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THESIS

Performance of a Wireless Network with Non-Orthogonal Multiple Access and Energy Harvesting

Presented by:
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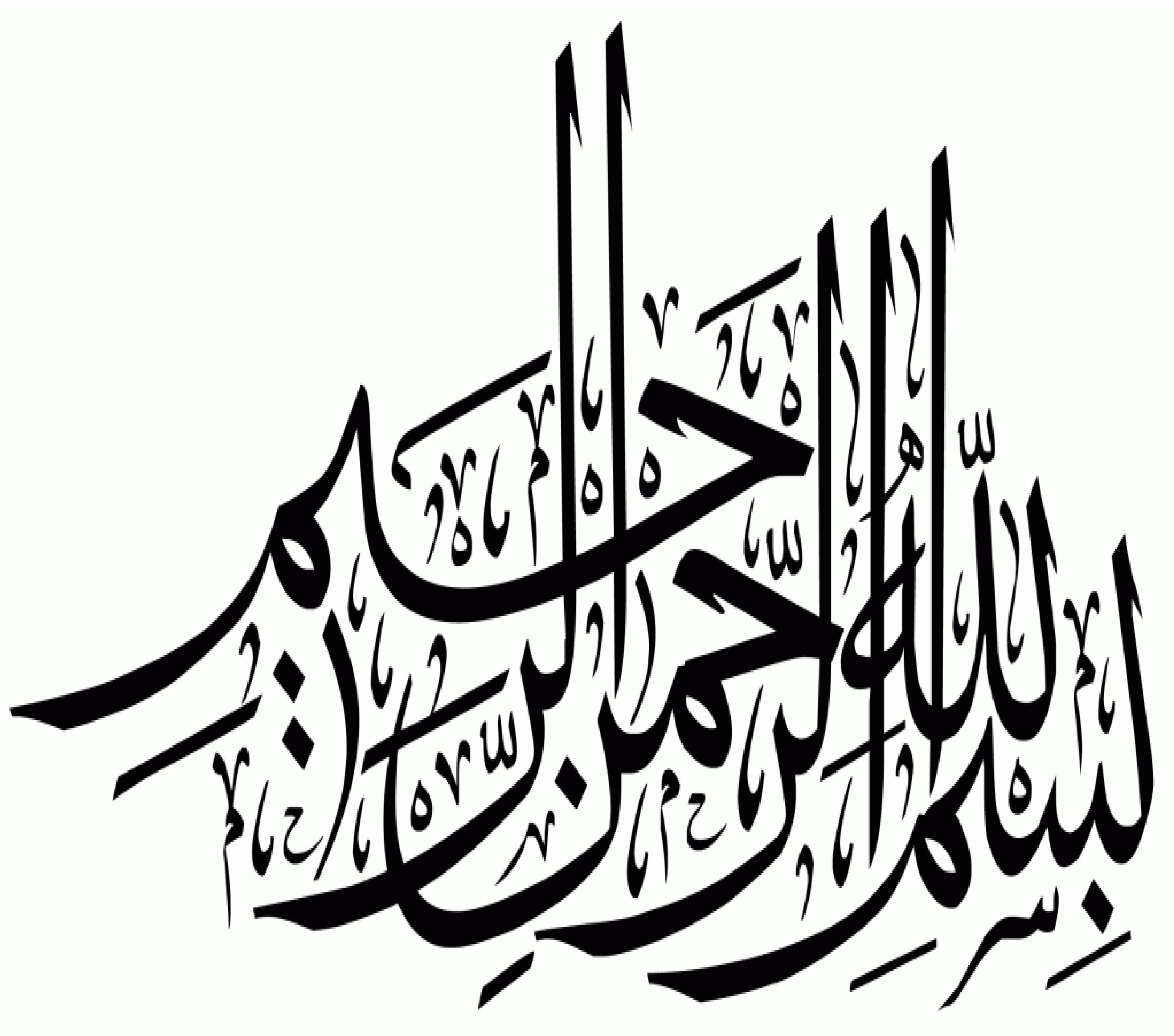
بسم الله الرحمن الرحيم

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Dedication

To my beloved ***father*** *and* ***mother****, whose unconditional love, endless support, and countless sacrifices have been the foundation of my success. Your unwavering belief in me and your guidance have shaped the person I am today. This achievement is a testament to your enduring influence in my life.*

To my dear ***brothers*** *and* ***sisters****, who have always stood by my side, offering their encouragement, motivation, and inspiration throughout this journey. Your presence has been a constant source of strength and joy.*

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and to my precious ***sons (****siradjeddine, zakaria, djaoued) the light of my life and my greatest motivation. May this achievement inspire you to always pursue knowledge, dream big, and strive for excellence in everything you do.*

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1. M. Atrouche, M. Belattar, and R. Bouchebbat, « **Optimized User Pairing and Fairness-Driven Power Allocation for Enhanced Hybrid NOMA Downlink Performance**” International Journal on Communications Antenna and Propagation (I.Re.C.A.P.), Vol. 14, N.4, August 2024, DOI: https://doi.org/10.15866/irecap.v14i4.24797.

2. M. Belattar, C. Soumali, and M. Atrouche, «**Non-Orthogonal Multiple Access Technique Performance Characterization in Downlink Network**” International Journal on Communications Antenna and Propagation (I.Re.C.A.P.), Vol. 12, N. 5 ISSN 2039 – 5086 October 2022.
3. M. Belattar, C. Soumali, and M. Atrouche, « **Analysis of Fair-NOMA Power Allocation: A Comparative Study Between NOMA and OMA Systems**” International Journal on Communications Antenna and Propagation (I.Re.C.A.P.), Vol. 12, N. 6 December 2022.

International Communications

1. M. Atrouche, S. Ayad, and B. Mounir, “**Comparative Study of Fairness and Fixed Power Allocation Algorithms: In Non-Orthogonal Multiple Access system**” IEEE 7TH International Conference on Image and Signal Processing and their Applications (ISPA), May 2022, Mostaganem, Algeria.

2. M. Atrouche, M. Belattar, and R. Bouchebbat, **“Exploring the Security Implications of Vehicular Networks in a NOMA-Based Intelligent System”**4th International Conference on Advanced Engineering in Process Intelligence 28-30 November 2023- Skikda-Algeria.

3. M. Atrouche, M. Belattar, “**Capacity and Bit Error Rate in Power allocation at NOMA versus OMA in 5G networks**” Fourth International Conference on Technological Advances in Electrical Engineering (ICTAEE’23.) may 23-24 2023.

4. M. Belattar, C. Soumali, and M. Atrouche, “**Performance of NOMA-Based Downlink Satellite-ground Network Under Nakagami-m Fading Distribution**” IEEE Fifth International Conference on Electrical Engineering and Control Applications, ICEECA’22, November 15-17th, 2022

5. S. Ayad, M. Atrouche **“The Impact of the Power Allocation coefficients and Imperfect SIC in PD NOMA Technique”** IEEE Fifth International Conference on Electrical Engineering and Control Applications ICEECA’22, November 15-17th, 2022.
6. M. Belattar, C. Soumali, and M. Atrouche, “**Analysis of Non-Orthogonal Multiple Access Technique Performance Using Nakagami-m Fading Distribution**” IEEE International Conference on Electrical, Computer and Energy Technologies (ICECET 2022) 20-22 July 2022, Prague-Czech Republic.

National Communications

1. M. Atrouche, M. Belattar, “**Performance Improvement of Non-Orthogonal Multiple Access systems in a fifth-generation wireless network with fair Power allocation algorithm**” 2ème Conférence Nationale sur les Télécommunications et ses Applications (CNTA’22), Ain-Témouchent, Algérie.

2. M. Atrouche, M. Belattar, **“Safety of industrial systems operation with Non-Orthogonal Multiple Access systems in a fifth-generation wireless network by Fairness Power allocation”** Conférence Nationale Sur le Contrôle et la Sécurité des Systèmes Industriels 05-06 Octobre 2022 Skikda-Algérie.

3. S. Ayad, M. Atrouche “**The Influence of Modulation Techniques on the Performance of NOMA Systems using Fixed Power Allocation Algorithm**” 2ème Conférence Nationale sur les Télécommunications et ses Applications (CNTA’22), Ain-Témouchent, Algérie.

4. M. Atrouche, M. Belattar, and R. Bouchebbat **“Safety and Efficiency in Industrial Systems : Leveraging NOMA for Environmental Monitoring”** 3ème Conférence Nationale Sur le Contrôle et la Sécurité des Systèmes Industriels 25-26 Novembre 2024 Skikda- Algérie.

5. M. Atrouche, M. Belattar, and R. Bouchebbat **“Revolutionizing Wireless Access: NOMA for Massive Connectivity in IoT”** 2nd National Conference on Electronics, Electrical Engineering, Telecommunications, and Computer Vision (C3ETCV’24), Held in Abdelhafid Boussouf University Centre of Mila, November 2024, Algeria.

Supervision of Bachelor's Final Year Projects (Licence)

1. Etudes des performances des systèmes de relais OMA et NOMA et comparaison entre les deux systèmes.
2. Etude, conception de convertir l'énergie des ondes électromagnétique au courant continué à baser d'un rectenna.
3. Etudes des performances de l'internet des objets appliquent pour contrôles les patients à domicile.
4. Etude et réalisation d'un système RFID pour détection et réduire l'énergie.
5. Etude de modélisation de déploiement des antennes HUF et VHF par des méthodes thermiques.
6. Etudes et simulation de transmission des données par code mors.
7. The role of relaying network coding in 5G wireless network.

Assistant Supervision of Master's Final Year Projects

1. Etudier proportionnelle dans les réseaux sans fil NOMA (5G) de liaison descendante.

Abstract

With the rapid advancement of wireless communication technologies and the increasing demand for high-quality services, communication networks face significant challenges in efficiently utilizing the available spectrum. These challenges include increasing network capacity, enabling massive connectivity, enhancing data rates, reducing latency, and minimizing spectrum bandwidth requirements. Traditional approaches, such as Orthogonal Multiple Access (OMA), allocate dedicated resources to each user. However, as the number of users increases, OMA suffers from efficiency limitations. For this reason, the wireless communication research community has been actively exploring more advanced multiple-access technologies to improve resource efficiency. In this context, Non-Orthogonal Multiple Access (NOMA) has emerged as an innovative solution, particularly for fifth-generation (5G) and beyond networks. In this thesis, we study the performance evaluation of OMA and NOMA systems in downlink networks, focusing on performance analysis in the presence of energy harvesting. NOMA stands out by providing better data transmission rates while reducing information loss. We propose an innovative pairing strategy for a hybrid NOMA system incorporating a fair power allocation algorithm in the downlink network to enhance system performance and user satisfaction. This strategy aims to achieve high performance while ensuring fairness among users. It is evident that NOMA represents the future of wireless communications and plays a crucial role in realizing next-generation 5G and beyond.

Keywords: NOMA, OMA, H-NOMA, user pairing, Fairness Power allocation, Fifth Generation (5G) and beyond.

Résumé

Avec l'avancement rapide des technologies de communication sans fil et la demande croissante de services de haute qualité, les réseaux de communication sont confrontés à des défis importants pour utiliser efficacement le spectre disponible. Ces défis incluent l'augmentation de la capacité du réseau, la connectivité massive, l'amélioration des débits de données, la réduction de la latence et la minimisation des besoins en bande passante du spectre. Les approches traditionnelles, telles que l'accès multiple orthogonal (OMA), allouent des ressources dédiées à chaque utilisateur. Cependant, à mesure que le nombre d'utilisateurs augmente, l'OMA souffre de limitations d'efficacité. Pour cette raison, la communauté de recherche en communication sans fil explore activement des technologies d'accès multiple plus avancées pour améliorer l'efficacité des ressources. Dans ce contexte, l'accès multiple non orthogonal (NOMA) est apparu comme une solution innovante, en particulier pour les réseaux de cinquième génération (5G) et au-delà. Dans cette thèse, nous étudions l'évaluation des performances des systèmes OMA et NOMA dans les réseaux de liaison descendante, en nous concentrant sur l'analyse des performances en présence de récolte d'énergie. Le NOMA se distingue en offrant de meilleurs taux de transmission de données tout en réduisant la perte d'information. Pour améliorer encore les performances du système et la satisfaction des utilisateurs, nous proposons une stratégie de couplage innovante pour un système NOMA hybride qui intègre un algorithme d'allocation équitable de puissance dans le réseau de liaison descendante. Cette stratégie vise à atteindre des performances élevées tout en garantissant l'équité entre les utilisateurs. Il est évident que le NOMA représente l'avenir des communications sans fil et joue un rôle crucial dans la réalisation des réseaux de prochaine génération 5G et au-delà.

Mots-clés : NOMA, OMA, H-NOMA, Appairage d'utilisateurs, allocation de puissance équitable, cinquième génération (5G).

