# Capacity, Spectral and Energy Efficiency of OMA and NOMA Systems

Mohammed Mubarak Salih
Al-Rafidain University College
Baghdad, Iraq
mohammed.mubarak@ruc.edu.iq

Basma Mohammed Khaleel
Al-Rafidain University College
Baghdad, Iraq
basma.khaleel@ruc.edu.iq

Nameer Hashim Qasim
Cihan University Sulaimaniya
Research Center (CUSRC),
Cihan University Sulaimaniya,
Sulaymaniyah 46001, Kurdistan Region, Iraq
nameer.qasim@sulicihan.edu.krd

Wasan Saad Ahmed
Al-Turath University College
Baghdad, Iraq
wasan.saad@turath.edu.iq

Svitlana Kondakova
Kyiv National University of
Construction and Architecture
Kyiv, Ukraine
kondakova.sv@knuba.edu.ua

Mohammed Yaseen Abdullah
Al-Noor University College
Nineveh, Iraq
mohammed.yaseen@alnoor.edu.iq

*Abstract* — **Background: As the demand for wireless communications grows, optimizing various access strategies becomes more important. This article compares Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) wireless communication methods.**

**Objective: The primary aim is to understand and assess the capacity, spectrum efficiency, and energy efficiency of both OMA and NOMA systems using real data from thorough simulations and analysis.**

**Methods: The study employs simulation data and practical analyses to assess multiple access approaches and their underlying technologies. It focuses on the two systems' performance metrics in real-world circumstances.**

**Results: The results show that NOMA systems outperform OMA systems regarding capacity and spectrum efficiency. NOMA supports more users within the same bandwidth and has greater system throughput. Furthermore, the energy efficiency study shows that NOMA outperforms OMA, implying a more energy-efficient system with improved overall network performance.**

**Conclusion: The findings provide light on the performance dynamics of OMA and NOMA systems. These discoveries are critical for designing, optimizing, and developing improved wireless communication networks capable of meeting the needs of current wireless applications.**

## I. Introduction

In the rapidly evolving world of wireless communications, the demand for data services and connectivity continues to grow exponentially. However, the limited availability of radio resources, such as radio spectrum and transmit power, poses a significant challenge in meeting the ever-increasing traffic demands [Guarnizo-Peralta1, #109]. To cope with this challenge and ensure efficient utilization of available resources, new technologies are required to enhance the capacity performance of wireless communication systems by orders of magnitude [Baldwin, #253].

A substantial body of literature has been dedicated to improving the downlink transmission performance in wireless communication systems [3-6]. Among the various technologies employed for multiplexing in multi-carrier wireless systems, Orthogonal Frequency Division Multiplexing (OFDM) has gained extensive popularity [7-9]. OFDM is known for its ability to convert frequency-selective fading channels into multiple narrowband flat fading sub-channels, which makes it a suitable technology for wireless multiple access systems [10].

In the realm of wireless multiple access, two prominent approaches have emerged: Orthogonal Frequency Division Multiple Access (OFDMA) and Non-Orthogonal Multiple Access (NOMA) [3, 11]. While OFDMA allocates separate frequency bands to different users, NOMA stands out by enabling multiple users to share the same frequency band, leading to enhanced spectrum utilization and accommodating a larger number of system connections [17,18]. NOMA achieves this by utilizing superposition coding (SC) on the sender side and successive interference cancellation (SIC) on the receiver side [12], [13].

Traditional Orthogonal Multiple Access (OMA) strategies, in contrast to NOMA, allocate separate resources to different users, serving them in distinct bands[14]. In contrast, NOMA employs a more efficient approach, allowing multiple user equipment to share identical resource units through power domain-based user classification [15].

This paper aims to provide an in-depth comparison between the two multiple access technologies, NOMA and OMA. The discussion will focus on various aspects, including system capacity comparison, spectral efficiency, and energy efficiency. Additionally, the paper will explore the application of Multiple-Input Multiple-Output (MIMO) technology in NOMA systems to further improve performance [16].

