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NOMA for advanced mobile generations

A graduation project is submitted to the Electrical Engineering Department in partial fulfillment of the requirements for the degree of Bachelor of Science in
College of Engineering - Electrical Engineering

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SUPERVISOR CERTIFICATION

I certify that the preparation of this project entitled (NOMA for advanced mobile generations) prepared by (Abbas Saadoun Jaafar and Ali Kazem Zabih and Fatima Anad Muhammad and Banin Hamed Juma and Sorour Mutlaq Fatin)was under my supervision at General Electrical Engineering Branch, Electrical Engineering Department, University of Misan in partial fulfilment of the requirements for the degree of Bachelor of Science in Electrical Engineering.

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CERTIFICATE OF EXAMINERS

We certify, as an examining committee, that we have read this project report entitled " NOMA for advanced mobile generations " examined the students (Abbas Saadoun Jaafar and Ali Kazem Zabih and Fatima Anad Muhammad and Banin Hamed Juma and Sorour Mutlaq Fatin) in its contents and found the project meets the standard for the degree of Bachelor of Science in Electrical Engineering.

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Finally, I wish to thank my parents for their support and encouragement throughout my study.

Abstract

The document explores the concept of Non-Orthogonal Multiple Access (NOMA) in wireless communication systems, particularly focusing on the downlink transmission. It discusses the application of NOMA in conjunction with various techniques such as beamforming, MIMO systems, and cooperative communication. The chapter elaborates on the implementation of NOMA with successive interference cancellation (SIC) and power-domain NOMA, highlighting the impact of imperfectness in SIC. Furthermore, the document delves into the analysis of NOMA with spatial multiplexing and user pairing, emphasizing the benefits of cooperative NOMA over non-cooperative NOMA and Orthogonal Multiple Access (OMA). It also addresses resource allocation, energy-efficient NOMA, and outage probability analysis, providing insights into the performance and trade-offs associated with NOMA systems. The chapter presents simulation results, including rate regions, sum capacity, and outage probabilities for NOMA, MIMO-NOMA, and cooperative communication schemes. These results demonstrate the advantages of NOMA over OMA, the impact of imperfect cancellation in SIC, and the performance order of different communication schemes. In summary, This paper provides a comprehensive overview of NOMA, covering its principles, applications, performance analysis, and simulation results, shedding light on its potential as a promising multiple access technique in future wireless communication systems

Abbreviations

NOMA………………… Non-Orthogonal Multiple Access

OMA………………….. Orthogonal Multiple Access

FDMA…………………Frequency Division Multiple Access

TDMA…………………Time Division Multiple Access

CDMA…………………Code Division Multiple Access

OFDMA………………. Orthogonal Frequency Division Multiple Access

5G………………………Fifth-generation

4G………………………Fourth-generation

3G………………………Third-generation

2G………………………Second-generation

IoT………………………Internet-of-Things

QoS…………………….. Quality-of-Service

SIC…………………….. Successive Interference Cancellation

BS………………………Base Station

BF………………………Beamforming

SNR…………………..……Signal to Noise Ratio

SINR…………………... Signal to Interference Noise Ratio

MIMO…………………Multiple-input multiple-output

MU-MIMO……………Multe user Multiple-input multiple-output

CoMP…………………coordinated multipoint

AP……………………..access point

LDS-CDMA…………..low-density spreading Code Division Multiple Access

SCMA…………………sparse code multiple access

CSI…………………….channel state information

PDMA…………………pattern division multiple access

CIRs……………………..channel impulse responses

SDR-MA……………….software defined radio for multiple access

GSM…………………….. Global System for Mobile Communications

SoDeMA……………….... Software Defined Multiple Access

SE…………………………spectral efficiency

EE…………………………energy efficiency

**BER………………………. **bit error rate

BPSK…………………….. Binary phase-shift keying

QPSK………………………Quadrature phase-shift keying

16-QAM……………………16-Quadrature amplitude modulation

PCA…………………………pilot contamination attacks

3GPP………………………3rd Generation Partnership Project

LTE…………………………Long-term evolution

MUST………………………multiuser superposition transmission

SM…………………………spatial multiplexing

UPPA………………………user-pair power allocation

TTPA………………………tree-search–based transmission power allocation

CQI…………………………..channel quality indicator

MCS…………………………modulation and coding scheme

VIC………………………….. Vehicle Internal Communications

VLC…………………………Visible light communications

RF………………………….. Radio frequency

LIST OF FIGURES

TABLE OF CONTENTS

Chapter Four: Results

Chapter Five: Conclusion and Future Work

Chapter 1
Introduction

1.1 Introduction

Orthogonally has always been the dominant paradigm when allocating resources for different users in a wireless communication scenario. Throughout the different generations of wireless technology, the users have been separated by orthogonally in the frequency domain (FDMA), in the time domain (TDMA), or the code domain (CDMA) etc. Orthogonally allowed the sharing of resources between users. In the absence of orthogonally, users would interfere with each other's communication and effective or error free communication becomes difficult.In practice, however, the wireless industry cannot forever rely on orthogonally. Frequency is a scarce resource, and orthogonally in the time and code domains can only go so far before they affect the performance of the system. For cellular systems, non-orthogonal multiple access (NOMA) has been studied to improve the downlink spectral efficiency in [1]. In NOMA, a radio resource block is shared by multiple users and their transmission power difference plays a key role in multiple access. In general, a pair of users of different transmission powers is considered to share a radio resource block as in [2]. In [5], practical NOMA schemes, called multiuser superposition transmission (MUST) schemes, are considered for downlink transmissions (with two users). In [3], NOMA is

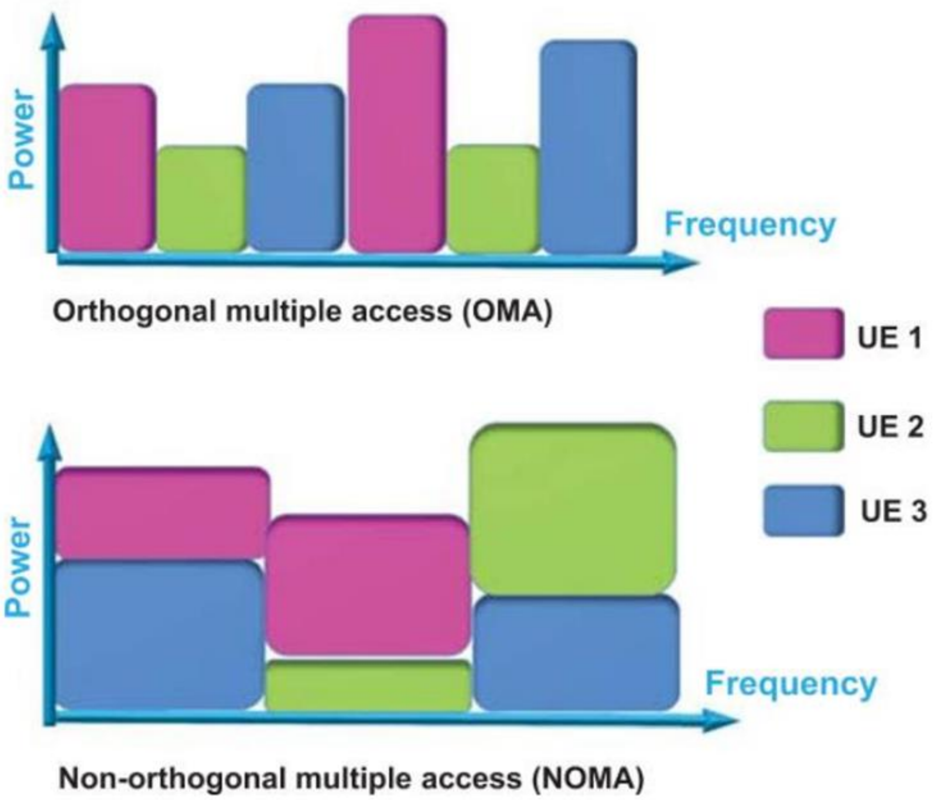

Figure (1.1) A comparison between NOMA and OMA in frequency domain.

employed for coordinated multipoint (CoMP) downlink in order to support a cell-edge user without degrading the spectral efficiency. In addition, in [6], an opportunistic base station (BS) or access point (AP) selection is studied for CoMP with NOMA to improve the spectral efficiency. NOMA is extended to multiple-input multiple-output (MIMO) systems in [4] and capacity analysis of NOMA-MIMO can be found in [7]. While NOMA has been extensively studied to apply to various transmission systems (e.g., CoMP and MIMO), there are also fundamental issues for NOMA. NOMA is based on superposition coding and successive interference cancellation (SIC). Due to SIC, the receiver's complexity can increase at users. Thus, NOMA without SIC in [8] would be helpful to decrease the receiver's complexity at users. In addition, the performance comparison with multiuser diversity schemes (e.g., the opportunistic user selection) is also an important issue in terms of the tradeoff between spectral efficiency and fairness. To address this issue, in [9], NOMA and multiuser diversity schemes are compared when a proportional fairness scheduler is employed.

In wireless communications, the power control has been extensively studied to overcome fading . In NOMA, the power allocation between users and the power control are also important issues not only to overcome fading, but also guarantee fairness between users. In [10], an optimal power allocation to maximize the minimum rate is studied with known channel state information (CSI). In [11], partial CSI or statistical CSI is considered for the power allocation between users for downlink NOMA.

1.2 BASIC CONCEPTS OF NOMA

There exist different NOMA solutions, which can primarily be classified into two major approaches. Fig. (1.2) presents a simple classification of the existing NOMA techniques. Unlike power-domain NOMA, which attains multiplexing in power domain, code-domain NOMA achieves multiplexing in code domain. Like the basic code division multiple access (CDMA) systems, code-domain NOMA shares the entire available resources (time/frequency). In contrast, code-domain NOMA utilizes user-specific spreading sequences that are either sparse sequences or non-orthogonal cross-correlation sequences of low correlation coefficient. This can be further divided into a few different classes, such as low-density spreading CDMA (LDS-CDMA) , low-density spreading-based OFDM (LDS-OFDM) , and sparse code multiple access (SCMA) . The use of low-density spreading sequences helps LDS-CDMA to limit the impact of interference on each chip of basic CDMA systems. LDS-OFDM can be thought of as an amalgamation of LDS-CDMA and OFDM, where the information symbols are first spread across low-density spreading sequences and the resultant chips are then transmitted on a set of subcarriers. SCMA is a recent code-domain NOMA technique based on LDS-CDMA. In contrast to LDS-CDMA, the information bits can be directly mapped to different sparse code words, because both bit mapping and bit spreading are combined. When compared to LDS-CDMA,

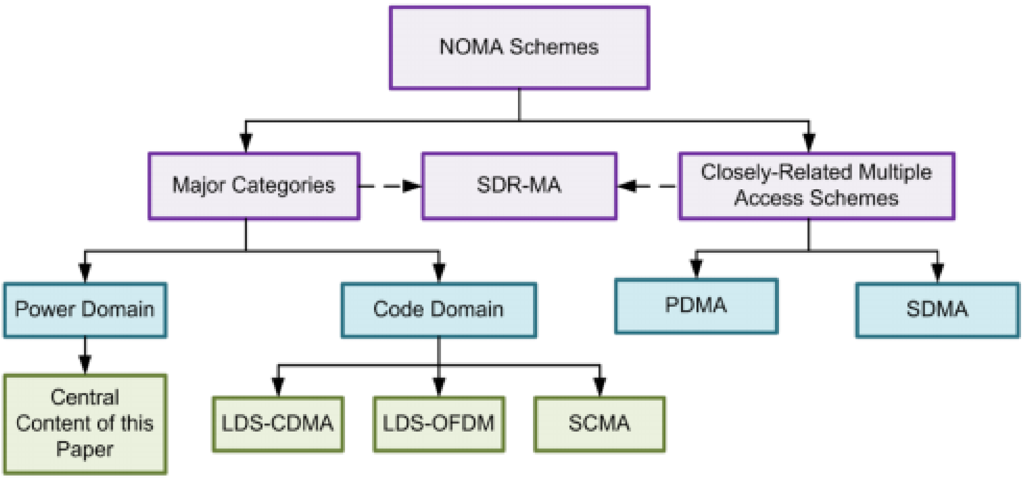

Figure (1. 2) A simple classification of NOMA techniques.