الملخص

مع التقدم السريع لتقنيات الاتصالات اللاسلكية وزيادة الطلب على الخدمات العالية الجودة، جعل شبكات الاتصالات تواجه تحديات كبيرة في الاستخدام الفعال للطيف المتاح. وتشمل هذه التحديات زيادة في سعة الشبكة، تسهيل الاتصال الواسع النطاق، وتعزيز معدلات نقل البيانات، وتقليل زمن الوصول، وتقليل متطلبات عرض النطاق الترددي. حيث تعتمد الأساليب التقليدية، مثل الوصول المتعدد المتعامد(OMA) ، على تخصيص موارد مخصصة لكل مستخدم لذلك، مع زيادة عدد المستخدمين، يعاني الوصول المتعدد المتعامد من قيود في الكفاءة. لهذا السبب، يبحث مجتمع الاتصالات اللاسلكية بنشاط عن تقنيات وصول متعدد أكثر تطورًا لتحسين كفاءة الموارد. وفي هذا السياق، ظهرت تقنية الوصول المتعدد غير المتعامد (NOMA) كحل مبتكر، خاصةً لشبكات الجيل الخامس (5G) وما بعدها. لهدا قمنا في هذه الأطروحة، بدراسة وتقييم ومقارنة أداء أنظمة OMA و NOMAفي شبكات الاتصالات، مع التركيز على تحليل الأداء في حصاد الطاقة. حيث أظهرت النتائج المحصل عليها تميز NOMA بتوفير معدلات نقل بيانات أفضل مع تقليل فقدان المعلومات. وتعزيز أداء النظام ورضا المستخدمين بشكل أكبر، اعتمادا على استراتيجية اقتران مبتكرة لنظام H-NOMA الهجين تتضمن خوارزمية تخصيص طاقة عادلة في شبكة الاتصال النازل. تهدف هذه الاستراتيجية إلى تحقيق أداء عالي مع ضمان العدالة بين المستخدمين. من خلال الأبحاث التي قمنا بها بذا من الواضح أن NOMA يمثل مستقبل الاتصالات اللاسلكية وسيؤدي دورًا حاسمًا في تحقيق شبكات الجيل القادم (5G) وما بعده.

الكلمات المفتاحية: OMA، NOMA،H-NOMA ، إقتران المستخدمين، تخصيص الطاقة بشكل عادل، الجيل الخامس (G5) وما بعده.

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Acronyms and Symbols

1G: First Generation
2G: Second Generation
3G: Third Generation
3GPP: 3rd Generation Partnership Project
4G: Fourth Generation
5G: Fifth Generation
BS: Base Station
CDMA: Code Division Multiple Access
FDMA: Frequency Division Multiple Access
GSM: Global System for Mobile Communications
H-NOMA: Hybrid-Non orthogonal multiple access
AI : Artificial Intelligent
MAI : Multiple Access Interference
IIoT: Industrial Internet of Things
IoT: Internet of Things
LTE: Long-Term Evolution
M: Clusters
MA: Multiple Access
MIMO: Multiple Input Multiple Output
NOMA: Non orthogonal multiple access
OFDM: Orthogonal Frequency Division Multiplexing
OFDMA: Orthogonal Frequency Division Multiple Access
LPMA: Location Division Multiple Access or Layered Partition Multiple Access
PDMA: Pattern Division Multiple Access
BOMA: Beam Division Multiple Access or Beamspace Multiple Access
SDMA: Space Division Multiple Access
OMA: Orthogonal Multiple Access
OPP: Optimal Power and Grouping Problem
PAPR: Peak-to-Average Power Ratio
PD-NOMA: Power domain NOMA
QoS: Quality of Service
QPSK: Quadrature Phase Shift Keying
RB: Resource Block

RF: radio frequency

SC: Superposition Coding

SC-FDMA: Single Carrier Frequency Division Multiple Access

SDMA: Spatial Division Multiple Access

SIC: Successive Interference Cancellation

SNR: Signal to noise ratio

SWIPT: Simultaneous Wireless Information and Power Transfer

TDMA: Time Division Multiple Access

AWGN: Additive white Gaussian noise

Mathematical Symbols and Notations:

$u_{j,i}$	Represents the j the user in the i cluster
$\sigma^2_{j,i}$	Variance [dBm/Hz]
$\left\|h_{j,i}\right\|^2$	Channel gain [dB]
$h_{j,i}$	Channel coefficient between the BS and the users
$p_{j,i}$	Power allocation [dB]
t_i	Time slote at user I [s]
$w_{j,i}$	Additive white Gaussian noise (AWGN) with zero-mean [W/Hz]
T	Transmission time [s]
p_t	Total transmitted power [dB]
R_t	The sum capacity [bit/sec/Hz]
x_1	the messages to be transmitted by near userU_n
x_2	the messages to be transmitted by far userU_f
α_i	Power allocation coefficient of the i user

General Introduction

GENERAL INTRODUCTION

The rapid development of wireless communication technologies, driven by the explosive growth of mobile devices, the need for high-speed internet, and the proliferation of the Internet of Things, have brought new challenges in various areas [1],[2]. Challenges addressed include data traffic growth, low latency, improved reliability, extended coverage acts, large connectivity support, efficient utilization of scarce bandwidth, and so on. To meet these demands, new and improved ways to make the systems capable and able to perform at a higher level are needed, especially for the new mobile world (e.g., 5G and beyond) [3],[4].

The next critical question: **How can we efficiently multiplex multiple users on the same resource block while ensuring fairness, quality of service, and minimal interference in wireless communication systems?**

To this end, the scientific community has worked on radio access technologies that create the conditions for multiple users to share available radio resources simultaneously in an efficient way. Generally, there are two classes of multiple access techniques can be utilized for these multiple access techniques which include Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) [5],[6],[7].

Existing OMA methods, e.g. FDMA, TDMA, and CDMA, have been already employed in 1G, 2G and 3G systems, respectively. Orthogonal schemes, such as SC-FDMA and OFDMA, became the cornerstone of 4G networks afterwards. However, as mobile Internet evolves rapidly and the number of connected devices grows, OMA techniques cannot accommodate large-scale connectivity due to its orthogonal resource allocation dependency [1].

To address these challenges, Non-Orthogonal Multiple Access (NOMA) has been developed as a potential technology for 5G and beyond. By using the power domain, NOMA enables multiple users to access identical resources in the frequency domain or the code domain and be separated in the power domain[6],[10]. The transmitter uses power levels to create signals, while the receiver uses Successive Interference Cancellation (SIC) to separate user signals. This significantly improves spectral efficiency, allows more devices to be supported, fairer towards users, and better data rates as well as lower latency. NOMA, which provides better spectral efficiency and scalability than traditional OMA, has been identified as one of the key technologies for future wireless communication systems [11],[12],[13].

Energy Harvesting (EH) is a technology that enables devices to capture energy from their surrounding environment from various sources including sun, thermal or radio frequency

(RF) signals. This makes it particularly useful for IoT devices and remote sensors, allowing them to run in a sustainable way without having to change or recharge the batteries very often[1],[14],[15].The period energy harvesting combined with NOMA is taken into consideration is promising for improving communication and energy transmission that is two of the greatest challenges within the common wireless communication, specifically spectrum bottleneck and power consumption.

Review of the state of the art

The integration of NOMA and Energy Harvesting (EH) technologies in wireless networks has garnered significant attention in recent research. Numerous studies have explored the performance of NOMA-EH systems, focusing on aspects such as capacity analysis, secrecy outage performance, physical layer security, resource allocation, and cooperative transmission protocols. These studies provide valuable insights into the potential of NOMA-EH systems to address the challenges of modern wireless communication.

For instance, S. Mohammad, O. Omarov, in [16] conducted a capacity analysis of wireless-powered cooperative NOMA networks over generalized fading, emphasizing the importance of considering hardware impairments in evaluating network performance, investigated the secrecy outage performance of cooperative NOMA networks with Simultaneous Wireless Information and Power Transfer (SWIPT), highlighting the role of SWIPT in enhancing network security. Additionally, The authors R. Lei, D. Xu, S. Member, and I. Ahmad, in [17] studied the outage performance of joint transmission coordinated multipoint cooperative NOMA networks with SWIPT, focusing on energy-constrained cell-center users.

In the realm of physical layer security, M. A. Germien, G. S. E. M. E. Mohamed, and M. Abd-elnaby in [18] The paper reviews NOMA for 5G and beyond, highlighting its superior spectral efficiency and resource allocation strategies like user pairing and power allocation. It explores NOMA’s integration with emerging technologies and future potential in 6G, addressing challenges like interference and complexity. The authors Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura In [7] This foundational study by Saito et al. (investigates the system-level performance of downlink NOMA in LTE-based networks. The authors demonstrate that NOMA can significantly enhance spectral efficiency and user throughput compared to traditional OMA schemes. By allowing multiple users to share the same time-frequency resources with different power levels, NOMA effectively increases the number of simultaneously served users, leading to improved system capacity.

The authors J. Li, C. W. Sung, and C. S. Chen in [19] explore a cooperative NOMA system where a near user harvests energy from the base station's transmissions and assists in relaying information to a far user. The study introduces a generalized energy harvesting scheme encompassing both power splitting and time switching methods. Performance evaluations reveal that this cooperative approach significantly improves the achievable data rate for the far user, especially under favorable channel conditions between the base station and the near user, and between the near user and the far user. The findings highlight the potential of integrating energy harvesting in cooperative NOMA systems to enhance network performance.

another approach is proposed by J. Xu and Z. Liang in [20] addresses the challenge of optimizing energy efficiency in NOMA-based IoT communications within 5G networks. The authors propose an improved particle swarm optimization algorithm to jointly optimize beam forming and power splitting ratios in a dual-user cooperative SWIPT-NOMA system equipped with full-duplex antennas. The proposed algorithm effectively balances the trade-off between computational complexity and optimization performance. Simulation results indicate that the algorithm achieves near-optimal solutions with reduced computational overhead, making it suitable for practical IoT applications in energy-constrained environments.

The authors J. He and S. Shi In [21] Recent research on NOMA-based IoT focuses on efficient user grouping and power allocation to support massive connectivity and diverse device requirements. proposed a low-complexity threshold-based grouping and bisection power allocation method, achieving near-optimal performance for space-based IoT. Compared to prior high-complexity or learning-based methods, their approach balances scalability and practicality for real-world deployment.

Overall, these studies highlight the diverse approaches and methodologies employed to enhance the performance of wireless networks with NOMA and EH technologies. They contribute valuable insights into capacity analysis, security, resource allocation, energy efficiency, and cooperative transmission protocols, paving the way for further advancements in wireless communication systems.

Research Objectives

The purpose of this thesis is to investigate the relationship between energy harvesting integration in communication systems and multiple access mechanisms, specifically NOMA. In addition to addressing the issues brought on by constrained spectrum resources and rising user demands, the study will concentrate on how these advances might work together to increase the dependability and effectiveness of wireless communications.

In particular, we will:

- Examine the benefits of NOMA over conventional OMA by contrasting the performance of different power allocation algorithms in terms of energy usage, fairness, and spectrum efficiency.
- Examine cooperative NOMA systems that use TDMA to harvest energy and compare how well they perform to OMA and pure NOMA systems.

Organization of Thesis

This thesis is organized into four chapters:

In the first chapter, we discuss a general overview of multiple-access wireless networks, which provide a foundation for wireless communication systems and their evolution.

In the second chapter, we study A Comprehensive Study of OMA and NOMA Systems: Comparative Analysis, advantages, and challenges.

In the third chapter, we do analyses and optimization of performance downlink NOMA that explore the principles, of NOMA compared to OMA.

In the fourth chapter, we analyze the performance of the downlink NOMA system with energy harvesting based on fair and fixed power allocation algorithms that we create. We compare these results with OMA.

The simulation results encourage their potential for future wireless networks.

By providing a comprehensive performance analysis, this study contributes to the understanding and potential deployment of NOMA and energy harvesting technologies, paving the way for more efficient, scalable, and sustainable wireless communication systems.

Chapter I

Overview of multiple access wireless networks

I.1 INTRODUCTION

Everything from smartphones and laptops to the Internet of Things and smart buildings needs wireless communication to tie everything together [22]. Its value comes from the flexibility, portability, and widespread coverage it gives us, liberating us from the traditional wired network ball and chain. For example, this cutting-edge technology focuses on creating innovation across various industries, including but not limited to healthcare, transportation, logistics, agriculture, and smart cities. It allows us to track and measure how humans and systems connect, revolutionizing our lives and work [23].

As the demand for wireless services continues to grow exponentially, driven by the proliferation of connected devices and data-intensive applications, the efficient management of the shared communication medium has emerged as a critical challenge. The finite nature of the wireless spectrum, coupled with the increasing density and heterogeneity of networks, necessitates advanced techniques to optimize resource allocation and mitigate interference. Multiple-access techniques, such as FDMA, TDMA, Code Division Multiple CDMA, [24] and OFDMA, play a pivotal role in addressing these challenges. These techniques enhance network capacity, reliability, and performance by enabling multiple users to share the same communication medium simultaneously, ensuring robust operation in complex and dynamic environments [18].

This chapter aims to provide a comprehensive overview of multiple-access wireless networks, focusing on the principles, methodologies, and applications that underpin their design and operation. The discussion is structured to guide readers from foundational concepts to advanced techniques, offering both theoretical insights and practical perspectives.

I.2 FUNDAMENTAL CONCEPTS AND PRINCIPLES

I.2.1 Definition of Wireless Communication Systems

Wireless communication systems enable data transmission using electromagnetic waves, such as radio frequency (RF) signals, without physical wired connections. These systems are designed to support mobility, flexibility, and scalable network configurations, making them essential for various applications [25], [26]. Fundamental principles and practices of these systems are detailed in comprehensive texts [27], while others delve into the theoretical underpinnings [28] and system-level design aspects. A broad introduction to the concepts and systems within wireless and mobile communications is also available.

I.2.2 Wireless Networks and Their Components

A typical Wireless Communication System can be divided into three elements: The Transmitter, the Channel, and the Receiver. The following image shows a block diagram of a wireless communication system [23].