The remaining sections of the paper are structured as follows:

Section II presents the system model of NOMA versus OMA, providing a detailed comparison of their capacity. In Section III, the focus shifts to evaluating the spectral efficiency and energy efficiency of both approaches. Section IV introduces the system model of MIMO-NOMA, exploring the potential benefits of combining MIMO with NOMA [17]. Finally, Section V presents the simulation results, showcasing a comprehensive comparison between OMA and NOMA in various scenarios.

By investigating the capacity, spectral efficiency, energy efficiency, and MIMO-NOMA system model, this paper seeks to shed light on the advantages and limitations of both NOMA and OMA, offering valuable insights for researchers and practitioners in the field of wireless communications. The results of the article have the potential to inspire further development of wireless technologies, opening the door to the creation of more advanced and trustworthy wireless communication systems that can keep up with the ever-increasing needs of the current day.

### *A. The Aim of the Article*

The primary aim of this article is to provide a comprehensive comparative examination of Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) systems, with a specific emphasis on their capacity, spectrum efficiency, and energy efficiency measures. With the continuous advancement of wireless communication technologies, there is an increasing emphasis on optimising system capacity and efficiency. The operational methodology and performance results of OMA and NOMA, which are two significant multiple-access strategies, are dissimilar. This article aims to provide a comprehensive analysis of the fundamental concepts governing both systems, emphasising their respective strengths and possible drawbacks. Through the analysis of real-world situations and simulations, our objective is to provide a complete comprehension of the performance of each system about data throughput, bandwidth utilisation, and energy usage. The primary objective of this article is to provide valuable insights and suggestions to network designers, legislators, and researchers. It highlights the suitability of various multiple access techniques for specific applications and addresses the future difficulties of wireless communication.

### *B. Problem Statement*

The effective allocation and management of spectrum and energy resources is a significant issue within wireless communication. The capacity restrictions of classic Orthogonal Multiple Access (OMA) systems are becoming a concern as data traffic grows, which might impede the advancement of communication networks. Non-Orthogonal Multiple Access (NOMA) is emerging as a potentially advantageous alternative, demonstrating enhanced spectrum and energy efficiency. Nevertheless, the practicality, benefits, and difficulties of Non-Orthogonal Multiple Access (NOMA) in contrast to Orthogonal Multiple Access (OMA) continue to be discussion topics. The critical issue at hand pertains to the identification of the most effective system in a variety of situations, taking into account factors such as capacity, spectrum utilisation, and energy usage. In addition, it is necessary to investigate the practical obstacles associated with implementing Non-Orthogonal Multiple Access (NOMA), including interference control and ensuring fairness among users. It is of utmost importance to address this issue, as the decision between OMA and NOMA will have a significant impact on the trajectory of wireless communication. This option will not only influence network architecture but also shape the user experience and contribute to the sustainability of energy use.

## II. BACKGROUND

Let's think about a scenario for downlink communication involving N users, a base station (BS), and the network. Assign the channel from the BS to the $i^{th}$ user as h. If there are N of the same kind channels are exits; as: $h1,\ h2, \dots\ h_N$.

Assuming user-1, who is transmitting via channel h, is the weakest user since he/she is the furthest away from the BS. User-2 comes after User-1, then so forth. User N would be fairly close or most powerful client [18]. That means the users' channel requirements are deployed as follows:

$$|\mathrm{h}_1|^2 < |\mathrm{h}_2|^2 < \cdots < |\mathrm{h}_\mathrm{N}|^2 \tag{1}$$

For Non - orthogonal multiple access signal structure. Letting x 1, x 2, ... x N representing the messages being sent to the users. With these messages, the BS performs superposition coding and sends the channel the following NOMA signal:

$$x_{NOMA} = \sqrt{P}\sum_{i=1}^{N}\sqrt{\beta_i}x_i \tag{2}$$

In which; P power transmitted $x_i$ - data intended for $i^{th}$ user and $\beta_i is$ fraction of power allocated for $i^{th}$ user.

