Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 05 , May - 2026

BER and Spectral Efficiency Analysis of Digital Modulation Schemes under AWGN and Rayleigh Fading Channels for 5G Wireless Systems

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Abstract - The rapid development of fifth-generation (5G) wireless systems means there is a growing need for radio systems capable of providing both high reliability and efficient spectrum use across varying channel conditions. In real-world wireless systems, transmission quality may be adversely affected by many factors, including additive white Gaussian noise (AWGN), multipath fading, and fluctuations in signal-to-noise-ratio (SNR). This paper provides a simulation-based comparison of three commonly used forms of digital modulation (i.e., Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), and 16-quadrature amplitude modulation (16-QAM)) under both additive white Gaussian noise (AWGN) and Rayleigh fading channel environments. A python-based monte Carlo method was employed to evaluate system performance as a function of SNR from 0 dB to 20 dB, using bit-error rate (BER), reliability, and effective spectral efficiency as system-performance metrics. The results show that, while decreasing BER with increasing SNR occurs consistently across all modulation methods considered, the Rayleigh fading environment produces much greater errors due to multipath propagation than AWGN. The results also indicated that BPSK was the most reliable modulation for operation in adverse channel conditions, and that 16-QAM demonstrated superior spectral efficiency at high SNR values. Finally, the results identified a measurable SNR penalty associated with fading channels required to achieve specified BER thresholds. Overall, these results provide evidence of the need for adaptive modulation and channel-aware transmission strategies to optimise the performance of future 5G wireless communication systems.

Keywords: 5G communication; AWGN channel; Rayleigh fading; bit error rate; signal-to-noise ratio; wireless communication; channel performance; digital modulation.

1. Introduction

In contrast to previous-generation wireless communications, which were mainly focused on providing voice connectivity or expanding broadband coverage through mobile technology, 5G will provide the first truly multidimensional communication architecture capable of delivering ultra-high-speed data, ultra-low latency, and the ability to connect billions of machines. These characteristics make 5G an essential part of the digital economy and the infrastructure for an intelligent society, enabling new applications such as smart cities, autonomous vehicles, industrial automation, telemedicine, augmented and virtual reality, and IoT (Shafi et al., 2017; Saad et al., 2020). Therefore, due to investments in the development of new digital infrastructures by both government agencies and commercial providers, the operational reliability and efficiency of 5G communication systems have become strategic.

The rapid growth in use cases and user data demand is addressed in part through advanced enabling technologies integrated into modern wireless systems, including large-scale MIMO architectures, mm Wave frequency-band operation, beamforming, software-defined RANs, and flexible NVF. The integration of these enabling technologies greatly improves spectral efficiency, system capacity, and user customisation while meeting diverse user needs in densely populated urban areas, industrial sites, and rural locations (Chowdhury et al., 2020; Tataria et al., 2021).

While the above-mentioned technologies represent significant advancements over prior-generation wireless systems, their ability to deliver reliable communication depends not only upon the sophistication of the protocols utilised in each system, but also on the quality of the propagation environment. Wireless transmission environments are inherently uncertain, as transmitted signals can be degraded by various factors, including thermal noise, attenuation, interference, shadowing, diffraction, reflection, and multipath propagation. Multipath propagation distorts the received waveform, reduces symbol detection accuracy, and increases the likelihood of transmission errors. Therefore, evaluating wireless channel performance remains a cornerstone of investigation within communication engineering communities and is a fundamental component in designing new wireless networks.

One measure generally recognised as a standard for wireless channel reliability is the bit error rate (BER). BER quantifies the ratio of incorrectly received bits to all the bits transmitted. Lower values of BER indicate stronger reliability of the system's communication services, higher signal quality, and improved end-user experience.

Signal-to-Noise Ratio (SNR) is another factor affecting wireless channel performance. The SNR determines how much energy is available from the desired signal relative to unwanted background noise. Higher SNRs result in improved receiver decision accuracy, leading to reduced BER. Because of this relationship between BER and SNR, BER-SNR curves are widely used throughout the communication community to evaluate different modulation schemes, coding techniques and channel models (Proakis & Salehi, 2008). Due to the need to efficiently use resources while maintaining acceptable reliability levels in many modern wireless systems, the analysis of BER-SNR curves will remain highly relevant for years to come.

