Online at: https://researchtrendsjournal.com **ISSN No:** 2584-282X
Indexed Journal **Peer Reviewed Journal**

INTERNATIONAL JOURNAL OF TRENDS IN EMERGING RESEARCH AND DEVELOPMENT

Volume 3; Issue 4; 2025; Page No. 96-102

Received: 02-04-2025
Accepted: 09-06-2025

BER Analysis of Modulation Techniques in Noisy Channels

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DOI: https://doi.org/10.5281/zenodo.16737467

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Abstract

Bit-error rate (BER) is a core performance measure of the strength of the modern digital communication systems under the influence of noise. The present article carries out a cross-frequency analysis of the BER of four widely used modulation strategies, namely, Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (16-QAM), and 64-QAM with respect to three of the traditional channel models, that is, Additive White Gaussian Noise (AWGN), Rayleigh fading and Rician fading. The same theoretical expressions of the BER obtainable by probability density functions (PDFs) and the Q-function are demonstrable and, subsequently, the MATLAB simulations confirm it over SNR range of 0 dB to 20 dB. With the Monte Carlo structure, the simulations availed in MATLAB give statistically sound performance at various noise levels. The results show the tradeoff between spectral efficiency and noise immunity in state of the art digital communication platforms: on the one hand, the BPSK and QSPK modulations are seen to perform better on fading channels but on the other hand the QAM of higher order is much better in very high SNR environments. The outcomes help shed light on factors that have to be considered when trying to maximize modulation schemes when designing communication systems.

Keywords: AWGN Channel, Bit Error Rate (BER), Digital Modulation, Monte Carlo Simulation, Rician Fading, Rayleigh Fading

1. Introduction

The faster growth of the wired and wireless technologies has significantly heightened the need of being robust, efficient in operations and in being adaptable with the digital communication networks. The Bit Error Rate (BER) is one of the many performance characteristics that measure the systems performance essentiality aspects because it determines the likelihood of incorrectly transmitted bits due to interference and signal degradation [1]. Definitive computation of BER is vital to data uniformity and preservation of the Quality of Service (QoS) in areas like mobile, satellites and the Internet of Things (IoT). Modulation schemes significantly affect the BER performance due to the fact it identifies the approach in which the digital information can be mapped on the carrier waveforms [2]. The most common digital modulations schemes include those of BPSK, QPSK and M-ary QAM including 16-QAM and 64-QAM. Despite the fact that higher order modulations are more efficient in terms of spectrum utilization, they are more vulnerable to noise and fading especially when signal to noise ratio (SNR) is low. It is necessary to have a good appreciation of this trade-off and hence one can choose the modulation scheme that is suitable to dominant channel conditions and system necessities [3].

There are several types of noise and fading in the communication channels that normally affect them. Although, AWGN has been employed as a theoretical random noise model to describe the behavior of thermal noise in the electronic system, it is not a sensitive input to be adopted in wireless. Rayleigh and Rician fading are more correct in terms of the variability of signals due to multipath and Doppler effects in such situations. Such fading models play an important role in affecting the BERs especially when a strong line-of-sight element is available or not present. Even though there are a few studies that examine the effect of various conditions on BER performance, few of them provide a systematized approach with comparison-based analysis of different modulation types and channel models [4]. To correct this shortcoming, this paper will endeavor to combine both theoretical expressions of BER with simulation results done in MATLAB using BPSK, QPSK, 16-QAM and 64-QAM using AWGN, Rayleigh, and Rician channels. The goal is to provide insight into the interplay between complexity of modulation and channel properties and to provide the guide on how robust efficient communication systems may be designed.

2. Theoretical Background

In the domain of digital communication, Bit Error Rate (BER) is a term which defines the proportion of received mangled bits in relation to the amount of received bits which are mangled out of total number of the sent out bits- a pertinent measure of reliability in a system [5]. Yet, it is also important to note that BER has dependencies on the selection of the type of modulation scheme and the type of channel used together with that modulation scheme. This current debate provides the mathematical derivations that must be used to compute BER in any three of the standard modulation systems; namely, Binary Phase-Shift Keying (BPSK), Quadrature Phase-Shift Keying (QPSK) and the M-ary Quadrature Amplitude Modulation (M-QAM, in the variants 16-QAM and 64-QAM) under three different noise environments; i.e., Additive White Gaussian Noise (AWGN), Rayleigh fading, and Rician fading.

