Journal of Information Systems Engineering and Management
2025, 10(3)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Evaluating BER and Throughput in 5G Networks Using Adaptive Modulation and Nakagami Fading

S Bhargavi[1], Reshma Verma[2], Anil Kumar C[3], Lavanya Vaishnavi D A[4], Jyothi H R[5], Harish S[6]

[1]*Professor, Department Electronics and Communication Engineering, S J C Institute of Technology , Chikkaballapura, India, bhargavisunil@gmail.com*

[2]*Assistant Professor, Department Electronics and Communication Engineering, Ramaiah Institute of Technology, Bengaluru, India, reshmaverma@msrit.edu*

[3]*Professor and Head, Department Electronics and Communication Engineering, R L Jalappa Institute of Technology, Doddballapur, India, canilkumarc22@gmail.com*

[4]*Assistant Professor, Department Electronics and Communication Engineering, R L Jalappa Institute of Technology, Doddballapur, India, lavanyavaishnavi@gmail.com*

[5]*Assistant Professor, Department Electronics and Communication Engineering, R L Jalappa Institute of Technology, Doddballapur, India, jyothi.hr050@gmail.com*

[6]*Associate Professor, Department Electronics and Communication Engineering, R L Jalappa Institute of Technology, Doddballapur, India, harishsrinivasaiah@gmail.com*

ARTICLE INFO

Received: 15 Nov 2024

Revised: 28 Dec 2024

Accepted: 15 Jan 2025

ABSTRACT

The rapid advancements in 5G wireless communication have necessitated the development of robust and adaptive technologies to ensure reliable, secure, and high-quality data transmission. Adaptive Modulation and Coding (AMC) is a vital technology in 5G systems, allowing the modulation and coding schemes to dynamically adjust based on channel conditions. This paper focuses on the performance analysis of AMC under Nakagami fading channels, a widely recognized model for real-world wireless environments characterized by multipath propagation. By varying critical parameters such as the shape parameter m and scale parameter Ω, and leveraging diverse modulation and coding schemes, the bit error rate (BER) and throughput performance are evaluated. Simulation results reveal the optimal conditions for minimizing BER and maximizing throughput, demonstrating the resilience of QPSK modulation at $m = 0.5$ and $\Omega = 0.5$. Additionally, potential security vulnerabilities inherent to adaptive wireless systems are acknowledged, emphasizing the need for integrating secure transmission mechanisms alongside performance optimization. The findings provide valuable insights for enhancing 5G network reliability, especially in urban and suburban settings.

Keywords: 5G Network Reliability, Adaptive Modulation and Coding (AMC), Doppler Shift and Shadowing, Dynamic Channel Adjustment, Multipath Propagation, Real-World Channel Impairments

1. INTRODUCTION

The exponential growth of mobile devices and data-driven applications has propelled the demand for high-speed and reliable wireless communication. Fifth-generation (5G) networks have emerged as the cornerstone for meeting these demands, offering enhanced data rates, reduced latency, and improved network efficiency. Among the key technologies driving 5G performance, Adaptive Modulation and

Coding (AMC) plays a pivotal role by dynamically adjusting the modulation and coding schemes to suit varying channel conditions [1].

In wireless communication, channel impairments such as fading, shadowing, and noise significantly affect the quality of transmitted signals [2]. To address these challenges, the Nakagami fading model has been extensively employed due to its flexibility in modeling different propagation environments, ranging from severe to mild fading. This paper examines the interplay between AMC and Nakagami fading channels, exploring how varying channel parameters impact system performance [3].

A. Nakagami Fading Channel

The Nakagami fading channel is a statistical model widely used to describe multipath propagation in wireless systems. It provides flexibility in modeling a range of fading scenarios through its two key parameters which are; Shape Parameter (m), this parameter determines the severity of fading. Lower values of mm (e.g., $m<1$) correspond to severe fading conditions, while higher values (e.g., $m>1$) indicate mild fading. In the context of this study, mm is varied from 0.5 to 4 to capture diverse fading environments. Scale Parameter (Ω), this parameter represents the average power of the received signal. By varying Ω (e.g., 0.5, 1, 1.5), the channel's power distribution can be adjusted to simulate different propagation scenarios. Nakagami fading is particularly suited for urban and suburban environments, where multipath effects are dominant due to reflections and scatterings [4] [5].

B. Adaptive Modulation and Coding (AMC)

AMC is a core component of modern wireless systems, enabling dynamic adjustment of modulation and coding schemes based on instantaneous channel conditions. The modulation schemes considered in this study include:

QPSK (Quadrature Phase Shift Keying): A low-order modulation scheme offering high robustness in low-SNR conditions.

16QAM, 64QAM, and 256QAM (Quadrature Amplitude Modulation): Higher-order schemes providing increased data rates at the expense of reduced resilience to noise.

Coding rates (e.g., 0.5, 0.75, 0.9) further enhance AMC performance by providing error correction capabilities. In conjunction with modulation schemes, coding rates ensure a balance between throughput and reliability [6].