SCMA provides a low complexity reception technique and offers improved performances. There exist some other multiple access techniques, which are also closely-related to NOMA, including pattern division multiple access (PDMA) [12] and spatial division multiple access (SDMA) . PDMA can be realized in various domains. At the transmitter side, PDMA first maximizes the diversity and minimizes the overlaps among multiple users in order to design non-orthogonal patterns. The multiplexing is then performed either in the code domain, spatial domain, or a combination of them. For SDMA, the working principle is inspired by basic CDMA systems. Instead of using user-specific spreading sequences, SDMA distinguishes different users by using user-specific channel impulse responses (CIRs). This technique is particularly useful for the cases where the number of uplink users is considerably higher than the number of corresponding receiving antennas in BS. However, accurate CIR estimation becomes challenging for a large number of users. The concept of software defined radio for multiple access (SDR-MA) allows various forms of NOMA schemes to coexist [13]. This technique provides a flexible configuration of participating multiple access schemes in order to support heterogeneous services and applications in 5G. It is worth noting that while the aforementioned list provides some insights into different forms of NOMA, it is not exhaustive, and the primary focus of this paper is on power-domain NOMA. In the following, a brief note about SC and SIC is presented, since these two basic techniques play important roles in understanding the class of NOMA on which this paper focuses on. Henceforth, this paper refers to power-domain NOMA simply by NOMA.

1.3 Historical Overview

Providing orthogonal time slots for different users was one of the essential philosophies of GSM or 2G communications. But the numbers of time slots were limited due to technical constraints such as the sampling theorem. GSM could not support a large number of users in the same channel. While the situation improved with 3G, which used Wideband CDMA (WCDMA), it was seen that as the number of orthogonal resources or users increased, the complexity of the transmitters and receivers also increased significantly. 4G again relied on orthogonality of frequency, but with subcarriers occupying a short strip of spectrum now rather than a long stretch of frequency. This Orthogonal Frequency Division Multiple Access (OFDMA) has carried data throughput and number of users to new levels, but is also slowly reaching its limit.

1.4 Motivation

nowadays, heterogeneous and stringent requirements for the 5G of the wireless communication system are imposed to equip with the fast growth of mobile internet and rapid development of IoT. For example, it is expected there will be 50 billion wireless communication devices by 2020 due to the roll-out of IoT [27]. Based on the released data from Cisco VNI Mobile Data Traffic Forecast (2015-2020), as provided in Figure 1.3, the global mobile data is expected to increase 8- fold from 2015-2020 and the data traffic predicts to reach to 30.6 exabytes per month [26]. However, spectrum resource is limited in practical systems. Therefore, the requirements for the next-generation of the wireless communication system should be upgraded to be able to handle explosive data traffic, in other words, achieving high spectral efficiency with limited spectrum is necessary. Due to the increasing demand of the Internet-of-Things (IoT) with various Quality-of-Service (QoS) requirements, the new multiple access technologies should be capable of supporting massive connectivity of users and/or devices, which demands low latency in transmission [28] . According to [29], "Leading the world to 5G", conducted by Qualcomm Technologies Inc., in addition to the requirements as stated above, deep and universal coverage is also one of the needs in 5G networks, which means the new qualified multiple access technologies are encouraged to reach challenging locations. Therefore, guaranteeing user fairness is required in the 5G networks and the weak users in the system should be considered as important as other users, instead of ignoring them. As a result, NOMA has been considered as a promising candidate for the 5G mobile networks to fulfil these stringent requirements. In fact, various industrial companies, such as Huawei technologies and NTT DOCOMO, are pushing this technology into the standard of 5G. So, there is an emerging need in.

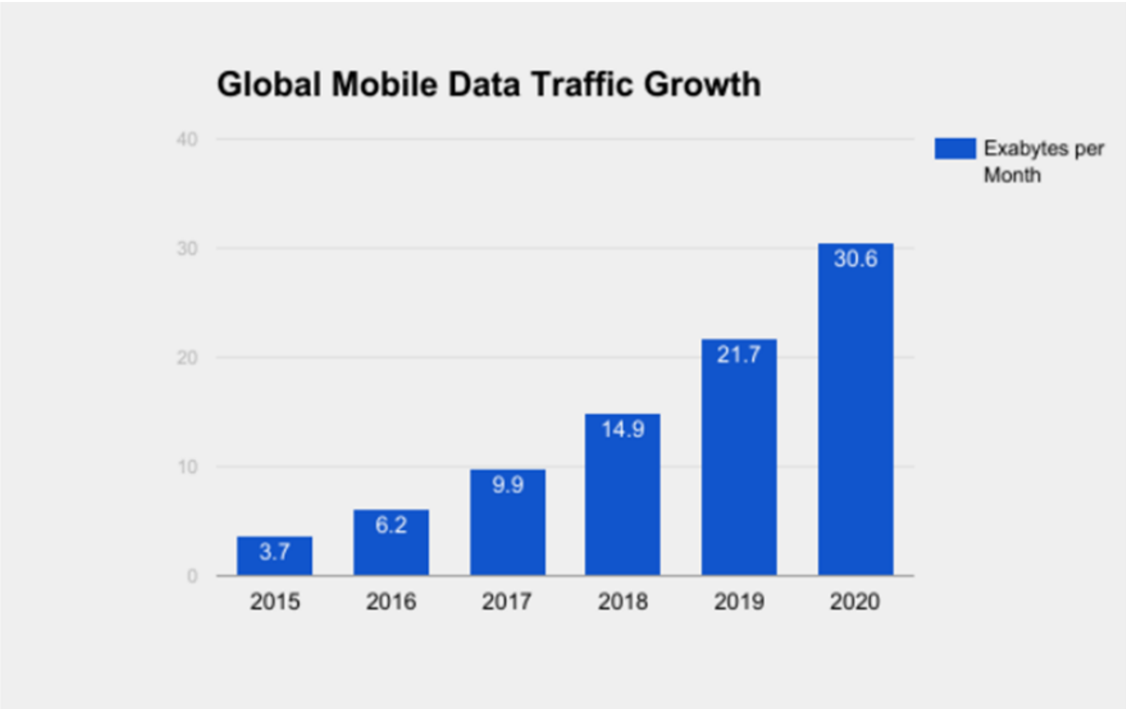

Figure 1.3 Global mobile data growth presented by histogram**.**

studying NOMA. Unfortunately, NOMA is yet to become a mature and qualified multiple access technology. There are various fundamental issues in practical implementation. For instance, one critical problem in NOMA scheme is that its system performance is sensitive to resource allocation [30]. However, the efficient algorithm is still unknown at this point in the literature on studying NOMA,based on [25] .

1.5 Advantages of NOMA

Compared to OMA, some of the key advantages offered by NOMA are summarized as follows:

1- High Spectral Efficiency*:* Since it can serve multiple users by employing the same resource block, NOMA is highly spectrum-efficient, and hence, improves the system throughput.

2-Massive Connectivity*:* Massive IoT is in reference to massive scale, billions of devices, objects and machines that need connectivity even in the most remote locations. The 5G and Beyond are expected to support this massive connectivity and NOMA can fulfill the expectation in some scale. Since the number of supportable NOMA users/devices is not strictly limited by the number of available orthogonal resources, NOMA is capable of serving them by using less resources.

3-Improved User Fairness: The power allocation of NOMA allows a system to perform a tradeoff between fairness among users and throughput [34]. Therefore, if an appropriate power allocation is adopted, the cell-edge users can also enjoy higher data rates while maintaining the system throughput.

4-Low latency: OMA depends on access-grant requests — an uplink user first has to send a scheduling request to the BS. The BS then sends a clear signal to the user in the downlink channel. The access-grant process thus increases latency (even with additional signaling overhead), which is not desirable on the next generation connectivity. Additionally, with massive connectivity, orthogonal pilots do not suffice and the access-grant procedure becomes even more complex. In contrast, grant-free multiple access can be realized in uplink NOMA schemes by blindly detecting active users and decoding their data streams [35]. The grant-free NOMA thus comes with reduced latency. Further, it should be mentioned that a reduction in latency can be obtained, as multiple users are simultaneously served in NOMA.

1.6 Applications

• Visible Light Communication: Similar performance gains as seen in the RF case can be expected if NOMA is implemented in VLC. As the channel generally does not change most of the time, the decoding becomes simpler.

• MIMO-NOMA: The combination of MU-MIMO which allows multiple beams and NOMA within a single beam can lead to a greater capacity of the system.

• Internet of Things: The scenario in IoT is massive connectivity. Exploitation of Non-Orthogonal resources as a means to enhance connectivity is subject to research.

• SoDeMA: Software Defined Multiple Access is an active research area where the best multiple access scheme is chosen based on the conditions of the system. For example, if we only have a small number of users and they do not have a large variance in SNR, OMA would be preferrable to NOMA. Similarly, different scenarios call for different multiple access schemes.

1.7 The Aim of This Project

The goal of this project is to make a comparison between NOMA technology and OMA technology in the energy field and prove that NOMA is better than OMA in spectral efficiency, BIT transmission rate, capacity, and user fairness through mathematical equations and creating illustrative charts in MATLAB.

Chapter 2

previous studies

2.1 M.TECH SEMINAR REPORT ON NON ORTHOGONAL MULTIPLE ACCESS Presented by ABHAY MOHAN

Non Orthogonal Multiple Access (NOMA) is a multiple access scheme proposed for future radio access, particularly for 5G cellular networks. Traditionally, wireless communication relied on orthogonality in the frequency, time, or code domains to separate users, but NOMA challenges this by multiplexing users in the power domain. In NOMA, the base station transmits signals with different power levels to multiple users in the same frequency band. It allocates less power to users near the base station and more power to those farther away, enhancing resource utilization and increasing user throughput by about 38%. The seminar focused on the concept of NOMA and practical considerations such as signaling overhead, power allocation, and interference cancellation.

NOMA has several advantages, including improved capacity, frequent scheduling, improved fairness, and enhanced spectral efficiency. It also supports massive connectivity and has applications in visible light communication, MIMO-NOMA, and the Internet of Things. Active research areas include power allocation, sum rate maximization, optimal user pairing, and energy-efficient resource allocation. Nevertheless, NOMA faces practical challenges, such as signaling overhead, multi-user power allocation, SIC error propagation, and performance in low and high mobility scenarios. The system requires efficient energy harvesting mechanisms and advanced analog-to-digital converters to mitigate challenges associated with error propagation and signal quantization. Despite these challenges, NOMA is considered a promising technology that is expected to play a critical role in shaping 5G wireless networks and beyond.

The technology has achieved several milestones, including theoretical work on superposition coding, the development of successive interference cancellation (SIC) schemes, and its inclusion in 3GPP Release 13 for study and development. Looking ahead, future research will focus on optimizing power allocation, enhancing performance under various scenarios, and developing software-defined multiple access (SoDeMA) for selecting the best multiple access scheme based on system conditions. Overall, NOMA offers significant potential for advancing wireless communication and network capacity in the era of 5G and beyond.

2.2 Non-Orthogonal Multiple Access (NOMA) for 5G Networks

The provided document introduces the concept of non-orthogonal multiple access (NOMA) and its potential application in 5G networks. It begins by highlighting the limitations of current cellular networks that implement orthogonal multiple access (OMA) techniques, such as time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA). NOMA, however, operates differently by allowing multiple users to access the same band and time through power level distinctions, enabling a more efficient use of spectral resources. The chapter delves into the technical aspects of NOMA for both downlink and uplink channels, discussing the power allocation, interference cancellation, and the impact of imperfect receivers.

Furthermore, the document explores the implications of imperfectness in NOMA systems and evaluates the spectral efficiency (SE) and energy efficiency (EE) of NOMA compared to conventional OFDMA. It presents MATLAB code for visualizing rate pairs and the trade-off between energy efficiency and spectral efficiency for NOMA and OFDMA. The results demonstrate that NOMA outperforms OFDMA in terms of sum capacity, energy efficiency, and spectral efficiency, positioning it as a strong candidate for future 5G networks. However, the document also acknowledges the existing challenges in implementing NOMA, such as the need for high computational power, power allocation optimization, and the sensitivity of the successive interference cancellation (SIC) receiver to cancellation errors.