2.1 Additive White Gaussian Noise (AWGN) Channel

In an AWGN channel, noise is modeled as a zero-mean Gaussian random process with power spectral density $N_0/2$. The received signal is given by:

r(t)= s(t)+n(t)r(t)

Where s(t) is the transmitted signal, $n(t) \sim \mathcal{N}(0, \sigma^2)$ is the additive Gaussian noise with variance $\sigma^2 = N_0/2$.

2.1.2 BER for BPSK in AWGN

For Binary Phase Shift Keying (BPSK), the transmitted symbols are $\pm\sqrt{E_b}$. The probability of bit error is derived using the Q-function:

$$P_b^{BPSK} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

Where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}\,dt$, E_B is the energy per bit, N_0 is the noise power spectral density.

2.1.3 BER for QPSK in AWGN

QPSK transmits two bits per symbol, using four constellation points. Since QPSK is essentially two orthogonal BPSK systems:

$$P_b^{QPSK} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

Thus, BPSK and QPSK have identical BER performance in AWGN for the same E_b/N_0.

2.1.4 BER for M-QAM in AWGN (e.g., 16-QAM, 64-QAM)

For square M-QAM (where $M=2^k$), the approximate BER expression is:

$$P_b^{QAM} \approx \frac{4}{k}\left(1-\frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3kE_b}{(M-1)N_0}}\right)$$

Where $k=\log_2 M$, M is the modulation order (e.g., M=16 for 16-QAM). This expression assumes Gray coding and a large number of transmitted symbols.

2.2 Rayleigh Fading Channel

In Rayleigh fading, the channel amplitude h is modeled as a Rayleigh-distributed random variable, which is appropriate for scenarios with no line-of-sight. The instantaneous SNR becomes a random variable:

$$\gamma = |h|^2 \frac{E_b}{N_0}$$

The PDF of γ under Rayleigh fading is:

$$f_\gamma = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right)$$

The average BER is computed by averaging the conditional BER over the fading distribution. For BPSK:

$$P_b^{Rayleigh} = \int_0^{\infty} Q\left(\sqrt{2\gamma}\right) f_\gamma(\gamma)\,d\gamma = \frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma}}{1+\bar{\gamma}}}\right)$$

where $\bar{\gamma} = E[\gamma]$ is the average SNR.

2.3 Rician Fading Channel

Rician fading accounts for a dominant line-of-sight (LOS) path in addition to multipath components. The channel amplitude h follows a Rician distribution characterized by the K-factor, defined as:

$$K = \frac{Power\ of\ LOS\ component}{Power\ of\ scattered\ component}$$

The PDF of the instantaneous SNR γ in Rician fading is:

$$f_\gamma(\gamma) = \frac{1+K}{\bar{\gamma}} \exp\left(-K - \frac{(1+K)\gamma}{\bar{\gamma}}\right) I_0\left(2\sqrt{\frac{K(1+K)\gamma}{\bar{\gamma}}}\right)$$

Where $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind. The BER for BPSK in Rician fading is approximated by $P_b^{Rician} = \int_0^{\infty} Q\left(\sqrt{2\gamma}\right) f_\gamma(\gamma)\,d\gamma$. Which has no closed form but can be numerically integrated or approximated using series expansions.

2.4 Summary of BER Expressions

Under each of the several channel models, the dominant formulations of bit-error-rate (BER) performance of BPSK, QPSK and M-QAM systems are compiled in Table 1 in the current review. The table acts as an abridged requirement in terms of gauging relative value of these methods in an evaluation of the different fading channels Additive White Gaussian Noise (AWGN), Rayleigh, and Rician fading channel operating conditions. The above expressions constitute the basis of analysis carried out in the simulation of study below.