C. Realistic Enhancements

To simulate real-world conditions, additional factors such as log-normal shadowing (representing large-scale fading) and Doppler shifts (induced by user mobility) were incorporated into the channel model. These enhancements provide a comprehensive understanding of AMC performance under practical scenarios [7] [8].

Real-time applications of this study are manifold. In urban environments, where signal degradation due to high-rise buildings and dense obstructions is prevalent, the insights from Nakagami fading can optimize cellular network performance. Similarly, in vehicular communication systems, which are integral to intelligent transportation, AMC ensures reliable data exchange even under fast-varying channel conditions. Other applications include smart grids, industrial automation, and remote healthcare systems, where robust communication is critical to operational success [9] [10].

This paper aims to provide a comprehensive analysis of AMC performance under Nakagami fading, highlighting the significance of channel parameters and their impact on BER and throughput. By doing so, it offers a roadmap for implementing more efficient and reliable 5G networks, particularly in challenging real-world scenarios.

Journal of Information Systems Engineering and Management
2025, 10(3)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

2. LITERATURE SURVEY

Magableh et. al. investigates the performance of Non-Orthogonal Multiple Access (NOMA) systems over NN-Nakagami-mm fading channels in 5G and beyond (B5G) networks. It analyzes key metrics such as capacity and pairwise error probability (PEP) under diverse channel conditions. The study highlights the impact of fading, interference cancellation, and signal-to-noise ratio (SNR) on NOMA performance. The findings provide insights into optimizing NOMA for future wireless systems, emphasizing its advantages in capacity enhancement and efficient resource allocation [11].

Boumaalif et. al., examines power distribution in device-to-device (D2D) communications under Nakagami fading channels within underlaid cellular networks. Using stochastic geometry and Poisson point process modeling, it analyzes interference, signal-to-noise ratio (SNR), and power optimization to improve network performance and device lifetime. The study contrasts Nakagami fading with Rayleigh channels to demonstrate its impact on D2D communication. The findings provide insights into power allocation strategies, interference management, and energy efficiency in D2D-enabled networks, contributing to the design of more robust and efficient cellular systems integrating D2D communication [12].

Men et. al., evaluates the performance of downlink relaying-aided Non-Orthogonal Multiple Access (NOMA) networks under Nakagami-mm fading with imperfect channel state information (ICSI). It investigates metrics such as outage probability, signal-to-noise ratio (SNR), and interference, emphasizing the effects of Nakagami fading and ICSI on system performance. By analyzing the impact of relaying strategies and channel imperfections, the study offers insights for enhancing reliability and efficiency in NOMA-based wireless communication systems, with comparisons to traditional Rayleigh channel models [13].

Ahmed et. al., presents an EXIT chart-based convergence analysis of recursive soft mm-sequence estimation (RSSE) in Nakagami-mm fading channels. It investigates key aspects such as signal-to-noise ratio (SNR), iterative decoding, and delay tracking loops. By leveraging EXIT charts, the study evaluates the performance of RSSE in challenging fading environments, providing insights into its reliability and efficiency. The research highlights advancements in sequence acquisition techniques for wireless communication systems, emphasizing their application in Nakagami fading channels for robust signal detection and tracking [14].

Kumar et. al., explores physical-layer security in underlay MIMO-enabled device-to-device (D2D) communications using a null steering method under Nakagami-mm and Norton fading channels. It addresses security challenges caused by imperfect channel state information (CSI) and interference. The study evaluates jamming resistance, signal alignment, and system reliability while examining the influence of Nakagami-mm and Norton distributions on performance. It provides insights into enhancing secure transmission and communication efficiency in wireless systems with emphasis on advanced antenna and signal processing techniques [15].

Yin et. al., introduces a channel classification scheme that integrates Nakagami-mm shadowing with the Fluctuating Two-Ray (FTR) fading model to enhance the accuracy of wireless communication analysis. By leveraging parameter estimation techniques, it captures the effects of shadowing and fading more effectively than traditional Rayleigh models. The approach highlights the probability density function and shadow mapping, offering insights into real-world radio frequency environments. This work contributes to improved modeling and understanding of wireless channel behavior under complex propagation conditions [16].

Journal of Information Systems Engineering and Management
2025, 10(3)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

3. METHODOLOGY

The Proposed methodology is explained in this section and is shown in the figure 1. The code runs in Python 3 with libraries like NumPy for numerical computations, Matplotlib for visualization, and the built-in CSV module for writing simulation results to a file. The input data in the code includes simulation parameters defined programmatically: the bandwidth (100 MHz), subcarrier spacing (30 kHz), and SNR range (0 to 28 dB). Modulation schemes (QPSK, 16QAM, 64QAM, 256QAM) and coding rates (0.5, 0.75, 0.9) are pre-defined. Nakagami fading parameters mmm (shape) range from 0.5 to 4, and Ω (scale) values are 0.5, 1, and 1.5. The channel effects like fading, shadowing, and Doppler shifts are simulated mathematically, not sourced externally, and stored for analysis.