In summary, the document provides a comprehensive overview of NOMA, emphasizing its potential advantages over traditional multiple access schemes in the context of 5G networks. It also highlights the need for further research and development to address the challenges associated with the practical implementation of NOMA.

2.3 Uplink Power-Domain Non-Orthogonal Multiple Access (NOMA): Bit Error Rate Performance with Channel Estimation Errors

The document explores the bit error rate (BER) performance of uplink power-domain Non-Orthogonal Multiple Access (NOMA) with channel estimation errors, focusing on BPSK, QPSK, and 16-QAM modulation schemes. The study aims to investigate the impact of modulation level on the SIC receiver BER. The paper delves into the significance of NOMA in 5G cellular systems, emphasizing its potential to enhance spectral efficiency, latency, reliability, and connectivity. It also discusses the use of power-domain NOMA in the uplink, where different users share the same time, frequency, and power levels, employing a Successive Interference Cancellation (SIC) technique at the base station receiver. The main contributions of the study include a simulation-based analysis of the BER performance for different modulation schemes under perfect channel estimation and with channel estimation errors. The simulation results reveal the effects of modulation level and channel estimation errors on the BER, demonstrating that increasing the modulation level escalates the SIC receiver BER, and higher channel estimation errors lead to degraded BER performance.

The paper's conclusion summarizes the findings of the simulation study, highlighting the impact of modulation level and channel estimation errors on the SIC receiver BER performance. It emphasizes that the BER of the SIC receiver increases with higher modulation levels and channel estimation errors. The study provides detailed insights into the performance of uplink NOMA systems, shedding light on the implications for different modulation schemes under ideal channel estimation and with estimation errors. Additionally, the document references various technological advancements and research initiatives related to NOMA, such as cooperative NOMA schemes and power allocation strategies for data rate optimization. The authors Faeik T. Al Rabee and Richard D. Gitlin have extensive experience in wireless systems, networking protocols, and multiple access techniques, positioning them as knowledgeable contributors to the field of 5G wireless communications and IoT networks. Overall, the study offers valuable insights into the BER performance of uplink NOMA systems, contributing to the ongoing research efforts in advancing wireless communication technologies and addressing the challenges of 5G cellular systems.

In conclusion, the document provides a comprehensive examination of the BER performance in uplink power-domain NOMA systems, offering valuable insights into the impact of modulation levels and channel estimation errors. The findings of the simulation study contribute to the understanding of NOMA's potential in enhancing 5G cellular systems, providing a foundation for further research and development in wireless communication technologies.

2.4 Pilot Contamination Attack Detection for NOMA in 5G Mm-Wave Massive MIMO Networks

The document discusses the detection of pilot contamination attacks (PCA) in non-orthogonal multiple access (NOMA) communication systems, focusing on both static and dynamic environments. In the static environment, the proposed scheme utilizes the sparsity of the virtual channel to distinguish between normal and PCA states. By estimating the number of peaks in the virtual channel, a binary hypothesis test is formulated, achieving a high detection rate of above 95% with a false alarm rate of 10^(-4) when the number of multipaths is 5. The simulation results also demonstrate that the detection performance improves as the length of the estimated virtual channel increases and with higher signal-to-noise ratios (SNRs). In the dynamic environment, a machine learning-based detection framework is discussed, involving peak estimation, feature selection, and an optimization model considering detection accuracy and delay. The proposed framework leverages a pseudo-attack model to transform the PCA detection into a binary classification problem, enabling the establishment of a binary classifier to detect PCA in NOMA. Additionally, an optimization model is presented to jointly minimize misclassification error and detection delay, achieving high detection accuracy while minimizing the detection delay. The computational complexity of the proposed detection scheme is also discussed, showing that it belongs to polynomial algorithms. Overall, the proposed detection schemes show promising performance in both static and dynamic environments, providing effective solutions for detecting PCA in NOMA communication systems.

Chapter 3

NOMA System

3.1 Non-orthogonal multiple access (NOMA)

We consider orthogonal frequency division multiplexing (OFDM) as the modulation scheme and NOMA as the multiple access scheme. In conventional 4G networks, as natural extension of OFDM, orthogonal frequency division multiple access (OFDMA) is used where information for each user is assigned to a subset of subcarriers. In NOMA, on the other hand, all of the subcarriers can be used by each user. Figure 1 illustrates the spectrum sharing for OFDMA and NOMA for two users. The concept applies both uplink and downlink transmission Superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver makes it possible to utilize the same spectrum for all users. At the transmitter site, all the individual information signals are superimposed into a single waveform, while at the receiver, SIC decodes the signals one by one until it finds the desired signal. The success of SIC depends on the perfect cancellation of the signals in the iteration steps. The transmitter should accurately split the power between the user information waveforms and superimpose them. The methodology for power split differs for uplink and downlink channels.

Power-Domain Downlink NOMA

Figure 1 presents a simple NOMA system consisting of a single BS and two users, each equipped with a single antenna. Suppose that $x1$ and $x2$ are the signals to be transmitted from the BS to users 1 and 2, respectively. The BS transmits the superposition coded signal as

$$s = \sqrt{P_1}\, x_1 + \sqrt{P_2}\, x_2 \tag{1}$$

where P_i, $i = 1, 2$, is the transmit power for user i and the message signal x_i, $i = 1, 2$, is of unit power, i.e., $E\{|x_i|^2\} = 1$, with $E\{\cdot\}$ as the expectation operator. The total transmit power of users 1 and 2 can then be written as $P = P1 + P2$. In practice, for a particular system setting, P is predefined and is thus divided into $P1$ and $P2$ according to the adopted power allocation (PA) scheme. The received signal at user i can be represented as

$$yi = his + ni \tag{2}$$

where hi is the channel gain between the BS and user i and ni represents the Gaussian noise plus interferences with power spectral density $N_{f,1}$. For a multi-cell scenario, the inter-cell interference is also included in ni.

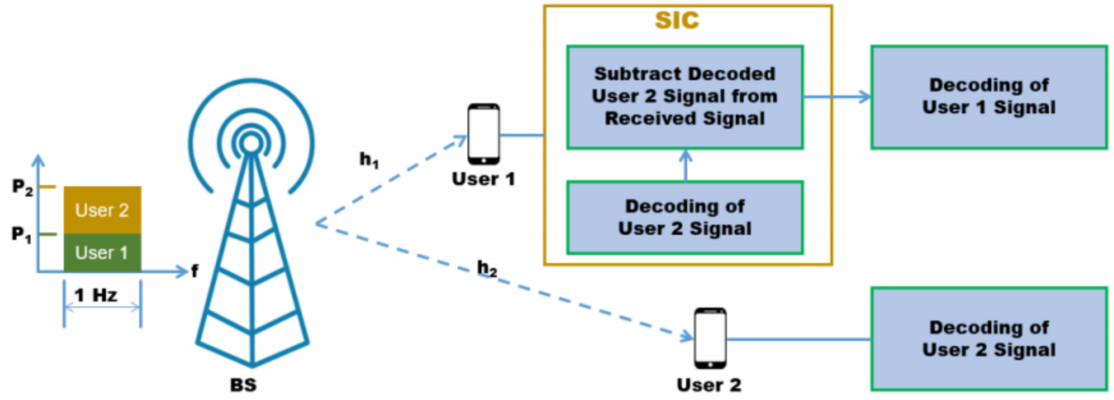

Fig 3.1 2-user power-domain downlink NOMA.

To separate different users' signals, SIC is used at the receivers. The optimal decoding order of SIC is in the decreasing order of the strengths of the users' channels, determined by $|hi|^2/N_{f,i}$. With this order, each user can substantially eliminate interferences from the signals of other users whose decoding orders appear after that user. Therefore, user 1 (with the maximum channel strength $|h_1|^2/N_{f,2}$), alternatively called the strong user, can cancel the interference from user 2 (with the least channel strength $|h_2|^2/N_{f,2}$), referred to as the weak user. It is worth noting that the BS periodically performs the SIC ordering based on the channel state information (CSI) feedback received from users, and the users get the updated information on the SIC ordering from the BS. Without loss of generality, it can be stated that a user with a weaker channel strength (i.e., weak user) is allocated higher power compared to a user with a stronger channel strength (strong user) to increase its signal-to-interference-plus-noise ratio (SINR). For the 2-user NOMA with $|h_1|^2/N_{f,1} > |h_2|^2/N_{f,2}$ (and hence $P_1 < P_2$), only user 1 performs SIC. It first decodes x_2, the signal of user 2, and subtracts it from the received signal y_1, after which it decodes its own signal. User 2 treats x_1, the signal of user 1, as noise and thus directly decodes its own signal from y_2 without SIC. If SIC is perfect, the achievable data rate of the NOMA user , R_i^{NOMA} for a transmission BW of 1 Hz can thus be written as

$$R_1^{NOMA} = \log_2 \left(1+\frac{P_1|h_1|^2}{N_{f,1}}\right) \quad (3)$$

$$R_2^{NOMA} = \log_2 \left(1+\frac{P_2|h_2|^2}{P_1|h_1|^2+N_{f,2}}\right) \quad (4)$$

The achievable sum capacity is $R^{NOMA} = R_1^{NOMA} + R_2^{NOMA}$. Equations (3) and (4) suggest that the BS can control the data rate of each user by tuning the power allocation coefficients α_1 and α_2, with $\alpha 1=\frac{P_1}{P}$ and $\alpha 2=\frac{P_2}{P}$. To get a comparative understanding of the data rate performance of NOMA and OMA, we consider the 2-user FDMA scheme sketched in Figure (3.2), where the 1 Hz transmission BW is divided for the two users — user 1 uses W Hz while user 2 uses the remaining $1 - W$ Hz of the BW and the power allocation ratio (α_1: α_2 = P_1: P_2) remains the same as for the NOMA scheme. Then, the achievable data rate of the OMA user i, R_i^{OMA} can be written as

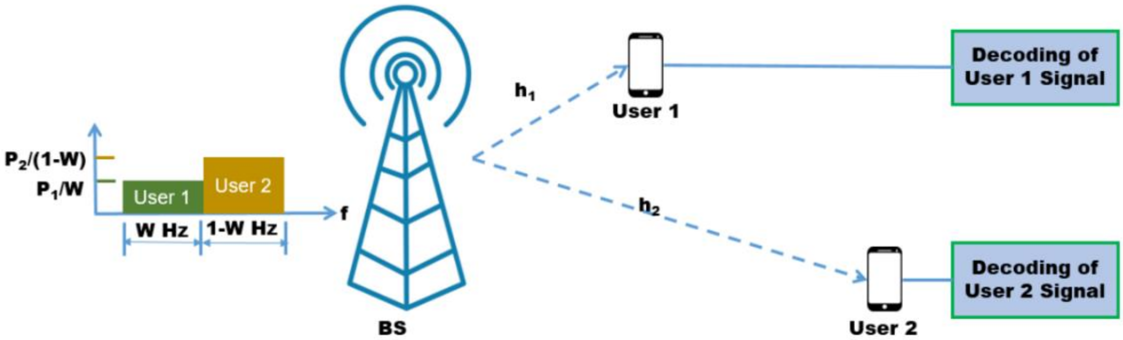

Figure 3.2 2-user downlink FDMA.

$$R_1^{OMA} = \log_2 \left(1 + \frac{P_1 |h_1|^2}{W N_{f,1}} \right) \quad (5)$$

$$R_2^{OMA} = \log_2 \left(1 + \frac{P_2 |h_2|^2}{(1-W) N_{f,2}} \right) \quad (6)$$

. Equations (5) and The achievable sum capacity is $R^{OMA} = R_1^{OMA} + R_2^{OMA}$ (6) suggest that no OMA user suffers from the interference from the signal of the other user, unlike NOMA as indicated by (4). Note that we considered asymmetric channel condition (different channel gains for users 1 and 2) to perform the above comparisons on the data rate regions. We can find that OMA and NOMA provide identical data rate regions in a symmetric channel environment multiplexing in power domain does not become advantageous as the signals of both users undergo the same interference and noise [32]. Therefore, compared to OMA, NOMA in cellular downlink provides higher sum capacity and performs a better tradeoff between system efficiency and user fairness when the channel conditions are different among users. It is demonstrated that other forms of OMA techniques including TDMA and orthogonal frequency-division multiple access (OFDMA) are also significantly outperformed by NOMA in terms of throughput under different settings [31].