Table 1: Theoretical BER Expressions for Different Modulation Schemes and Channel Types

Modulation	Channel Type	BER Expression
BPSK	AWGN	Q $(\sqrt{2E_b/N_0})$
QPSK	AWGN	Q $(\sqrt{2E_b/N_0})$
M-QAM	AWGN	$\frac{4}{log_2 M}(1-\frac{1}{\sqrt{M}})Q(\sqrt{\frac{3log_2 M.E_b}{(M-1)N_0}})$
BPSK	Rayleigh	$\frac{1}{2}(1-\sqrt{\frac{\bar{\gamma}}{1+\bar{\gamma}}})$
BPSK	Rician	$\int_0^\infty Q(\sqrt{2\gamma})\, f_\gamma\ (\gamma)d\gamma$

The theoretical framework that follows forms the background behind the simulation and analysis of the MATLAB that are later described. Direct comparison of the theoretical expression and that of the simulation will evaluate the magnitude in which ideal systems would match with realistic systems in the case of various noise models and modulation schemes.

3. Literature Review

The Bit Error Rate (BER) has been a standards marker in the evaluation of the digital modulation scheme in view of distinct channel conditions in the last few decades. The interaction between the order of modulation, the structure of symbols and channel characteristics have been studied both theoretically and experimentally several times, and particularly in the wireless channels where the level of noise and propagation impairments is large [6]. In Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) communication with Additive White Gaussian Noise (AWGN), Proakis (2001) developed an original form of the overall process by developing a sufficient closed form of BER. Such formulas are based on the Q-function and thus BER becomes a related simple function of signal to noise ratio (SNR) presenting a starting point when comparing idealized modulation codes [7]. More analysis was done with respect to M-ary modulation with of specific interests in Quadrature Amplitude Modulation (QAM). QAM is spectrally more efficient and less sensitive to noise that is caused by publicity.

In the emergence of the fading channels, researchers focused on the degradation of performance injected by the multipath propagation. Statistical description of Rayleigh and Rician fading were also introduced by Simon and Alouini (2000) and proved that the lack of line-of-sight component could significantly degrade the performance of BER. In such scenarios, other forms of modulation, such as BPSK and QPSK, perform much more admirably than QAM since they feature higher average noise margins. Approximations of the BER and asymptotic bounds on Fading in Rayleigh and Rician have been done but with most of the calculations being through numerical integration [8]. In the simulation area, programs like MATLAB have become almost de-facto tools, allowing the evaluation of the theoretical predictions in a controllable channel. Sharma *et al*. (2017) and Nasir *et al*. (2019) presented the Monte Carlo simulation-based performance analysis of multiple modulation schemes based on the AWGN and Rayleigh fading conditions with the reported performance trends being rather close to the analytically predicted ones. But most of such work are limited to AWGN or a single type of modulation and this created a gap in the literature in comparative analysis that considers multiple modulation schemes over all the three major channel models (AWGN, Rayleigh, Rician).

At the same time, numerous works describe adaptive modulation and behavioral channels to communicate. However, the majority of them employ the idealized or simplified BER curves, therefore, being appropriate in dynamic wireless networks. Other research does not even turn to serious mathematical proving, confining itself to simulation; without the comparison between the theory and experiment, it is impossible to understand the quality of their conclusions. The current study builds upon these previous works through combination of analytical development and simulation on MATLAB platform to study BPSK, QPSK, 16-QAM and 64-QAM in AWGN, Rayleigh and Rician channels. Compared to previous literature, it gives a detailed side-by-side comparison at the modulation type level but also at the channel type level providing some theory and an empirical validation. The research also tries to strike a balance between theories and practice by making the plots and discussions of the present extremely well documented, relevant to real-world system design.

4. Materils and Methods

The current section reports the methodology used to determine the Bit Error Rate (BER Performance) of the four digital modulation schemes (BPSK, QPSK, 16-QAM and 64-QAM) in the presence of three canonical channel (Additive White Gaussian Noise (AWGN), Rayleigh and Rician channel). MATLAB R2023a was the platform where the analyses were done by applying Monte Carlo simulations in a manner that allow provision of statistically sound results and less statistical bias.