The Nakagami channel models wireless fading environments with customizable parameters mmm (shape) and Ω (scale). Lower mmm values represent severe fading, while higher values depict less fading. Shadowing, caused by obstacles, is modeled using log-normal distribution with a standard deviation of 3 dB. Doppler effects, caused by relative motion, are simulated as a sinusoidal variation with a frequency shift of 100 Hz. These conditions replicate realistic wireless environments, including urban and mobile scenarios. The synthetic channel response combines fading, shadowing, and Doppler effects to evaluate performance under varying SNRs and modulation-coding combinations.

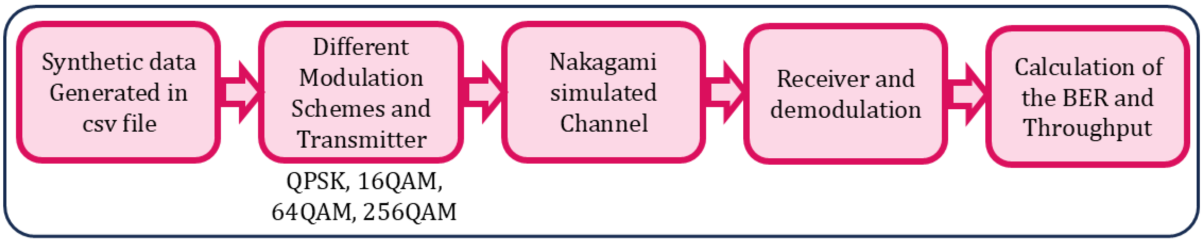

Figure 1: Block diagram of Methodology

Transmitter Block, In the block diagram, the transmitter is the initial stage responsible for preparing the data for transmission. This includes:

Data Source: Represents the generation of input data, such as binary bits, which is the starting point in any wireless communication system.

Modulation and Coding, In the code, this corresponds to the choice of Modulation and Coding Schemes (MCS) such as QPSK, 16-QAM, 64-QAM, and 256-QAM, coupled with coding rates (0.5, 0.75, 0.9). The modulation maps binary data to symbols, while the coding adds redundancy to improve reliability [18][19].

Channel Block, The channel block in the diagram represents the medium through which signals are transmitted. Wireless channels are subject to fading, interference, and noise. The code models the Nakagami fading channel, a realistic channel model used in scenarios with multipath propagation. Parameters such as the shape (m) and scale (omega) determine the severity of fading [20][21] [22].

Receiver Block, The receiver block in the diagram includes stages to demodulate and decode the received signals, estimate errors, and evaluate system performance.

4. ALGORITHM

Algorithm for Simulating Adaptive Modulation and Coding (AMC) in Nakagami Fading Channel

Step 1. **Initialize Parameters**:

Journal of Information Systems Engineering and Management
2025, 10(3)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

Set the system parameters, including bandwidth, subcarrier spacing, number of subcarriers, and the SNR range in dB. Define modulation schemes (e.g., QPSK, 16QAM, 64QAM, 256QAM) and their respective modulation orders. Specify coding rates for each modulation scheme.

Step 2. **Nakagami Channel Simulation**:

Design a function to simulate the Nakagami fading channel, incorporating additional impairments like shadowing (log-normal fading) and Doppler shift. Combine the Nakagami fading, shadowing, and Doppler effects to model a realistic wireless channel.

Step 3. **Bit Error Rate (BER) Calculation**:

Implement a function to calculate BER for different modulation schemes using analytical expressions derived for each modulation order.

Step 4. **Throughput Calculation**:

Design a function to compute throughput as a function of SNR, modulation order, and coding rate.

Step 5. **Simulation Iterations**:

Iterate over combinations of Nakagami shape parameters (mm), scale parameters (Ω\omega), modulation schemes, and coding rates. For each combination: Simulate the Nakagami channel with shadowing and Doppler effects for a defined number of subcarriers. Calculate the faded SNR using the channel response and compute the average faded SNR. Use the average SNR to calculate BER and throughput. Store the BER values for each configuration.

Step 6. **Track Best Condition**:

Monitor the configuration (shape parameter, scale parameter, modulation scheme, and coding rate) that yields the lowest BER.

Step 7. **Export Results to CSV**:

Save all simulation results, including BER values for different configurations and SNR levels, to a CSV file.

Step 8. **Display Results**:

Print all BER results along with the best-performing configuration. Visualize the BER performance for the best configuration as a function of SNR.

The algorithm is designed to simulate the performance of an adaptive modulation and coding (AMC) system operating in a Nakagami fading channel, incorporating real-world channel impairments like shadowing and Doppler shift. The simulation begins with parameter initialization, setting up the necessary variables for the system. These include the bandwidth, subcarrier spacing, modulation and coding schemes, and the SNR range. This foundation ensures the system reflects the characteristics of a 5G network operating in the n78 band.

The heart of the simulation is the Nakagami fading channel, which models small-scale fading in wireless communication systems. To make the model more realistic, shadowing is introduced as log-normal fading, representing large-scale variations due to obstacles, and a Doppler effect is added to account for mobility-induced frequency shifts. These impairments are combined to generate a more comprehensive channel response, which influences the received signal strength and quality.