As a generalization of the 2-user scenario, for a K -user downlink NOMA with ($|h_1|^2/N_{f,1} > |h_2|^2/N_{f,2} > \cdots |h_k|_2/N_{f,k} \ldots > |h_k|^2/N_{f,k}$) (and hence $P_1 < P_2 < \cdots P_k \ldots < P_k$) and 1 Hz BW, the data rate of user 1 remains the same as of (3), while the data rate of any other user k is represented as

$$R_K^{NOMA} = \mathrm{Log}_2 \left(1 + \frac{P_K |h|^2}{\sum_{j=1}^{K-1} P_j |h_k|^2 + N_{f,k}} \right) \quad (7)$$

cluster; for a large number of users, there is a degradation in the bit error rate due to error propagation primarily originated from imperfect SIC. Also, as the number of users in a cluster increases, end user devices require more computing power and higher energy, which might not be feasible in practice, especially for resource-constrained devices. Also, it is worth noting that power-domain NOMA in downlink has been standardized in the 3rd Generation Partnership Project (3GPP) LTE Release 13, referred to as multiuser superposition transmission (MUST) [33].

3.2 Imperfectness in NOMA

Our discussions so far in the previous sections assume perfect cancellation in the SIC receiver. In actual SIC, it is quite difficult to subtract the decoded signal from the received signal without any error. In this section, we revisit the NOMA concept with cancellation error in the SIC receiver.

Here, we consider the downlink only; however, the discussions can easily be extended for the uplink. Recall that SIC receiver decodes the information signals one by one iteratively to obtain the desired signal. In SIC, after decoding the signal, one should regenerate the original individual waveform in order to subtract it from the received signal. Although it is theoretically possible to complete this process without any error, in practice, it is expected to experience some cancellation error. In downlink, the SNR for the kth user with cancellation error is written as [36]

$$\mathrm{SNR}_K = \frac{P_K|h|^2}{\epsilon\sum_{j=1+k}^{K} P_j|h_k|^2 + \sum_{j=1}^{K-1} P_j|h_k|^2 + N_{f,k}} \tag{8}$$

Where ϵ is cancellation error term that represents the remaining portion of the cancelled message signal. In the previous section, the third term in the denominator is not included since perfect cancellation is assumed there.

3.3 Multiple-input Multiple-output NOMA (MIMO-NOMA)

The basic NOMA can be extended by using them in conjunction with Massive MIMO systems. The power allocation to the antennae is based on distance and direction of the user. As a result, we will have beams with possible slight overlaps directed towards different users. The inter beam interference that results is suppressed by spatial filtering, and the inter user interference can be removed using intra-beam SIC. Such a system can improve the spectral efficiency by using the large number of available antennas.

3.3.1 System model

Consider a 2 x 1 downlink MIMO system as shown in Fig. 1. Let d_1 and d_2 denote the distances of U_1 and U_2 respectively from the

MIMO transmitter. Here, we assume $d_1>d_2$. That is, U_1 is the weak user and U_2 is the strong user. We know that MIMO can be used for either spatial multiplexing (increase achievable rate) or diversity gain (decrease BER). Here, we are using MIMO for achieving diversity gain. Hence, both the transmit antennas 1 and 2 transmit the same information.

Let x_1 and x_2 denote the information intended for U1 and U2. Following the notation conventions of MIMO, let h_{rt} denote the Rayleigh fading channel between the t^{th} transmit antenna and r^{th} receiver.

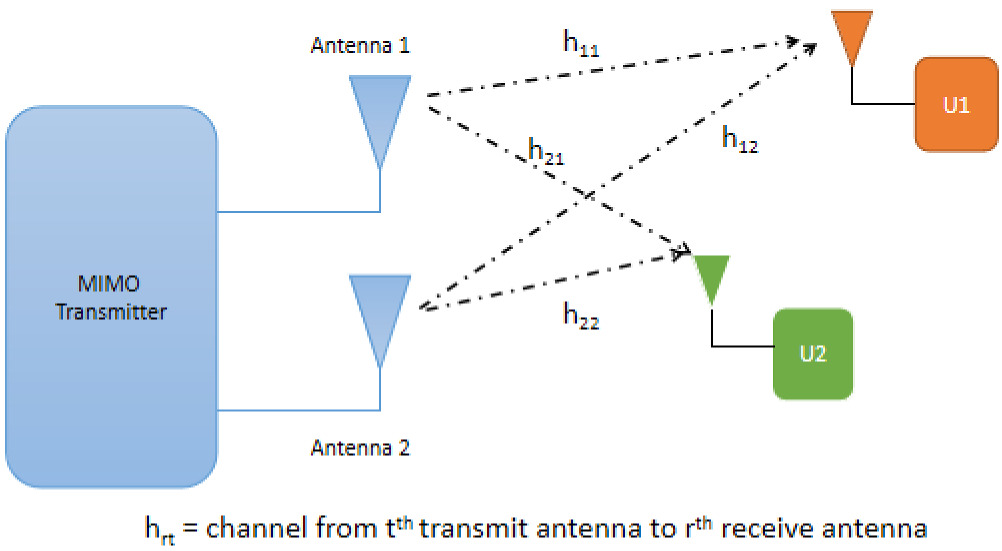

Fig. 3.3 : MIMO-NOMA system mode

Signal model

Transmit signal

Signal transmitted by both the transmit antennas are given by,

$$X=\sqrt{p}(\sqrt{\alpha_1}x_1+\sqrt{\alpha_2}x_2) \quad (9)$$

Where α_1 and α_2 are the NOMA power allocation coefficients. Since U1 is the weak user, we have $\alpha_1 > \alpha_2$

Received signals

X is transmitted simultaneously by both the transmit antennas. Therefore, the received signal at U_1 is,

$$Y_1 = xh_{11} + xh_{12} + n_1 = x(h_{11}+h_{12}) + n_1 \quad (10)$$

Similarly, the signal received by U2 is given by,

$$Y_2 = xh_{21} + xh_{22} + n_2 = x(h_{21}+h_{22}) + n_2 \quad (11)$$

Here, n_1 and n_2 are AWGN noise samples with mean zero and variance σ^2

Decoding at user 1

Now, U_1 has to decode x_1 from y_1 . Since U_1 is the weak user, his signal, x_1 is allocated more power. That is, $\alpha_1 > \alpha_2$ Therefore, he can directly decode x_1 from y_1 , treating the x_2 term as interference.

Substituting for x in **(10)**, we get,

$$Y1 = \sqrt{p}(\sqrt{\alpha_1}x_1 + \sqrt{\alpha_2}x_2)(h_{11}+h_{12}) + n_1 \quad (12)$$

Expanding,

$$Y1 = \sqrt{p}(\sqrt{\alpha_1}x_1)(h_{11}+h_{12}) + \sqrt{p}(\sqrt{\alpha_2}x_2)(h_{11}+h_{12}) + n_1 \quad (13)$$

$(\sqrt{\alpha_1}x_1)(h_{11}+h_{12})$ ……………desired$\sqrt{p}$

$(\sqrt{\alpha_2}x_2)(h_{11}+h_{12})$ …………interference.$\sqrt{p}$

Now, we can write the SINR equation for U_1 in decoding x_1 as follows,

$$\gamma_1 = \frac{P\alpha_1|h_{11}+h_{12}|^2}{\sigma^2+P\alpha_2|h_{11}+h_{12}|^2} \quad (14)$$

Therefore, the achievable rate at U_1 is given by,

$$R_1 = \log_2 (1 + \gamma_1) \quad (15)$$

Decoding at user 2

U_2 must decode x_2 from y_2 . Since U_2 is the strong user, his signal, x_2 is allocated less power. Therefore, in y_2, the power of the x_1 term will be dominating. So, U_2 will first perform direct decoding on y_2 to obtain x_1. Then successive interference cancellation (SIC**)** is carried out to remove x_1.

Then, x_2 is decoded.

Substituting for x in **(13)** and expanding, we get,

$$Y_2 = \sqrt{p}(\sqrt{\alpha_1}x_1)(h_{21}+h_{22}) + \sqrt{p}(\sqrt{\alpha_2}x_2)(h_{21}+h_{22}) + n_2 \quad (16)$$

$(\sqrt{\alpha_1}x_1)(h_{21}+h_{22})$ …………undesired &dominating$\sqrt{p}$

$(\sqrt{\alpha_2}x_2)(h_{21}+h_{22})$ ………… desired$\sqrt{p}$

The SINR at U_1 for direct decoding of x_1 is,

$$\gamma_{12} = \frac{P\alpha_1|h_{21}+h_{22}|^2}{\sigma^2+P\alpha_2|h_{21}+h_{22}|^2} \quad (17)$$

After SIC, the first term of **(16)** will be removed and the remaining signal will be,

$$= \sqrt{p}(\sqrt{\alpha_2}x_2)(h_{21} + h_{22}) + n_2 \quad (18) Y_2^{`}$$

Now, the SNR for U_2 to decode its own signal is given by,

$$\gamma_2 = \frac{P\alpha_2|h_{21}+h_{22}|^2}{\sigma^2} \quad (19)$$

Finally, the achievable rates at U_2 for decoding x_1 and x_2 are given by,

$$R_{12} = \log_2 (1 + \gamma_{12}) \quad (20)$$

$$R_2 = \log_2 (1 + \gamma_2) \quad (21)$$

3.3.2 MIMO-OMA for comparison

To see how well our MIMO-NOMA network performs, we are going to use a MIMO-OMA network as our baseline. In MIMO-OMA, let's divide our transmission into two equal time slots. In the first time slot, both th/ antennas transmit to U_1 and in the second time slot, both the antennas transmit to U_2.

Signal transmitted by both antennas in time slot 1 to U_1 is Px_1. Signal received at U_1 is,

$$Y_{1,oma} = \sqrt{p}x_1(h_{11} + h_{12}) + n_1 \quad (22)$$

Similarly, signal transmitted by both the antennas in time slot 2 to U_2 is Px_2 and the received signal at U_2 is,

$$Y_{2,oma} = \sqrt{p}x_2(h_{21} + h_{22}) + n_1 \quad (23)$$

The SNRs at U1 and U2 are, $\gamma_{1,oma} = \frac{P|h_{11}+h_{12}|^2}{\sigma^2}$

and $\gamma_{2,oma} = \frac{P|h_{21}+h_{22}|^2}{\sigma^2}$

Therefore, the achievable rates of MIMO-OMA for U_1 and U_2 are,

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

$$R_{2,oma} = 1/2 \log_2 (1 + \gamma_{2,oma}) \quad (25)$$

The factor 1/2 in **(25)** and **(24)** is due to the fact that only half of the time slot is used for communicating to each user. (whereas in MIMO-NOMA, the entire time slot is used for simultaneous transmission to both users).