4.1 Simulation Framework

Four digital modulation schemes commonly used, which include BPSK, QPSK, 16-QAM, and 64-QAM are going to be investigated in their BER performance and to this end, a simulation model was developed in MATLAB R2023a. A Monte Carlo procedure was used to ensure that the results could be relied upon to be reliable when the channel conditions change and when the SNR changes [9]. The process started by the creation of a very lengthy series of uncorrelated, identical distributed (i.i.d.) binary symbols that were then interpreted into modulation symbols as per the chosen scheme. These modulated signals were fed into three channel models: (i) Additive White Gaussian Noise (AWGN) that is done using built-in awgn () function; (ii) Rayleigh fading using complex fading coefficients; (iii) The Rician fading with K-factor of 5 to represent application of moderate line-of-sight component. This codeword was demodulated at the receiver and BER was computed between a recovered sequence and original one. The present framework allowed reproducible outcomes to be obtained on every modulation scheme and channel type and hence a steaming analysis of their behavior in several noise and fading conditions could be easily made.

4.2 Simulation Parameters

To carry out a systematic and comparative evaluation of Bit-Error Rate (BER) performance of different modulation schemes, a set of simulator parameters was established in a uniform way. These parameters defined conditions in which the results achieved of any specific modulation could be usefully compared under different environments of the channel.

Table 2: Simulation parameters used for evaluating BER performance under varying modulation schemes and channel conditions

Parameter	Value
Number of bits	10^6
Modulation schemes	BPSK, QPSK, 16-QAM, 64-QAM
SNR range	0 dB to 20 dB (step size: 2 dB)
Channel types	AWGN, Rayleigh, Rician
K-factor (Rician)	5 (moderate LOS component)
Fading type coherence	Flat fading, slow fading
Receiver	Coherent detection
BER estimation method	Monte Carlo simulation

The parameter values in the table 2 below were being applied throughout the simulations done in this research. The standardization of the kind of modulation, signal to noise ratio and channel parameters enables that the BER values can be used to compare the performance of each modulation scheme on relative level in more or less comparable environmental conditions.

5. Results and Discussion

BPSK, QPSK, 16-QAM and 64-QAM will be the modulation schemes to be tested and AWGN, Rayleigh fading, Rician fading will however act as the channel impairments. These performance measures are bit-error-rate (BER), which is measured over bit error interval of 0 dB to 20 dB and step of 2-dB.

5.1 BER Performance in AWGN Channel

The minimum Euclidean distance between points defines the distinction of the constellation points in the Additive White Gaussian Noise (AWGN) channel to a great extent. Under such ideal conditions, BPSK and QPSK have exactly the same and optimal BER performance because they both have a symmetrical and orthogonal constellation structure. Simulation leads to the fact that these systems have BERs below 10^{-5} at 10 dB SNR and can therefore be very dependable to even low and medium SNR applications. The 16-QAM and 64-QAM on the other hand, have better spectral efficiencies however, low SNRs have very poor BER due to the close spacing of constellation points. But as SNR is increased it leads to their BER to begin to decrease sharply, and hence they can be used in high throughput systems where the SNR is high. It concurs with the theory and indicates the compromises between strength and bandwidth effectiveness where the system with AWGN dominant is taken into account.

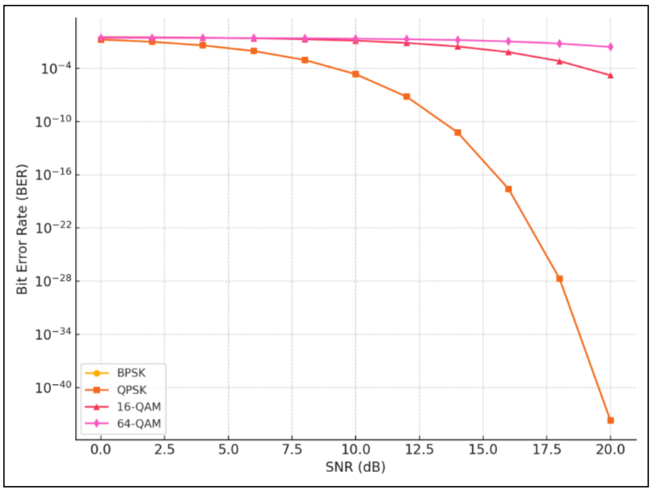

Fig 1: BER vs. SNR performance comparison for BPSK, QPSK, 16-QAM, and 64-QAM under AWGN channel conditions.