The signal obtained from user i is given by:

$$\mathrm{y}_{\mathrm{i,NOMA}} = \mathrm{x}_{\mathrm{NOMA}}\mathrm{h}_\mathrm{i} + \mathrm{w}_\mathrm{i} \tag{3}$$

With h has been channel response, x is transmitted message additionally $w_i$ is the AWGN with zero mean and variance $= \sigma^2$

An attainable rate to every average user will be as follows, to make the comparison it assumes the bandwidth is the fix for both OMA and NOMA

$$R_{i,NOMA} = \log_2(1 + \gamma_{i,NOMA}) \tag{4}$$

Where $\gamma_{i,NOMA}$ is the SNR intended for $i^{th}$ user. Eventually, the cumulative NOMA user rate is provided by,

$$R_{NOMA} = \sum_{i=1}^{N} R_{i,NOMA} \quad (5)$$

### A. Signal mapping for Orthogonal-Multiple-Access

Let's examine the standard OMA transmission, taking TDMA as an example. TDMA requires (N*N) time slots to service N users. The data of user-1 will be broadcast in the initial time slot, data from user-2 is transmitted in the next time slot, and so on. Moreover, suppose each of the time slots are of identical duration. Making the assumption that user i's signal is broadcast in the $i^{th}$ time slot [19]. The transmit signal is then provided by,

$$x_{i,OMA} = \sqrt{P}x_i \quad (6)$$

Where P represent the transmitted signal power and $x_i$ data intended for $i^{th}$ user

Once equations (1) and (5) are compared, it can be seen that NOMA users benefit from simultaneous transmission with manageable interference, but OMA users benefit from interference-free transmission. The signal received by user I would become:

$$y_{i,OMA} = \sqrt{P}x_i h_i + w_i \quad (7)$$

Where P represent the transmitted signal power, h denotes the channel response and x are the transmitted data and $w_i$ was AWGN which has zero mean and variance = $\sigma^2$. Attainable rate for the $i^{th}$ OMA user can be calculated as,

$$R_{i,OMA} = \frac{1}{N}\log_2(1 + \gamma_{i,OMA}) \quad (8)$$

We assumed the bandwidth is one. The OMA total rate can be finally is computed from,

$$R_{OMA} = \sum_{i=1}^{N} R_{i,OMA} \quad (9)$$

### B. Spectral efficiency and energy efficiency

In the proposed study for NOMA systems; the static power consumption for network owing of power amplifiers is included besides the power consumed by the information waveform.

The overall power consumption at the transmitter is determined by combining the power consumed by the transmitter's circuits with the power expended by the information signal, primarily by the power amplifiers [20]. The total power required by the Base Station (BS) can be expressed as:

$$P_{\text{total}} = P_T + P_{\text{static}} \quad (10)$$

Here, SE represents the Spectral Efficiency, and EE denotes the Energy Efficiency. The Energy Efficiency (EE) is calculated as the ratio of the achievable data rate (R_T) to the total power consumption (P_total), given by:

$$EE = \frac{R_T}{P_{\text{total}}} = SE\frac{W}{P_{total}}\left(\frac{\text{bits}}{joule}\right) \quad (11)$$

In equation (11), W refers to the available bandwidth for communication. By analyzing the spectral and energy efficiencies, we can evaluate the performance and power consumption characteristics of the system.

According to Shannon theory, the energy efficiency with spectral efficiency connection (EE-SE) ignores power consumed by the circuit that’s why its monotone, so greater SE will result to lower EE.

Taking into account the circuitry power, the EE rises mostly through the lower SE zone and falls thought out the rising SE region [21]. The maximum energy efficiency of the system is depicted by the peak of the curve (or the corresponding derivative of the EE-SE equation, as illustrated in Fig. 3.