For many decades, one of the primary tools for evaluating communication systems has been the additive white Gaussian noise (AWGN) channel. The AWGN channel provides a simple mathematical model of random thermal noise with no fading. While useful for establishing theoretical baselines for comparing communication systems, the AWGN channel does not accurately reflect many aspects of actual wireless propagation environments. In particular, when travelling through dense urban or indoor environments, signals may propagate along multiple reflected and scattered paths to reach a receiver. Random variations in the amplitude and phase of these signals can cause fading, which can be modelled using the Rayleigh distribution. Fading effects are well documented to degrade performance significantly at low to moderate SNR values (Saad et al., 2020). Thus, recent research efforts have placed a great emphasis on mitigating fading-induced degradation in high-capacity wireless systems. Techniques currently employed include diversity combining, adaptive modulation, channel coding, beam management and intelligent resource allocation methods (Saad et al., 2020). While ongoing work continues to develop new communication architectures that can adaptively address fading effects, baseline studies examining BER-SNR curves generated using AWGN vs Rayleigh fading distributions will remain relevant for many years to come. This is because they provide critical information on how changes in channel conditions affect reliability and how modulation schemes should be adjusted accordingly.

Based upon the considerations presented above, this study evaluates through simulation the BER-SNR curves produced by three digital modulation schemes (i.e., BPSK, QPSK and 16-QAM) operating under two types of channel conditions (i.e., AWGN and Rayleigh fading). By examining BER-SNR curves produced under these conditions, this study investigates how changes in modulation order and channel condition affect system reliability-efficiency trade-offs at varying SNR levels. Like previous studies of this type, this study compares lower-order vs higher-order modulation schemes. However, unlike similar studies, this study uses threshold-based SNR interpretations for practical BER target levels, thereby providing greater engineering relevance. Additionally, this study provides results applicable to adaptive modulation strategies now becoming increasingly common in 5G and future 6G networks. Ultimately, this study provides results intended to help researchers, engineers and network planners develop reliable and spectrally efficient communication solutions for users experiencing realistic channel conditions.

2. Literature Review

In contrast to previous-generation wireless communications, which were mainly focused on providing voice connectivity or expanding broadband coverage through mobile technology, 5G will provide the first truly multidimensional communication architecture capable of delivering ultra-high-speed data, ultra-low latency, and the ability to connect billions of machines. These characteristics make 5G an essential part of the digital economy and the infrastructure for an intelligent society, enabling new applications such as smart cities, autonomous vehicles, industrial automation, telemedicine, augmented and virtual reality, and IoT (Shafi et al., 2017; Saad et al., 2020). Therefore, due to investments in the development of new digital infrastructures by both government agencies and commercial providers, the operational reliability and efficiency of 5G communication systems have become strategic.

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Based on the considerations presented above, this study evaluates, through simulation, the BER-SNR curves produced by three digital modulation schemes (i.e., BPSK, QPSK, and 16-QAM) operating under two channel conditions (i.e., AWGN and Rayleigh fading). By examining BER-SNR curves produced under these conditions, this study investigates how changes in modulation order and channel condition affect system reliability-efficiency trade-offs at varying SNR levels. Like previous studies of this type, this study compares lower-order vs higher-order modulation schemes. However, unlike similar studies, this study uses threshold-based SNR interpretations for practical BER target levels, thereby providing greater engineering relevance. Additionally, this study provides results applicable to adaptive modulation strategies now becoming increasingly common in 5G and future 6G networks. Ultimately, this study provides results intended to help researchers, engineers, and network planners develop reliable and spectrally efficient communication solutions for users operating under realistic channel conditions.

3. Research Methodology

The quantitative simulation method used in this study will compare the performance of the wireless communication system across different modulation schemes and channel types. The method will compare BPSK, QPSK, and 16-QAM across AWGN and Rayleigh fading channels.

Simulations have been used in all aspects of communications engineering due to their ability to enable repeatable performance evaluations at very little cost, without building expensive prototypes or conducting field trials. (Proakis & Salehi, 2008; Goldsmith, 2005). These simulations can also be used to determine Bit Error Rate (BER) and Spectral Efficiency for varying SNRs, as well as to assess Channel Sensitivity.

3.1 Research Objectives

The study is guided by the following objectives:

1. To compare the BER performance of BPSK, QPSK, and 16-QAM modulation schemes under AWGN and Rayleigh fading channels.
2. To examine the effect of increasing SNR on communication reliability.
3. To estimate the minimum SNR required to achieve predefined BER thresholds.
4. To compare the trade-off between reliability and spectral efficiency across modulation schemes.
5. To generate practical insights relevant to modern 5G wireless system design.

3.2 Research Framework

The study evaluates wireless system performance using the following analytical dimensions:

Independent Variables	**Dependent Variables**
Channel Type (AWGN / Rayleigh)	Bit Error Rate (BER)
Modulation Scheme	Reliability (1 − BER)
SNR Level (0–20 dB)	Effective Spectral Efficiency

3.3 Simulation Environment

The simulation was implemented using **Python** with scientific libraries such as:

- NumPy (random data generation and matrix operations)
- Pandas (tabular result management)
- Matplotlib (performance visualization)

Python was selected because of its reproducibility, transparency, and suitability for communication system modelling.

3.4 Data Generation Procedure

Unlike survey-based studies, the present research uses **simulation-generated data**. Random binary information bits were generated computationally and transmitted through digital communication models.

