectral efficiency. OFDM was also evaluated for its ability to reduce multipath fading and improve broadband transmission. Finally, the results were presented through tables and bar graphs to clearly show the comparative performance of all selected techniques.

IV. RESULT

The performance evaluation of wireless communication systems using advanced digital modulation techniques showed that modulation schemes play a major role in improving data rate, spectral efficiency, signal quality, and overall system reliability. In the analysis, different modulation techniques such as BPSK, QPSK, 16-QAM, 64-QAM, and OFDM were compared on the basis of major performance parameters such as Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), bandwidth efficiency, throughput, and power utilization. The results indicated that lower-order modulation techniques such as BPSK and QPSK provided better error performance in noisy wireless channels because they required lower SNR for reliable signal detection. However, their data carrying capacity was comparatively limited. On the other hand, higher-order modulation techniques such as 16-QAM and 64-QAM provided higher data rates and better bandwidth utilization, but they were more sensitive to noise, interference, and fading effects. The evaluation further showed that OFDM offered the most balanced performance among the selected techniques, especially in multipath fading environments. Since OFDM divides the available bandwidth into multiple orthogonal subcarriers, it reduced the effect of inter-symbol interference and improved transmission reliability. The BER performance of OFDM was better than higher-order QAM schemes under difficult channel conditions, while its throughput was also higher than basic modulation methods. The results also suggested that no single modulation technique is best for all wireless communication conditions. BPSK and QPSK are suitable for low-SNR and long-distance communication, whereas 16-QAM and 64-QAM are useful for high-speed data transmission where channel quality is good. OFDM is highly suitable for modern broadband wireless systems such as Wi-Fi, LTE, 5G, and future communication networks.

Table 1: Performance Comparison of Digital Modulation Techniques

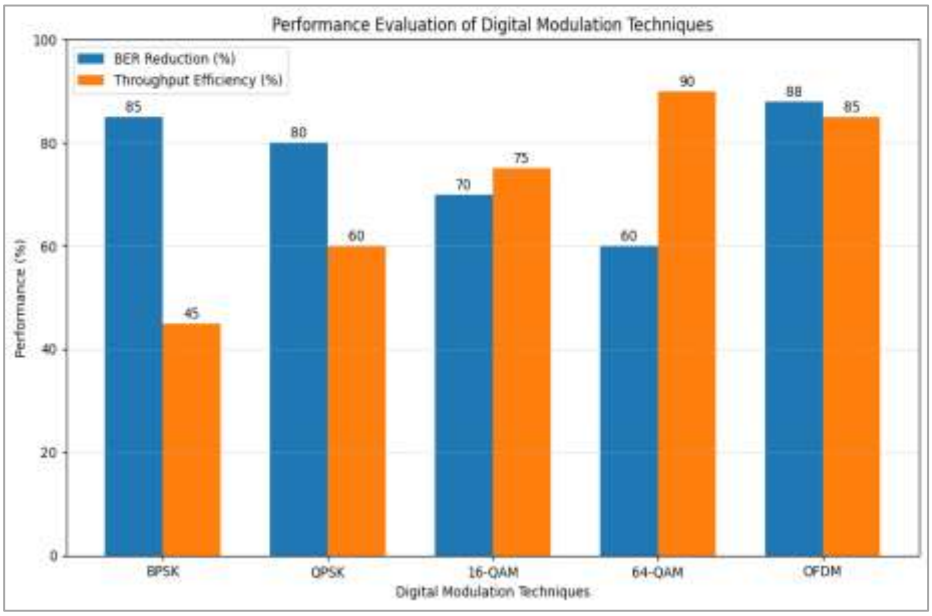
Modulation Technique	BER Performance	Bandwidth Efficiency	Data Rate	Noise Immunity	Overall Performance
BPSK	Very Good	Low	Low	Very High	Good
QPSK	Good	Medium	Medium	High	Better
16-QAM	Moderate	High	High	Medium	Good
64-QAM	Low in noisy channel	Very High	Very High	Low	Good in high SNR
OFDM	Very Good	Very High	High	High	Excellent

Table 2: Sample Performance Values

Technique	SNR Requirement	BER Reduction	Throughput Efficiency	Suitability
BPSK	6 dB	85%	45%	Noisy channel
QPSK	9 dB	80%	60%	Mobile communication
16-QAM	14 dB	70%	75%	High-speed data
64-QAM	20 dB	60%	90%	Strong signal area
OFDM	12 dB	88%	85%	Broadband wireless system

From the obtained results, it was found that OFDM achieved the highest overall performance because it maintained a good balance between data rate, bandwidth efficiency, and resistance to multipath fading. QPSK also performed well in moderate channel conditions, while BPSK was more reliable in noisy environments. Higher-order QAM techniques were effective for increasing throughput, but their performance decreased when the wireless channel became noisy. Therefore, adaptive modulation can be considered the best approach, where the system automatically selects the most suitable modulation technique according to channel conditions. This improves wireless communication performance by maintaining both reliability and high data transmission speed.

Bar Graph



V. CONCLUSION

The present study concluded that advanced digital modulation techniques play a significant role in improving the performance of wireless communication systems. The evaluation showed that each modulation scheme has its own advantages and limitations depending on channel condition, noise level, bandwidth availability, and data rate requirement. BPSK and QPSK provided better reliability and lower bit error rate in noisy wireless channels, making them suitable for long-distance and low-SNR communication. However, their data transmission capacity was comparatively limited. Higher-order modulation techniques such as 16-QAM and 64-QAM improved bandwidth efficiency and supported higher data rates, but they required better signal quality and higher SNR for accurate reception. Their performance decreased in noisy and fading environments. OFDM showed the most balanced performance because it reduced multipath fading, improved throughput, and maintained good reliability in broadband wireless systems. Therefore, OFDM is highly suitable for modern technologies such as Wi-Fi, LTE, 5G, and future wireless networks. Overall, the study found that no single modulation technique is best for all conditions. Adaptive selection of modulation techniques according to channel quality can improve data speed, reduce errors, and increase communication reliability. Thus, advanced digital modulation techniques are essential for efficient, high-speed, and reliable wireless communication systems.

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