## III. METHODOLOGY

In Fig. 1, we observe a 2x1 downlink Multiple-Input Multiple-Output (MIMO) setup. Let d1 and d2 represent the distances of U1 and U2 from the MIMO transmitter, respectively. In this scenario, we assume that d1 > d2, indicating that U1 is the user located at a greater distance, while U2 is the user closer to the MIMO transmitter and, thus, experiences a stronger signal.

We use x1 and x2 to symbolize the information transmitted to U1 and U2, respectively. The channel between the tth transmit antenna and rth receiver, following MIMO terminology, is represented by hrt. In this case, both antenna 1 and antenna 2 deliver the same data[22].

It's important to note that the MIMO setup allows for multiple antennas to be used at both the transmitter and the receiver, which can significantly enhance the system's performance by exploiting spatial diversity and multiplexing gains. The distances of U1 and U2 from the MIMO transmitter play a crucial role in determining the signal strengths and overall system performance. Additionally, the channel fading effect (Rayleigh fading) can further influence the received signals' quality and reliability [21].

The MIMO technology is widely used in modern wireless communication systems to improve data throughput, increase spectral efficiency, and enhance overall link reliability. By utilizing multiple antennas and advanced signal processing techniques, MIMO systems can mitigate the impact of fading and interference, leading to better communication performance, particularly in challenging wireless environments.

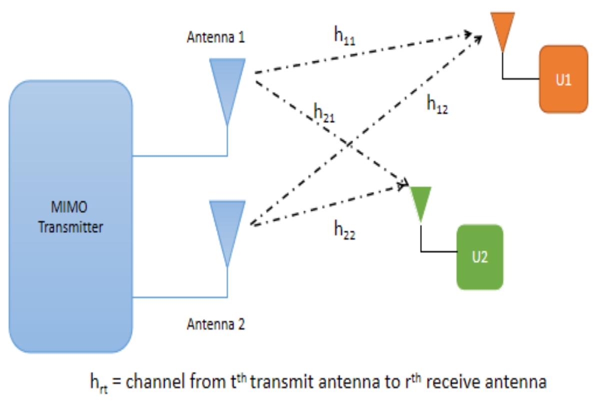


Fig. 1. MIMO-NOMA System Model

U1's received signal becomes

$$y_1 = xh_{11} + xh_{12} + n_1 = x(h_{11} + h_{12}) + n_1 \quad (12)$$

U2's received signal is given as

$$y_2 = xh_{21} + xh_{22} + n_2 = x(h_{21} + h_{22}) + n_2 \quad (13)$$

U1 must now decode x 1 from y 1. Because U1 is the furthest user, his signal, x 1, is given higher power. That is, $\beta_1 = (1-\varepsilon)P_s$ and $\beta_2 = \varepsilon$ Ps; As a result, x 1 can be decoded straightly from y 1, with the x 2 term acting as interference. The output will be

$$y_1 = \sqrt{P}(\sqrt{\beta_1}x_1 + \sqrt{\beta_2}x_2)(h_{11} + h_{12}) + n_1 \quad (14)$$

$$y_1 = \underbrace{\sqrt{P}(\sqrt{\beta_1}x_1(h_{11}+h_{12})}_{desired} + \underbrace{\sqrt{P}\sqrt{\beta_2}x_2(h_{11}+h_{12})+n_1}_{interference} \quad (15)$$

SINR equation for U1 in decoding $x_1$as follows:

$$\gamma_1 = \frac{P\beta_{1|h_{11}+h_{12}|^2}}{P\beta_{2|h_{11}+h_{12}|^2}+\sigma^2} \quad (16)$$

