SSRG International Journal of Computer Science and Engineering
ISSN: 2348–8387 / https://doi.org/10.14445/23488387/IJCSE-V12I13P104

Volume 12 Issue 3, 23-32, March 2025

Original Article

OMA to NOMA-mmWave: A Paradigm Shift for Enhanced 5G Throughput – Trade-offs and Future Directions

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Received: 14 January 2025 Revised: 28 February 2025 Accepted: 17 March 2025 Published: 30 March 2025

Abstract *- Today, the demand for wireless communication has increased exponentially, and multiple access technologies are constantly evolving to provide high throughput, spectral efficiency, and maximum resource utilization in 5G networks. Recently, Non-Orthogonal Multiple Access (NOMA) appeared as an important technique to increase utilization of the spectrum, allowing different users to transmit simultaneously over the same time and frequency resources. This paper presents a comprehensive analysis of NOMA based system with access technologies and diversity techniques to improve the performance of a 5G network system. The paper further emphasises machine learning models, including polynomial regression and XGBoost, which can further enhance spectral efficiency while keeping better outage probability among users. Finally, the evolution of access technologies in terms of the transition from orthogonal multiple access (OMA) to NOMA features is investigated to enhance resource allocation. Further, the proposed methodology discusses the hybrid concept of NOMA with mmWave frequency, and experimental results on increasing throughput and reducing the latency are presented. Future research directions of the paper show the comparison study of outage probability using regression and XGBoost. This paper discusses the superpower NOMA mmWave that becomes the foundation for the next Generation 6G wireless networks in terahertz (THz) and provides useful information in the optimization of heterogeneous networks.*

Keywords *- OMA, NOMA, 5G Networks, Spectral Efficiency, Resource Allocation.*

1. Introduction

Fast changes in wireless communication technologies have made it possible to transmit and process data globally at the point of transmission. Following the basic idea of 1G communication, 2G and 3G added measurable enhancements to the speed and coverage of data. 4G was later the main stem of today's broadband communication, with high data rates and better spectral efficiency. However, the capabilities of these earlier generations cannot handle the demands of today's world, which is hyper-connected devices. The spotlight of the 5th Generation (5G) system has now moved away from the conventional speed and capacity but has been propelled towards the extremely fast growth of the number of connected devices and data-intensive applications, leading to a fundamental shift in network architecture. Within this broader context, Non-Orthogonal Multiple Access (NOMA) is an essential aspect that presents huge spectrum efficiency improvements and creates an environment for ultra-high throughput for 5G networks and beyond

One major reason for wireless technology is the evolving nature of applications and users. Emerging use cases cover cloud computing and online gaming, telemedicine, autonomous vehicles and immersive realities, and from them, they require extremely low latency, high speed transmission and robust reliability [3]. Due to such different demands, the International Mobile Telecommunications (IMT) 2020 specifications came up with three kinds of services broadly known as the categories (eMBB)-Enhanced-Mobile-Broadband, (URLLC) Ultra-Reliable Low Latency Communication, (mMTC) massive Machine Type Communication. The required network capabilities in each category signify each category as a major shift from a different era. For instance, eMBB is for peak data rates for applications such as augmented (AR) and Virtual Reality (VR), URLLC is aimed at mission-critical services, such as industrial automation and remote surgeries that do not accept any delays, and mMTC is for connecting of billions of IoT sensors globally [4].

However, several access improvements must appear for network slicing to succeed. Because they are preventing interference, traditional OMA strategies like Frequency Division, Time Division, Code Division, Orthogonal Frequency (FDMA), (TDMA), (CDMA) (OFDMA), and multiple access, respectively, allocate distinct radio resources for each user. This orthogonality is quite simple and robust but suffers from inherent inefficiencies in cases of networked devices that grow in magnitude in terms of the volume of data traffic and the number of connected devices. Also, OMA suffers from further unaddressed gaps: Inadequate spectral efficiency, unscaling of throughput, limited connectivity with devices, and low energy efficiency. However, to the contrary, NOMA synchronously assigns the user signals in the power or code domain and separates them at the receiver undergoing Successive Interference Cancellation. The overlapping enables resource reuse, which greatly increases spectral efficiency [5]. Overall, NOMA is more beneficial in the wider scope of 5G. It then allows the network to support a much more numerous user population on the same time-frequency resources than in OMA. As user signals are separated at the receiver based on their power levels or coding schemes, NOMA is flexible as to user conditions, ranging from being vastly different. In the case of typical cells, the received power users closer to the base station are higher, and cell edge users have worse conditions. By assigning different power levels to user users and permitting them to transmit simultaneously, NOMA takes advantage of variations in user channel states to increase the overall throughput [6]. As a result, this approach meets one of the fundamental objectives of 5G, i.e., maximizing resource utilization without disregarding edge or disadvantaged users.

In response to these challenges, a large body of efforts in interference cancellation to reach the goals include methods and signal processing algorithms. For example, in systems using NOMA, user pairing or clustering becomes indispensable for power allocation among up to multiple users occupying common time-frequency resources [3]. However, wisely pairing centre and edge users individually can boost cell edge performance by an order of magnitude while increasing fairness and throughput. The detection of successive interference cancellation is also being further developed as new detectors to solve real-world problems like channel estimation error and hardware impairment. At the same time, advanced interference management strategies become more critical due to densification practices, i.e., small cell deployments or mmWave frequency utilizations. As for mmWave bands (e.g., around 26~28 GHz or even more than 60 GHz), although they provide tremendous bandwidth, they are extremely prone to high path loss and atmospheric absorption [7]. However, for such mmWave systems, employing NOMA can help retain capacity lost due to these absorptions, but beamforming and interference mitigation are crucial.