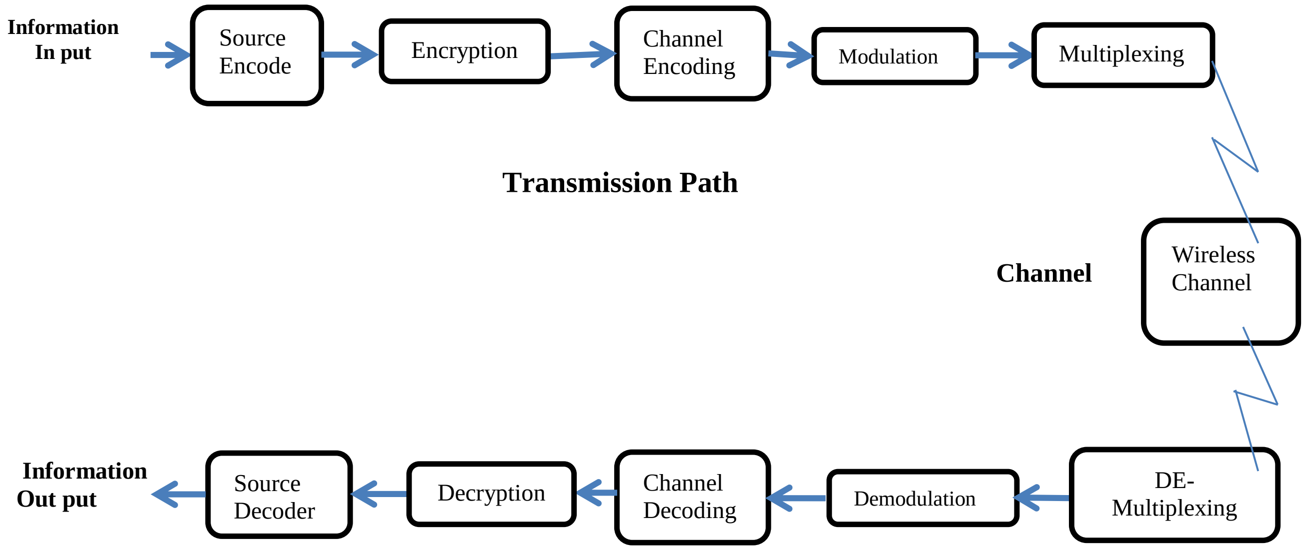


Figure I 1:Block diagram of communication system [29]

I.2.2.1 The Transmission Path

A standard transmission pathway in a Wireless Communication System comprises Encoder, Encryption, Modulation, and Multiplexing. The signal from the source is transmitted through a Source Encoder, which transforms the signal into an appropriate format for applying signal processing techniques [30]. This method eliminates duplicate information from the signal to optimize resource utilization [31]. Subsequently, the signal is encrypted using an Encryption Standard to ensure security and prevent illegal access [32]. Channel encoding is a method employed to mitigate defects such as noise and interference in signals. A minimal redundancy is incorporated into the signal to enhance its resilience to noise [33] . Subsequently, the signal is modified by employing an appropriate modulation technique (such as PSK, FSK, or QPSK) to facilitate its transmission via an antenna [34] . To optimize bandwidth utilization, the modulated stream is subsequently multiplexed with other signals via various multiplexing techniques, such as (TDM) or (FDM) [35].

I.2.2.2 The Channel

In wireless communication, the channel is the medium through which the signal is transmitted, typically open space [36]. A wireless channel is inherently unpredictable, exhibiting significant randomness and variability [37]. It is susceptible to various impairments such as interference, distortion, noise, and dispersion, which can introduce errors into the received signal [38].

I.2.2.3 The Reception Path

The receiver's job is to collect the signal from the channel and reproduce it as the source signal. The reception path of a Wireless Communication System comprises Demultiplexing, Demodulation, Channel Decoding [39]. Decryption, and Source Decoding. From the components of the reception path, it is clear that the receiver's task is just the inverse of that of the transmitter.

The channel signal is received by the De-multiplexer and separated from other signals. The individual signals are demodulated using appropriate Demodulation Techniques, and the original message signal is recovered. The redundant bits from the message are removed using the Channel Decoder [30].

Since the message is encrypted, Decryption removes the security and turns it into a simple sequence of bits. Finally, this signal is given to the Source Decoder to return the original transmitted message or signal [32].

I.2.3 Radio Wave Propagation

Propagation refers to the movement of electromagnetic waves through various media. It can be categorized into two types:

- **Free space propagation** (e.g., air, vacuum, glass, etc.)[40].

- **Guided propagation** (e.g., transmission lines, waveguides, cables, optical fibers, etc.)[41].

I.2.3.1 Electromagnetic Waves

Wireless communications rely on radio waves. A wave is the result of the combination of two components: the electric field (E) and the magnetic field (B).

These two fields are perpendicular to each other, with amplitudes in a constant ratio and variations in phase.

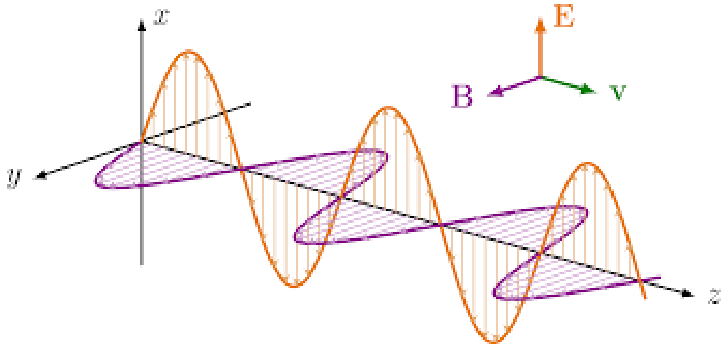


Figure I 2:Electromagnetic wave [42]

In a vacuum, these waves propagate at a speed of $3\times10^{8}\,\mathrm{m/s}$ (the speed of light), though this speed varies depending on the medium through which the wave travels.

The following physical quantities characterize an electromagnetic wave:

- **Wavelength (λ)**: his represents the distance between two successive wave peaks, measured in meters (m).
- **Period (T)**: This refers to the time required for the wave to complete one cycle, measured in seconds (s).
- **Frequency (f)**: This indicates the number of wave oscillations per second, measured in Hertz (Hz). The higher the frequency, the shorter the wavelength (λ). The formula relates these two quantities:

$$\lambda = \frac{C}{f} \tag{I.1}$$

Where C is the speed of light in a vacuum.

This relationship highlights the inverse proportionality between wavelength and frequency, a fundamental principle in understanding electromagnetic wave behavior.

I.2.3.2 Classification of waves

Electromagnetic waves are classified as follows:

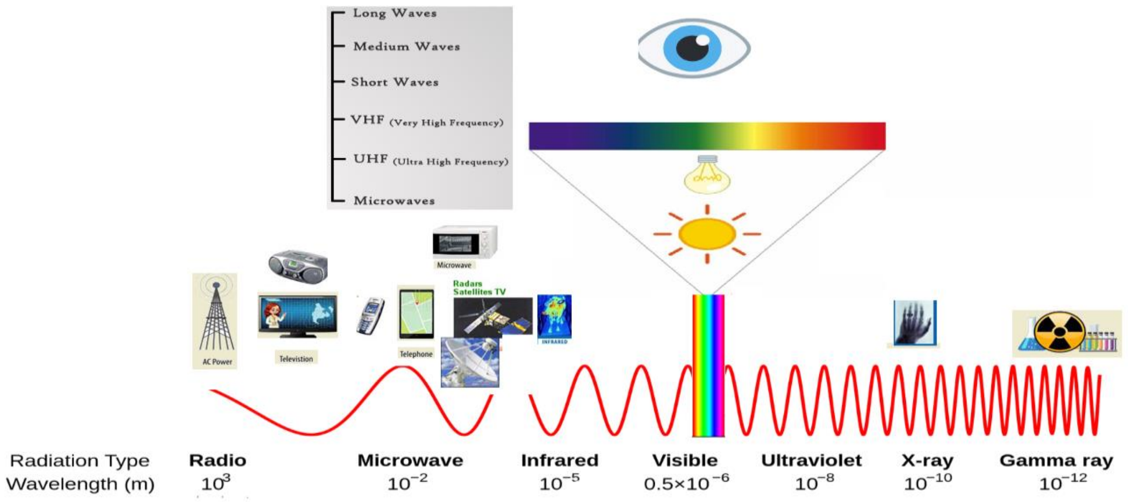


figure I 3:Classification of waves

I.2.3.3 Propagation Mechanisms

Wireless signal propagation refers to the process by which radio waves travel from a transmitter to a receiver. The behavior of these signals is influenced by several key factors, including frequency, distance, and the environment through which they propagate [43].

a) **Free Space Propagation**

Free space propagation occurs when there is a direct line of sight (LOS) between the transmitter and the receiver, meaning there is only one path, and the waves encounter no obstacles that could cause reflections[44].

The study of electromagnetic waves between a transmitter (E) and a receiver (R) involves dividing the propagation space into a family of Fresnel ellipsoids, with E and R as the focal points. Any point (M) on one of these ellipsoids satisfies the following relation[45]:

$$EM + RM = ER + n\frac{\lambda}{2} \qquad \text{(I.2)}$$

Where:

- n: an integer characterizing the specific ellipsoid
- λ: the wavelength

The radius of the n-th ellipsoid at a point along the path, located at a distance d_2 from R (with d_1+d_2, assuming d_1 and d_2 are much larger than the radii of the ellipsoids), is given by [46],[45]:

$$r_n = \sqrt{\frac{n\lambda \mathrm{d}_1 \mathrm{d}_2}{d_1 + d_2}} \tag{I.3}$$

This is illustrated as follows:

According to the Friis transmission equation (telecommunications equation), the received power is expressed as[46] :

$$P_r = \frac{P_e G_e G_r \lambda^2}{(4\pi d)^2} (\text{watt}) \tag{I.4}$$

where:

- P_e: transmitted power
- G_r: receiver gain
- λ: wavelength
- d: distance between transmitter and receiver
- f: signal frequency

The free space path loss is calculated (FSPL)as [47]:

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2 = 32.4 + 20 \log_{10} (f) + 20 \log \tag{I.5}$$

Where:

- L: Path loss in **dB**,
- f: Frequency in **MHz**,
- d: Distance in **km**.

Additional losses ($L \geq 1$) are typically due to transmission line attenuation, filtering losses, and antenna losses in the communication system. $L=1$ indicates no losses in the system hardware [48].

b) Other Mechanisms

- **Line-of-Sight (LOS):** Direct, unobstructed path between the transmitter and receiver, providing the clearest signal[49].
- **Reflection:** Occurs when radio waves bounce off surfaces like buildings or the ground, potentially creating multiple paths[50].
- **Diffraction:** Bending of waves around obstacles, enabling communication even when direct LOS is blocked[51].
- **Scattering:** Occurs when radio waves encounter rough surfaces or small objects, causing the waves to disperse in many directions[52].

c) Path Loss and Attenuation

- **Free-Space Path Loss:** The reduction in signal strength as the distance between the transmitter and receiver increases[53].
- **Environmental Attenuation:** Additional losses due to obstacles, atmospheric conditions, and absorption by materials[54].
- **Frequency Dependency:** The behavior of radio waves varies with frequency. For instance, lower-frequency signals can travel longer distances and penetrate obstacles better, while higher-frequency signals can carry more data but are more susceptible to physical obstructions[55].

I.3 CHALLENGES IN WIRELESS TRANSMISSION

Wireless transmission faces several challenges that can degrade signal quality and affect communication reliability. These challenges include:

- **Interference**: Interference is the disruption of a desired signal's reception caused by unwanted signals. These unwanted signals can originate from various sources, such as other communication devices, environmental factors, or hardware imperfections[56].
- **Fading**: Fading refers to the variation in signal strength over time or distance due to multipath propagation or environmental changes[57].

- **Multipath Propagation**

Multipath propagation occurs when multiple copies of a transmitted signal arrive at the receiver via different paths. This phenomenon is typically caused by reflection, diffraction, or scattering of the signal off objects in the environment, such as buildings, terrain, or other obstacles[58].

Noise: Noise refers to unwanted random signals that distort the transmitted signal, degrading its quality and potentially causing errors in communication.

- **Sources**: Thermal noise, atmospheric noise, and man-made noise.

Path Loss:

Path loss refers to the reduction in signal strength as it propagates through space. This attenuation occurs due to distance, obstacles, and the inherent spreading of the signal as it travels away from the transmitter[54].

- **Impact**: Limits the coverage area of wireless systems.

I.4 TYPES OF COMMUNICATION SYSTEMS

Wireless communication systems can be broadly classified based on how data is transmitted and received:

I.4.1 Point-to-Point Communication

- Involves a direct connection between two nodes.
- Often used for dedicated links such as microwave or satellite links.
- Provides high reliability and bandwidth for dedicated communication channels.

I.4.2 Broadcast Communication

- One transmitter sends data to all devices within its coverage area.
- Commonly used in television, radio, and some cellular network operations.
- Emphasizes wide coverage over individual user specificity.

I.4.3 Multicast Communication

- Data is transmitted from one source to a selected group of receivers.
- It is efficient for applications such as video conferencing, live streaming, and group communications, where data needs to be sent simultaneously to multiple specific users.

- Balances the benefits of broadcast (wide distribution) with the need for targeted delivery.