3.4 Successive Interference Cancellation (SIC)

To decode the superposed information at each receiver, Cover first proposed the SIC technique [14]. SIC is conceivable by exploiting specifications on the differences in signal strength among

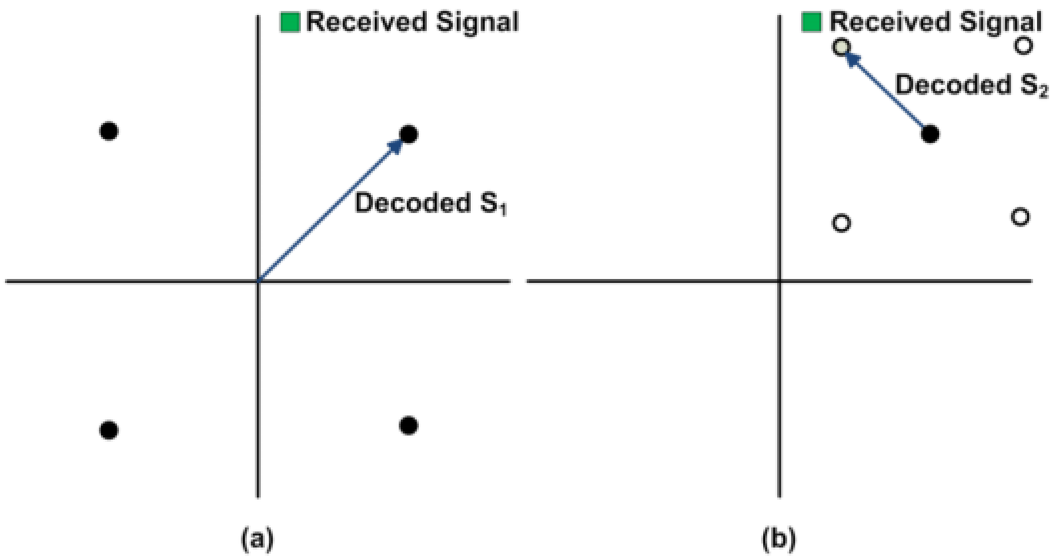

Fig. 3.4. An example of SC decoding (a) decoding the signal of user 2 (b) decoding the signal of user 1.

the signals of interest. The basic idea of SIC is that user signals are successively decoded. After one user's signal is decoded, it is subtracted from the combined signal before the next user's signal is decoded. When SIC is applied, one of the user signals is decoded, treating the other user signal as an interferer, but the latter is then decoded with the benefit of the signal of the former having already been removed. However, prior to SIC, users are ordered according to their signal strengths, so that the receiver can decode the stronger signal first, subtract it from the combined signal, and isolate the weaker one from the residue. Note that each user is decoded treating the other interfering users as noise in signal reception. Fig. 3.4 presents the technique for decoding the superposed signal at the receiving side. Here, the constellation point of user 1 is decoded first from the received signal. Then, the decoding of the constellation point of user 2 is performed with respect to decoded constellation point of user 1. To gain a deeper understanding of how SIC performs in wireless communications in general, and in OFDM (and MIMO systems) in particular, interested readers are referred to . In brief, the particular process involved in decoding the superposed messages can be mathematically expressed as follows :

1- At user 1, a single-user g_1: $c^T \rightarrow \{0,1\}^{2^{TR_1}}$ decoder decodes the message $S_1(n)$ by treating $S_2(n)$ as noise Fig (3.5).

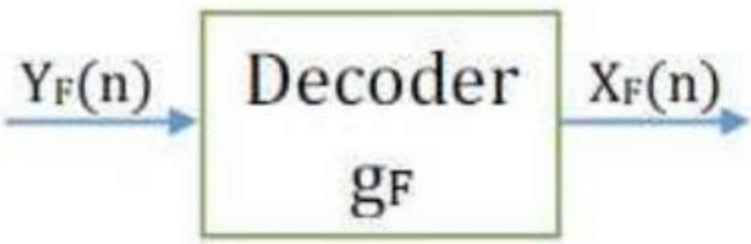

Fig 3.5: Receiver for far-UE

2- User 2 performs the following steps to successively recover its message from its received signal $Y_2(n)$:

a) Decode user 1's message $S_1(n)$ by using the single-user decoder g_1:

$c^T \rightarrow \{0,1\}^{2^{TR_1}}$

b) Subtract   from the received signal $Y_2(n)$

$Y_2^{`}(n) = Y_2(n) - \sqrt{P\beta_1}h_2 S_1(n)$

where h_2 is the complex channel gain at user 2.

c) Decode user 2's messages $S_2(n)$ by applying another single-user decoder

$g_1 : c^T \rightarrow \{0,1\}^{2^{TR_2}}$ on $Y_2^{`}(n)$

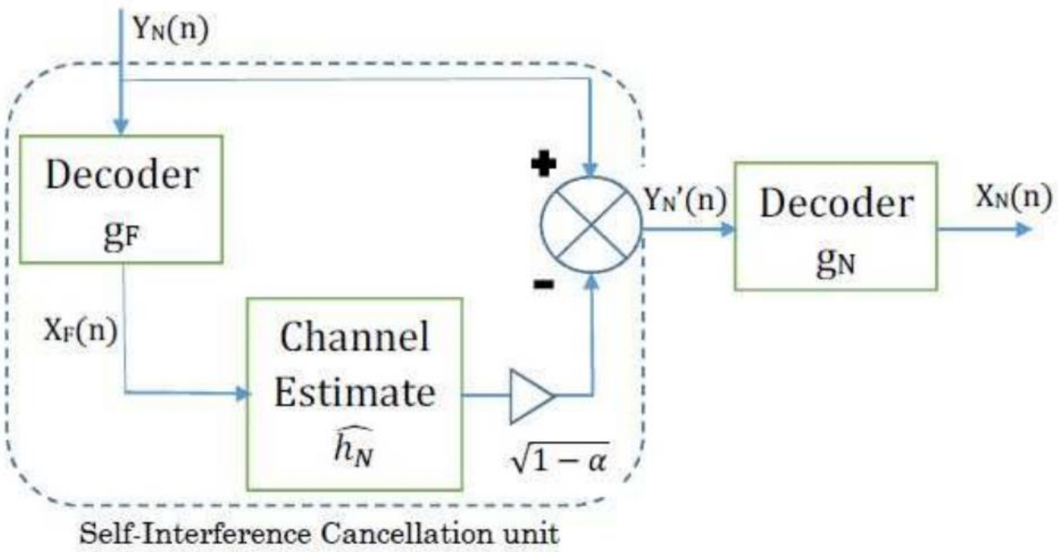

Fig 3.6: SIC receiver Near –UE

3.5 cooperative NOMA transmissions

We know that NOMA involves successive interference cancellation (SIC), where one user decodes the message of the other user, from the superposition coded received signal, before decoding his own message. Specifically, the near user decodes the information of the far user while performing SIC. There is no escaping this step. The near user must decode the far user's data anyway.

Now that the near user has far user's data, he may as well relay that information to the far user to aid him. Since the far user has a poor channel with the transmitting base station (BS), the retransmission of his data by the near user will provide him diversity. That is, he will receive two different copies of the same message. One from the base station, and one from the near user who is acting like a relay. Thus, we can expect the outage probability of far user to decrease.

This concept is called cooperative communication/cooperative relaying. We can see that NOMA naturally allows cooperative communication because the near user has the far user's data because it must decode it anyway.

3.5.1 advantages of cooperative communication

1-The advantage of cooperative communication is that we have established two links to transmit the same message. Even if one link is in outage, chances are the other link is good. The probability that both links simultaneously go into outage is very less compared to the probability that any one link fails.

2-We get reduced outage probability and hence diversity gain without the need of additional antennas (i.e., MIMO).

3-Another advantage is that relaying can virtually extend the coverage area of the base station.

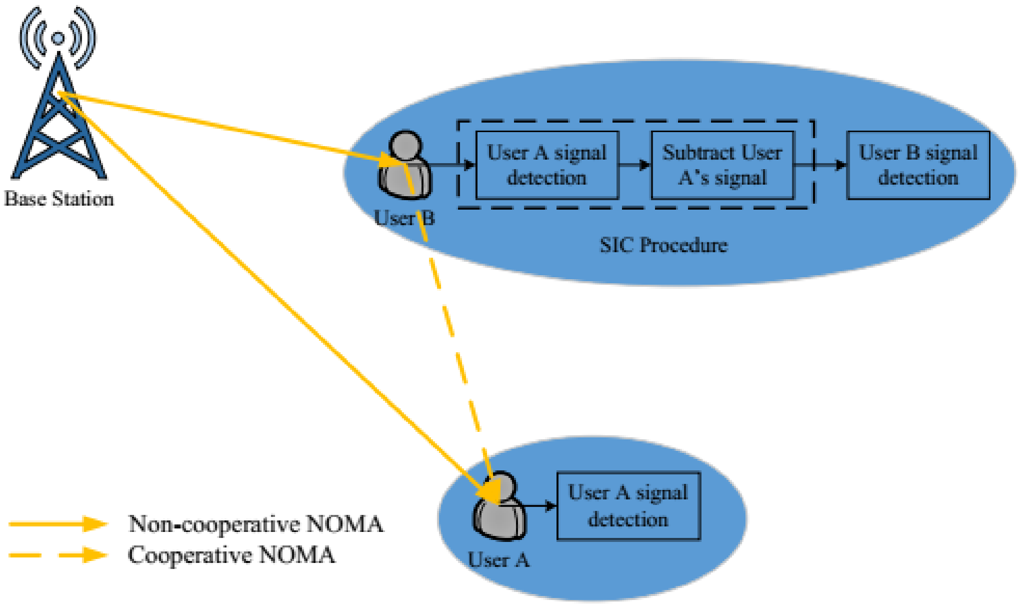

Fig. 3.7: Illustration of a two-user NOMA network that involves non-cooperative NOMA transmission without considering the cooperative phase illustrated by the dashed line.

3.5.2 System model

Now that we have seen what cooperative communication is, and how it is useful to our network, let us design a cooperative NOMA network. We are going to consider downlink transmission where there is a base station (BS) and two NOMA users. We have a near user who has a stronger channel with the BS and a far user with weak channel conditions.

The transmission occurs in two time slots. Let's call the first time slot as direct transmission slot and the second slot as relaying slot.

3.5.2.1 Direct transmission slot

In the direct transmission slot, the BS uses NOMA to transmit data intended for the near user (xn) and the far user (xf). The near user does SIC to decode the far user's data first, and then proceeds to decode its own data. The far user just performs direct decoding.

At the end of the direct transmission slot, the achievable data rates at the near user and far user are,

$$R_n = 0.5 \log_2 (1+\alpha_n \rho |h_n|^2) \quad (26)$$

$$R_{f,1} = 0.5 \log_2 (1+\frac{\alpha_f \rho |h_f|^2}{1+\alpha_n \rho |h_f|^2}) \quad (27)$$

Notation

- α_n - power allocation coefficient for near user
- α_f - power allocation coefficient for far user
- h_n - channel between BS and near user
- h_f - channel between BS and far user
- ρ - transmit SNR = Pσ2, where P is the transmit power and σ2 is the noise variance
- As usual, $\alpha_f > \alpha_n$, and, $\alpha_n + \alpha_f = 1$

We have this factor of 1/2 in front of the achievable rates because we have two time slots of equal duration and Rn, Rf are the achievable rates during the first time slot alone.

3.5.2.2 Relaying slot

The next half of the time slot is called relaying slot. As we saw, the near user already has the far user's data because he decoded it in the previous time slot. In the relaying time slot, the near user just transmits this data to the far user. The achievable rate of the far user at the end of the relaying slot is,

$$R_{f,2} = 0.5 \log_2 (1+\rho|h_{nf}|^2) \qquad (28)$$

Here, h_{nf} is the channel between the near user and far user. We can already see that $R_{f,2} > R_{f,1}$ because of two reasons:

1-There is no interference from other transmissions

2-There is no fractional power allocation. The whole transmit power is given to the far user

3.5.3 Diversity combining

Now, at the end of the two time slots, the far user has two copies of the same information received through two different channels. The far user can now use a diversity combining technique. For example, he can use selection combining to choose the copy which was received with high SNR. After selection combining, the achievable rate of the far user would be,

$$R_f = 0.5 \log_2 (1+\max(\frac{\alpha_f \rho |h_f|^2}{\alpha_n \rho |h_f|^2}, \rho|h_{nf}|^2)) \qquad (29)$$

If we did not use cooperative relaying, the achievable rate of far user would be,

$$R_{f,noncoop} = 0.5 \log_2 (1+\frac{\alpha_f \rho |h_f|^2}{1+\alpha_n \rho |h_f|^2}) \quad (30)$$

The factor of 1/2 is not here because the entire time slot will be used for transmission in non-cooperative communication. If we did not use NOMA, for example, if we use TDMA, we will allocate half of the time slot for transmission of far user data. Hence, the achievable rate of far user would be,

$$R_{f,oma} = 0.5 \log_2 (1+\rho |h_{nf}|^2) \quad (31)$$

3.6 NOMA with Beamforming.

NOMA with beamforming (NOMA-BF) can exploit the power domain as well as the spatial domain to to increase the spectral efficiency by improving the SINR. To see this, we consider a system of four users as shown in Fig. 3.8. There are two clusters of users. User 1 and User 3 belong to cluster 1, while User 2 and User 4 belong to cluster 2. In each cluster, the users' spatial channels should be highly correlated so that one beam can be used to transmit signals to the users in the cluster. For example, we can assume that h3 = ch1 for cluster 1, where hk is the channel vector from the antenna array at the BS to user k, and for cluster 2, we have h2 = c′h4, where c and c′ are constants. Furthermore, we assume that the beam to cluster 1 is orthogonal to the channel vectors of the users in cluster 2, and vice versa. That is, w1 ⊥ h2, h4 and w2 ⊥ h1, h3, where wm denotes the beam to cluster m.