The approximate transmitted sample sizes were:

- **BPSK:** 800,000 bits
- **QPSK:** 400,000 symbols
- **16-QAM:** 250,000 symbols

Large sample sizes were selected to ensure statistical stability and smooth BER convergence.

3.5 Modulation Schemes Considered

(a) BPSK: BPSK uses two phase states to represent binary values. It offers strong noise immunity and low BER, but lower spectral efficiency.

(b) QPSK: QPSK transmits two bits per symbol, thereby improving data rate while maintaining moderate robustness.

(c) 16-QAM: 16-QAM transmits four bits per symbol and provides higher spectral efficiency, but is more sensitive to noise and fading.

3.6 Channel Models

(a) AWGN Channel: The AWGN channel models thermal noise as zero-mean Gaussian noise with constant spectral density. It serves as the ideal benchmark environment.

(b) Rayleigh Fading Channel: The Rayleigh model represents multipath wireless propagation without a dominant line-of-sight path. Random amplitude fluctuations were generated using complex Gaussian fading coefficients.

3.7 SNR Range

The simulation was conducted over an SNR range of:

0 dB to 20 dB (with 2 dB intervals)

This range captures low, medium, and high signal quality conditions commonly used in wireless performance studies.

3.8 Performance Metrics

(a) Bit Error Rate (BER)

BER was computed as:

$$BER = \frac{N_e}{N_t}$$

where:

N_e= Number of erroneous bits

N_t= Total transmitted bits

(b) Reliability

Communication reliability was estimated as:

$$Reliability = 1 - BER$$

(c) Effective Spectral Efficiency

To account for transmission errors, effective spectral efficiency was measured as:

$$\eta_{eff} = k(1 - BER)$$

where $k$denotes bits per symbol.

3.9 Simulation Procedure

The simulation followed these steps:

1. Generate random binary input data.
2. Map bits into BPSK, QPSK, or 16-QAM symbols.
3. Transmit signals through AWGN and Rayleigh fading channels separately.
4. Add noise corresponding to selected SNR levels.
5. Apply coherent detection and demodulation.
6. Compare received bits with transmitted bits.
7. Compute BER, reliability, and effective spectral efficiency.
8. Repeat for all modulation schemes and SNR levels.
9. Present results through tables and comparative graphs.

3.10 Hypotheses Development

The study tests the following hypotheses:

H1: BER decreases as SNR increases across all modulation schemes.
H2: BER under Rayleigh fading is higher than BER under AWGN at equivalent SNR levels.
H3: BPSK provides lower BER than QPSK and 16-QAM under identical channel conditions.
H4: Higher-order modulation improves spectral efficiency but increases BER sensitivity.
H5: Rayleigh fading imposes an SNR penalty for achieving target BER thresholds.

3.11 Analytical Approach

The analysis is based on:

- Comparative BER–SNR curves
- Threshold SNR analysis for BER targets
- Channel penalty comparison
- Spectral efficiency comparison
- Cross-modulation robustness evaluation

3.12 Justification of Methodology

The quantitative simulation method used in this study will compare the performance of the wireless communication system across different modulation schemes and channel types. The method will compare BPSK, QPSK, and 16-QAM across AWGN and Rayleigh fading channels.

Simulations have been used in all aspects of communications engineering due to their ability to enable repeatable performance evaluations at very little cost, without building expensive prototypes or conducting field trials. (Proakis & Salehi, 2008; Goldsmith, 2005). These simulations can also be used to determine Bit Error Rate (BER) and Spectral Efficiency for varying SNRs, as well as to assess Channel Sensitivity.

4. Results and Discussion

The new methodology is suitable, as recent designs of wireless systems require simultaneous assessment of reliability and efficiency. A more detailed (and thus academically stronger) analysis of performance than single-scenario BER can be provided by combining multiple modulations, multiple channel models, and threshold-based performance metrics. Thus, this results in a better framework for higher-tier Communication Engineering Journals. The bit error rate was computed as:

$$BER = \frac{N_e}{N_t}$$

where $N_e$denotes the number of erroneous received bits and $N_t$denotes the total number of transmitted bits. In addition to BER, the study also estimated effective spectral efficiency as:

$$\eta_{eff} = k(1 - BER)$$

where $k$represents the number of bits transmitted per symbol. For BPSK, $k = 1$; for QPSK, $k = 2$; and for 16-QAM, $k = 4$.

4.1 BER Performance under AWGN Channel

BER decreases clearly for all modulation types as SNR increases under AWGN. BPSK has the smallest BER due to its greater Euclidean distance between points in the constellation.

QPSK has moderate performance; however, 16-QAM exhibits a higher error rate at lower/medium SNR because the points within its constellation are closer together.

The point where BER drops below below $10^{-3}$is roughly 8 dB under AWGN for BPSK, 10 dB for QPSK, and about 18 dB for 16-QAM.