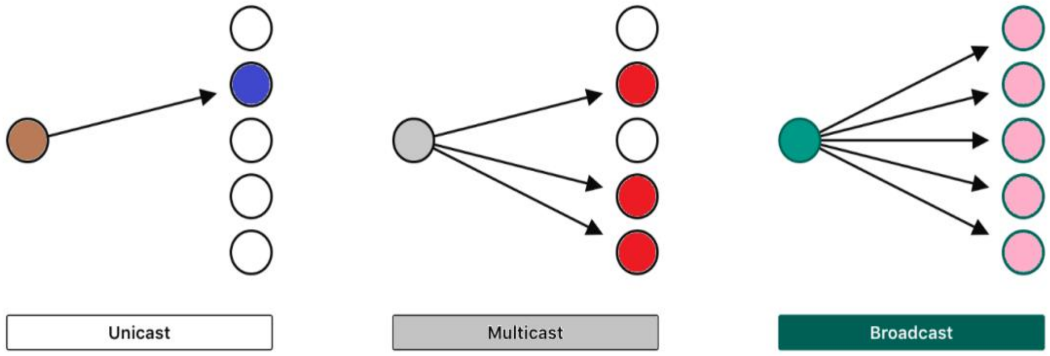


Figure I 4:Types of communications systems

I.5 APPLICATIONS OF COMMUNICATION SYSTEMS

People use cell phones today for various purposes, including multimedia, internet access, and communication, expecting seamless mobility [59]. Wireless systems enable transmission of voice, data, videos, and images, supporting applications like video conferencing, cellular networks, and broadcasting [60]. Key systems include:

- Television and Radio Broadcasting
- Satellite Communication
- Mobile Telephone System (Cellular Communication)
- Global Positioning System (GPS)
- WLAN (Wi-Fi)
- Bluetooth
- Paging
- Radio Frequency Identification (RFID)
- Infrared Communication
- Radar

There are many other systems, each useful for different applications. Wireless communication systems can be classified as simplex, half-duplex, or full-duplex. Simplex communication is one-way communication. An example is the Radio broadcast system.

Half Duplex is two-way communication but not a simultaneous one. An example is walkie–talkie (civilian band radio). Full Duplex is also two-way communication, and it is a simultaneous one. The best example of a full Duplex is mobile phones.

The devices used for Wireless Communication may vary from one service to another, and they may have different sizes, shapes, data throughput, and costs. The area covered by a Wireless Communication system is also an important factor. Wireless networks may be limited to a building, an office campus, a city, a small regional area (greater than a city), or global coverage.

We will see a brief note about some of the important Wireless Communication Systems.

I.5.1 Television and Radio Broadcasting

Radio is considered to be the first wireless service to be broadcast. It is an example of a Simplex Communication System where the information is transmitted only in one direction and all the users receiving the same data[61].

I.5.2 Satellite Communication

Satellite Communication System is an important type of Wireless Communication. Satellite Communication Networks provide worldwide coverage independent to population density.

Satellite Communication Systems offer telecommunication (Satellite Phones), positioning and navigation (GPS), broadcasting, internet, etc [62]. Other wireless services like mobile, television broadcasting and other radio systems are dependent of Satellite Communication Systems.

I.5.3 Mobile Telephone Communication System

Perhaps the most usually used wireless communication system is Mobile Phone Technology. The development of mobile cellular devices changed the world like no other technology. Today’s mobile phones are not limited to just making calls but are integrated with numerous other features like Bluetooth, Wi-Fi, GPS, and FM Radio.

I.5.4 Global Positioning System (GPS)

GPS is exclusively a subcategory of satellite communication. GPS provides different wireless services like navigation, positioning, location, speed etc.[63]. With the help of dedicated GPS receivers and satellites.

I.5.5 Bluetooth

Bluetooth is another important low range wireless communication system. It provides data, voice and audio transmission with a transmission range of 10 meters. Almost all mobile phones, tablets and laptops are equipped with Bluetooth devices. They can be connected to wireless Bluetooth receivers, audio equipment, cameras etc[64].

I.5.6 Paging

Although it is considered an obsolete technology, paging was a major success before the wide spread use of mobile phones. Paging provides information in the form of messages and it is a simplex system i.e. the user can only receive the messages[65].

I.5.7 Wireless Local Area Network (WLAN)

Wireless Local Area Network or WLAN (Wi-Fi) is an internet related wireless service. Using WLAN, different devices like laptops and mobile phones can connect to an access point and access internet.

I.5.8 Infrared Communication

Infrared Communication is another commonly used wireless communication in our daily lives. It uses the infrared waves of the Electromagnetic (EM) spectrum. Infrared (IR) Communication is used in remote controls of Televisions, cars, audio equipment etc [66].

I.5.9 Radar

Radar is a critical wireless technology that uses radio waves to detect objects' range, velocity, and angle. Modern radar systems integrate with communication networks for applications like autonomous vehicles, smart cities, and defense[67].

I.6 DEVICES AND APPLICATIONS UTILIZING WIRELESS COMMUNICATION

The exponential proliferation of wireless devices has transformed modern connectivity, with smartphones emerging as the most ubiquitous dual-mode platform—enabling both human communication and machine data exchange (5G/Wi-Fi 6) [68]. While consumer electronics dominate user interactions, infrastructure devices (e.g., LEO satellites, mmWave base stations) underpin global networks, handling >80% of traffic at latencies <10 ms . A critical shift is evident in **wired-to-wireless transitions**, where peripherals (Bluetooth 5.3

mice, 802.11ax printers) enhance workplace efficiency by 30–40% through multi-user access [69]. This ecosystem's growth is propelled by:

1. **Human-centric applications** (e.g., social media, IoT-enabled homes),
2. **Machine-driven infrastructure** (e.g., M2M sensor networks),
3. **Hybrid devices** (e.g., AR/VR headsets merging user input and cloud data) [70].

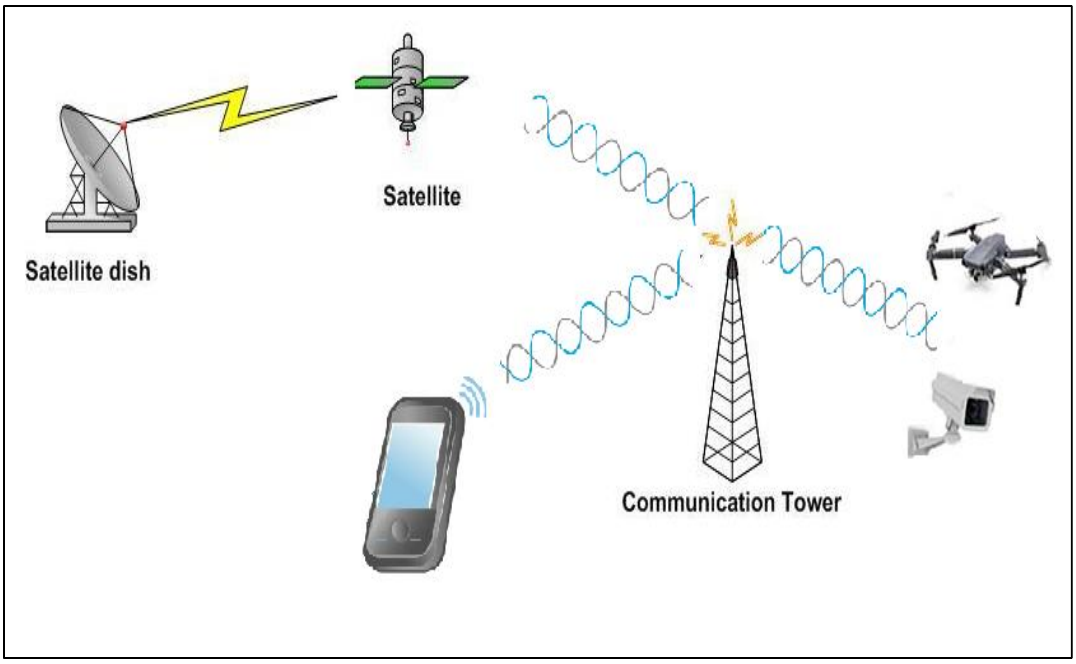


Figure I 5:Devices utilizing wireless communication

I.7 EVOLUTION OF WIRELESS NETWORKS (1G TO 5G AND BEYOND)

The evolution of wireless networks has been a transformative journey, characterized by groundbreaking technological advancements and paradigm shifts. It started in the 1980s with 1G, which introduced analog voice communication, enabling basic mobile telephony but with limited coverage and subpar voice quality. The 1990s saw the rise of 2G, which brought digital communication, improved voice quality, text messaging (SMS), and basic data services through technologies like GSM and CDMA[18]. The shift to 3G in the early 2000s marked a revolution in mobile communication, offering higher data rates, support for multimedia services, and the foundation for mobile internet access [71].

The 2010s ushered in 4G, delivering unprecedented speeds, low latency, and enhanced capacity, which enabled high-definition video streaming, online gaming, and the widespread adoption of smartphones [72]. Today, 5G represents the latest leap forward, providing ultra-reliable low-latency communication, massive device connectivity, and support for emerging technologies like the Internet of Things (IoT), augmented reality (AR), and autonomous vehicles[73].

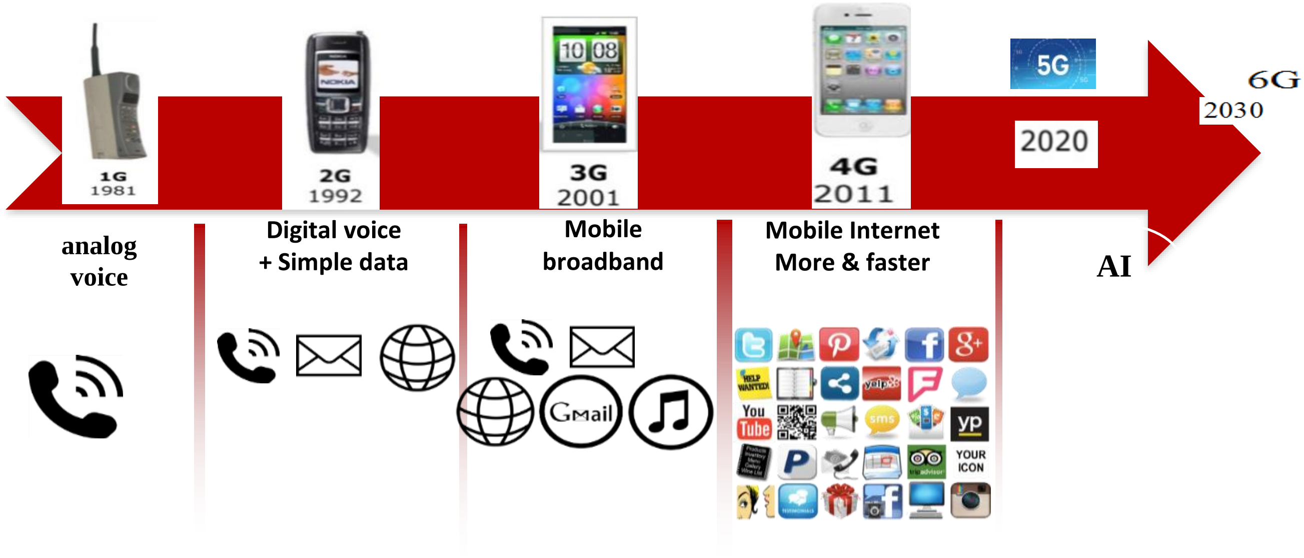


Figure I 6:Evolution of cellular mobile

I.8 MULTIPLE ACCESS TECHNIQUES

In wireless networks, resource sharing is a fundamental concept that enables multiple users or devices to access a shared communication medium efficiently and without significant interference. The limited bandwidth of the wireless spectrum typically constrains the resources available for sharing [18].

Multiple access techniques are employed to address this challenge to allocate resources across four primary dimensions: time, frequency, code, and space. Each dimension offers unique advantages and trade-offs, and their combination forms the basis of modern wireless communication systems.

I.8.1 Definition and Purpose of Multiple Accesses in Wireless Networks

Multiple accesses are the means by which multiple users or devices sharing a common communication medium, such as a wireless channel, can communicate simultaneously and in an efficient and non-interfering manner. It is important to ensure that there are some mechanisms that make sure if there are multiple transmitters or receivers in one single location, they can still work together without having much interference. Due to this, the performance will lower. These methods distribute resources (i.e., time, frequency, code, or space) in an organized way to allow concurrent communication among users.

- **Purpose**

The primary purpose of multiple accesses in wireless networks is to optimize the utilization of the shared communication medium while ensuring reliable and efficient data transmission. This are achieved through the following key objectives:

1. **Resource Efficiency**: Multiple access techniques maximize the use of limited spectral resources by allowing multiple users to share the same frequency band or time slot without overlapping or conflicting transmissions.
2. **Interference Mitigation**: By coordinating access to the shared medium, multiple access mechanisms minimize interference between users, thereby improving signal quality and reducing packet loss.
3. **Scalability**: Multiple access enables networks to support a growing number of users and devices, making it essential for modern wireless systems such as cellular networks, IoT, and Wi-Fi.
4. **Quality of Service (QoS)**: These techniques ensure that users receive the required level of service, such as latency, throughput, and reliability, by dynamically allocating resources based on demand and network conditions.
5. **Flexibility and Adaptability**: Multiple access protocols can adapt to varying traffic patterns, channel conditions, and user requirements, making them suitable for diverse applications and environments.
6. **Enabling Diverse Applications**: From voice calls and video streaming to machine-to-machine (M2M) communication and IoT, multiple access techniques underpin a wide range of wireless applications, ensuring seamless connectivity and performance.

I.8.2 Radio Transmission and Reception

Radio transmission and reception are fundamental processes in wireless communication systems, enabling the transfer of information between devices over the air using electromagnetic waves. Understanding the principles of wireless signal propagation and the challenges associated with it is essential for designing robust and efficient wireless networks.

I.8.2.1 Multiple Access Wireless

A telecommunications concept refers to methods that simultaneously allow multiple users or devices to share the same communication resources (such as bandwidth or frequency) in a network [74]. This is achieved by dividing the resources through various techniques, such as time, frequency, code, or space, to minimize interference and optimize data transmission.