Next, the BER is calculated for each modulation scheme using theoretical expressions. These expressions approximate the error probability for various modulation orders, such as QPSK, 16QAM, 64QAM, and 256QAM. The BER is a critical metric as it directly impacts system performance, reflecting how reliably data can be transmitted over the channel.

The throughput calculation follows, considering the modulation order, coding rate, and SNR. Throughput measures the effective data rate, making it an important performance metric for evaluating the efficiency of different modulation and coding schemes. By integrating BER and throughput, the algorithm provides a holistic view of system performance.

The simulation iterates over various combinations of Nakagami shape parameters, scale parameters, modulation schemes, and coding rates. For each combination, the Nakagami channel is simulated, and the average faded SNR is computed. This SNR is used to determine the BER, which is stored for further analysis. Additionally, the algorithm continuously tracks the configuration that yields the lowest BER, identifying the best condition for system operation.

To facilitate post-simulation analysis, all results are exported to a CSV file. This file includes detailed BER values for each configuration and SNR level, allowing for further exploration and validation of the results. The best condition, defined by the lowest BER, is highlighted, offering insights into the optimal parameters for the system.

Finally, the algorithm visualizes the results, plotting the BER performance for the best configuration. This plot provides an intuitive understanding of how BER varies with SNR under optimal conditions. The inclusion of shadowing and Doppler effects makes the simulation more applicable to real-world scenarios, where such impairments significantly influence communication system performance.

The algorithm combines theoretical modeling, computational simulations, and practical considerations to analyze AMC performance in Nakagami fading channels. It offers valuable insights into the interplay between modulation, coding, and channel conditions, providing a robust framework for evaluating and optimizing wireless communication systems. By exporting results and visualizing key metrics, the algorithm serves as a comprehensive tool for both theoretical research and practical system design.

5. RESULTS AND DISCUSSION

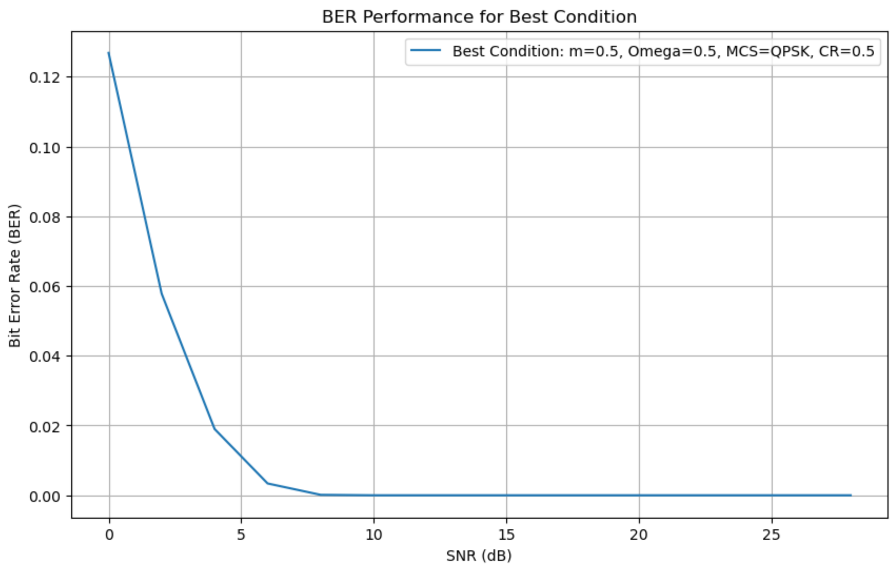

Figure 2: BER Performance for Best condition

The graph in figure 2, illustrates the Bit Error Rate (BER) performance for a wireless communication system operating under a Nakagami fading channel with optimal parameters. The x-axis represents the Signal-to-Noise Ratio (SNR) in decibels (dB), while the y-axis shows the BER on a linear scale. The best condition for minimizing BER is achieved with a shape parameter m=0.5, scale parameter Ω=0.5, modulation scheme as QPSK, and a coding rate (CR) of 0.5. The performance trend reveals that at low SNR values (0–5 dB), the BER is high due to noise dominance. However, as the SNR increases, the BER

Journal of Information Systems Engineering and Management
2025, 10(3)
e-ISSN: 2468-4376
https://www.jisem-journal.com/ **Research Article**

reduces exponentially, approaching near-zero at around 10–15 dB, signifying reliable communication. This result highlights the effectiveness of QPSK with a low coding rate in handling environments with significant fading, ensuring robust performance despite noise. The graph emphasizes the importance of adapting modulation and coding parameters to achieve reliable communication in varying channel conditions.

The graph in the figure 3 showcases the Adaptive Modulation and Coding (AMC) performance in a 5G n78 band under Nakagami fading, highlighting the throughput as a function of Signal-to-Noise Ratio (SNR) for various Modulation and Coding Schemes (MCS) and coding rates (CR). The x-axis represents the SNR in dB, while the y-axis indicates the throughput in bits per second (bps). Higher-order modulations like 256QAM exhibit the highest throughput, particularly at higher SNRs, but require robust channel conditions. Lower-order modulations, such as QPSK, demonstrate lower throughput but maintain stability even in lower SNR regions, making them suitable for challenging channel conditions. The coding rate also significantly influences performance; higher coding rates (e.g., CR=0.9) yield better throughput but are more sensitive to noise.