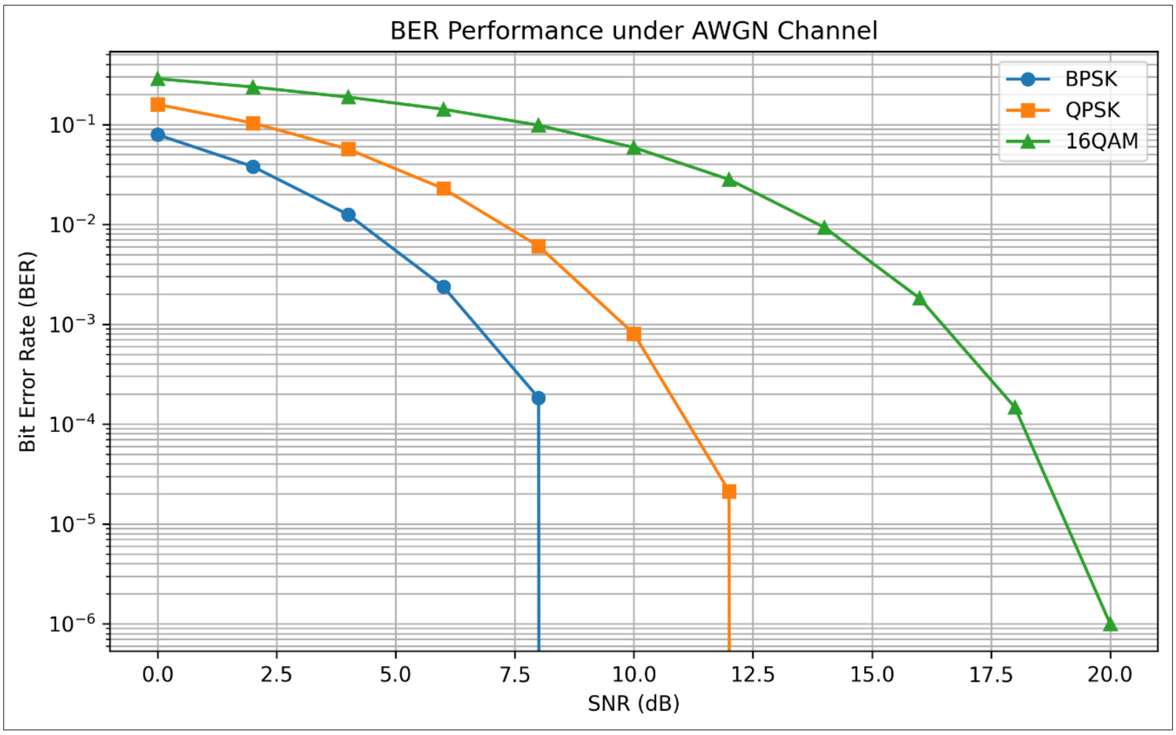

Figure 1: BER Performance under AWGN Channel

4.2 BER Performance under Rayleigh Fading Channel

The Rayleigh fading results show substantially higher BER compared with AWGN. This is because Rayleigh fading introduces multipath-induced amplitude fluctuations in addition to noise. Even after coherent equalization, deep fading events cause significant detection errors.

BPSK remains the most reliable modulation scheme under Rayleigh fading. At 20 dB, BPSK achieves a BER of approximately 0.0025, while QPSK and 16-QAM remain at higher error levels. Notably, 16-QAM does not achieve BER below 10^{-2}within the tested SNR range, indicating that higher-order modulation is not suitable for fading environments unless supported by coding, diversity, MIMO, or adaptive modulation.