The continuous battle to sixth generation (6G) networks is going beyond 5G as data rates are extendable beyond the terabit per second range, and communications happen almost in an instant [17]. Research efforts in exploring sub-terahertz and terahertz frequency bands, i.e., from around 100 Giga Hertz to 10 terahertz [8], are ongoing. These high-frequency bands offer wonderful provision of massive bandwidths for unprecedented data speed but also large propagation and penetration loss. As cost-effective, energy-efficient solutions for THz communications, scholars are looking to THz communications [10] to render advanced beam forming and Reconfigurable Intelligent Surfaces (RISs). NOMA continues to be a leading contender in the 6G sphere for multiple access. However, as far as ultra-high frequencies with massive device connectivity, NOMA's capacity to provide resource overlapping for users in time and frequency becomes even more attractive.

Additionally, research on the synergy between NOMA and the new network architecture paradigms, such as Mobile Edge Computing (MEC), is considered a very interesting domain of enquiry. The proximity to end-users and, therefore, reduced latency is what MEC brings when it pushes computational and storage resources closer. By merging MEC and NOMA, the computing process could be distributed so that operators can efficiently accomplish the fastest processing and maximum throughput. This is an extremely viable strategy for the real-time needs of extended reality (XR), autonomous systems and Industry 4.0 applications that require fast and high data exchange with immediacy. However, designing effective resource allocation protocols that will be able to overcome the issues of overlapping transmissions and distributed computing is not a simple task.

Furthermore, from an energy efficiency point of view, whether NOMA can always be better than the OMA base system depends on parameters like the number of users served simultaneously, their channel condition and the sophistication of power control algorithms. As the latter works well, NOMA is highly promising. At the same time, standardization of a unified NOMA satellite standard might need further refinement in standardization bodies and collaborative research among academia and industry.

Now that 6G is likely to support the futuristic uses that include holographic communication and multi-sense experiences, the principle of overlapping user transmissions will be commonplace and not an exception as it will be coupled with the elements of dynamic spectrum usage and cognitive radios. However, recent studies have proposed exploiting the adaptability of the propagation environment itself via RIS to complement the inherent high attenuation in sub-THz and THz channels [9]. Controlling reflections and transmissions at a granular level can further improve system performance for these environments at sufficiently fine scales, especially when linked to advanced multiple access strategies that determine how signals are added and decoded in a system.

The efforts on NOMA-based solutions are still standardized in their direction shaping. Initial 5G releases (e.g., 3GPP Release 15 and after) introduce the orthogonal OFDMA. However, later releases (e.g., 3GPP Release 16) started to investigate non-orthogonal schemes in more detail [1]. The leading line of future enhancement for the NOMA technology involves convergence with existing industry standards to maintain interoperability and backward compatibility of existing infrastructure. Such alignment is critical to encourage the commercial adoption of 5G, especially for regions of the world whose 5G rollout continues in the early stages.

To sum up, the leap from the old cellular network generations to 5G was utterly revolutionary in terms of speed, capacity, and architectural thinking. NOMA is part of such an ecosystem. To feature widespread bandwidth, mmWave is hybrid to NOMA to increase data rates. Forward into 6G networks with even more aggressive performance targets, such as Tbps data rates and full coverage,[11] much more ambitious performance targets are introduced on the road ahead. Future wireless networks have great potential to create a paradigm shift once more by utilizing the THz spectrum with new tools like RIS. However, the underlying logic behind the resource allocation that overlaps with NOMA seems immune to change. It will continue to be a principal enabler to facilitate the support of next-generation systems, which can offer high-density connectivity and demanding QoS.

This paper has been arranged as follows to get the flow and understanding of the topic. Section 2 discusses the work done on NOMA technology. Section 3 highlights the methodology used for evaluating and predicting using Machine Learning (ML) algorithms, section 4 depicts a mathematical model, and section 5 imparts the related results followed by future work.

2. Related Work

Nonetheless, numerous studies have explored the benefits of NOMA techniques to 5G networks in increasing spectral efficiency, throughput, and resource allocation. With the growing need for high throughput applications, power allocation, interference management, and multiple access strategies are being optimized for most of the NOMA capabilities that enable it.

A notable research issue of power allocation optimization in such systems based on NOMA exists. Youssef et al. [14] provide an iterative water-filling-based power allocation strategy considering the user's channel gains with achievable throughput gains at the cell edge user. Nevertheless, the two approaches have difficulty in real-time and computational complexity in dynamic 5G networks. Several studies have established that NOMA can further increase throughput and energy efficiency with respect to advanced network architectures. Through the Lagrangian Duality and Dynamic Programming (LDDP) framework, Author Lei [15] developed a resource allocation strategy based on OMA and bearing near-optimal solutions at the price of better spectral efficiency. This research has been extended to Multi-Carrier NOMA (MC NOMA) systems, and the resource allocation by monotony optimization substantially improves the weighted system throughput.