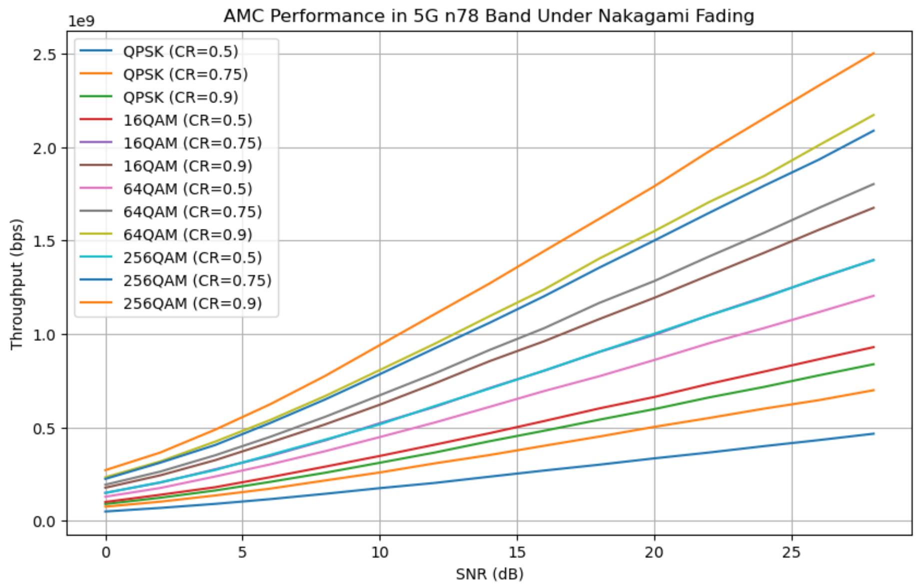

Figure 3: AMC Performance in 5G N78 band under Nakagami fading channel

Conversely, lower coding rates (e.g., CR=0.5) provide improved error resilience, especially under poor SNR conditions. The graph underscores the importance of adaptive MCS selection in optimizing communication performance, balancing between reliability and spectral efficiency based on channel quality. This demonstrates how 5G systems leverage AMC to maximize throughput and maintain robust connectivity under diverse fading conditions.

The BER results saved in the CSV file offer a comprehensive dataset for analyzing performance trends across varying mm, Ω\Omega, modulation schemes, and coding rates. By systematically examining these results, network operators can identify optimal configurations for specific deployment scenarios. The best condition identified in this study (m=0.5m=0.5, Ω=0.5\Omega=0.5, QPSK, coding rate 0.5) is particularly suited for scenarios with severe fading, such as urban centers with dense obstructions or emergency communication systems operating in challenging terrains.

Journal of Information Systems Engineering and Management
2025, 10(3)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

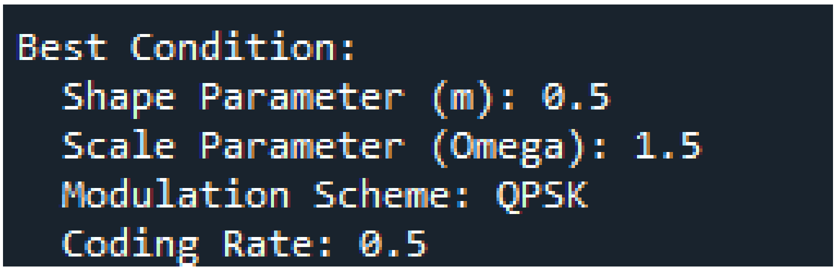

Figure 4: Console window showing the best conditions

The best condition obtained from the simulation indicates that for a shape parameter (m) of 0.5 and a scale parameter (Ω) of 1.5 in the Nakagami fading channel, the QPSK modulation scheme provided the optimal performance which is shown in the figure 4. QPSK's robustness against noise and fading makes it suitable for challenging channel conditions, ensuring reliable communication. This configuration effectively balances error resilience and performance, demonstrating its suitability for scenarios where channel conditions are significantly impacted by severe fading, as modeled by low shape and high scale parameters.