At U1, the feasible rate is determined from:

$$R_1 = \log_2(1+\gamma_1) \quad (17)$$

In the communication process, user U2 needs to extract the signal $x_2$ from the received signal $\acute{y}_2$. As U2 is considered the most powerful user, the strength of his signal, x1, is intentionally reduced. Consequently, the power of the $x_1$ term becomes dominant in the received signal $\acute{y}_2$. Given this situation, U2 employs direct decoding on $y_2$ to obtain $x_1$ initially. Then, utilizing successive interference cancellation (SIC), U2 eliminates $x_1$ from the received signal, enabling the successful decoding [23] of the desired signal $x_2$.

$$\acute{y}_2 = \underbrace{\sqrt{P}(\sqrt{\beta_1}x_1(h_{21}+h_{22})}_{undesired/\&dominating} + \underbrace{\sqrt{P}\sqrt{\beta_2}x_2(h_{21}+h_{22})+n_2}_{desired} \quad (18)$$

Following SIC, (15)'s initial term would be eliminated, leaving:

$$\acute{y}_2 = \underbrace{\sqrt{P}\sqrt{\beta_2}x_2(h_{21}+h_{22})+n_2}_{desired} \quad (19)$$

The SNR for U2 decoding its data can be obtained by:

$$\gamma_2 = \frac{P\beta_2|h_{21}+h_{22}|^2}{\sigma^2} \quad (20)$$

Moreover, the feasible rates of U2 while decoding x1 & $x_2$can be determined as,

$$R_{12} = \log_2(1+\gamma_{12}) \quad (21)$$

$$R_2 = \log_2(1+\gamma_2) \quad (22)$$

MIMO-OMA attainable rates for U1 and U2 have become,

$$R_{1,\text{oma}} = \frac{1}{2}\log_2(1+\gamma_{1,\text{oma}}) \quad (23)$$

$$R_{2,\text{oma}} = \frac{1}{2}\log_2(1+\gamma_{2,\text{oma}}) \quad (24)$$

If the distant client (U1achievable)'s rate , $R_1^*$ ,is below his desired rate, he is offline. Mathematically, this can be written as,

$$P^1_{\text{noma}} = \Pr(R_1 < R_1{}^*) \quad (25)$$

In the context of the nearby user in a communication system, successful decoding of both U1's message and the nearby user's own message is essential. This means that the strong user (nearby user) must achieve both U1's target rate and its own target rate. If U1's target rate is not met, OR if U1's target rate is met but U2's target rate is not met, the nearby user's decoding will fail. This can be expressed as follows:

$$P^2_{\text{noma}} = \Pr(R_{12} < R_1{}^*) + \Pr(R_{12} > R_1^*, R_2 > R_2^*) \quad (26)$$

MIMO-OMA breakdown formulas are straightforward.

$$P^1_{\text{noma}} = \Pr(R_{1,\text{oma}} < R_1{}^*) \quad (27)$$

$$P^2_{\text{noma}} = \Pr(R_{2,\text{oma}} < R_2{}^*) \quad (28)$$

## IV. RESULTS

First will demonstrate the result of comparison between OMA and NOMA as in Fig. 2 the first comparison based on the capacity of each system now consider a cell having 3users then compare their results. At low SNR, we can see that OMA outperforms NOMA little. That's due to the fact that NOMA users experience interference (as a result of simultaneous transmission), but OMA clients would not. In contrast, owing of its large capacity, NOMA performs better OMA at high SNR.

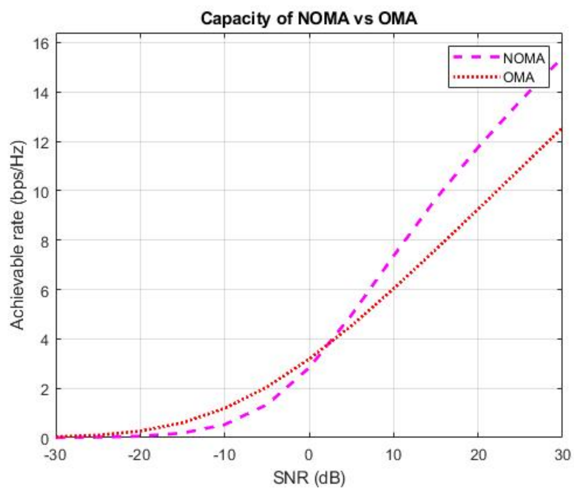


Fig. 2. Capacity OF NOMA versus OMA

Fig. 3 depicts a comparison of the two systems in terms of spectral efficiency and energy efficiency.