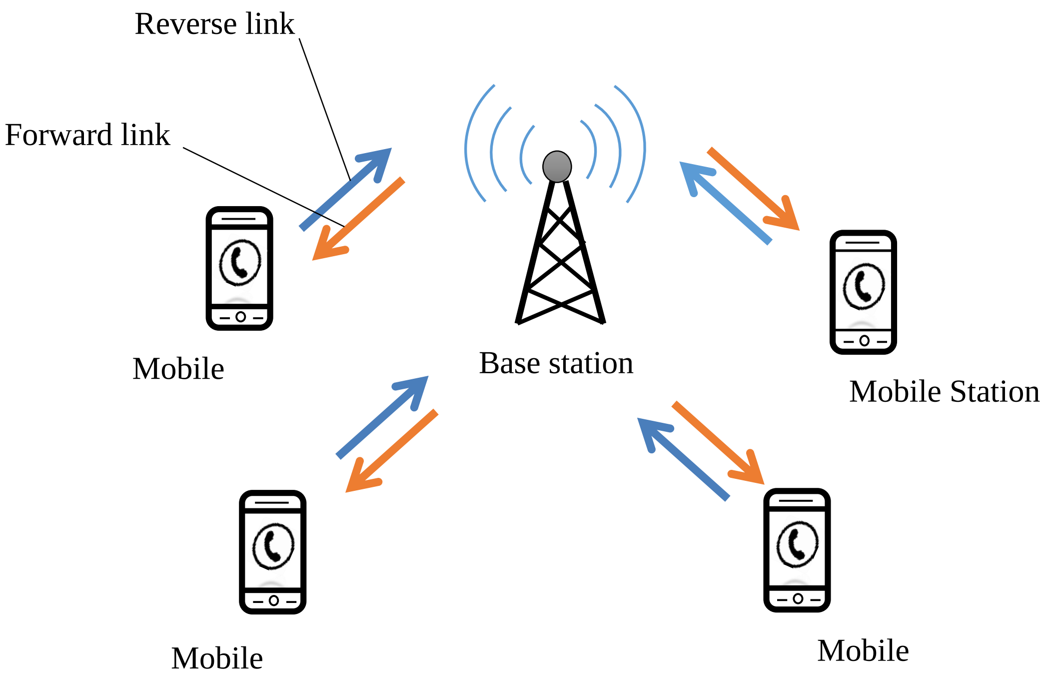


figure I 7:Multiple access wireless

Wireless networks are characterized by two primary operations:

- **Downlink (Download)**: The transmission of data from the network infrastructure (e.g., base station or wireless access point) to the end-user device.

- **Uplink (Upload)**: The transmission of data from the end-user device to the network infrastructure.

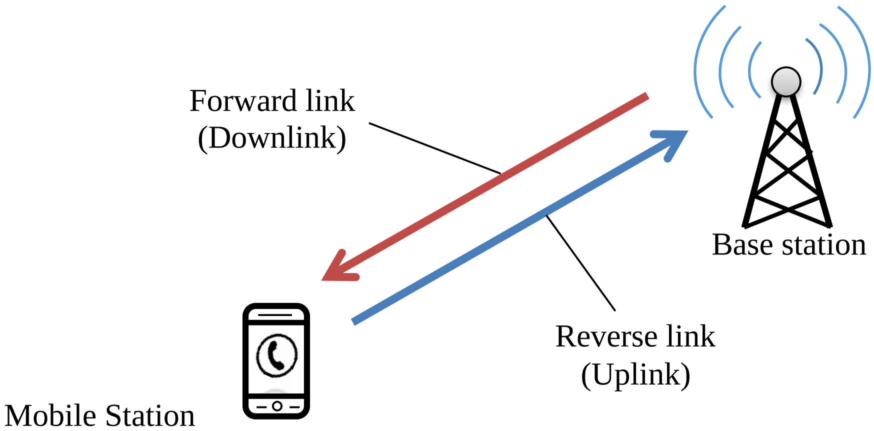


Figure I 8:Downlink uplink transmission

Wireless networks are used for mobile communications, sensor networks, and internet connectivity, allowing devices to communicate and exchange data dynamically. These networks are subject to several challenges, including signal attenuation, interference, and the need for efficient bandwidth allocation to maintain network performance.

In theory, wireless networks involve elaborate interactions among hardware components (antennas, transmitters, and receivers) and software systems (modulation, coding, and error correction protocols). Together, these interactions will influence how efficiently and reliably data can be exchanged, especially in environments that require great mobility, scalability, and flexibility.

I.8.2.2 Digital Information Transmission

Digital information transmission systems transfer data between a source and a destination via physical mediums like cables, optical fibers, or radio waves. A key challenge in communication networks is managing who has the right to transmit data at any given time, which is addressed through protocols and channel allocation techniques. Multiple access techniques are paired with duplexing methods, such as those enabling communication between mobile devices and base stations, to facilitate efficient information exchange.

Among the duplexing methods, we distinguish the following:

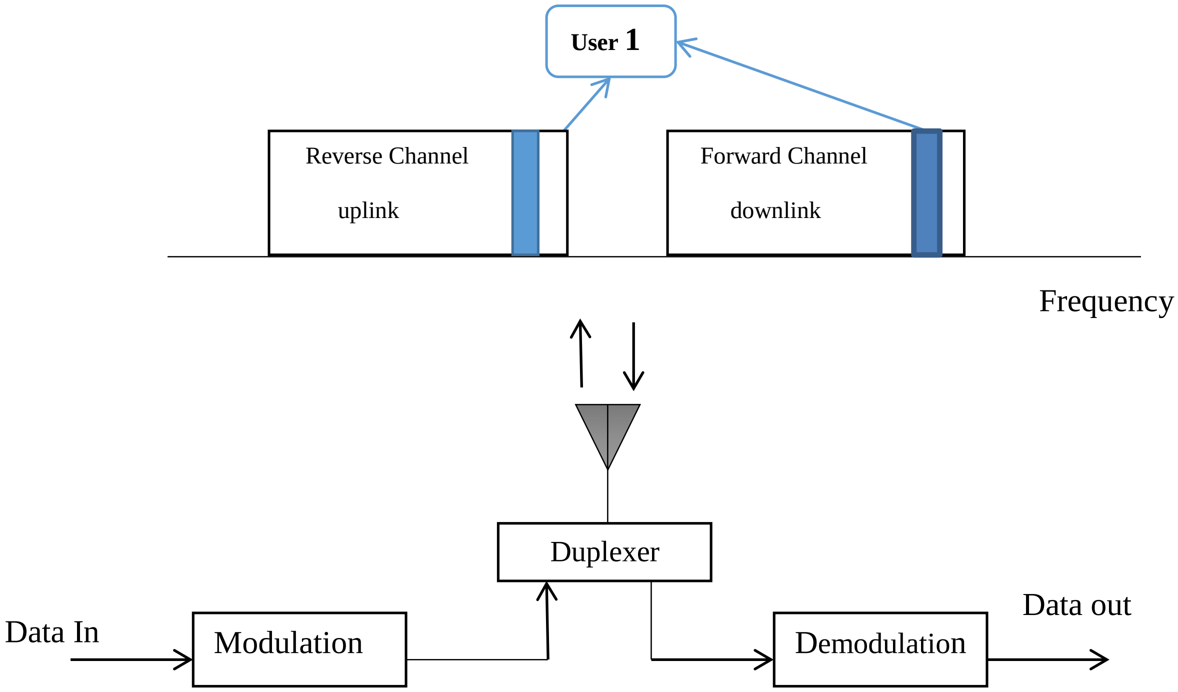


Figure I 9:Frequency division duplexing (FDD)

a) **Frequency Division Duplex (FDD)**

This method uses two independent frequency bands, one for uplink (transmitting to the base station) and the other for downlink (receiving from the base station). A frequency gap (guard band) is required between the uplink and downlink channels to reduce interference[29].

Advantages

- Continuous uplink and downlink transmission (without interruption).
- No interference between uplink and downlink, as long as the guard band is sufficiently wide.

Disadvantages

- Inflexible traffic allocation requires guard bands.
- The transmitter and receiver don’t use the same channel.
- Requires a duplexer.
- FDD needs a pair of frequency channels.

b) Time Division Duplex (TDD)

In TDD, transmission and reception occur on the same frequency band but at different times. A TDD system requires a guard period to minimize interference between transmission and reception moments. The length of this guard period is determined by the maximum time it takes for the signal to make a round trip between the transmitter and receiver.

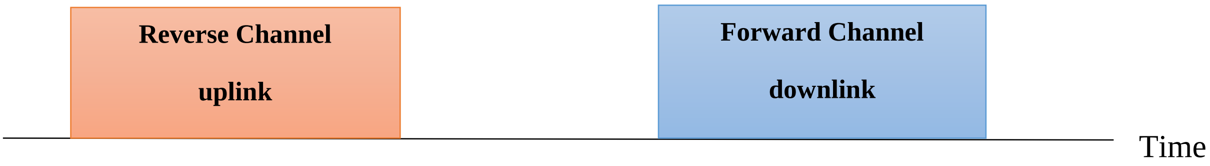


Figure I 10:Time division duplexing (TDD)

Advantages:

- Requires only one frequency channel.
- No need for a duplexer.
- Ensures channel reciprocity, meaning better channel adaptation (as the same channel is used).
- Allows for dynamic traffic allocation.

Disadvantages

- Requires guard periods to prevent interference between uplink and downlink.
- Not truly full-duplex communication.
- Cross-slot interference.

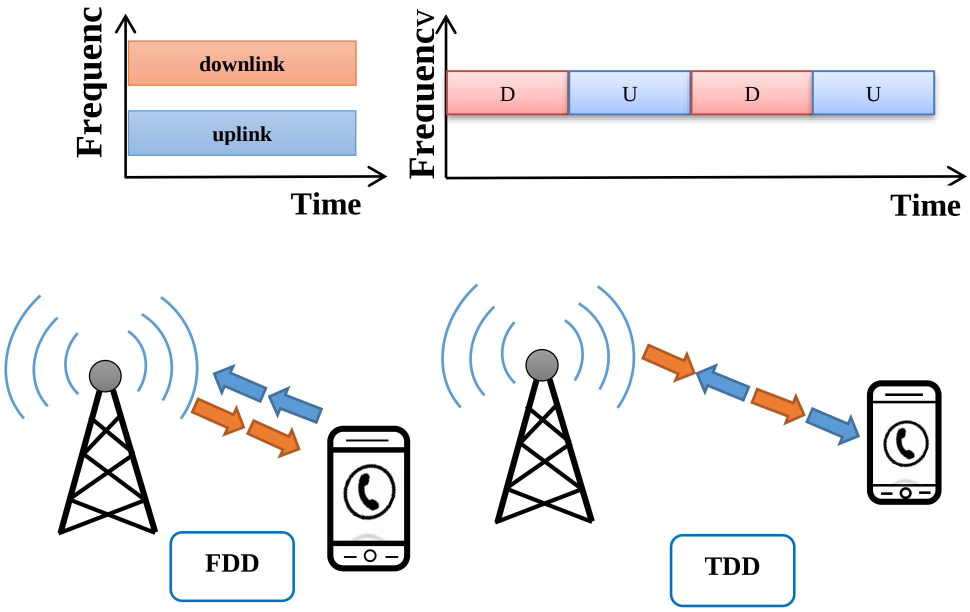


Figure I 11:Comparison of FDD and TDD

I.9 CLASSIFICATION OF MULTIPLE ACCESS TECHNIQUES

Multiple access techniques are classified based on how they allocate and manage the shared communication medium among multiple users.

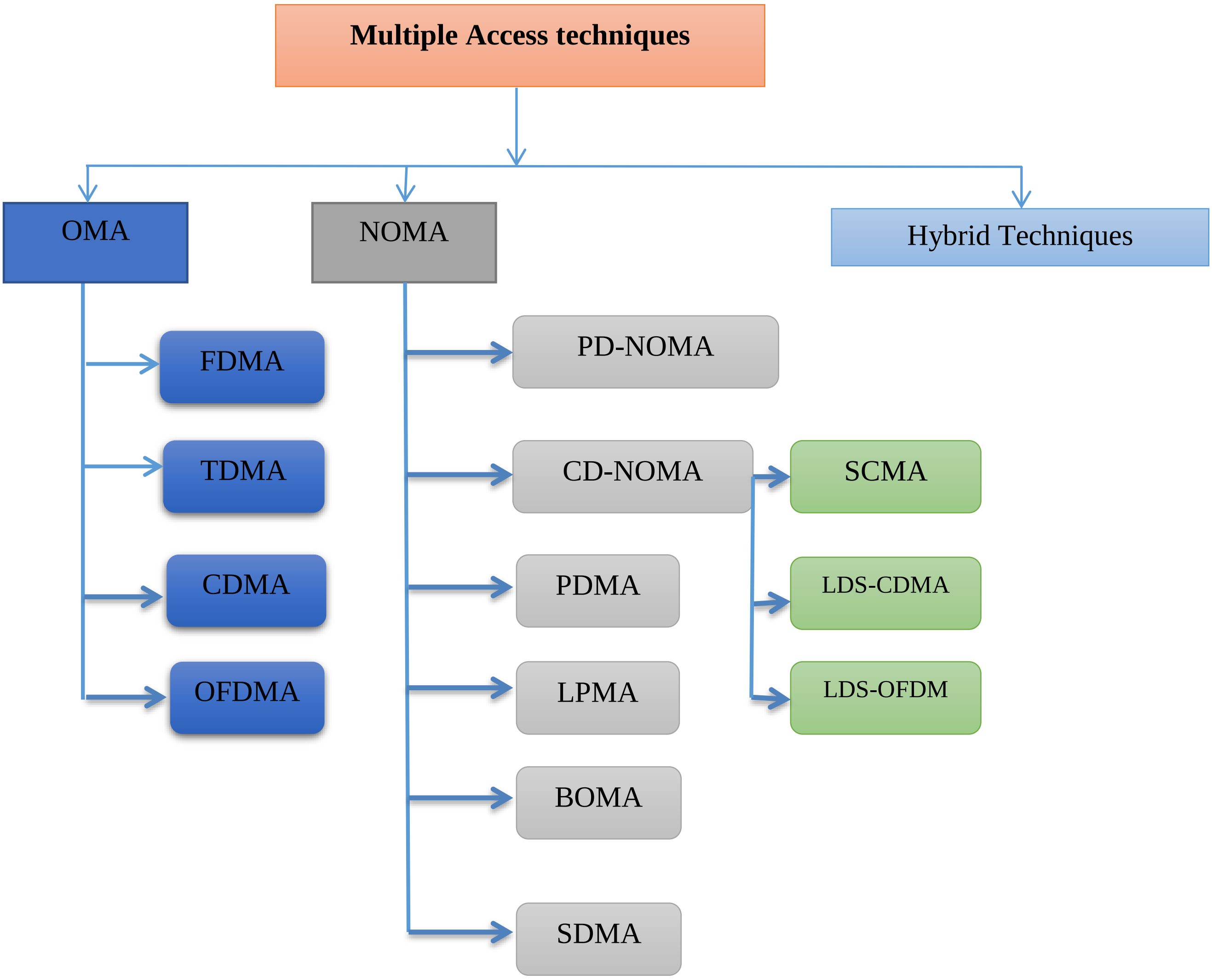


Figure I 12:Classification of multiple access techniques

I.10 APPLICATIONS OF MULTIPLE ACCESS NETWORKS

Multiple access networks are essential in modern communication systems, enabling efficient resource sharing and simultaneous connectivity for multiple users. Their applications span a wide range of domains, from cellular networks and IoT to satellite communication and emerging technologies. This section explores the role of multiple access techniques in these areas, highlighting their significance and challenges.