Due to beamforming, the signals from one cluster to the other are suppressed. Thus, at a user in cluster 1, the received signal would be a superposition of x1 and x3, while a user in cluster 2 receives a superposition of x2 and x4, where xk is the signal to user k. As shown in Fig. 3.8, if User 3 is closer to the BS than User 1, User 3 would first decode x1 and subtract it to decode x3 using SIC. User 1 decodes x1 with the interference, x3. Clearly, conventional NOMA of two users can be applied in each cluster. In [37], this approach is studied to support 2N users in the same frequency and time slot with N beams that are obtained by zero-forcing (ZF) beamforming to suppress the inter-cluster interference. A two-stage beamforming approach is proposed using the notion of multicast beamforming in [38].

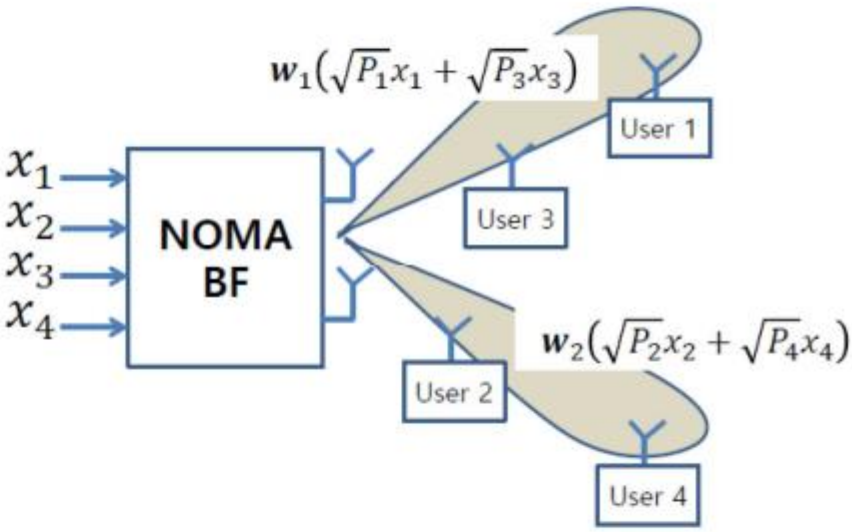

Fig 3.8 An illustration of NOMA with beamforming.

In [39], it is assumed that the users have multiple receive antennas. Thus, receive beamforming can be exploited at the users to suppress the inter-cluster interference. In this case, the BS can employ a less restrictive beamforming approach than ZF beamforming.

3.7 NOMA with Spatial Multiplexing

Unlike NOMA-BF, the purpose of NOMA with spatial multiplexing (NOMA-SM) is to increase the spatial multiplexing gain using multiple antennas. In NOMA-SM, each transmit antenna sends an independent data stream. Thus, the achievable rate can be increased by a factor of the number of transmit antennas. This requires multiple antennas at the user as well. This requires multiple antennas at the users. In [40], the achievable rate is studied for NOMA-SM. In principle, NOMA-SM can be seen as a combination of MIMO and NOMA. Recall that the achievable rate of MIMO channels grows linearly with the minimum of the numbers of transmit and receive antennas under rich scattering environments, and therefore, this scaling property of MIMO should also be valid in NOMA with spatial multiplexing. Fig. 4.8 shows the achievable rate results of NOMA-SM and OMA with different number of antennas (denoted by M) under a rich scattering environment. It is assumed that the number of antennas at the BS is the same as that at a user. The power of the channel gain of the weak user is four-times less than that of the strong user. The total powers allocated to the strong and weak users are 3 and 6 dB, respectively. For OMA, we consider time division multiple access (TDMA) with equal time slot allocation. Thus, each user's achievable rate in OMA is the same as that of conventional MIMO. However, since a given time slot is equally divided between two users, each user's achievable rate is halved. On the other hand, in NOMA, each user can use a whole time slot and have a higher achievable rate that could be two-times higher than that in OMA as shown in Fig. 4.8.

3.8 NOMA User Pairing

Since NOMA is an interference-limited system, it is practically unwise to ask all users in the system to perform NOMA jointly. In this regard, users can be divided into multiple groups, where NOMA is implemented within each group, and different groups are allocated with OMA. Clearly, the performance of this hybrid MA scheme depends on which users are grouped together. The impact of user pairing/grouping was investigated mathematically in [18]. This work demonstrates that the performance gain of NOMA with fixed power allocation over conventional OMA can be further increased by selecting users whose channel conditions are more distinctive. A two-step method for user pairing based on proportional fairness (PF) was introduced [19]. In the first step, the power allocation for each candidate user set is optimized to find the highest scheduling metric. In a subsequent step, the optimal user pair, or single user with the maximum metric, is scheduled. Since this user-pair power allocation (UPPA) technique avoids unnecessary comparison of candidate user pairs by formulating the prerequisites for user pairing, this method comes with considerably lower computation complexity compared to tree-search–based transmission power allocation (TTPA). Suppose, the upper and lower bounds of the allocated power coefficient of are and , respectively. Now, if any of the following conditions, termed the prerequisites, are not satisfied by a candidate user pair, the computation and comparison of their PF scheduling factor can be omitted. So the compared number of user pairs can be substantially reduced.

$$(32)\beta_1^u > 0 \quad \leftrightarrow \quad I_2 > \rho_0 > 0$$

$$(33)\beta_1 \geq \rho_0 I_1^{-1} \triangleq \beta_1^l$$

$$(34)\beta_1^l < 1 \quad \leftrightarrow \quad I_1 > \rho_0 > 0$$

where is the channel quality indicator (CQI) of user , and is the minimum required SINR threshold, while the modulation and coding scheme (MCS) with the lowest coding rate is selected for an expected block error rate. Eventually, the solution to the optimal power ratio provided by the two-user proportional fairness-based NOMA can be given by:

$$\acute{\beta}_1 = \begin{cases} \beta_1^* & \beta_1^l \leq \beta_1^* \leq \beta_1^u \\ \beta_1^u & R_1 < R_2 \\ \beta_1^l & others \end{cases} \quad (35)$$

where β_1^* is the solution to the modified scheduling factor . As (35) indicates, the available scheduling factor of every valid pair of users can be computed, and the largest one can be selected. A similar user set–selection algorithm is formulated based on the mathematical characteristics of the PF metric [20]. This method can also reduce the computational complexity by judging whether a user set is worth multiplexing based on a simple condition between the weakest two users within the set. Also, the impact of user pairing on the performance gain of NOMA with a MIMO system was investigated [24], demonstrating that the performance gain of MIMO NOMA over MIMO OMA increases as the number of users in each group increases.

3.9 Energy-Efficient NOMA

NOMA employs some controllable interference via non-orthogonal resource allocation and realizes overloading at the cost of slightly increased receiver complexity. Consequently, higher SE can be achieved by NOMA for 5G. Although SE shows how efficiently a limited spectrum resource is utilized, it fails to provide any insight on how efficiently energy is utilized.

With the rise in desire for green communications in recent years, reducing energy consumption has become of prime importance for researchers, and 5G has also targeted EE as one of the major parameters to be achieved. Nonetheless, Shannon's information capacity theorem illustrates that the two objectives of minimizing consumed energy and maximizing SE are not achievable simultaneously, and calls for a trade-off. It can be noted that with circuit power under consideration, there always exists an optimal point in the EE versus SE (EE-SE) curve. An energy-efficient two-user single-cell NOMA was studied in [17]. Under fixed total power consumption, the EE-SE relationship was found to be linear with a positive slope. Appropriate power allocation between two users allows achieving any point in the EE-SE curve. For a given SE for each user, maximum EE performance can be achieved. The degree of efficiency can be adjusted by varying total power using power-control schemes. If the sum rate capacity of the cell is R_{sum} with total power consumption p_{cell} , EE can be written as

$$\mathrm{EE} = \frac{R_{sum}}{P_{cell}} = SE\,\frac{W}{P_{cell}} \qquad (36)$$

Where SE is the spectrum efficiency. The EE optimization can be achieved in both single input single output and MIMO systems [21].

3.10 Resource Allocation

In order to accommodate a diverse set of traffic requirements, 5G systems should be capable of supporting high data rates at very low latency and in reliable ways. However, this is a very difficult task, since resources are limited. So, resource management has to assist with effective utilization. Wireless resource management is a series of processes required to determine the timing and amount of related resources to be allocated to each user . It also depends on the type of resources. According to the Shannon’s information capacity theorem, BW is one of these wireless resources. As a part of the effective management of the system BW in a communications system, the total BW is first divided into several chunks. Each chunk is then assigned to a particular user or a group of users, as in the case of NOMA. Also, the number of packets for each user varies over 31 time. Therefore, user-pairing and optimum power allocation among users in NOMA requires a sophisticated algorithm to provide the best performance with the usages of minimum resources. Resource allocation in NOMA can also be explored from a mathematical optimization theory point of view. For example, Lei et al. considered joint power and channel allocation for NOMA in 5G networks in [23]. They take user power control and SIC implementation into account to solve the power and channel allocation problem.

3.11 Outage Probability Analysis

Outage analysis is fundamental to understanding the performance of any wireless system. As a matter of fact, the achievable capacity depends upon the outage behavior of users. Various researchers have investigated the outage probability of the basic NOMA scheme, in general. For example, compared to OMA, less outage occurs in NOMA for users randomly deployed in a cell [15]. That analysis considered the impact of path loss. Also, it was observed that a NOMA-BF system improves the sum capacity, compared to the conventional multi-user BF system . However, when NOMA comes with beamforming, the outage probability of users will be changed. On that, outage performance analysis of NOMA-BF can be investigated. Similarly, network NOMA [17] primarily focuses on inter-cell interference mitigation by designing a precoder. But it needs explicit analysis to understand the outage behaviors of cell-edge users. Other NOMA works, for example, NOMA with VLC [22] and NOMA with coding , can be further investigated to analyze outage performance.

Chapter 4

Results

4.1 Simulation of NOMA

In Figure (4.1) , we present the data rate regions of both downlink NOMA and OMA by plotting the data rate of a user with respect to the data rate of the other user at different power allocation ratios with h_1 = 10 and h_2 = 1. As noticed, the rate region of NOMA is much wider compared to OMA. For example, if we expect the data rate of user 2 to be 1 bit/Hz, the achievable rate of user 1 for NOMA is approximately 9 bits/Hz, which is much higher than that for OMA with equal BW sharing. This is because the data rate of NOMA user 1 is bandwidth limited rather than power-limited. Although a small transmission power is allocated to user 1 compared to user 2, its high channel gain (i.e., $|h1|2/Nf,1$) and the use of SIC allows the user to take advantage of the utilization of the full BW. It is possible to increase the rate of OMA user 2 if a significant fraction of BW is assigned to this user. However, it causes a severe reduction in the data rate of OMA user 1. Moreover, as presented in Figure (4.2), we notice that NOMA significantly outperforms OMA in terms of the sum capacity irrespective of the BW allocation ratio.