The BER trends of BPSK and QPSK were the same since BPSK and QPSK have matching symmetric constellation structures as shown in Figure 1. The two of them achieve a BER of lower than 10^{-5} at 10 dB SNR. Sixteen-QAM and 64-QAM, on the other hand, had the BERs of about 10^{-2} and 10^{-1}, respectively, at the same SNR level because the symbols in these constructions are densely arranged. Increasing the SNR to 18-20 dB showed that 64-QAM BER was again below 10^{-4} and this indicated the trade-off between spectrally efficient and robust signal. It is these trends that provide justification of the simulation results with these claims being similar to theoretical BER curves.

5.2 BER Performance in Rayleigh Fading Channel

As a model of wireless channels that do not provide a line-of-sight (LOS) path, Rayleigh fading imparts significant variations in signal amplitudes because of the multipath effects. All the modulation schemes also did not perform well in this environment. Still, the BPSK performed the best of all schemes, but in the face of 20 dB SNR, the BER was greater than 10^{-3} demonstrating how deep fading has a dreadful impact. Unsurprisingly, QPSK too exhibited a similar or a little worse nature with even higher SNRs because it had comparatively higher BERs at higher SNRs also. The modulations of much higher order such as the 16-QAM and 64-QAM were very vulnerable since they had floors in the BER that transgressed to the SNR spectrum. This is mainly because they have closeness of symbol space which increases the effect of amplitude distortion and signal distortion. The foregoing outcomes emphasize the fact that lower-order modulation should be used in the channel whereby the count of the paths is large unless error processing or diversity methods are added unless.

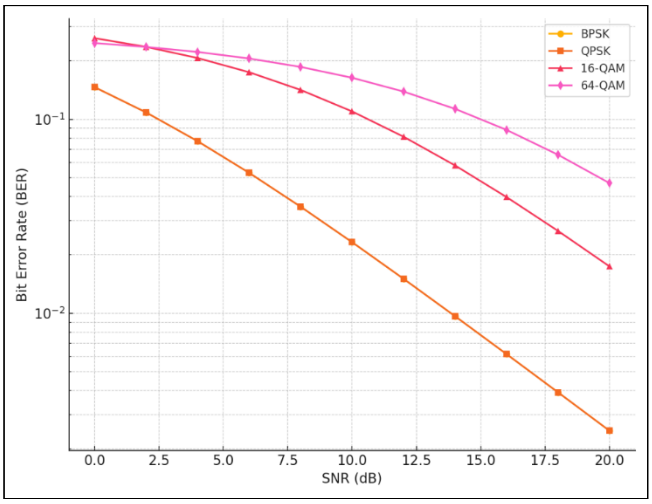

Fig 2: BER vs. SNR performance for BPSK, QPSK, 16-QAM, and 64-QAM in a Rayleigh fading channel.

The empirical experiment provided in Figure 2 explains the deterioration in the performance of all the schemes that are witnessed in Rayleigh fading. The problem is that by using the multipath effects it is possible to achieve deep fades; however, since there is no line-of-sight component to maximize the fades it can increase the error rate. The BPSK had a BER of about 1.5 x 10^{-3} at the same signal-to-noise ratio of 20 dB, whereas 64-QAM was still in excess of 10^{-1}. The performance of the 16-QAM was also demonstrated to be close to that of 16-QAM in mid region. The findings support the assertion that the plans of lower orders are stronger when the circumstances are abating.