- **Cellular Networks**

  Multiple access methods such as FDMA, TDMA, CDMA, and OFDMA are the backbone of cellular communication, enabling efficient spectrum utilization and connectivity for millions of users[75].

- **Satellite and Broadband Communication Systems**

  Multiple access techniques facilitate efficient data transmission between satellites and ground stations, supporting global communication, broadcasting, and internet services.

- **Broadband Communication Systems**

  These systems rely on multiple access methods to deliver high-speed internet and seamless connectivity to users in both wired and wireless environments.

- **Emerging Applications**

  Advanced multiple access technologies drive innovation in 5G/6G networks, enabling ultra-reliable, low-latency communication for futuristic use cases[76].

- **Smart Cities**

  Multiple access networks support interconnected systems for traffic management, energy distribution, public safety, and environmental monitoring, enhancing urban efficiency and sustainability[77].

- **Autonomous Vehicles**

  Multiple access techniques enable reliable communication between vehicles and infrastructure (V2X), ensuring safe and efficient transportation systems[78].

- **Industrial IoT (IIoT)**

  In industrial settings, multiple access networks enable real-time monitoring, automation, and control of machinery and processes, improving productivity and operational efficiency[79].

- **Extended Reality (XR)**

  Technologies like augmented reality (AR), virtual reality (VR), and mixed reality (MR) depend on robust multiple-access networks for immersive, low-latency experiences.

I.11 CONCLUSION

This chapter has provided a comprehensive overview of multiple-access wireless networks, exploring their fundamental principles, classification, and applications. Key points discussed include the definition and purpose of multiple-access techniques, the general principles of resource sharing (time, frequency, code, and space), and the challenges associated with wireless signal propagation, the chapter highlighted the critical role of multiple-access techniques in enabling efficient and scalable wireless networks across various domains, including cellular networks, IoT , satellite communication, and emerging applications like smart cities and autonomous vehicles.

The importance of multiple-access techniques lies in their ability to optimize the utilization of limited spectral resources, mitigate interference, and support a growing number of users and devices. These techniques form the foundation of modern wireless systems by enabling simultaneous communication over shared channels, ensuring reliable and high-performance connectivity in increasingly dense and heterogeneous environments.

Looking ahead, future trends and research directions in multiple-access wireless networks are focused on addressing the challenges of next-generation communication systems.

Chapter II

Comprehensive Study of OMA and NOMA Systems: Comparative Analysis

II. 1 INTRODUCTION

In the rapidly evolving field of wireless communication systems, effective multiple access methods are crucial to address the growing demands for low latency, high data rates, and massive connectivity. These techniques allow multiple users to share the same communication resources—time, frequency, and code—while minimizing interference and optimizing spectral efficiency[10].

Orthogonal multiple access (OMA) techniques, such (TDMA), (FDMA), and (OFDMA), have been widely adopted in wireless networks due to their simplicity and reliability. By allocating orthogonal resources to users, OMA ensures minimal interference[80].

Thus, these techniques can suffer from low spectral efficiency and scalability, which can affect their performance in highly demanding scenarios.

In contrast, (NOMA) has developed as a powerful alternative, particularly for 5G and beyond. NOMA enables multiple users to share the same resource block non-orthogonally, significantly improving spectral efficiency and user capacity[11].

This is achieved through advanced techniques like successive interference cancellation (SIC) at the receiver and superposition coding (SC) at the transmitter. By operating in the power or code domains, NOMA can serve multiple users simultaneously, even with limited resources, making it a more flexible and efficient solution than OMA[81].

NOMA is especially well-suited for applications requiring high connectivity, such as the Internet of Things (IoT) and ultra-reliable low-latency communications.

In this chapter, we investigate the ideas, benefits, and challenges of OMA and NOMA and their importance in enhancing the present and future wireless communication systems.

II. 2 ORTHOGONAL MULTIPLE ACCESS (OMA)

Orthogonal Multiple Access is a key technique in wireless communication systems, engineered to make optimal use of the limited radio spectrum by allowing multiple users to share bandwidth without interference. With spectrum resources being scarce, efficient allocation is vital for maximizing network capacity and guaranteeing dependable communication across coverage zones. OMA achieves interference-free transmission by allocating distinct, non-overlapping resources—such as frequency, time, or code domains—to users, enabling simultaneous transmissions while upholding high Quality of Service (QoS). In cellular networks, OMA divides coverage areas into cells, supporting smooth communication between mobile devices and base stations. Through effective bandwidth distribution, OMA delivers consistent service quality and enhances spectrum efficiency[24].

To accomplish its objectives, OMA employs several essential methods:

- **Frequency Division Multiple Accesses (FDMA):** Assigns distinct frequency bands to each user.
- **Time Division Multiple Access (TDMA):** Allocates specific time slots to users within a common frequency band.
- **Code Division Multiple Access (CDMA):** Distinguishes user signals with unique codes, enabling concurrent transmissions over the same frequency and time resources.
- **Orthogonal Frequency Division Multiple Accesses (OFDMA):** Splits the spectrum into multiple orthogonal subcarriers, facilitating efficient resource distribution and enhanced performance for high-speed data transfers.

- Each of these techniques offers distinct advantages, but they all share the common goal of enhancing network capacity, spectral efficiency, and service reliability. As wireless communication systems continue to evolve, OMA remains a cornerstone of traditional cellular networks, where maintaining stable, interference-free communication is essential. Its proven effectiveness in managing spectrum resources assures its continued relevance in modern and future wireless technologies.

II. 2 .1 Frequency Divisions Multiple Accesses

In communication systems, frequency division multiple access (FDMA) is an early and fundamental method for letting several users share the accessible frequency spectrum. It assigns every user a different channel by separating the spectrum into discrete frequency ranges. FDMA is straightforward and dependable since it allows simultaneous transmissions without interference. Its simplicity of use and consistent performance have made it rather common in radio transmission, analog cellular systems, and satellite communications.

However, FDMA has drawbacks, including inefficient use of the spectrum. Fixed frequency bands mean unused portions cannot be reassigned, leading to wasted resources, especially with inactive users or low data needs.

It also lacks flexibility for handling varying traffic, making it less efficient than newer methods like TDMA and CDMA. Despite this, FDMA's simplicity and reliability have become a key stepping stone in developing modern wireless communication technologies[24].

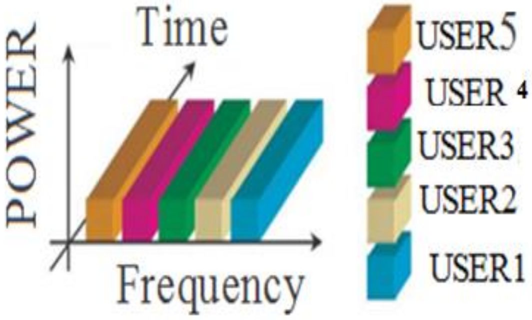


Figure II 1: Power/Time/frequency diagram of FDMA

II. 2 .2 Time Division Multiple Accesses

Widely used multiple access method Time Division Multiple Access (TDMA) divides communication channels into discrete time slots, allocating each user a unique time interval for data transmission or reception. This method dynamically allocates time slots depending on user demand, guaranteeing effective bandwidth use. Particularly in the Global System for Mobile Communications (GSM), TDMA is a pillar of digital cellular systems. It has been important in developing second-generation (2G) mobile networks. It supports several users on the same frequency channel, optimizing spectral efficiency and enabling scalable network architecture. However, exact timing is needed to guarantee correct time slot assignment and use, which adds further difficulty to the application. Notwithstanding this, TDMA is still a strong and dependable multiple-access method, especially when effective spectrum use and scalability are vital [82].

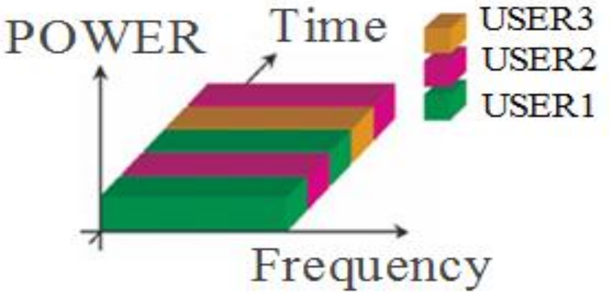


Figure II 2: Power/Time/frequency diagram of TDMA

II.2.3 Code Division Multiple Access

Code Division Multiple Access (CDMA) is a technique where multiple users simultaneously share the same frequency spectrum by encoding their signals with unique spreading codes. This allows for more flexible and efficient use of available bandwidth, unlike Frequency

Division Multiple Access (FDMA) or Time Division Multiple Access (TDMA). CDMA is robust against interference and noise, making it useful in environments with high user density or signal degradation. It is also more resistant to eavesdropping due to the spreading codes providing security. CDMA is a key technology in third-generation (3G) mobile networks, such as Wideband CDMA, providing high-capacity data transmission for mobile internet and multimedia services. However, CDMA systems require complex processing techniques and careful power level management and can degrade overall system performance due to "multi-user interference." Despite these challenges, CDMA has significantly enhanced network capacity and spectral efficiency, especially in 3G systems, and laid the groundwork for more advanced communication technologies.

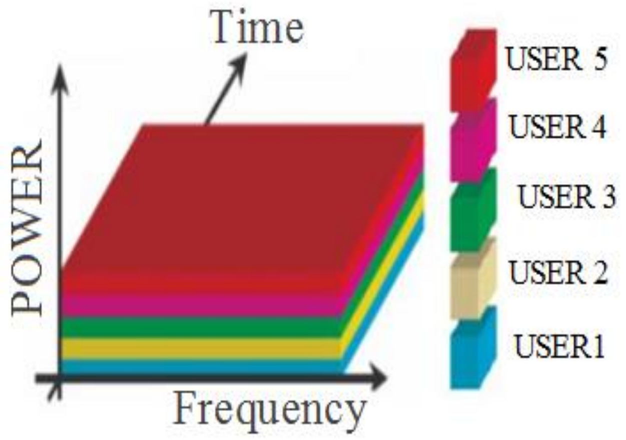


Figure II 3: Power/Time/frequency diagram of CDMA

II.2.4 Orthogonal Frequency Divisions Multiple Accesses

Orthogonal Frequency Division Multiple Access (OFDMA) is an efficient way for multiple users to access the same communication channel. It is especially important in modern wireless systems like 4G (LTE) networks. OFDMA divides the available frequency spectrum into orthogonal subcarriers, each of which can be assigned to different users. The orthogonality helps prevent interference between the subcarriers, which means that multiple users can send data simultaneously over the same frequency band without losing efficiency in the spectrum.

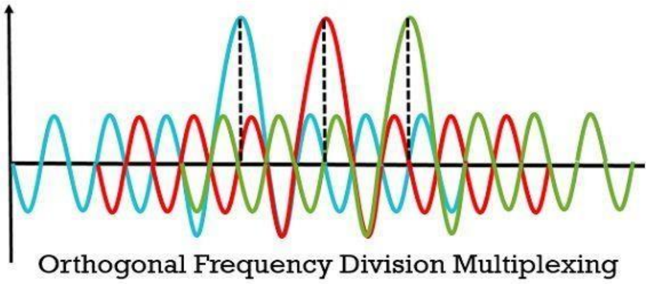


Figure II 4: Time/frequency diagram of OFDMA

One of OFDMA's main benefits is that it can adjust subcarriers for users depending on what they need for data and the conditions of their channels. This makes it a great fit for traffic demands and users moving around at different speeds. Also, OFDMA helps users with different quality of service (QoS) needs, making it perfect for current applications such as video streaming, VoIP, and IoT services. This technique helps improve the network by reducing interference and boosting data speeds.