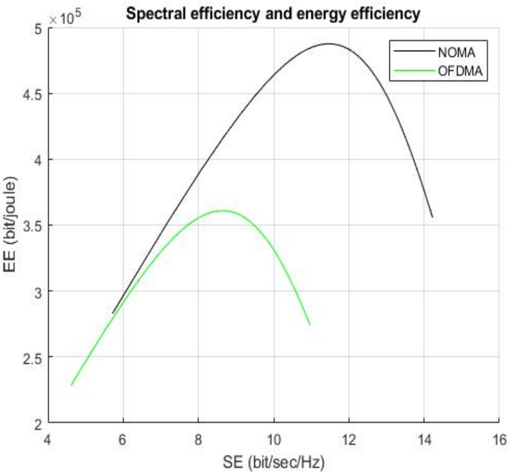


Fig. 3. Spectral and Energy Efficiency

Examining NOMA's EE as well as SE over OFDMA. We take another look at the downlink. System's bandwidth has assumed to be 5 MHz. Channel's gain at UE1 also UE2 are calculated as $G_1^2 = -120$ & $G_2^2 = -140$, respectively. The noise density $N_o$is set to 150 dBW/Hz. The BS's static power consumption was assumed to be 100. It shows that the spectral efficiency of NOMA s.

Fig. 4 illustrates the comparison between MIMO-NOMA and MIMO-OMA systems. It is evident from the graph that the achievable sum rate for MIMO-NOMA is represented as R1+R2, whereas MIMO/OMA's it is denoted as $R_{1OMA}$+$R_{2OMA}$.

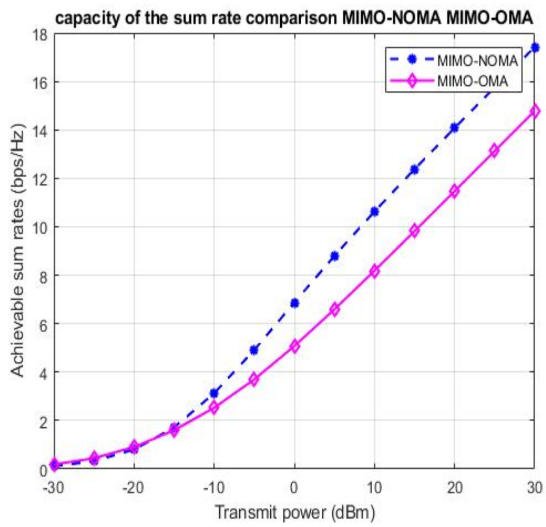


Fig. 4. Capacity of Overall System

Because both users are serviced concurrently with the same frequency resource, MIMO-NOMA clearly gives a higher sum rate than MIMO-OMA.

Fig. 5 depicts the simulated rate shown for each user. The simulation findings show that the distant user experiences saturation within its feasible rate upon a broadcast power of 10 dBm. That would be a recurring topic throughout the NOMA system. Such saturation of feasible rate will not be a concern if the far user's necessary data rate be lower than the saturation limit; but that issue does not exist in OMA as the weak user isn’t affected by interference caused by concurrent broadcasts.