5.3 BER Performance in Rician Fading Channel

In mathematical expression of wireless propagation, models that deal with togetherness of LOS and NLOS are more realistic than the classical Rayleigh fading: the Rician fading is commonly used as an improved model that includes the togetherness [10]. R is a ratio between deterministic and scattered power that has been defined and that quantifies this ratio; fading is a statistically Rician. The analyses carried out in this study used a K-factor of 5, therefore, reflecting a moderate component of LOS. Gains in receiver performance in Rician fading were anticipated to be significant over the same comparisons in pure Rayleigh fading across all modulation schemes and as expected, binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK) showed most improvement over their corresponding results in Rayleigh fading due to added signal stability under LOS path. Even then, other schemes with orders equal to or greater than 16-quadrature amplitude modulation (16-QAM) and 64-QAM that would have been capable of producing better results with reduced signal-to-noise ratios (SNRs), due to the effects implemented on the constellations to ensure they were compact, reached their performance limits. Even though the superiority of Rician fading did indeed become more noticeable at higher SNRs, it never really reached the same levels as on AWGN conditions. These findings reveal that even though Rician channels introduce certain reduction in the effects of fading, it can be easily observed that when combined with one of the robust modulation techniques the total effect is improved.

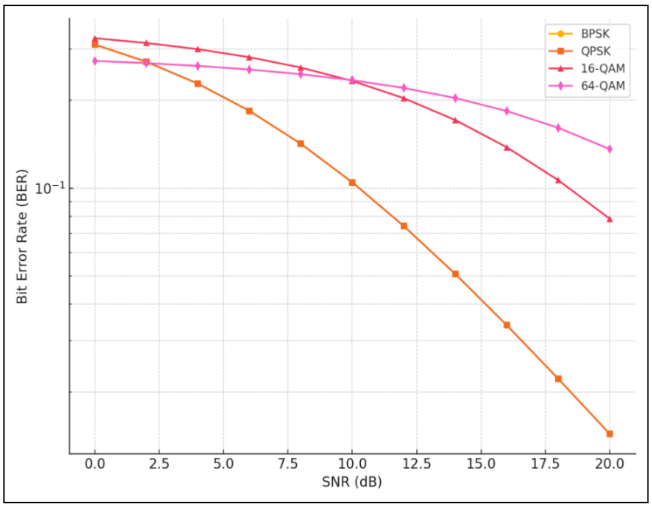

Fig 3: BER vs. SNR performance for BPSK, QPSK, 16-QAM, and 64-QAM under Rician fading with K-factor = 5.

Rician fading enables a better direction path as compared to the Rayleigh fading, along the K = 5 (Figure 3). This course reduces bit-error rate (BER) of each and any kind of modulation in all SNR points. BPSK and QPSK experience an obvious BER decrease of 18 db at the SNR and drop to below 10^{-4}; on the other hand, 16-QAM and 64-QAM do not do very well within a little SNR range yet they are quick within a large SNR to achieve the AWGN performance. Partial blockage of view can also bring about a difference in wireless systems as illustrated by these results.

5.4 Comparative Plots and Interpretation

Comparative Bit Error Rate (BER) is also used to explain the differences in performance between different Modulation schemes; we have set up MATLAB to draw several performance curves using AWGN, Rayleigh, and Rician channel. The BER curves obtained are plotted in log scale which acts as a measurement of objectivity regarding the robustness of the modulation. According to steeper slopes, which in this case shall be one of BPSK, suggest a faster rate of BER decrease with rising Signal-to-Noise Ratio (SNR), i.e. better noise immunity. On one hand, in the BER levels, the linearity of the level is less so on the high order Quadrature Amplitude Modulation (QAM) like 16-QAM and 64-QAM which are highly sensitive to channel errors particularly within a fading channel.