OFDMA's ability to effectively manage multiple users and provide high data throughput is a key reason it became the main multiple access method for 4G networks. However, managing many subcarriers and ensuring they stay in sync can be challenging, especially in fast-changing situations. Even so, OFDMA has changed the game in wireless communications by boosting capacity, increasing flexibility, and meeting the rising needs for mobile data services.

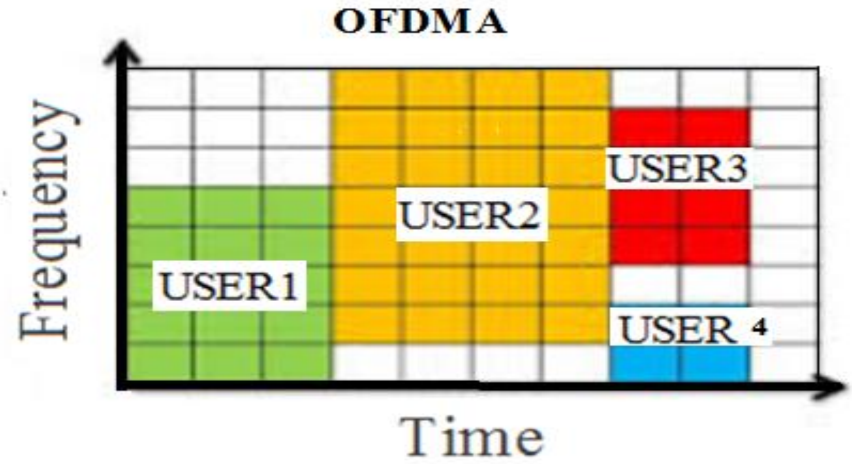


Figure II 5: Time/frequency diagram of OFDMA

II. 3 CHALLENGES AND LIMITATIONS OF TRADITIONAL MULTIPLE ACCESS SYSTEMS

Despite their widespread use in wireless communication, traditional multiple-access techniques face several challenges that limit their efficiency, scalability, and adaptability to the growing demands of modern networks. Below are some of the key limitations:

II. 3 .1 Spectral Inefficiency in OMA Systems

– **Fixed resource allocation:** Orthogonal Multiple Access (OMA) schemes, such as FDMA, TDMA, and OFDMA, allocate dedicated resources (frequency, time, or code) to each user. While this minimizes interference, it leads to inefficient spectrum utilization, as unused resources cannot be dynamically reassigned.

– **Limited user capacity:** The available bandwidth constricts the number of users that can be supported, making OMA less suitable for massive connectivity. High Complexity of CDMA Systems for Large User Bases

II. 3 .2 High Complexities of CDMA Systems for Large User Bases

– **Multi-user interference (MUI)**

CDMA allows multiple users to share the same frequency band, but as the number of users increases, the system experiences higher interference, requiring complex signal processing techniques.

– **Computational burden**

Advanced CDMA techniques (e.g., multi-user detection) involve high decoding complexity, making them less efficient for supporting massive IoT applications and ultra-low-latency scenarios. Limitations in Scalability and Interference Management

II. 3 .3 Limitations in Scalability and Interference Management

- **Interference handling**

Traditional systems struggle with interference management, particularly in dense networks with active users.

- **Lack of flexibility**

OMA and CDMA-based systems are limited in adapting to dynamic traffic loads, making them inefficient in highly variable environments.

- **Energy consumption**

Managing interference and optimizing power allocation in traditional systems often lead to higher energy consumption, a major concern for battery-powered IoT devices.

II. 4 NEED FOR ADVANCED MULTIPLE ACCESS SCHEMES

To overcome these limitations, Modern wireless systems require more flexible, efficient, and scalable multiple-access techniques to overcome these limitations. Non-orthogonal multiple Access (NOMA) addresses many challenges by allowing multiple users to share the same resources through power-domain and code-domain multiplexing, improving spectral efficiency, scalability, and user fairness.

II. 5 NON-ORTHOGONAL MULTIPLE ACCESS

Modern wireless networks must support a growing number of connected devices, but traditional Orthogonal Multiple Access (OMA) techniques—like FDMA and TDMA—struggle to deliver the needed spectral efficiency, massive connectivity, and low latency. To solve this, Non-Orthogonal Multiple Access (NOMA) has become a key technology for 5G and beyond, allowing multiple users to share the same time and frequency resources at once—something OMA cannot do.

Unlike OMA, which assigns separate (non-overlapping) frequency, time, or code slots to users, NOMA improves capacity by overlapping user signals and separating them using:

- **Power-Domain NOMA (PD-NOMA)** – Users are distinguished by different power levels, with weaker signals getting more power and stronger signals less.
- **Code-Domain NOMA (CD-NOMA)** – Users are separated using special codes (e.g., PDMA, SCMA).

While Code-Domain NOMA (like PDMA) uses special codes to separate users, it has some drawbacks. It can be complicated to implement and doesn’t work as well in very crowded networks. Because of these challenges, we chose to focus on Power-Domain NOMA in this thesis. This method is simpler and more efficient—it assigns different power levels to users sharing the same frequency, then uses smart decoding to separate their signals. This makes Power-Domain NOMA a better choice for real-world 5G and future networks, where reliability and efficiency matter most.

II.5.1 Types of NOMA

II.5.1.1 Power-Domain NOMA

Power-Domain NOMA, a pioneering technique, leverages differences in users' channel conditions by assigning different power levels to multiple users sharing the same frequency and time resources[83]. This ingenious approach significantly enhances spectrum efficiency and network capacity.

Its key components include:

- **Superposition Coding (SC), a highly efficient method, is** used at the transmitter to combine multiple user signals into a single transmitted signal with varying power levels.
- **Successive Interference Cancellation (SIC), a precise technique,** is applied at the receiver to decode and separate signals by subtracting known interference from stronger signals.

II. 5.1.2 Code-Domain NOMA

Unlike PD-NOMA, Code-Domain NOMA separates users by assigning unique low-correlation spreading sequences to differentiate their signals.
This allows multiple users to share resources efficiently at the same time and frequency. Examples include:

- **Parse Code Multiple Access**

Uses sparse spreading codes to improve detection efficiency and enhance system capacity.

- **Pattern Division Multiple Access**

Optimizes user-specific pattern design to reduce interference and improve system performance.

II.6 FUNDAMENTALS OF PD-NOMA

II.6.1 Concept of Downlink NOMA

Downlink Non-Orthogonal Multiple Access (NOMA) is a multiple access technique where a base station (BS) simultaneously transmits signals to multiple users over the same time and frequency resources. Unlike Orthogonal Multiple Access (OMA), which assigns dedicated resources to each user, NOMA differentiates users based on their power levels, improving spectral efficiency and supporting massive connectivity in 5G and beyond[84].

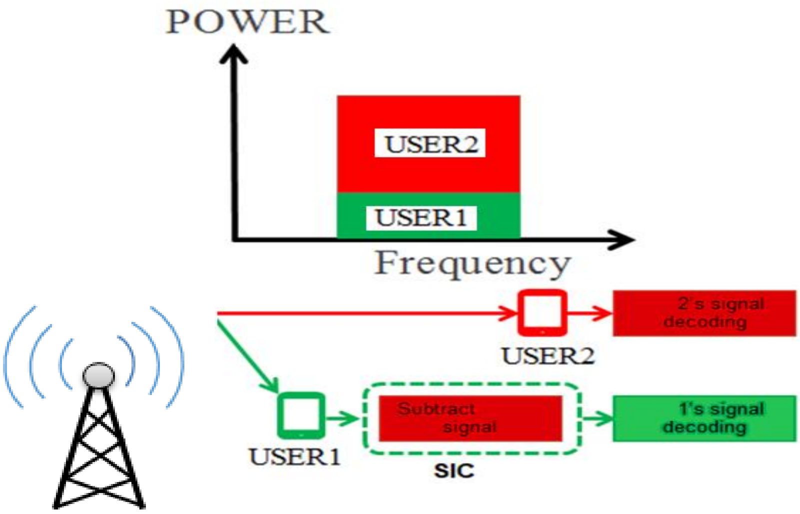


Figure II 6: Downlink NOMA network of PD- NOMA

II.6.1.1 Power-Domain Multiplexing in Downlink NOMA

Downlink NOMA operates in the power domain, where:

- Users with better channel conditions (closer to the BS) are assigned lower power, as their strong channel allows them to decode signals easily.
- Users with weaker channel conditions (farther from the BS, such as cell-edge users) receive higher power to improve their reception.
- This power allocation ensures that both near and far users can receive data without additional bandwidth consumption.

a- Successive Interference Cancellation

SIC represents the optimal decoding scheme for recovering user messages from superimposed signals in superposition coding (SC) systems. The fundamental principle of SIC leverages the inherent power disparity among multiplexed users in SC transmission[85]. The decoding process operates sequentially: first, users are ranked in descending order of their received signal strength. The receiver initially decodes the strongest user signal, subtracts it from the composite signal through interference cancellation, and subsequently extracts the weaker signal from the residual. This iterative cancellation proceeds until all user signals are recovered. During implementation, each decoded user signal is treated as interference for subsequent decoding stages, though this interference is progressively eliminated through successive cancellation. Figure II.8 demonstrates this decoding mechanism for the superimposed signal (shown in Figure II.7), where the receiver first decodes User 1's constellation points from the received signal before proceeding to decode User 2's constellation points after perfect cancellation of User 1's contribution.

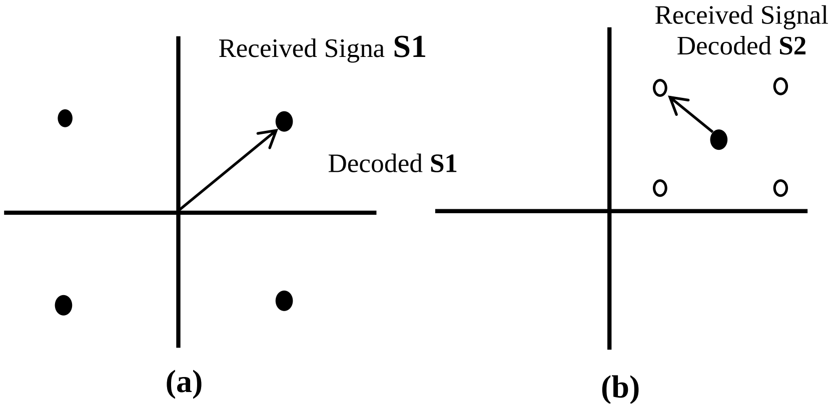


Figure II 7: Superposition Coding Decoding Stages:(a) User 1 signal decoding (strongest user)

At the receiver, stronger users decode and remove the weaker users' signals first before decoding their data.[7]

- This technique reduces intra-cell interference, ensuring efficient decoding.

b- Successive Interference Cancellation (SIC) at the Base Station

To ensure efficient decoding, the base station follows a stronger-user-first approach:

1. The user with the strongest channel gain (high power) is decoded first.
2. The decoded signal is subtracted from the received signal.
3. The process is repeated for the next strongest user.

For a two-user uplink NOMA scenario, let’s assume User 1 (stronger channel, near BS) and User 2 (weaker channel, far from BS):

SINR for decoding User 1 (stronger user) at BS:

$$\mathrm{SINR}_1 = \frac{|h_1|^2 P_1}{|h_2|^2 P_2 + \sigma^2} \tag{II.1}$$

If SINR_1 is sufficient, the base station decodes x_i first and removes it.

SINR for decoding User 2 (weaker user) after SIC:

$$\mathrm{SINR}_2 = \frac{|h_2|^2 P_2}{\sigma^2} \tag{II.2}$$

Once User 1's signal is removed, User 2's signal can be decoded without interference

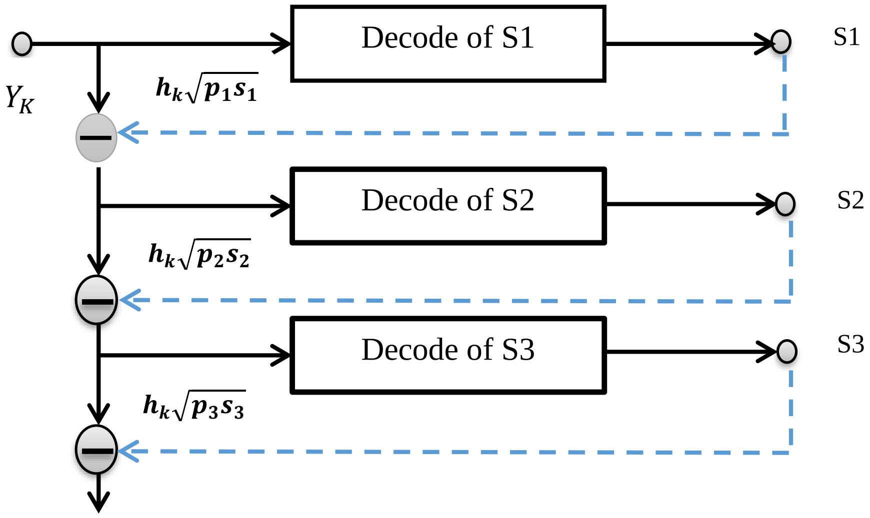


Figure II 8: Successive Interference Cancellation

II.6.1.2 Example of Downlnk NOMA Transmission

Consider a two-user downlink NOMA scenario, where a base station (BS) transmits a superimposed signal to multiple users sharing the same time and frequency resources. In this example, near user is located closer to the BS and experiences a stronger channel, while far user is farther from the BS and has a weaker channel.

- **(near user):**
    - Receives the superimposed signal, which contains both its own data and User B's data.
    - First, decodes User B's data, which was assigned a higher power level to compensate for its weaker channel.
    - Removes User B's data using the Successive Interference Cancellation (SIC) technique.
    - Finally, decodes its own data after eliminating interference.
- **(far user):**
    - Directly decodes its own data, as it was assigned a higher power level to ensure proper reception.