Furthermore, research on diversity in NOMA-based 5G systems has also been considered for mitigation of fading effects and reliability enhancement. Recently, relay-aided NOMA was studied by Tregancini [16], and it has been shown how the spectral efficiency using the outage performance of NOMA can be improved by having spatial diversity. Kumar and Mishra [17] also studied frequency diversity mechanisms and demonstrated the QoS of users under dynamic network conditions.

Recently, Reconfigurable Intelligent Surfaces (RIS) have been investigated to enhance NOMA; however, their real role is mostly in the energy efficient communication and interference suppression rather than directly contributing to high throughput NOMA applications. For instance, Hou et al. [5] studied a SISO system utilizing RIS to assist NOMA in optimizing RIS phase configurations for increasing the ergodic rate and energy efficiency. Moreover, Zheng, Wu, and Zhang [19] further showed that NOMA under RIS asymptotically achieves the target user rates with a substantially lower power than RIS-assisted OMA. However, while these studies primarily care about power conservation rather than throughput maximization, RIS correlates more with NOMA's efficiency than as a direct enabler of high throughput applications. Overall, the literature emphasizes that NOMA should serve as a primary enabler for 5G high throughput networks, which can be achieved by synergistic deployment of NOMA, power allocation, diversity techniques, and resource management frameworks. Future work should exploit hybrid NOMA models for multi-cell and heterogeneous network environments based on investigating trade-offs between inter-carrier interference cancellation complexity and spectral efficiency.

2.1. NOMA System Optimized through Power Allocation

Power Allocation (PA) in NOMA systems is primarily responsible for verifying the performance of network throughput, spectral efficiency, and user fairness. Statistical dynamics Channel State Information (CSI), power distribution across sub-bands, number of configurations with multiplexed users and its antenna are a number of key factors that affect the ability to adopt PA strategies. In order to address these challenges, researchers have proposed different PA schemes to enhance system capacity with reduced computational complexity.

Single-user distance to the BS is considered a fundamental metric in the context of user pairing; hence, a prominent approach is to use the joint detection scheme. This scheme uses distance-based clustering to improve spectral efficiency by assigning resources optimistically. Youssef et al. [14] first introduced an iterative water-filling base PA, where the channel gains are prioritised in the key channel allocation.

This approach greatly reduces throughput at the cell edge while degrading roughly the same amount of throughput for users closer to the BS. Moreover, the strategy put forth by the author in terms of Proportional Fairness (PF) uses SVD to rank users according to their channel conditions and guarantees balanced resource allocation. However, this method increases system complexity due to additional computational steps in multiuser Multiple Input Multiple Output (MIMO) environments.

2.2. Evolution and Optimization of Access Technologies for High-Throughput 5G Networks

Wireless communication networks have become an important constituent of access technology. The growth of users exponentially, calls, capacity, quality of service, and resource use, and hence the need of the hour is efficient utilization of limited Radio Access Network (RAN) resources such as spectrum, bandwidth, energy efficiency, power allocation, and resource blocks. The fifth generation of mobile network access technologies, from 1G to 5G, has evolved enormously.

Frequency Division Multiple Access (FDMA) was used in the 1G era, and circuit switching was employed to establish the calls. With the advent of the 2G network, spectral efficiency was increased using the TMA-time division multiple access and CDMA-code division multiple access techniques combined with channel coding mechanisms. Thereafter, 3G networks improved access technologies by adopting CDMA, among whose related standards were wideband Code Division Multiple Access (WCDMA) and Code Division Multiple Access 2000. In 4G RAN, OFDMA, scalable OFDMA (SOFDMA), and MIMO transmission protocols were used in the future.

At the same time, 5G networks have brought in NOMA as a key enabler for increased connectivity and gaining spectral efficiency. This study discusses the access technologies only on OMA and NOMA. To integrate the network services in real-world deployments, 5G plans to use network slicing, a technique that divides a physical infrastructure between many isolated ends-to-end network partitions referred to as slices. This allows networks to serve specific application requirements. As for physical layer spectrum slicing, the same principle is applied to guarantee that users with diverse requirements are provided with enough resources. Spectrum slicing on the RAN side is necessary to simultaneously provide differentiated services with spectral and energy efficiency.

2.3. Frequency Diversity and Throughput Optimization in NOMA-Based 5G Networks

An important factor in boosting communication capability and performance in NOMA-based 5G systems is frequency diversity, specifically for URLLC, which has become one of the major contenders for 5G. Frequency diversity transmits the same signal on several frequency bands, which helps minimize the strong fading effects and enhance the reliability of services [9]. Particularly in NOMA-based multi-antenna systems, frequency selective fading can cause throughput performance to suffer.

Regarding resource allocation strategies for hybrid eMBB-URLLC services, frequency diversity was advantageous for NOMA-enabled multi-antenna networks. In the uplink NOMA networks, Liu et al. [21] investigated network slicing that employs Rate Split Multiple Access (RSMA) and Successive Interference Cancelation (SIC) to serve high-density user deployments, which enhance the throughput. We find that NOMA and RSMA combined with frequency diversity outperform ordinary OMA schemes significantly.