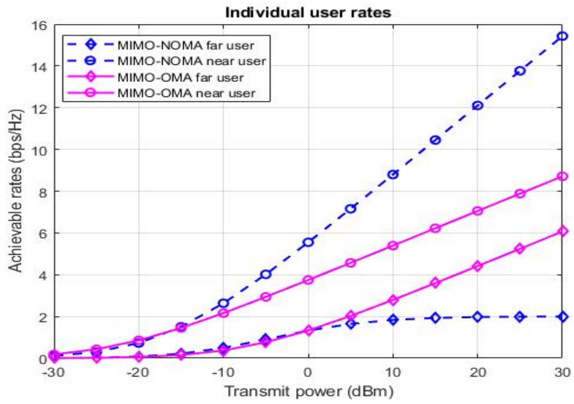


Fig. 5. Rate of Individual User

A comparison based on simulating the users' outage probability in both MIMO-NOMA and MIMO-OMA methods. The utilization of fixed power allocation, as depicted in Fig. 6, highlights the importance of selecting appropriate goal rates and power allocation coefficients. For the distant user (U1) we set the goal rate as R 1=1bps/Hz , while the target rate for the close user (U2) is set as R2=3bps/Hz. As expected, the results clearly demonstrate that MIMO-NOMA outperforms MIMO-OMA in terms of outage probability for both users. The implementation of non-orthogonal multiple access (NOMA) in MIMO systems leads to reduced outage probability, providing a more efficient and reliable communication experience for users compared to the traditional orthogonal multiple access (OMA) methods. The promising outcomes of MIMO-NOMA in minimizing outage probability further highlight its potential as an effective technique to enhance wireless communication systems.

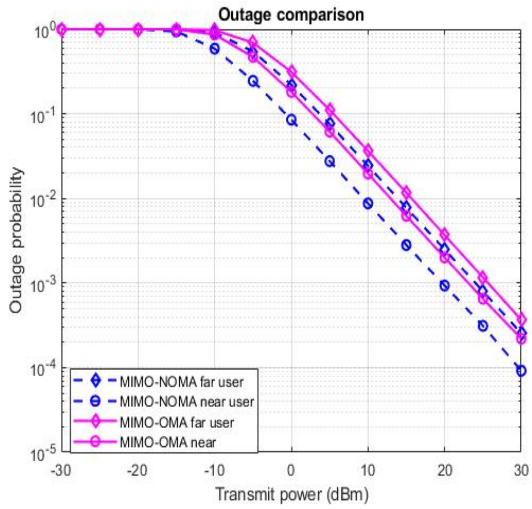


Fig. 6. Comparing Outage Probability between MIMO-NOMA and MIMO-OMA Systems

## V. Discussion

The article presents a comprehensive investigation into the performance of Orthogonal Multiple Access (OMA) and Non-

Orthogonal Multiple Access (NOMA) systems in terms of capacity, spectral efficiency, and energy efficiency. The research aims to address the increasing demand for wireless communication systems and the limitations imposed by the finite radio resources, such as radio spectrum and transmit power [Guarnizo-Peralta1, #109].

Comparing this article with other research in the field, it stands out as an extensive study that provides valuable insights into the benefits and drawbacks of both OMA and NOMA techniques. While previous studies have primarily focused on improving downlink transmission performance [24-27], this article emphasizes the importance of optimizing channel capacity and resource utilization in both uplink and downlink scenarios.

One of the key contributions of this research is the evaluation of the capacity comparison between NOMA and OMA systems. The analysis considers multiple aspects, including the goal rates and power allocation coefficients for distant and close users. By utilizing fixed power amplifiers, the study demonstrates that NOMA outperforms OMA in terms of users' outage probability. The NOMA technique delivers lower outage probabilities to both users, as predicted, indicating its potential to enhance system reliability and performance [15], [28].

The paper delves into spectral and energy efficiency aspects, highlighting the significance of these metrics in modern wireless communication systems. NOMA emerges as a promising solution for improving spectral efficiency and enabling a higher number of system connections by allowing users to share the frequency band [13]. Also, the article discusses the overall power consumption at the transmitter, which includes power consumed by the circuits and the power spent by the information signal, mainly through power amplifiers. This analysis is essential in understanding the trade-offs between capacity and energy efficiency in OMA and NOMA systems.