Table 3: Optimal Modulation Schemes under Varying Channel Conditions

Channel Type	Best Performing Scheme (Low SNR)	Best Performing Scheme (High SNR)
AWGN	BPSK / QPSK	64-QAM (for high data rate)
Rayleigh	BPSK	QPSK
Rician	BPSK	QPSK / 16-QAM (if SNR > 18 dB)

Simulation based estimation of optimum modulation schemes at various regimes of SNR, at various forms of channel type, is summarized in table 3. What remains true is that BPSK always provides the best performance at low SNRs regardless of the nature of channels, and 64-QAM is derived as the best methodology at high SNRs when dealing with AWGN channels.

A point it is worth noting empirically is that there are BER floors in both Rayleigh and Rician fading channels with 16-QAM and also 64-QAM. The above facts would suggest that, at high SNRs, probably still would be likely to be present unless something other than cochannel compensation (e.g., diversity schemes or equalization) is added. Moreover, the BPSK gives a good performance in all the three channel conditions consistently, and thus its application in low-SNR or otherwise unfriendly transmission channels is made clear. All these findings help reaffirm the significance of introducing channel-conscientious modulation techniques to the practice of practical communication systems.

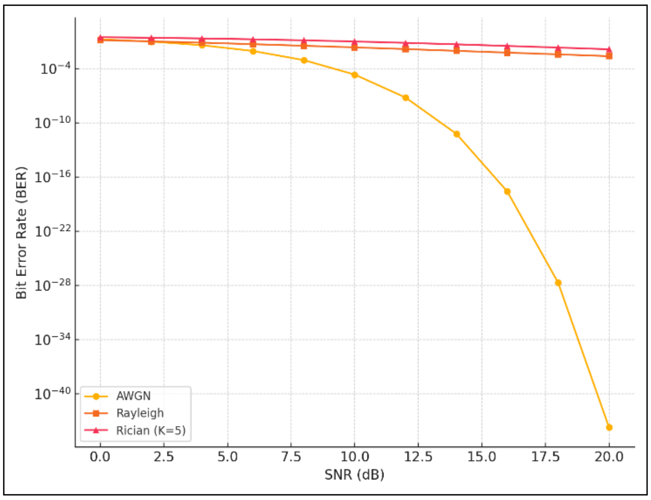

Fig 4: BER comparison of BPSK modulation in AWGN, Rayleigh, and Rician channels.

Figure 4 displays the experimental data that contains the performance of BPSK in three different channel conditions i.e. additive white Gaussian noise (AWGN), Rayleigh fading and Rician fading. These results confirm the above ranking: AWGN possesses the most desirable properties, next Rician fading, and lastly, Rayleigh fading. The analysis suggests that the higher order codes such as 16-QAM and 64-QAM perform with noticeable performance penalty when operating Rayleigh condition, and with a small penalty when operating medium-SNRs condition in Rician condition, at low SNRs. On the contrary the performance of BPSK and QPSK stabilize relatively well even when there are three channels. Due to such results, the value of applying channel-adaptive modulation mechanisms is proven.

5.5 Practical Implications

The results of this research have strong practical implications in terms of designing a system especially in adaptive communication systems. Sixteen-phase binary phase-shift keying, binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK) are the most feasible options to be used in low-signal-to-noise-ratio (SNR) or high-mobility systems (generally characteristic of wireless networking in an urban setting) as well as in mobile edge computing because they have good robustness relative to other modulation schemes and simple implementation. Comparatively, a convenient alternative could be the 64-quadrature-amplitude modulation (64-QAM) at applications having high SNR, i.e. the applications where no interference occurs, e.g. fixed microwave backhaul system and fiber-optic network, since in high SNR systems 64-QAM is far better spectrally efficient. The modulation scheme switching can be done in the dynamically changing systems, 4G long-term evolution (LTE), 5G new radio (NR), satellite communications involve switching their modulation schemes in real time, maximizing the throughput and reliability, depending on the available channel conditions by use of adaptive modulation/coding (AMC) schemes. Collectively these results indicates a very strong case to adopt an holistic perspective of the modulation solution integration with forward-error-code coding and diversity techniques so as to achieve balanced performance, reliability and spectral efficiency.