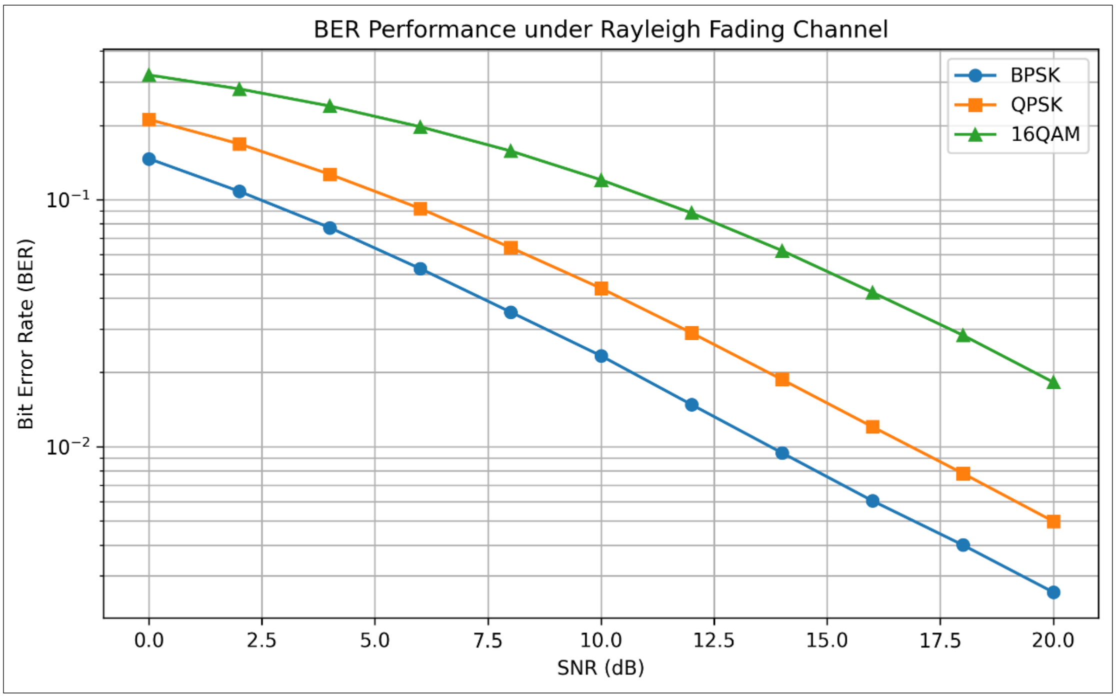

Figure 2: BER Performance under Rayleigh Fading Channel

4.3 Reliability Threshold Analysis

The threshold analysis provides a stronger engineering interpretation than simple BER comparison. Table 1 reports the minimum SNR required to achieve BER targets of $10^{-2}$and 10^{-3}.

Table 1. Minimum SNR Required to Achieve Target BER

Modulation	Channel	BER Target	Minimum SNR Required
BPSK	AWGN	10^{-2}	6 dB
BPSK	AWGN	10^{-3}	8 dB
BPSK	Rayleigh	10^{-2}	14 dB
BPSK	Rayleigh	10^{-3}	Not achieved
QPSK	AWGN	10^{-2}	8 dB
QPSK	AWGN	10^{-3}	10 dB
QPSK	Rayleigh	10^{-2}	18 dB
QPSK	Rayleigh	10^{-3}	Not achieved
16-QAM	AWGN	10^{-2}	14 dB
16-QAM	AWGN	10^{-3}	18 dB
16-QAM	Rayleigh	10^{-2}	Not achieved
16-QAM	Rayleigh	10^{-3}	Not achieved

The table shows that Rayleigh fading imposes a large SNR penalty. For example, BPSK requires only 6 dB to achieve BER below 10^{-2}under AWGN, but requires 14 dB under Rayleigh fading. This indicates an approximate 8 dB channel penalty caused by multipath fading. Similarly, QPSK requires 8 dB under AWGN but 18 dB under Rayleigh fading, showing a 10 dB penalty.

4.4 Channel-Induced BER Gap

At 10 dB SNR, Rayleigh fading produces a substantially higher BER than AWGN for all modulation schemes. The gap is smallest for BPSK and largest for 16-QAM, indicating that higher-order modulation is more vulnerable to fading.