Researching NOMA networks' power allocation further on spectral efficiency, one such point of attention is multiuser diversity. Khan et al. [4] proposed an adaptive power allocation framework to dynamically allocate resources among multiple frequency bands, such that the throughput of users with cell edge and central users remains fair in the sense of channel inequity. In Nakagami-m fading environments, Gong et al. [23] studied cooperative performance enhancement, demonstrating that frequency diversity enhances transmission reliability with the constraint imposed by fading.

In Santos et al. [24], max matching diversity principles were used for network slicing optimization of the fifth generation's URLLC and eMBB systems of NOMA. According to their findings, these strategies can improve both network security and spectral efficiency. At the same time, we studied SCA-aware heterogeneous resource allocation for throughput gains in dynamic multi-cell NOMA environments. The author in [26] discusses machine-to-machine with NOMA for higher SNR values. Author Kue Tang in [27] highlights the coverage performance compared to OMA by pairing concept. Author Shaik Rajak has surveyed OMA and NOMA and discussed the way interference is affected by frequencies.

3. Motivation and Contribution

These theoretical studies made is having less empirical validation on the metrices of NOMA. Not much was explored in the relationship between the metrices such as bandwidth, SNR, and efficiency, which are crucial for resource allocation optimization for the researchers involved. The proposed methodology focuses on the metrices of NOMA in the mmWave method to show the novelty that contrasts with prior studies. So, this paper presents a few practical insights and predictions needed to understand the metrics behind the performance of network conditions using NOMA mmWave. The results validate the throughput with data rate improvements at the frequency of mmWave. Further, the findings place suitable groundwork for motivating researchers toward 6G in enhancing resource allocation.

4. Materials and Methods

4.1. Problem Definition

Predicting outage probabilities of users, far and near, in a 5G NOMA-mmWave system under dynamic real-time conditions. The performance is evaluated by two regression models, Polynomial Regression and XGBoost, for their suitability in real-time applications.

4.2. Dataset Generation

Generate a synthetic dataset using Python to simulate a 5G NOMA mmWave system with two users (far and near users). The parameters considered are:

- Distance to Base Station (d1, d2)
- Path Loss Exponent (η)
- Transmit Power (Pt) in the range of 0-40 dBm, converted to Watts
- Rayleigh Fading Channels (h1, h2) for modeling multipath fading
- Noise Power (n0) based on system bandwidth (BW)

The dataset consists of 10,000 samples with features:

- Transmit Power (Pt)
- Outage Probability for User 1 (far user) (P1)
- Outage Probability for User 2 (near user) (P2)

4.3. Mathematical Modeling

The mathematical models used are:

- Path Loss: PL = d^(-η)
- SINR for far users:
  γ1 = (a1 * Pt * g1) / (a2 * Pt * g1 + n0)
- SINR for near user:
  γ2 = (a2 * Pt * g2) / n0
- Rate Calculation:
  R1 = log2(1 + γ1),
  R2 = log2(1 + γ2)
- Outage Probabilities:
  $P1 = Pr (R1 < R_{threshold})$,
  $P2 = Pr (R2 < R_{threshold})$

4.4. Models for Prediction

Two regression models are used:

4.4.1. Polynomial Regression

- Perform polynomial regression to fit the relationship between Pt and P1, P2
- Experiment with different polynomial degrees

4.4.2. XGBoost

- Train an XGBoost model using the same input output pairs
- Utilize hyperparameter tuning (e.g., learning rate, max depth, number of estimators)

4.5. Evaluation Metrics

Mean Squared Error (MSE) is used to evaluate model performance

$$MSE = (1/n) * \Sigma (y_{true} - y_{\_pred})^2 \tag{1}$$

4.6. Implementation

- Data Preparation
- Apply Polynomial Regression
- Apply XGBoost
- Compare both models

4.7. Visualization

- Plot the actual vs predicted outage probabilities for both users
- Polynomial regression (true vs predicted values).
- XGBoost (true vs predicted values).
- Plot for MSE comparison across models.
- Plot relationship between transmit power (Pt) and outage probabilities (P1, P2).

5. Equations

A 5G NOMA-mmWave system is designed, incorporating realistic channel conditions such as Rayleigh fading, path loss, and noise power. The system model is described by the following:

5.1. Rayleigh Fading Channel Model

Each user experiences a fading channel represented by the complex channel gain h, where the magnitude |h| follows a Rayleigh distribution.

The channel gain for the h1 and h2 are given by:

$$h1 = \sqrt{d_1^{-n}} \cdot \frac{1}{\sqrt{2}}(X_1 + jX_2) \tag{1}$$

$$h2 = \sqrt{d_2^{-n}} \cdot \frac{1}{\sqrt{2}}(Y_1 + jY_2) \tag{2}$$

Where,

d1 and d2: Distances of the far and near users
η: path loss exponent
X1, X2, Y1, Y2 : Random Gaussian independent variables

5.2. Path Loss Model

$$L = \frac{d^n}{d_0^n} \tag{3}$$

Where,

L = Path Loss (dB)
d = Distance between Base Station and User (m)
η = Path Loss Exponent

Users are categorized into near-far groups based on their distances starting from the base station, where d1>d2. Power allocation between users is performed using the power domain separation approach, where the far user is allocated a1 fraction of the net power with the near user a2=1−a1

5.3. SINR and Outage Probability Calculation

5.3.1. The Signal Interference plus Noise Ratio (SINR) for each user is given by the expression

$$\gamma 1 = \frac{a_1 P_t |h_1|^2}{a_2 P_t |h_2|^2 + N_0} \quad (4)$$

$$\gamma 2 = \frac{a_2 P_t |h_2|^2}{N_0} \quad (5)$$

Where,
Pt : transmit power
|h1| and |h2| : squared magnitudes of the channel gains for the far and near users
N0: noise power.