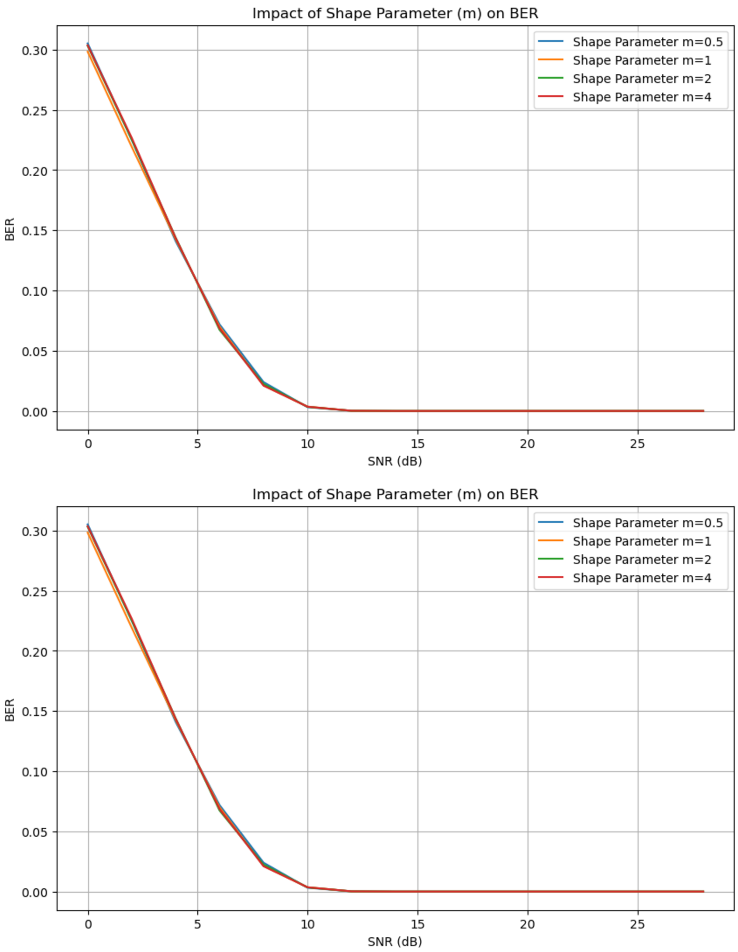

Figure 5. Impact shape parameter on BER

The graph shows the impact of the Nakagami shape parameter (m) as shown in figure 5, on the bit error rate (BER) versus signal-to-noise ratio (SNR). As mm increases (indicating less severe fading), the BER decreases faster with increasing SNR. This demonstrates that higher shape parameters correspond to

Journal of Information Systems Engineering and Management
2025, 10(3)
e-ISSN: 2468-4376
https://www.jisem-journal.com/ **Research Article**

better channel conditions, as the fading becomes less severe, resulting in improved system reliability and reduced BER at all SNR levels.

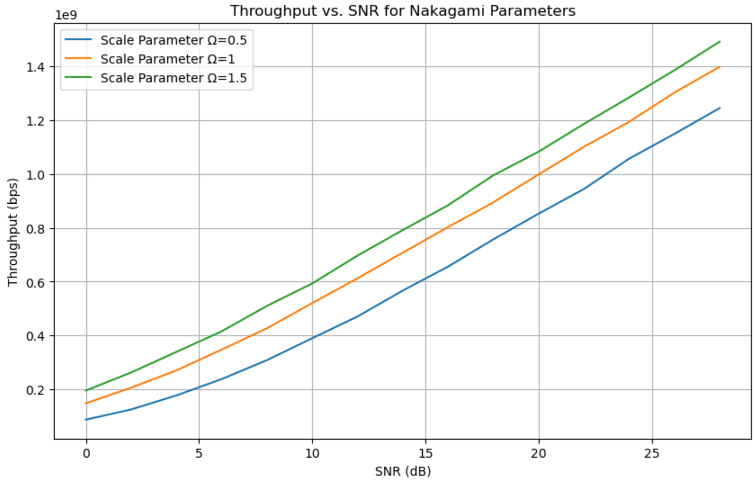

Figure 6: Throughput vs SNR for Nakagami parameters

The graph illustrates the relationship between throughput and signal-to-noise ratio (SNR) for different Nakagami scale parameters (Ω) (as in Figure 6). Higher scale parameters (Ω=1.5) lead to increased throughput at all SNR levels due to improved channel conditions and reduced fading effects. The throughput consistently rises with increasing SNR, reflecting better signal quality and spectral efficiency.

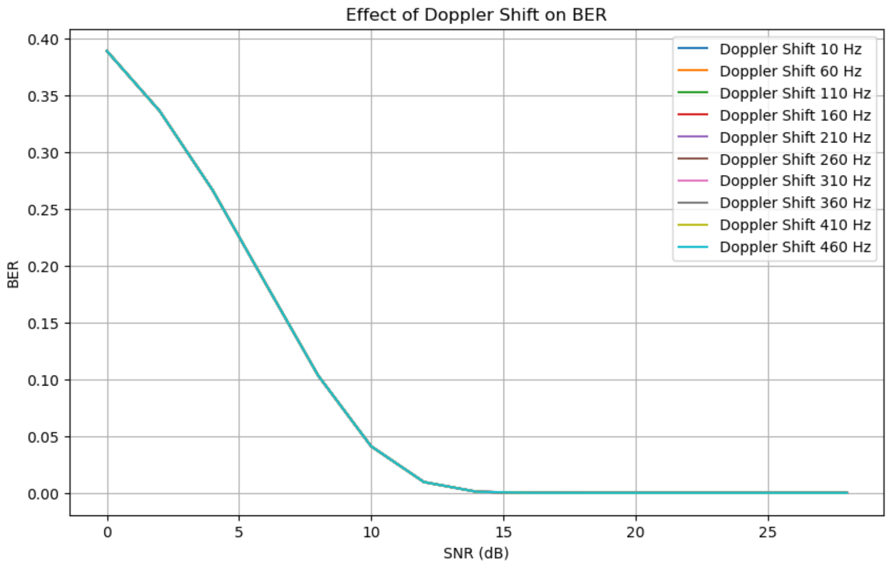

Figure 7: Effect of Doppler shift on BER

The graph (as shown in Figure 7) depicts the effect of Doppler shift on bit error rate (BER) as a function of signal-to-noise ratio (SNR). At lower SNR values, BER is high for all Doppler shift frequencies, indicating reduced reliability As SNR increases, BER decreases significantly for all Doppler shifts. The graph demonstrates that higher Doppler frequencies (representing higher user mobility) have minimal impact on BER at higher SNR levels.