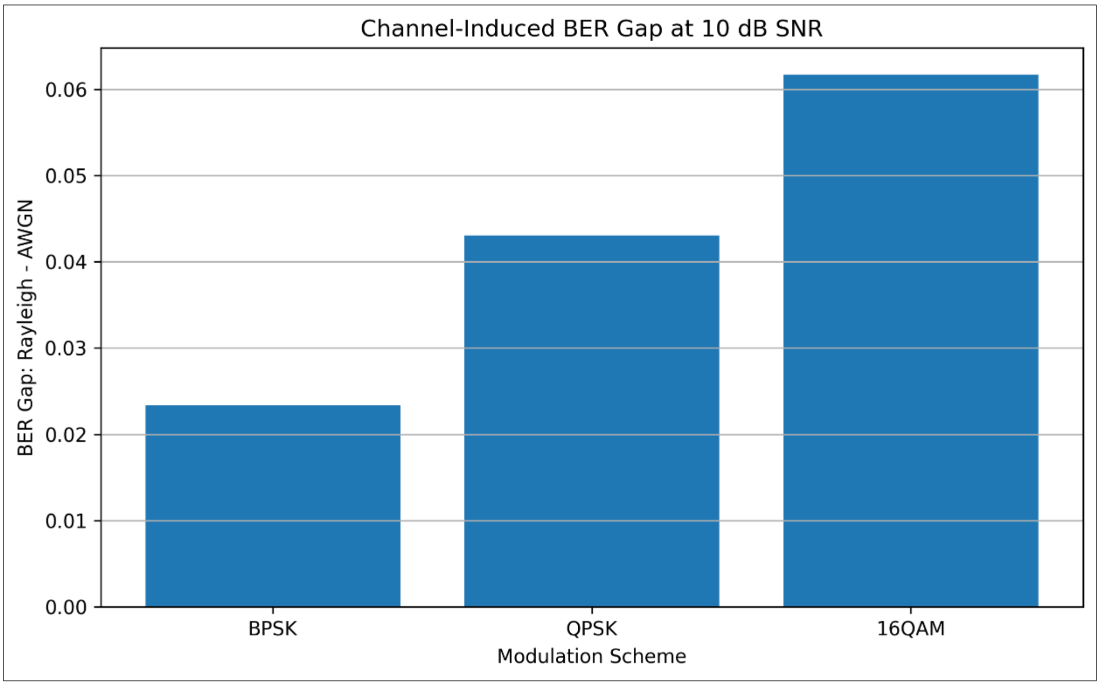

Figure 3: Channel-Induced BER Gap at 10 dB SNR

This result is important because it shows that channel impairment does not affect all modulation schemes equally. While BPSK maintains relatively stable performance, 16-QAM experiences a significant reliability loss due to its dense constellation structure.

4.5 Effective Spectral Efficiency

The study also examined effective spectral efficiency at 20 dB SNR. Although 16-QAM provides the highest theoretical spectral efficiency, its effective performance depends strongly on channel condition. Under AWGN, 16-QAM approaches nearly 4 bits/s/Hz, while under Rayleigh fading its effective spectral efficiency is reduced because of higher BER.

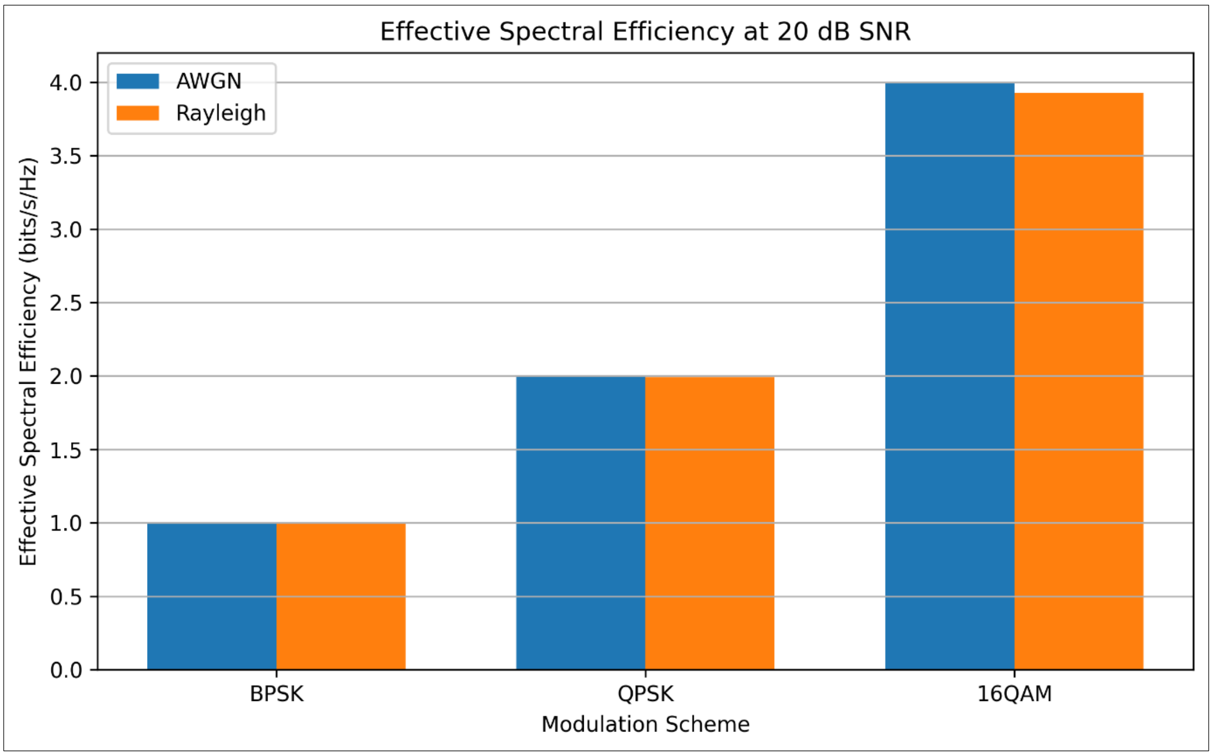

Figure 4: Effective Spectral Efficiency at 20 dB SNR

This confirms that higher-order modulation is beneficial only when the channel condition is sufficiently strong. In fading environments, lower-order modulation may provide better reliability, while higher-order modulation may require adaptive switching, coding, or diversity support.