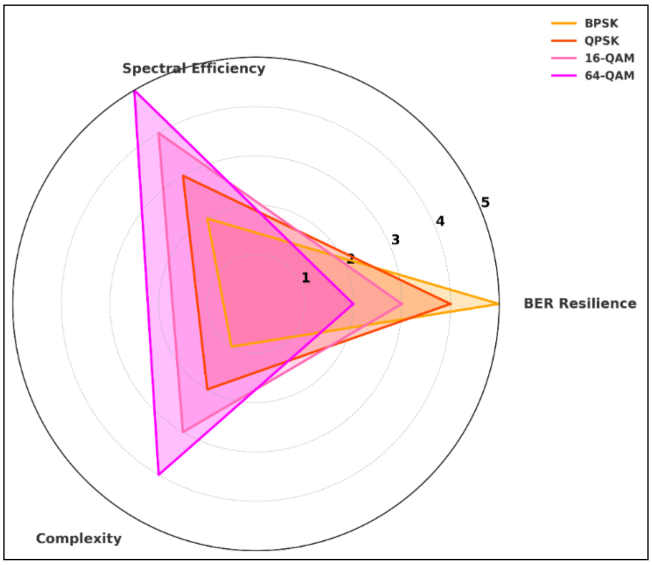

Fig 5: Radar chart comparing modulation schemes based on BER performance, spectral efficiency, and complexity.

Figure 5 is another radar graph which performs a comparative analysis in a rather systematic manner of demands and advantages of various modulation schemes. It is also relevant to point out 64-QAM is higher in terms of spectral efficiency, but with a rather poor BER. On the other hand, BPSK and QPSK are good in BER Cat. with the disadvantage of wider bandwidth. The graphical representation combines the trade-offs in design of modulation and helps the practitioners to identify reasonable schemes to be used in adaptive system designs.

6. Conclusion and Future Work

6.1 Conclusion

This paper will provide a systematic comparative analysis of the Bit Error Rate (BER) performance of four of the more common digital modulation formats namely, BPSK, QPSK, 16-QAM and 64-QAM under the three statistically different channel models, namely, Additive White Gaussian Noise (AWGN) channel environment, Rayleigh fading channel environment and the Rician fading channel environment. This examination will be conducted using a combination of theoretical BER derivation and Monte Carlo simulation which have been included to MATLAB, it is going to illuminate some of these which work of the system as far as an excellent variety of SNRs is concerned. With the results it may be observed that BPSK and QPSK is preferential in noisy and fading distractions and the BERs are also reduced as per the channels involved in the test. High-order modulation, e.g. 16-QAM or 64-QAM, are used at high SNR, in particular, when AWGN is the case, but it has large BER at low to moderate SNR. The situation that Rician fading still has a line-of-sight (LOS) component makes BER better than Rayleigh fading but fail to eliminate the susceptibility of high order QAM in relation to noise. These findings emphasize that there is an inbuilt trade-off between spectral effectiveness and noise-shielding capacity and the fact that it is of the utmost importance to select among modulation schemes, which are suiting in respect to the channel characteristics and to the system designing needs. The findings have direct applicability on the modern wireless communications, such as those used in 5G, 4G, and the dynamic and variable transmission strategies being used in development technologies.

6.2 Future Work

The present work can be overridden in the future by conducting a research to add on the analysis by comparing the joint efficiency of channel coding and modulation vis-a-vis the respective performances of both channel coding and modulation on BER [11]. Also it will be interesting to see the impact of the multiple-input multiple-output (MIMO) techniques in addition to spatial diversity in fading channel and the implications this has on improving the overall system performance. The applicability of the given results can also be expanded in work with environments of high mobility that allow a significant Doppler shift [12]. To have better practical applicability, the results can be confirmed by taking actual measurements of channels or by testing bed application in hardware. Also, a second direction with as well positive connotation is a second way to go which is the application of adaptive modulation and coding (AMC) techniques along real-time channel state information (CSI) optimization to maximize throughput and reliability. Finally, BER simulations are recommendable to be modified so that they incorporate the issue of energy-efficiency, including applications of IoT and the functionality of battery-connected equipment, to encourage a sustainable future systems behavior.

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