The ability to maintain low BER under such conditions ensures reliable data transmission, a critical requirement for applications like autonomous vehicles, remote monitoring, and disaster recovery operations. In contrast, configurations involving higher-order modulation schemes and coding rates are more suitable for suburban or rural areas, where channel conditions are relatively stable, and the focus is on maximizing throughput.

6. CONCLUSION

The study delves into the integration of Adaptive Modulation and Coding (AMC) with Nakagami fading models, aiming to optimize 5G network performance under varying channel conditions. By systematically evaluating the interplay of shape and scale parameters, modulation schemes, and coding rates, this research provides a nuanced understanding of their collective impact on Bit Error Rate (BER) and throughput.

Key findings reveal that QPSK modulation, combined with a coding rate of 0.5 under severe fading conditions ($m = 0.5$, $\Omega = 0.5$), consistently ensures low BER and reliable communication. The study underscores the significance of dynamically adjusting AMC parameters to maintain robust performance across diverse environments, from urban areas with high multipath effects to vehicular communication systems prone to Doppler shifts. The research's methodology integrates real-world impairments like shadowing and Doppler effects into the Nakagami fading model, enhancing its relevance to practical scenarios. Simulation results indicate that while higher-order modulations such as 256QAM maximize throughput in favorable conditions, their susceptibility to noise makes them less reliable under severe fading. Conversely, lower-order modulations like QPSK strike a balance between reliability and spectral efficiency, making them ideal for challenging channel environments. This comprehensive analysis bridges the gap between theoretical modeling and practical application, offering a robust framework for deploying AMC in 5G networks. It highlights the trade-offs between error resilience and throughput, providing actionable insights for network operators. Moreover, the findings emphasize the adaptability of 5G systems in optimizing resource allocation and maintaining connectivity, even in adverse channel conditions. Applications include urban cellular networks, vehicular communication systems, smart grids, industrial automation, and remote healthcare systems requiring robust data transmission. Higher Nakagami shape parameters significantly enhance system performance by reducing BER in fading environments. Higher Nakagami scale parameters (Ω) significantly enhance throughput by mitigating the effects of fading, resulting in better system performance. Higher SNR levels mitigate the impact of Doppler shifts, ensuring reliable communication even under high mobility conditions.

In conclusion, the study contributes to the ongoing evolution of 5G communication technologies, paving the way for future advancements in network design and deployment. By addressing real-world challenges and exploring diverse channel scenarios, it establishes a solid foundation for enhancing 5G reliability and performance. Future work could integrate machine learning algorithms for real-time AMC optimization, leveraging predictive analytics to adapt modulation and coding schemes dynamically. Additionally, extending the study to include higher-frequency bands, like millimeter-wave, and multi-user scenarios will enhance the understanding of AMC performance in next-generation wireless systems.

ACKNOWLEDGMENT:

The authors would like to acknowledge R L Jalappa Institute of Technology for providing the necessary infrastructure, support, and resources to carry out this research work successfully.

CONFLICT OF INTEREST:

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. The research was conducted independently, and no financial or personal relationships influenced the results or interpretations presented in this work.

COMPETING INTERESTS

The authors declare that there are no competing financial or non-financial interests that could have influenced the work reported in this manuscript.

FUNDING INFORMATION

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors and was conducted using the authors' own resources.

AUTHOR CONTRIBUTION

All authors contributed equally to the conception, methodology, analysis, and writing of the manuscript. All authors reviewed and approved the final version of the paper prior to submission.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request. No publicly archived datasets were used or generated during the current study.

RESEARCH INVOLVING HUMAN AND /OR ANIMALS

Not Applicable. (This research did not involve any experiments on human participants or animals. Ethical approval was therefore not required for this study.)

INFORMED CONSENT

Not applicable. (No human participants were involved in the study, and therefore no informed consent was required or obtained.)

REFERENCE

[1]. Y.-C. Liang, K.-C. Chen, G. Y. Li, and P. Mahonen, “Cognitive radio net- working and communications: An overview,” IEEE Trans. Veh. Technol., vol. 60, no. 7, pp. 3386–3407, Sep. 2018.

[2]. F. Hu, B. Chen, and K. Zhu, “Full spectrum sharing in cognitive radio networks toward 5G: A survey,” IEEE Access, vol. 6, pp. 15754–15776, Apr. 2018.

[3]. S. Sasipriya and R. Vigneshram, “An overview of cognitive radio in 5G wireless communications,” in Proc. IEEE Int. Conf. Comput. Intell. Comput. Res., Dec. 2016, pp. 1–5.