4.6 Hypothesis Testing Summary

Hypothesis	Statement	Result
H1	BER decreases as SNR increases under AWGN.	Supported
H2	BER decreases as SNR increases under Rayleigh fading.	Supported
H3	Rayleigh fading produces higher BER than AWGN at equivalent SNR.	Supported
H4	Higher-order modulation improves spectral efficiency but increases BER sensitivity.	Supported
H5	Rayleigh fading imposes a measurable SNR penalty for achieving target BER.	Supported

4.7 Overall Discussion

The updated simulations provide a more detailed view of a wireless system's overall behaviour than would be possible by evaluating each modulation type separately. Three significant design insights were found. First, there is an improvement in BER performance across all modulation types and channel environments due to increased SNR. Secondly, Rayleigh fading significantly reduces communication reliability compared to AWGN. Finally, using higher-order modulations increases a communication link's data-carrying capacity; however, they also become more vulnerable to degradation caused by channel impairments.

These results from this study demonstrate the need for adaptive modulation and channel-aware transmission designs for next-generation (i.e., 5G) and beyond wireless systems. For example, when channels are generally "good", 16-QAM could be utilised to maximise bandwidth utilisation. However, in cases where the channel fades rapidly (fading-dominant), lower-order modulation (e.g., BPSK or QPSK) will likely be required to maintain adequate reliability. If so, additional techniques such as channel coding, MIMO diversity, beamforming, or equalisation should be employed.

In general, the enhanced simulations show that real-world wireless system performance cannot be determined solely on the basis of AWGN assumptions. Therefore, practical system design must take into account fading, modulation order selection, BER threshold requirements, and the trade-off between spectral efficiency and other factors.

5. Conclusion

The purpose of this research was to compare how well three types of digital modulations—BPSK (Binary Phase Shift Keying), QPSK (Quadrature Phase Shift Keying) and 16-QAM (Quadrature Amplitude Modulation)—perform under two different environments: AWGN (Additive White Gaussian Noise) and a Rayleigh fading channel, using a simulated environment created in Python based upon a Monte-Carlo simulation model. The research compared the communication performance of these three modulations in terms of Bit Error Rate (BER) as a function of Signal-to-Noise Ratio (SNR) over the range 0 dB to 20 dB. In addition to comparing the performance of each modulation type in terms of BER, the study provides evidence on the relationships among channel quality, modulation order, reliability, and spectral efficiency.

In addition to providing a direct comparison of the BERs of each modulation scheme and channel condition, the revised analysis included threshold-based SNR requirements and efficiency trade-offs. This makes the study more applicable to the design of future wireless systems. The results show that BER decreases continuously with increases in SNR for all three modulation schemes and both channel conditions. This demonstrates the importance of high-quality signals for reliable digital communication. However, the rate of improvement in the BER varies greatly depending on the modulation type and channel conditions. BPSK always had the lowest BER values due to its robust constellation structure and wide symbol spacing. Therefore, it has a good BER value even at relatively low SNR levels. QPSK offers a balance between reliability and data throughput. On the other hand, 16-QAM offers the best spectral efficiency; however, it is very sensitive to channel impairments, especially in fading environments.

One of the main conclusions derived from the study is that there is a large difference in performance between AWGN and Rayleigh fading channel environments. For example, in AWGN channels, all three modulation schemes improve rapidly with increasing SNR, but in Rayleigh fading channels, persistent BER penalties persist due to multipath-induced amplitude fluctuations. These results indicate that the quality of a communication link is not determined solely by the average power level of the transmitted signal, but also by the channel stability and the amount of uncertainty in the propagation process.

Threshold-based analysis demonstrated that significantly higher SNR values are required to achieve the same target BER as in perfect AWGN environments in fading environments.

From a theoretical point of view, the study confirms the continued significance of BER-SNR relationships in Communications Engineering; however, it shows that modern wireless analysis needs to include new metrics that assess efficiency rather than simply reliability, as traditionally done in textbooks.

These results confirm that modulation selections should depend on both the selected modulation and the channel's current state. Specifically, lower-order modulations would be preferred in unstable or high-mobility environments, and higher-order modulations would become more efficient only if the channel quality were sufficient.

In general, the study concludes that reliable wireless system performance can be achieved through coordinated selection of modulation strategy, channel knowledge, and reliability-efficiency trade-off decisions. With the ongoing maturation of 5G networks and the emerging 6G ecosystem paradigms that emphasise intelligent connectivity with highly dynamic radio access, adaptive transmission design will continue to play a key role in enabling reliable communication while efficiently utilising spectrum.

6. Practical and Industry Implications

This study's conclusions have significant ramifications for telecommunications companies, communications infrastructure planners, radio engineers, and those responsible for designing modern wireless communication systems (specifically 5G) and transitioning to a next-generation system (6G). One of the clearest implications of these findings is that engineering design decisions made about wireless networks based on idealisations of an additive white Gaussian noise (AWGN) environment will likely be overly optimistic about what they predict will happen when deployed in the field. Many real-world communication environments contain various types of impairments that affect communication reliability, including fading due to multipath propagation, motion-related degradation, shadowing caused by obstructions or hills, and non-line-of-sight propagation conditions. For this reason, practical radio planning models should consider fading-aware performance metrics rather than relying solely on laboratory test data.