5.3.2. Outage Probability

$$P_{\text{out}} = \mathbb{P}(\gamma < \gamma_{\text{th}}) \quad (6)$$

Where,
γ is the SINR value, and P1 and P2 are the outage probability for far and near users.

$$P_1 = \mathbb{P}(\gamma_1 < \gamma_{\text{th},1}) \quad (7)$$

$$P_2 = \mathbb{P}(\gamma_2 < \gamma_{\text{th},2}) \cup \mathbb{P}(\gamma_{12} < \gamma_{\text{th},1}) \quad (8)$$

6. Results and Discussion

The overall performance of the NOMA-mmWave system is done for various scenarios according to the sum rate, data rate, Bit Error Rate (BER), and outage probability. They are assessed in terms of transmitter power, signal noise ratio (SNR), bandwidth, and number of users, which are essential for the effectiveness and dependability of NOMA systems. The relationships provided by the graphs depict the system's performance in terms of coping with multiple users while preserving a reasonable performance level.

Examining the sum rate behaviour observed as the number of users increases, as depicted in Figure 1, confirms the supportability of additional users within the system. This graph shows how scalable NOMA is under mmWave conditions where user population and transmission power are essential for performance optimization. At Pt=15dBm, the sum rate increases from 17.45 bps/Hz (2 users) to 22.33 bps/Hz (20 users), Pt=20 dBm, Pt = 20dBm rises from 19.06 bps/Hz (2 users) to 24.06 bps/Hz (20 users), reflecting moderate improvement. The system efficiency is maximized at high power where (Pt = 35 dBm) and the system peaks at (24.12) bps/Hz with two users and (29.14) bps/Hz with 20 users. So, choosing an appropriate Pt is a trade-off between power consumption and achieving a desirable sum rate, especially as the number of users scales up.

In Figure 2, a 3D plot evaluates the relationship between data rate, SNR, and bandwidth, showcasing how system performance adapts to varying resource constraints. At a constant SNR, the data rate increases linearly with bandwidth. Higher bandwidth values of $4{\times}10^8$ Hz correspond to significantly higher data rates, reaching up to 10^{10} bits/sec. At a constant bandwidth, it is seen that data rate increases logarithmically with SNR. Even with high bandwidth, the data rate remains limited for lower SNR values of 10 dB. However, at higher SNR values of 30 dB, the data rate approaches its theoretical maximum. Maintaining a high SNR is critical for maximizing performance in real-world deployments. The maximum data rate achieved is shown on the upper surface of the plot.

In Figure 3. The graph highlights both high bandwidth and high SNR, with bandwidth providing direct scaling and SNR enhancing efficiency. For a given SNR of 30 dB, the bandwidth of 200 MHz achieves ~2 Gbps, 300 MHz achieves ~3 Gbps, and 400 MHz achieves ~4 Gbps. These are essential for achieving maximum data rates in communication systems.

In Figure 4. The graph illustrates the relationship between the sum rate (bps/Hz) and the number of users in a NOMA system for different antenna gain values (10 dB to 50dB at a rate of 10 dB scaling up. The sum rate initially increases as the number of users increases to a peak value, after which it decreases due to interference in the NOMA system. For 10 dB, the peak sum rate is 23.67 bps/Hz at six users. 20 dB is 30.58 bps/Hz at eight users, 30 dB is 36.89 bps/Hz at eight users, 40 dB is 37.47 bps/Hz at eight users, 50 dB, the peak is 37.81 bps/Hz at eight users. It is seen that antenna gain significantly enhances the sum rate. For instance, the sum rate increases with eight users from 23.67 bps/Hz (10 dB) to 37.81 bps/Hz (50 dB). Beyond the optimal number of users (8 in this case), the sum rate decreases more steeply for lower antenna gains. Higher antenna gains maintain better performance, with the sum rate being 27.97 bps/Hz (30 dB), 33.20 bps/Hz (40 dB), and 36.62 bps/Hz (50 dB). The decline in performance seen as users rise in numbers highlights the impact of inter-user interference in NOMA, emphasizing the importance of optimal user allocation and interference mitigation strategies. This analysis demonstrates that leveraging higher antenna gains enhances spectral efficiency in NOMA systems but requires balancing the number of users to maximize the sum rate.

Figure 5 graph shows the Bit Error Rate (BER) performance and transmit power (dBm) for two users in a

NOMA system using the NYU path loss model: User 1 (far user) and User 2 (near user). BER decreases as transmit power increases for both users, indicating improved communication reliability at higher power levels. The near user (User 2) consistently achieves a lower BER than the far user (User 1) for all transmit power levels. User 1 beyond 35 dBm, BER is 10^{-3}, suggesting reliable communication and for user two at 40 dBm, BER drops below 10 to 3, showing near error-free communication. The results highlight and try to show the trade-off in NOMA systems where users require more transmit power to achieve acceptable BER. In contrast, near users maintain better performance with lower power.