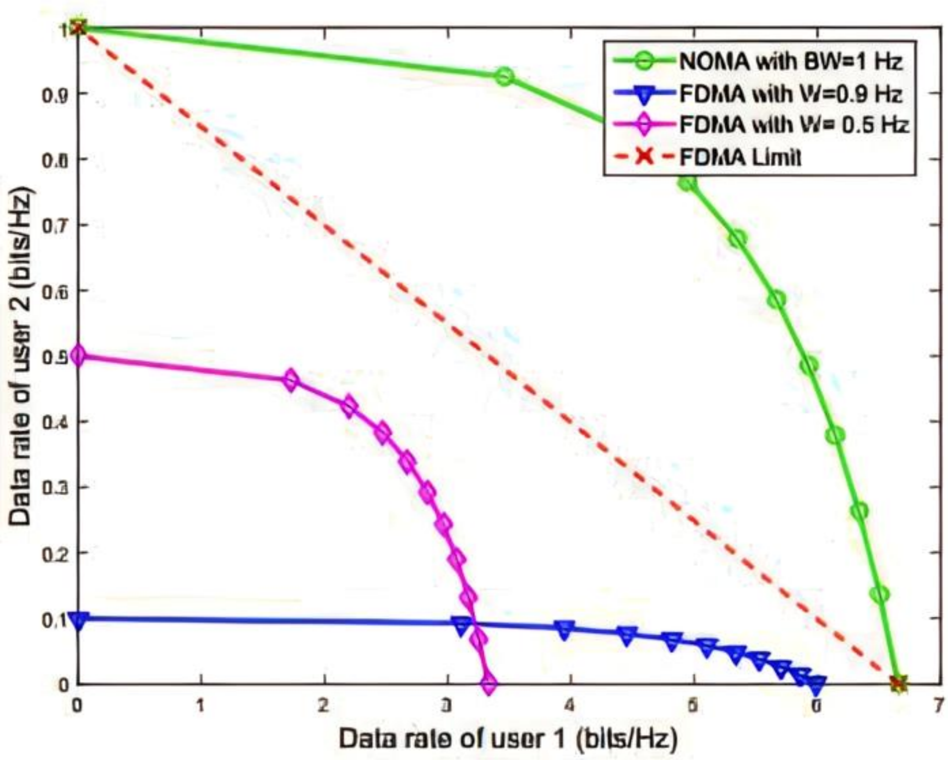

Fig 4.1. Rate region in 2-user downlink NOMA and OMA.

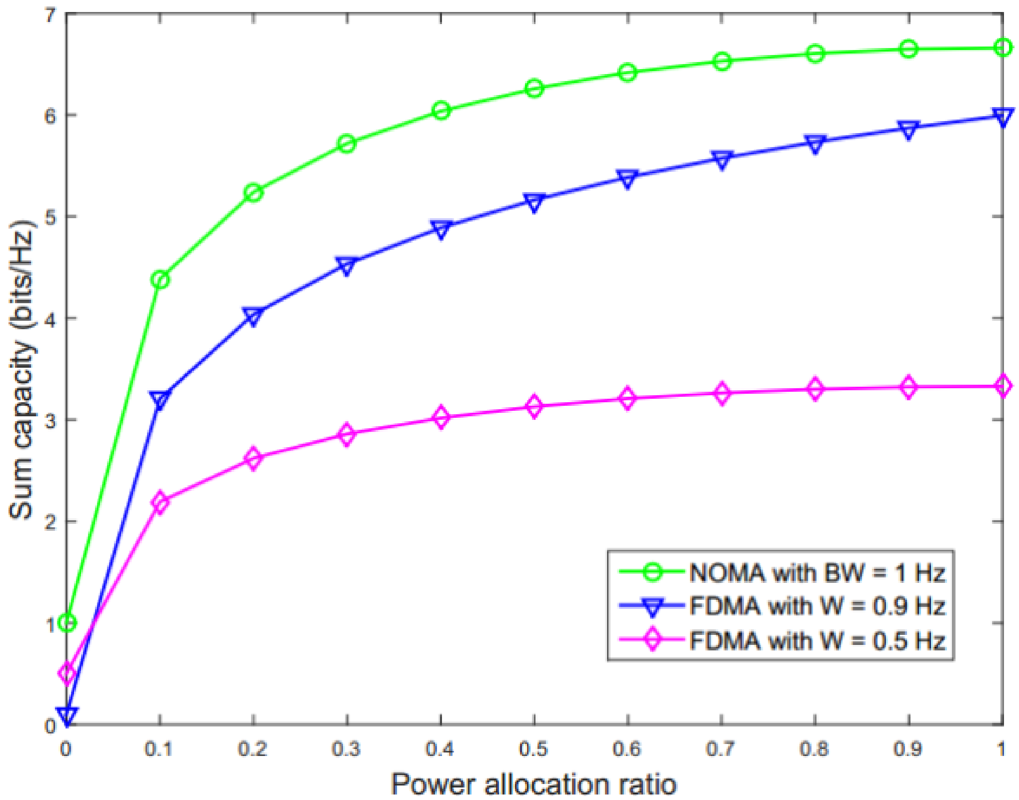

Fig 4.2. Sum capacity in 2-user downlink NOMA and OMA.

4.1.1 Impact of imperfect cancellation

In Figure (4.3), we repeat the same conditions for the asymmetric downlink channel in the previous section with imperfectness in SIC. The case for perfect cancellation is given as reference which is the same as the results in Figure (4.1). We then analyze the impact of imperfect cancellation by setting the cancellation error term (ϵ) at 1, 5 and 10%. For instance, when (ϵ) =1%, UE_1 cannot perfectly cancel the signal for UE_2 in the first iteration, and 1% of the power of the second user's signal still remains as interference. When (ϵ) =1%, the individual rate pairs and accordingly overall capacity slightly reduce. When (ϵ) = 10%, on the other hand, the reduction is more distinct.

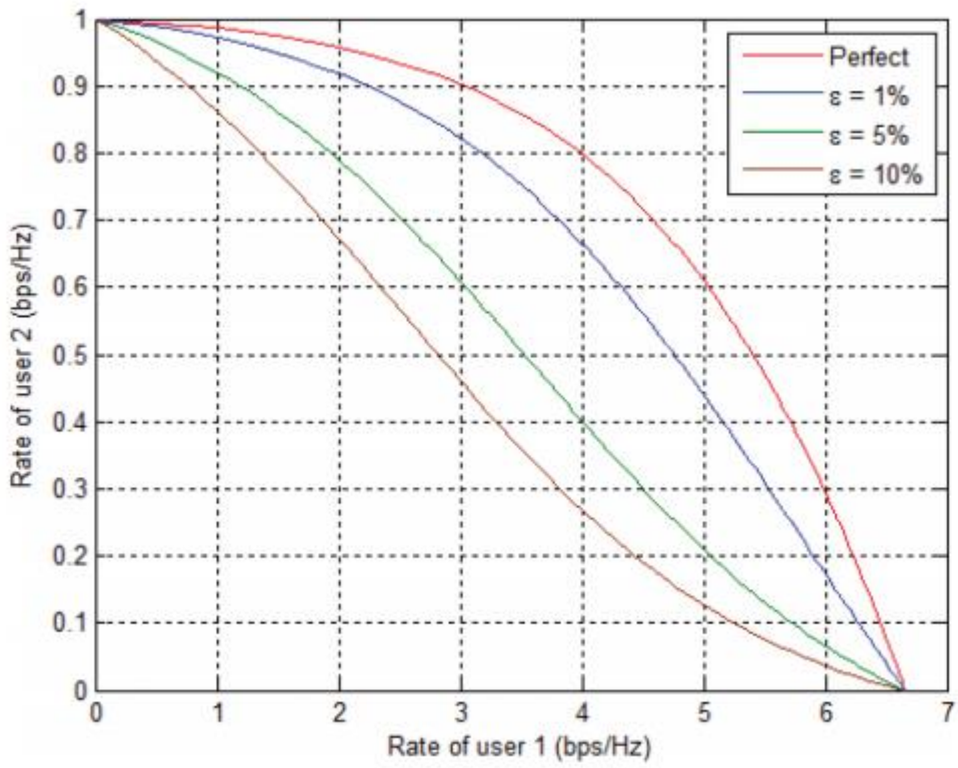

Figure 4.3 Impact of imperfect cancellation in SIC

4.2 simulation of MIMO-NOMA

In this section, let's study the sum rate and outage performance of our MIMO-NOMA network. The following simulation parameters were used: d1=500m, d2=200m. Path loss exponent, η=4. α1=0.75, α2=0.25. Bandwidth = 1 MHz.

4.2.1 Sum rates

The achievable sum rate of MIMO-NOMA is, $R_1 + R_2$ while that of MIMO-OMA is, , $R_{1,OMA} + R_{2,OMA}$

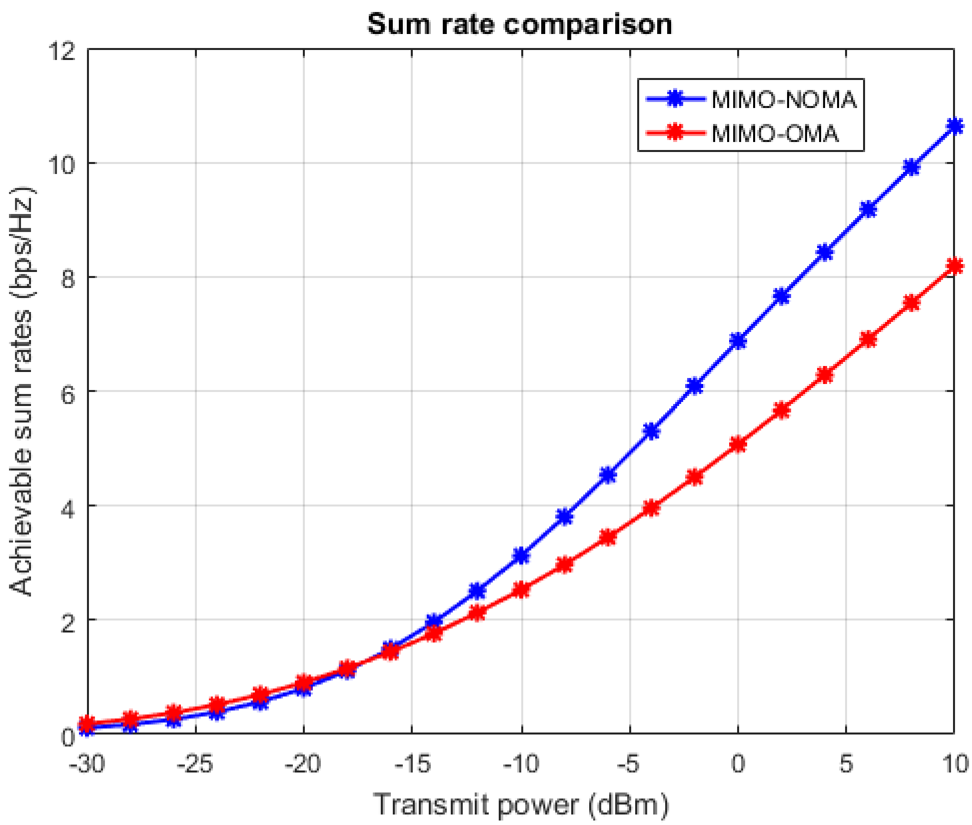

Fig 4.4. Rate region in 2-user downlink NOMA-MIMO.

It is very clear that MIMO-NOMA provides greater sum rate than MIMO-OMA, due to the fact that both users are served simultaneously with the same frequency resource.

If we plot the individual achievable rates, we get the following interesting graph:

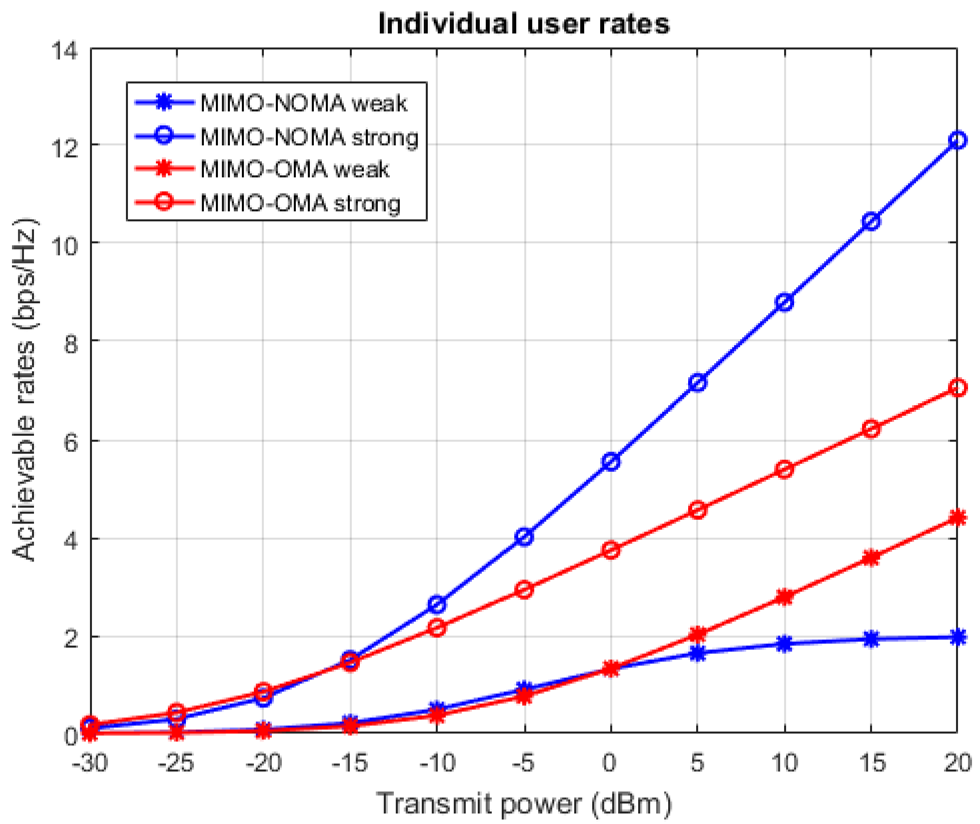

Fig 4.5 The individual achievable rates

We can notice that the weak user suffers from a saturation in its achievable rate after a transmit power of 10 dBm. This is a characteristic theme that we observe in all NOMA networks. The interference experienced by weak user translates to a saturation in its achievable rate. This saturation of achievable rate won't be a problem if the required data rate of the weak user is less than the saturation limit. This problem is not present in OMA because, the weak user does not suffer from interference due to simultaneous transmissions.