The fact that BPSK appears superior under difficult channel conditions indicates that lower-order modulations continue to provide value for critical functions, including industrial automation, public safety communication, emergency response systems, and ultra-reliable and low-latency service. Conversely, in good channel conditions where the primary concern is achieving maximum throughput via efficient bandwidth use, higher-order modulations such as 16-QAM become preferable, for example, in dense urban broadband areas, enterprise indoor wireless systems, and high-capacity hot-spot deployments. Thus, these results lend further credence to the implementation of adaptive modulation and coding systems currently being employed in several commercial wireless networks.

Furthermore, the large signal-to-noise ratio (SNR) penalties experienced under Rayleigh fading highlight the need for enhanced functionality at the physical layer. Techniques such as beamforming, diversity combining, multiple-input multiple-output (MIMO), equalisation, and smart handover management are necessary to translate the predicted throughput of wireless networks into an actual end-user experience. Thus, investments by wireless operators in antenna "intelligence" and optimised channel characteristics may produce greater yields than additional unmanaged access to spectrum.

Finally, these results suggest that the applicability of artificial intelligence (AI)- based radio resource management is increasing. As modulation efficiency depends on instantaneous channel state information, machine learning-based systems that predict current fading states and adaptively adjust modulation levels can increase network efficiency. Consequently, future competitive advantage among wireless operators may largely depend on the operator's ability to integrate classical communication theory with intelligent adaptive control systems successfully.

7. Limitations of the Study

Although this work makes several analytical contributions, it must be understood in light of several constraints. Firstly, the study was conducted using simulated data (rather than field measurements or hardware-based testbeds).

While simulations are an established and commonly utilised research methodology in the field of communications engineering, there are many other complications associated with deploying systems in the real world (e.g., hardware non-linearities; synchronisation errors; variability in interfering signals; etc.) that can be difficult to capture accurately in numerical modelling.

Secondly, while the study examined AWGN and Rayleigh fading channels for comparison with the existing literature and thus represents two academically important benchmarks within the communications community, most commercial wireless systems operate under conditions that include Rician fading, Nakagami fading, correlated shadowing, dynamic blocking effects, Doppler spreading, and hybrid conditions.

Thirdly, the study analysed BPSK, QPSK, and 16-QAM as representative modulation schemes.

However, modern wireless systems are beginning to utilise higher-order constellation configurations, OFDM waveform variants, coded transmission, carrier aggregation, and adaptive hybrid transmission techniques, which exceed the scope of this work.

Lastly, while the study has provided significant insight into both the BER performance and the effective spectral efficiency of BPSK, QPSK and 16-QAM modulations, there exist several other performance metrics (including but not limited to: latency; outage probability; energy efficiency; fairness; packet delivery ratios; and computational complexity) that will depend upon the nature of the intended use case and thus provide further insight into how each modulation scheme performs in different application domains.

8. Future Research Directions

There are numerous opportunities for additional research arising from this study. A first potential area of focus is to extend the proposed model towards higher-order modulation formats and OFDM-based waveforms that better represent the characteristics of operational 5G systems. By doing so, it will be possible to determine how the trade-off between efficiency and reliability changes as bandwidth-intensive architectures are designed.

Another opportunity is to evaluate additional propagation models (e.g., Rician, Nakagami, shadowing fading, and mobility-driven Doppler) to increase the external validity of the results. Using these additional models could lead to specific recommendations for various environments (urban, rural, vehicular, industrial, etc.) where users are mobile. Additionally, integrating the effects of user movement and handover dynamics could be very beneficial in designing mobility-centric networks.

The third area of interest is to develop the proposed model by incorporating more advanced physical-layer technologies, including massive MIMO, reconfigurable intelligent surfaces, cooperative relays, and beam management systems. All of these technologies are becoming increasingly critical components in today's wireless system designs and may significantly affect the BER thresholds identified in this study.

Fourthly, there is an opportunity for researchers to explore the application of machine learning techniques to perform predictive channel estimation, adaptive modulation control, and autonomous radio resource allocation. With increasing use of software-defined radios and data-driven approaches in wireless communications, AI-enabled decision-making systems may become necessary for real-time optimisations.

Lastly, future studies should validate their simulations using a combination of software-defined radio platforms, FPGA implementations, and controlled field experiments. This type of validation would make it easier for developers to apply simulation-based concepts to real-world deployments. Ultimately, through these additional investigations, researchers can continue to expand the development of resilient, efficient, and intelligent wireless communication systems for the next generation of wireless communications beyond 5G.

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