[4]. X. Foukas, G. Patounas, A. Elmokashfi, and M. K. Marina, “Network slicing in 5G: Survey and challenges,” IEEE Commun. Mag., vol. 55, no. 5, pp. 94–100, May 2017.

[5]. G. Gui, H. Huang, Y. Song, and H. Sari, “An effective NOMA scheme based on deep learning,” IEEE Trans. Veh. Technol., vol. 67, no. 9, pp. 8440–8450, Sep. 2018.

[6]. Y. Li, X. Cheng, and G. Gui, “Co-robust-ADMM-net: Joint ADMM framework and DNN for robust sparse composite regularization,” IEEE Access, vol. 6, pp. 47943–47952, 2015.

[7]. D. Middleton, “Man-made noise in urban environments and transporta- tion systems: Models and measurements,” IEEE Trans. Veh. Technol., vol. VT-21, no. 11, pp. 1232–1241, Nov. 2023.

[8]. T. M. Taher, M. J. Misurac, J. L. LoCicero, and D. R. Ucci, “Microwave oven signal interference mitigation for Wi-Fi communication systems,” in Proc. 5th IEEE Consum. Commun. Netw. Conf. (CCNC), Jan. 2008, pp. 67–68.

[9]. N. Lu and B. Eisenstein, “Detection of weak signals in non-Gaussian noise,” IEEE Trans. Commun., vol. COM-27, no. 6, pp. 755–771, Nov. 2016.

[10]. L. Izzo, L. Paura, and M. Tanda, “Signal interception in non-Gaussian noise,” IEEE Trans. Commun., vol. 40, no. 6, pp. 1030–1037, Jun. 2017.

[11]. A. M. Magableh, T. Aldalgamouni, O. Badarneh, S. Mumtaz and S. Muhaidat, "Performance of Non-Orthogonal Multiple Access (NOMA) Systems Over N-Nakagami-m Multipath Fading Channels for 5G and Beyond," in IEEE Transactions on Vehicular Technology, vol. 71, no. 11, pp. 11615-11623, Nov. 2022, doi: 10.1109/TVT.2022.3189589.

[12]. A. Boumaalif and O. Zytoune, "Power Distribution of Device-to-Device Communications Under Nakagami Fading Channel," in IEEE Transactions on Mobile Computing, vol. 21, no. 6, pp. 2158-2167, 1 June 2022, doi: 10.1109/TMC.2020.3035543.

[13]. J. Men, J. Ge and C. Zhang, "Performance Analysis for Downlink Relaying Aided Non-Orthogonal Multiple Access Networks With Imperfect CSI Over Nakagami- ${m}$ Fading," in IEEE Access, vol. 5, pp. 998-1004, 2017, doi: 10.1109/ACCESS.2016.2631482.

[14]. A. Ahmed, P. Botsinis, S. Won, L. -L. Yang and L. Hanzo, "EXIT Chart Aided Convergence Analysis of Recursive Soft m-Sequence Initial Acquisition in Nakagami-m Fading Channels," in IEEE Transactions on Vehicular Technology, vol. 67, no. 5, pp. 4655-4660, May 2018, doi: 10.1109/TVT.2018.2789912.

[15]. A. Kumar, S. Majhi and H. -C. Wu, "Physical-Layer Security of Underlay MIMO-D2D Communications by Null Steering Method Over Nakagami-m and Norton Fading Channels," in IEEE Transactions on Wireless Communications, vol. 21, no. 11, pp. 9700-9711, Nov. 2022, doi: 10.1109/TWC.2022.3178758.

[16]. C. Yin, G. Giunta, D. Orlando, C. Hao and C. Hou, "A Channel Classification Scheme Accounting for Nakagami-m Shadowing and FTR Model," in IEEE Wireless Communications Letters, vol. 10, no. 10, pp. 2289-2293, Oct. 2021, doi: 10.1109/LWC.2021.3099907.

[17]. S. A. Kassam and J. B. Thomas, Signal Detection in Non-Gaussian Noise. New York, NY, USA: Springer-Verlag, 2018.

[18]. F. F. Digham, M.-S. Alouini, and M. K. Simon, “On the energy detection of unknown signals over fading channels,” IEEE Trans. Commun., vol. 55, no. 1, pp. 21–24, Jan. 2017.

[19]. J. Ma, G. Y. Li, and B. H. Juang, “Signal processing in cognitive radio networks,” Proc. IEEE., vol. 97, no. 5, pp. 805–823, May 2017.

[20]. X. Zhu, P. Jiang, and Y. P. Bao, “Spectrum sensing based on fractional lower order moments for cognitive radio under impulsive noise,” in Proc. 4th Electron., Commun. Netw. CNET, Nov. 2014, pp. 1807–1812.

[21]. J. Proakis, Digital Communications. New York, NY, USA: McGraw-Hill, 2000.

[22]. M. Nardon and P. Pianca, “Simulation techniques for generalized Gaussian densities,” J. Stat. Comput. Simul., vol. 79, no. 11, pp. 1317–1329, Nov. 2019.