In Figure 6, The graph shows the relationship between Outage Probability and Transmit Power NOMA-mmWave. This graph demonstrates the trade-off between transmit power and system reliability in mmWave NOMA. At a low transmit power of 0-25 dBm, both users experience high outage probabilities of close to 1. At higher transmit power of 25–40 dBm, both users' outage probability decreases significantly. The findings underline the importance of optimizing transmit power and implementing fairness techniques to support far users in mmWave NOMA net. Figures 7 and 8 are the results of the proposed methodology on polynomial regression and XGBoost, respectively. XGBoost outperformed both Polynomial and Linear Regression with the lowest MSE values for both users, indicating that it effectively captures the complex relationships between transmit power and outage probabilities. Additionally, we identified the optimal transmit power range (30–35 dBm).

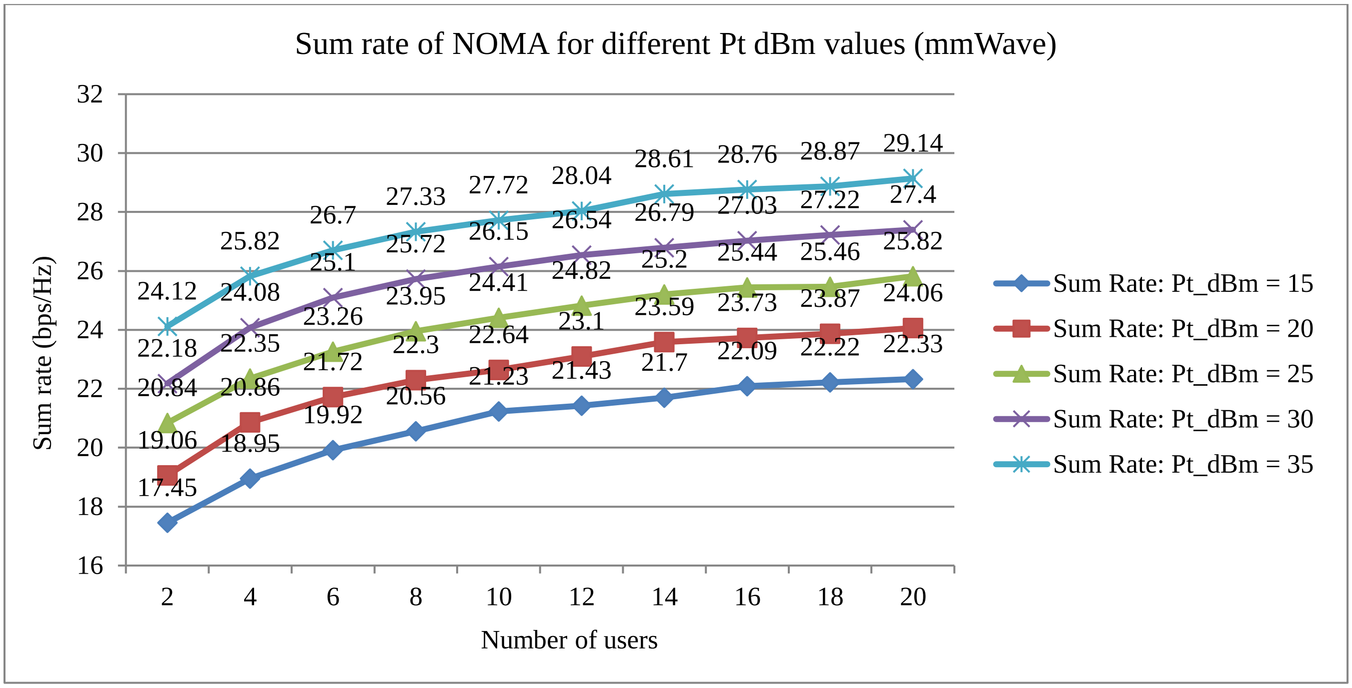

Fig. 1 Maximization of sum rate using NOMA-mmWa

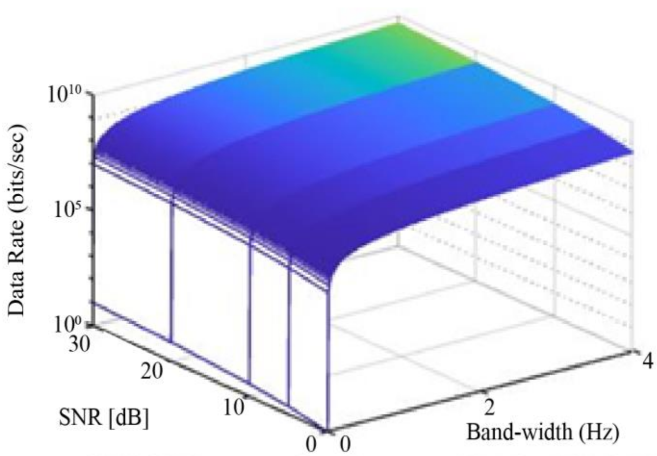

Fig. 2 Logarithmic scale- NOMA-mmWave data rates

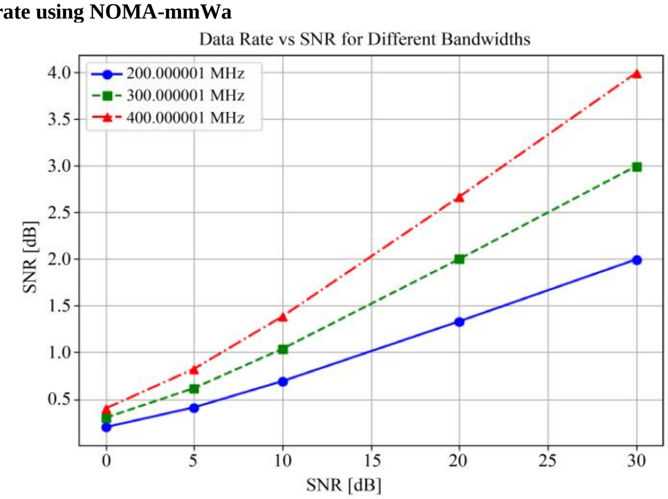

Fig. 3 Throughput for bandwidths in NOMA-mmWave

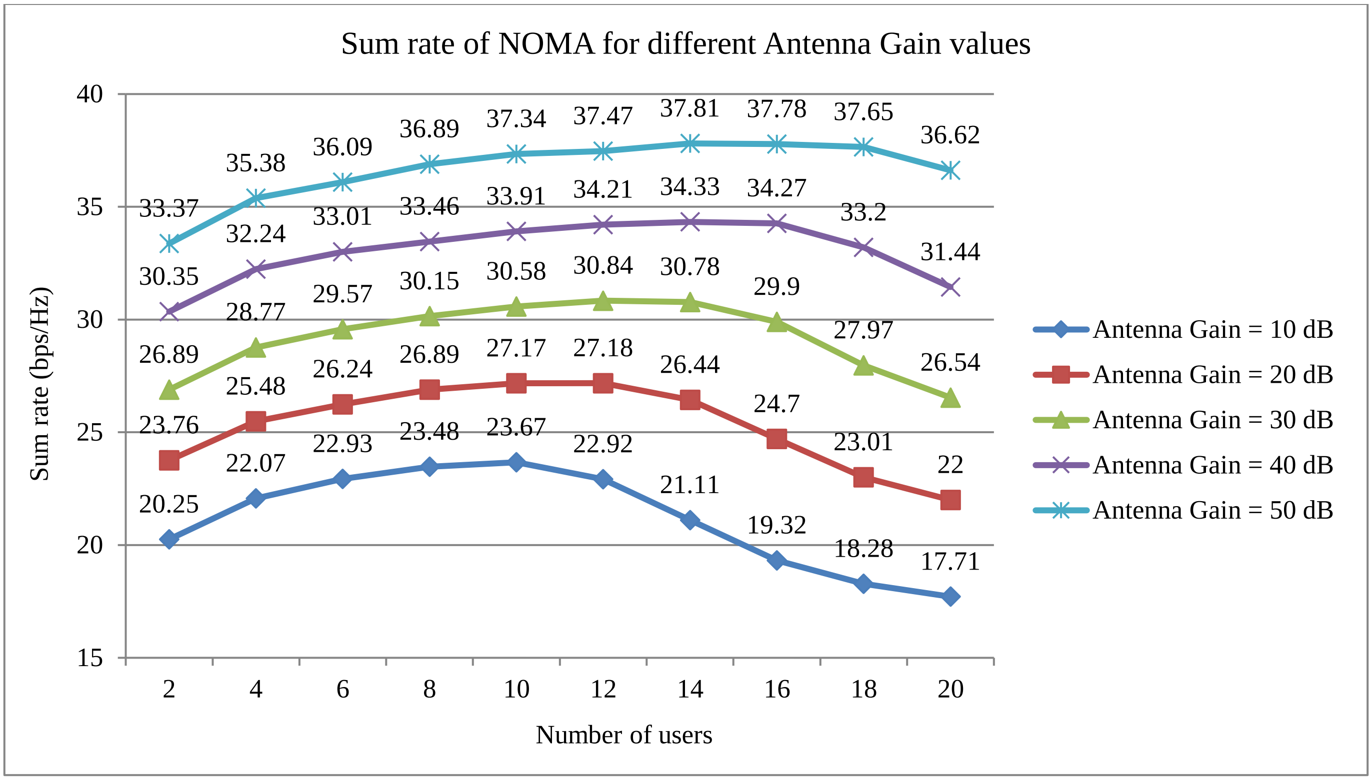

Fig. 4 Sum rate for antenna gain of 6dbi

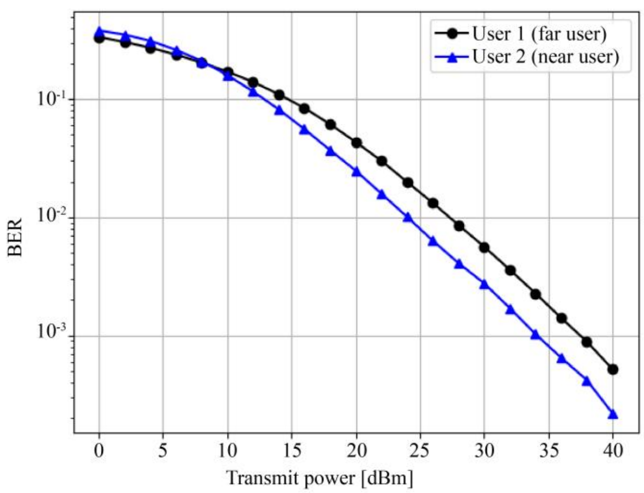

Fig. 5 Estimate Channel resilience using NYU path loss