Comparing the findings of this article with other research, it becomes evident that NOMA offers advantages in terms of capacity, spectral efficiency, and energy efficiency [12]. Several studies have recognized the potential of NOMA in improving system performance and accommodating a larger number of users [26] The present article adds to this growing body of knowledge by providing a comprehensive comparison between OMA and NOMA techniques [29, 30] under various scenarios, making it a valuable resource for researchers and practitioners in the field of wireless communications.

Furthermore, the paper offers insights into the performance of MIMO (Multiple-Input Multiple-Output) systems in combination with NOMA, which is another noteworthy contribution. The investigation of MIMO-NOMA and MIMO-OMA systems allows for a deeper understanding of the benefits of NOMA in multiple antenna configurations [31, 32].

The article presents a comprehensive study that investigates the performance of OMA and NOMA techniques in wireless communication systems. By comparing various metrics, such as capacity, spectral efficiency, and energy efficiency, the research highlights the advantages of NOMA in improving system performance and accommodating a higher number of users. The findings contribute to the growing body of knowledge on NOMA, making it a valuable resource for researchers and practitioners in the field of wireless communications. Future research can build upon these findings to further explore the potential of NOMA and its applications in emerging communication technologies.

## VI. Conclusion

NOMA system has better capacity performance than OMA in the overall system but the far user would have had saturation in 10 db. As predicted, outage probability of NOMA seems to be smaller than that of MIMO/OMA including both users.

Lastly, the derivations throughout this document can be simply expanded for M-QAM framework via taking counts constellations alternative channel estimation while using probability density functions.

The article examines the capacity, spectral efficiency, and energy efficiency of Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) systems in wireless communications. The research aimed to explore new technologies that can significantly improve the channel capacity performance and support the increasing traffic demands in wireless networks.

Through a systematic comparison of OMA and NOMA systems, several key findings emerged. The utilization of Orthogonal Frequency Division Multiplexing (OFDM) as the multiplexing technology in multi-carrier wireless communication systems provided numerous benefits, including transforming frequency selective fading channels into multiple narrowband flat fading sub-channels. OFDM-based systems supported both OMA, known as OFDMA, and NOMA techniques.

NOMA demonstrated its superiority in terms of spectrum utilization and enabling a larger number of simultaneous user connections by allowing users to share the same frequency band. Unlike traditional OMA strategies that allocate separate frequency bands to individual users, NOMA simultaneously served multiple user equipment with identical resource units, classified based on power domains. By employing superposition coding on the sender side and successive interference cancellation on the receiver side, NOMA efficiently managed multiple users.

In evaluating the power consumption at the transmitter, which encompassed both circuit power consumption and power spent by the information signal (particularly by power amplifiers), it was evident that NOMA presented a promising approach to enhance spectral efficiency and energy efficiency.

The comparison of outage probabilities between MIMO-NOMA and MIMO-OMA systems indicated that NOMA outperformed OMA in reducing outage for both users. With a carefully selected goal rate for the distant user (U1) and the target rate for the close user (U2), MIMO-NOMA achieved lower outage probabilities, fulfilling the predicted advantages of this approach.

The article provides valuable insights for researchers, engineers, and practitioners in the field of wireless communication and network design. The utilization of NOMA techniques, particularly in conjunction with MIMO systems, can lead to significant improvements in spectral efficiency, energy efficiency, and overall system capacity. These advancements have the potential to cater to the ever-increasing demands for high-speed and reliable wireless connections in today's fast-paced digital era.

While the article sheds light on the benefits of NOMA over OMA, further investigations may delve into more complex scenarios and diverse network environments to evaluate the performance of these techniques under various conditions. Additionally, incorporating adaptive power allocation strategies and considering other performance metrics, such as latency and fairness, could be promising avenues for future studies.

The findings presented in this paper contribute to the growing body of knowledge on the potential of NOMA systems to revolutionize wireless communication technology, paving the way for more efficient and robust communication networks to meet the demands of the digital age.

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