4.2.2 Outage probabilities

Next, let's plot the outage graphs of the users for both MIMO-NOMA and MIMO-OMA schemes. Since we are using fixed power allocation, it is very important to choose the target rates and power allocation coefficients properly. Let's choose the target rate for the weak user (U1) to be $R^*_1=1$ bps/Hz and that of the strong user (U2) to be $R^*_2=3$ bps/Hz.

MIMO-NOMA

The weak user (U_1) is in outage if his achievable rate, R_1 is less than his target rate, R^*_1. Mathematically, we can denote this as,

$$P^1_{NOMA} = P_r (R_1 < R^*_1)$$

The strong user must decode both U_1 's message and his own message correctly. That is, the target rates of both U_1 and U_2 must be met by the strong user. If the target rate of U_1 is not met OR if the target rate of U_1 is met but that of U_2 is not met, then U_2 will be in outage. Mathematically,

$$P^2_{NOMA} = P_r (R_{12} < R^*_1) + P_r (R_{12} > R^*_1 , R_2 < R^*_2)$$

MIMO-OMA

Outage equations for MIMO-OMA are straightforward.

$$P^1_{OMA} = P_r (R_{1,oma} < R^*_1)$$

$$P^2_{OMA} = P_r (R_{2,oma} < R^*_2)$$

The outage graph looks like this

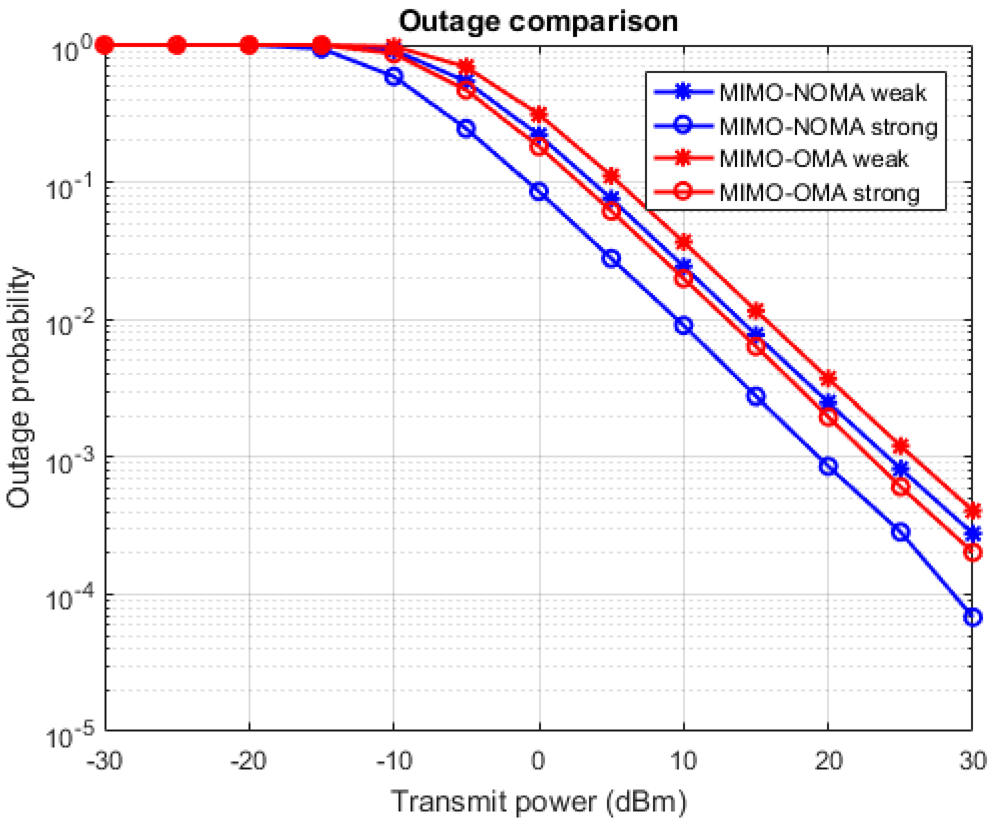

Fig 4.6 Outage probabilities

It is clear that MIMO-NOMA achieves less outage than MIMO-OMA for both the users, as expected.

4.3 cooperative communication

Now, let's simulate cooperative communication network using MATLAB and plot the outage probabilities. If we plot the outage probabilities, we get a graph like this Fig 4.7 . From this graph, we order the performances of different schemes as: cooperative NOMA > non-cooperative NOMA > OMA. So, cooperative communication is clearly beneficial.

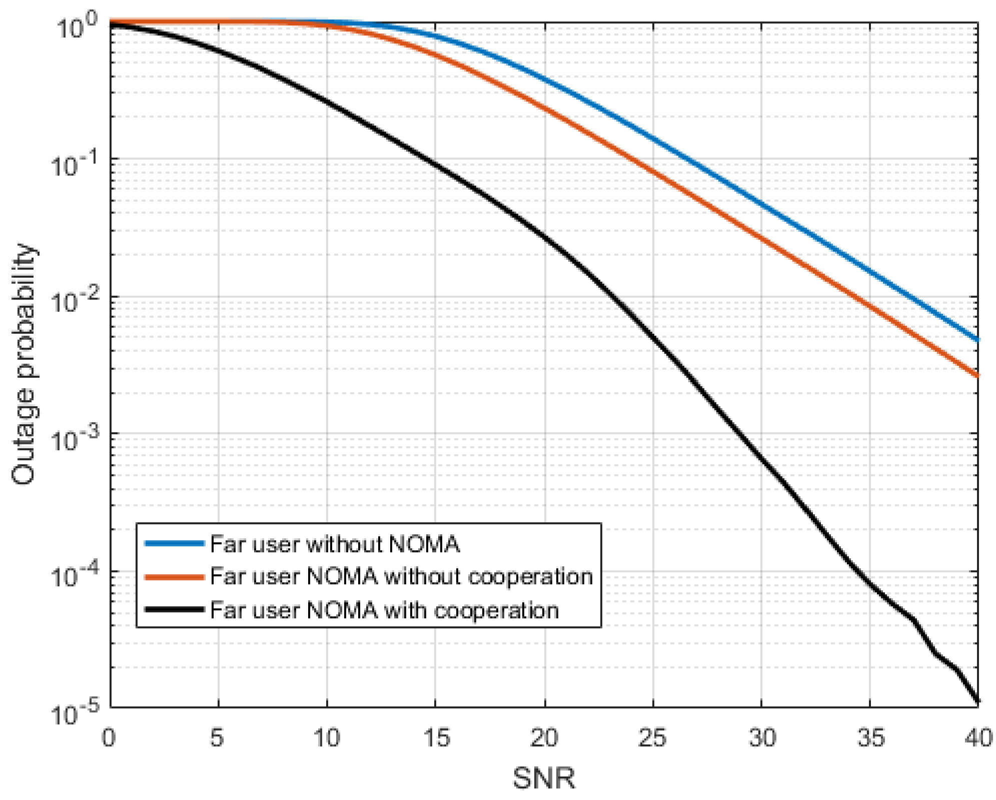

Fig 4.7 schemes cooperative communication.

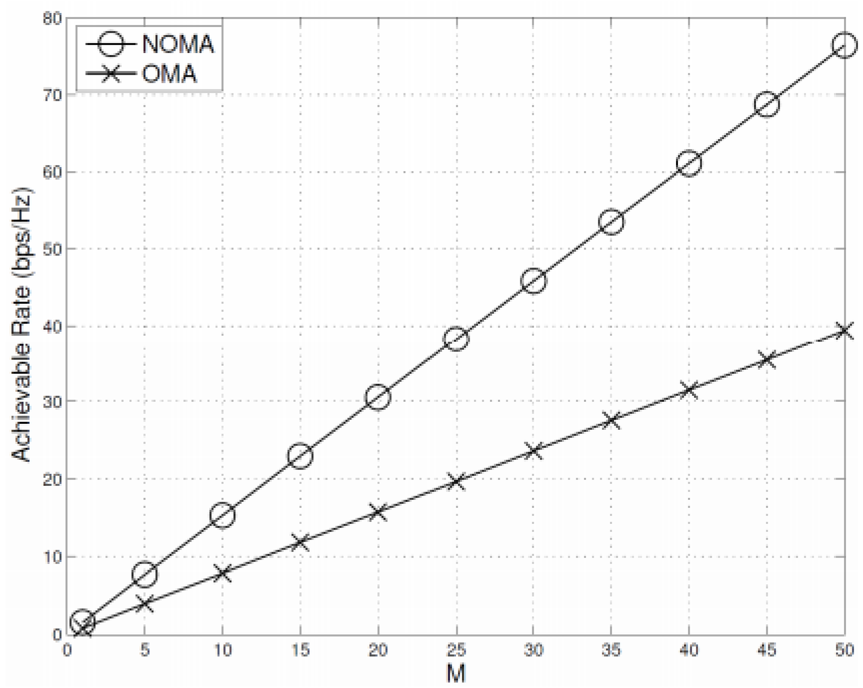

Fig 4.8 Scaling property of NOMA with spatial multiplexing.

Chapter 5

5.1. Conclusion

we have presented the fundamentals of NOMA and demonstrated its superior performance over conventional OFDMA in terms of sum capacity, energy efficiency and spectral efficiency. We have further mentioned the impact of imperfectness at the SIC receiver on the system performance. With its distinct features, NOMA stays as the strongest candidate for 5G networks and beyond. There are, however, still some challenges for successful implementation of NOMA. First of all, it requires high computational power to run SIC algorithms particularly for high number of users at high data rates. Second, power allocation optimization remains as a challenging problem, particularly when the UEs are moving fast in the network. Finally, SIC receiver is sensitive to cancellation errors which can easily occur in fading channels. It can be implemented with some other diversity techniques like multiple-input-multiple-output (MIMO) or with coding schemes in order to increase the reliability and accordingly reduce the decoding errors.

This search provides aoverview of the present and emerging power-domain SC-based NOMA research into 5G, and discusses NOMA performance with numerical results. It is clear that NOMA is a candidate multiple access technology for next-generation radio access. Its diversity gain originates from the power domain of the signals to be transmitted in a superposed fashion. Many research results have been found in favor of NOMA in terms of outage probability, achievable capacity, weak users' rate guarantees, and cell-edge user experiences. In addition to perfect SC at the transmitter and error-free SIC at the receiver, optimum power allocation, QoS-oriented user fairness, appropriate user pairing, and good link adaptation are also required to obtain the maximum benefits offered by NOMA. In addition, this search discusses how NOMA works with various standard wireless technologies, including cooperative communications and MIMO.

5.2 Future work

For multiple users pairing and power allocation problems, it is much more complex. For example, when applying SIC, user with good channel condition need to decode several other user signals and remove them from the original signal to achieve high data rate. While, it will consume more circuit on decoding, as the simulation result shows the circuit power consumption is a big influence against energy efficiency. Therefore, there is a tradeoff between reducing the circuit power consumption and maximizing data rate at the same time, which need to do further analysis.

In addition, another future direction is to design a computational resource allocation algorithm including beamforming design, user scheduling design and successive interference cancellation order design.

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