As per the fundamental communication principle, higher transmit power reduces outage probability. The experiment successfully validates a predictive model for outage probability with near-theoretical accuracy with a Mean Squared Error below 7×10−7, indicating near-perfect alignment between theoretical and predicted outage probabilities, as shown in Table 1. This provides a practical guideline for balancing reliability and energy efficiency in communication system design. It underscores its potential for deployment in resource-constrained or multiuser communication systems. Simulation results closely agree with the theoretical outcomes.

Table 1. Outage probability of the models

Model	User1	User2
XGBoost	6.72×10−7	6.39×10−7
Polynomial Regression	4.46×10−4	1.98×10−3
Linear Regression	1.78×10−3	1.60×10−2

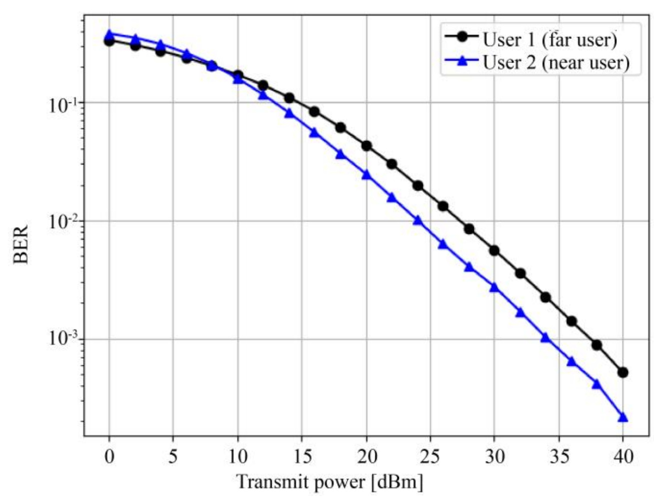

Fig. 6 Outage probability with NOMA-mmWave

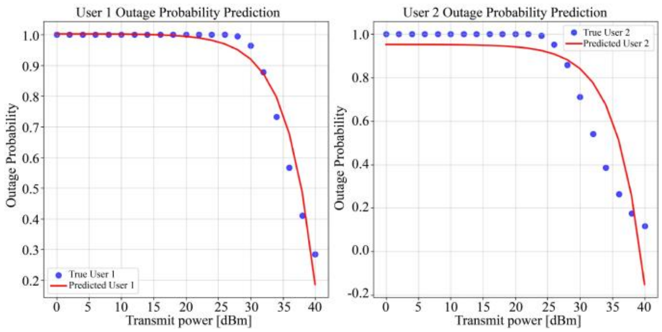

Fig. 7 Outage probability prediction using Polynomial regression

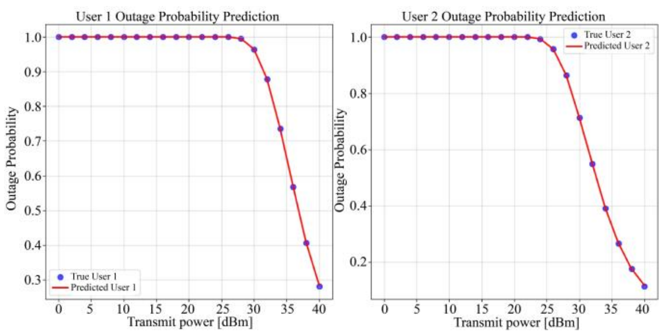

Fig. 8 Outage probability prediction using XGBoost

7. Conclusion

Based on the analysis, the findings suggest that the linear regression model effectively predicts outage probability for both Users in the NOMA with very low Mean Squared Error (MSE) values on the order of 10^{-7}. In real-time 5G applications, XGBoost offers several advantages over polynomial regression by adapting to dynamic network conditions. XGBoost captures the complex, non-linear relationships between transmit power, interference, and outage probabilities, making it more suited for the dynamic nature of 5G systems. As users in the 5G network grow, XGBoost can scale effectively, providing reliable predictions for real-time decision-making in resource allocation and network management. Low prediction errors are particularly valuable in designing energy-efficient and reliable communication systems, especially in 5G and IoT networks where outage prediction accuracy is critical for power optimization.

This research highlights the performance improvements and challenges of adopting NOMA in high-frequency mmWave environments in BER, sum rate, and outage probability. Future research can explore the integration of dynamic power allocation schemes with AI-driven resource management techniques. Additionally, experimental validation in real-world 5G deployments and extending the framework to 6G scenarios, such as THz communications and intelligent reflective surfaces, will provide valuable insights into its broader applicability.

NOMA will then be concluded to be a revolutionary technology for the 5G era with high gains in Spectral Efficiency, latency reduction and massive connectivity as per the demand in the real world. NOMA mmWave becomes the footing to 6G technology that will continue to play an important role in the progression of wireless communication by addressing current limitations and exploring new hybrid communications models for different applications such as industrial automation, smart cities, and autonomous systems.

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