This power-domain multiplexing approach allows multiple users to share the same resources efficiently, leading to improved spectral efficiency, reduced latency, and enhanced performance for cell-edge users. As a result, downlink NOMA plays a crucial role in enabling massive connectivity and optimized resource allocation in 5G and beyond.

At the transmitter side, the BS employs superposition coding for non-orthogonal user multiplexing, where each user's data is independently channel-coded and modulated before being combined into a single transmission.

At the receiver side, each user must remove the signal interference of users with lower channel gains by applying the Successive Interference Cancellation (SIC) technique. This ensures accurate signal separation, enabling efficient communication across multiple users within the same bandwidth.

- superposition coded signal transmitted by the BS is given by:

$$\sum_{i=1}^{i} \sqrt{P_T}\,\alpha_i x_i \tag{II.2}$$

Where $\boldsymbol{y}$ the signal transmitted by the base station (BS),and P is power allocation to user E_i , x_i represents signal transmitted by BS.

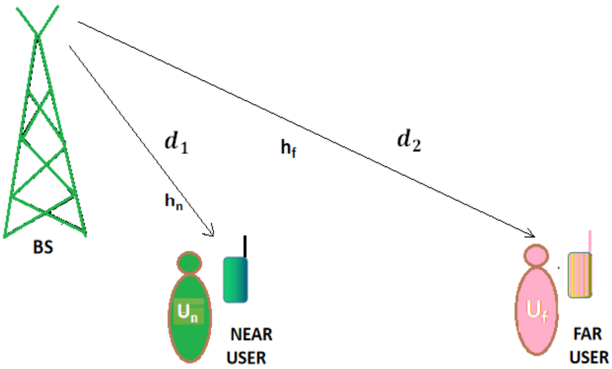


Figure II 9: Downlink NOMA network model for 2 users

The signal transmitted for tow users is represented by:

$$x = \sqrt{P}(\alpha_1 x_1 + \alpha_2 x_2)h \tag{II.3}$$

Where $\boldsymbol{x}$ represents signal transmitted by the BS and $\boldsymbol{P}$ equivalent Transmit power, $\boldsymbol{h}$ represents Rayleigh fading coefficient between the BS and users , $\mathbf{x}$ the messages to be transmitted to users

Received signal at user1 is given by:

$$x = h_1\sqrt{P_T}\,\alpha_1 x_1 + h_1\sqrt{P_T}\,\alpha_2 x_2 + w_1 \qquad \text{(II.5)}$$

Where:

- h_1 - Rayleigh fading coefficient between the BS and near user.
- α_1 - fraction of power allocated to near user.
- α_2 - fraction of power allocated to far user
- P -Transmit power.
- x_1 - the messages to be transmitted to near user.
- x_2 - the messages to be transmitted to far user.
- w - Gaussian noise.

Received signal at user2 is given by:

$$x = h_2\sqrt{P_T}\,\alpha_1 x_1 + h_2\sqrt{P_T}\,\alpha_2 x_2 + w_2 \qquad \text{(II.6)}$$

Where:

- h_2 - Rayleigh fading coefficient between the BS and far user.
- α_1 - fraction of power allocated to near user.
- α_2 - fraction of power allocated to far user.
- P -Transmit power.
- x_1 - the messages to be transmitted by near user $\boldsymbol{U_n}$
- x_2 - the messages to be transmitted by far user $\boldsymbol{U_f}$
- w - Gaussian noise.

When NOMA is used, the throughput for each UE_i

Can be written as:

$$\boldsymbol{R_i = w\ \log_2(1 + SNR_i)} \qquad \text{(II.7)}$$

$$R_i = w\ \log_2\left(1 + \frac{P_i g_i^2}{N + \sum_{k=1}^{i-1} P_k g_i^2}\right) \qquad \text{(II.8)}$$

- The sum capacity for NOMA can be written

$$R_t = \sum_{i=1}^{i} R_i \tag{II.9}$$

- The sum power allocation coefficient for the UE_i

$$\alpha_i = \sum_{i=1}^{n} P \leq 1 \tag{II.10}$$

$$\sum_{i=1}^{i} P_i \leq P_t, P_i \geq 0, \forall$$

II.6.2 Concept of Uplink NOMA

Uplink NOMA is a multiple access technique that allows multiple users to transmit data to a base station (BS) simultaneously over the same time and frequency resources. Unlike traditional OMA, where users are assigned separate frequency or time slots, uplink NOMA differentiates users based on their power levels, optimizing spectrum efficiency and increasing system capacity.

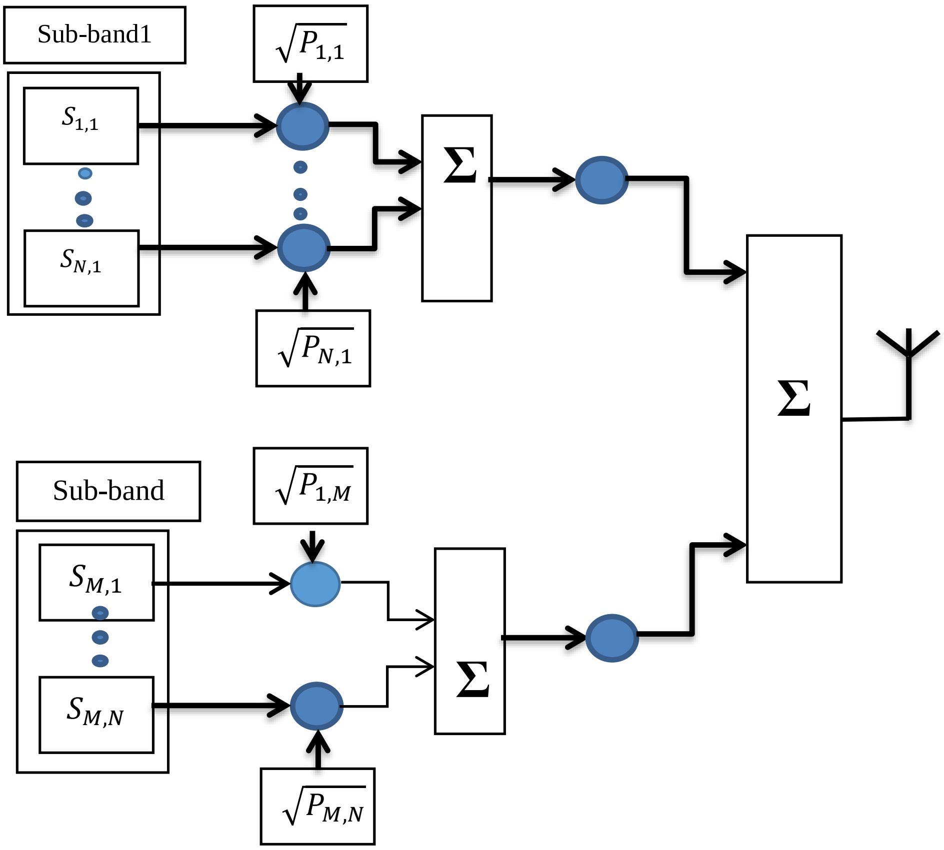


Figure II 10: general PD- NOMA transmission

II.6.2.1 Power-Domain Multiplexing in Uplink NOMA

In uplink NOMA, users are typically allocated different power levels based on their channel conditions, but in contrast to downlink NOMA, the power control is performed at the users' side rather than the base station. Key principles include:

- Near users (stronger channels, closer to the BS) transmit with lower power, as their signals experience less path loss and are easily detectable.
- Far users (weaker channels, farther from the BS) transmit with higher power to compensate for their higher path loss and ensure reliable reception at the BS.
- The base station receives a superimposed signal from multiple users and applies Successive Interference Cancellation (SIC) to separate and decode each user's data.

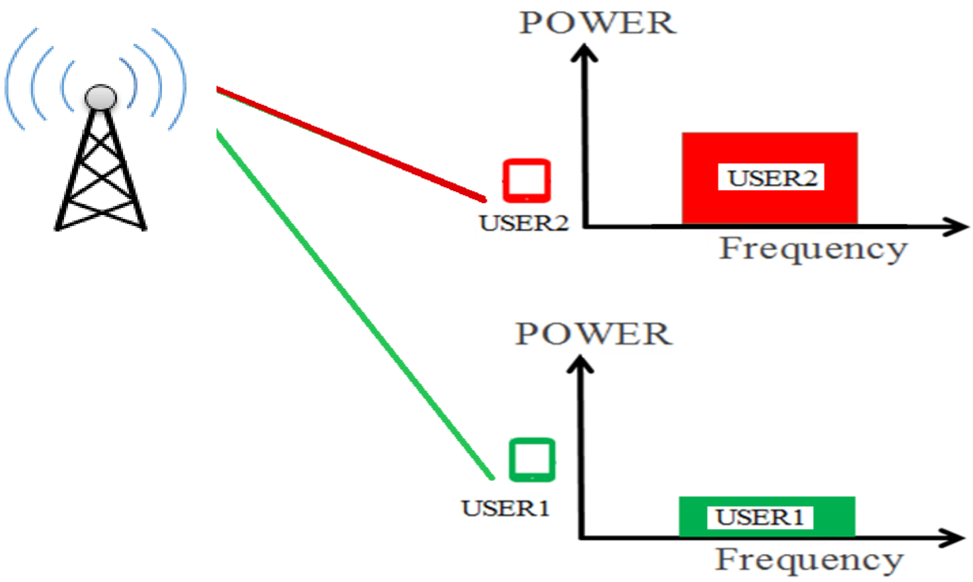


Figure II 11: uplink NOMA network of PD- NOMA

II.6 .2.2 Key Techniques in Uplink NOMA

- **Power Control Mechanism**

Users adjust their transmission power based on their channel conditions to maintain a balanced signal-to-noise ratio (SNR) at the base station.

- **Superposition Coding (SC)**

Superposition Coding (SC) is a non-orthogonal multiplexing technique that enables a base station (BS) to transmit multiple user signals simultaneously over the same time-frequency resource by exploiting **power-**domain multiplexing. Each user's signal is independently encoded and modulated, with power allocation inversely proportional to channel quality: near-users (strong channels) are assigned lower power**,** while far-users (weak channels) receive higher power to compensate for path loss. This hierarchical power allocation ensures that the superimposed signal can be decoded via SIC at the receiver. For instance, in a two-user SC system, the BS combines a high-power QPSK constellation (User 2, cell-edge) with a low-power QPSK constellation (User 1, cell-center), achieving capacity bounds for the scalar Gaussian broadcast channel**.** SC's spectral efficiency and compatibility with SIC make it a foundational strategy for 5G non-orthogonal multiple access (NOMA) schemes.

- The base station superimposes multiple user signals into a single transmitted signal with different power levels.
- Each user receives the same signal but with different power allocations.

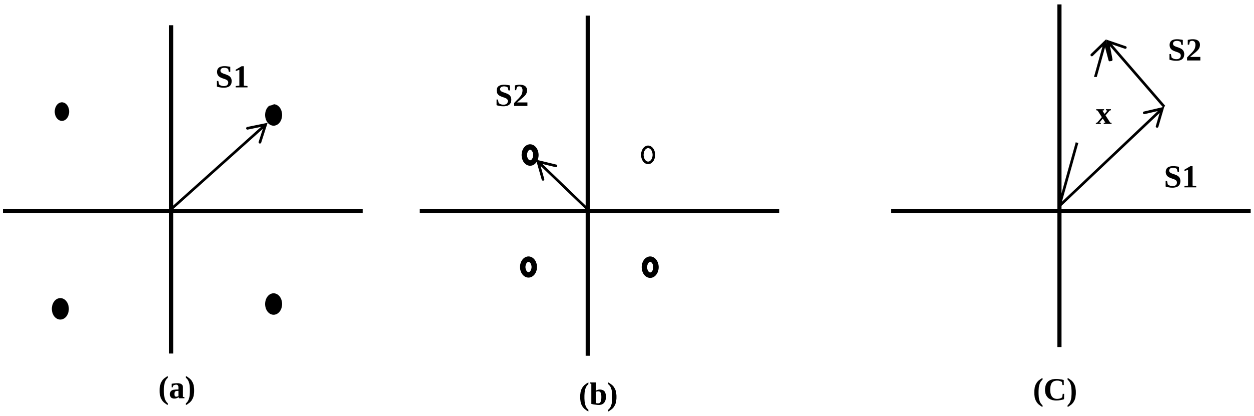


Figure II 12: Superposition Coding (SC) example illustrating: (a) User 1's signal constellation; (b) User 2's signal constellation; (c) Resultant superimposed constellation

II.6.2.3 Challenges of Uplink NOMA

- Inter-user interference: Proper power allocation is crucial to minimize interference and ensure correct decoding at the BS.
- Complex signal processing: SIC implementation at the BS increases computational complexity, requiring advanced signal processing techniques.
- Fairness and power control: Effective power control strategies are necessary to maintain network fairness among users with different channel conditions.

II.6 .2.4 Mathematical Equations for Uplink NOMA

In Uplink NOMA, multiple users transmit their signals to the BS simultaneously over the same frequency and time resources. Unlike Downlink NOMA, where power allocation is controlled at the base station, in Uplink NOMA, each user independently determines its power level, often based on channel conditions and fairness constraints.

a- Received Signal at the Base Station

The superimposed signal received at the base station from multiple users (K users) is given by:

$$y = \sum_{i=1}^{K} h_i \sqrt{P_i}\, x_i + w \qquad \text{(II.11)}$$

Where:

- h_i → Rayleigh fading coefficient for the *ith* user.
- P_i → Transmit power of the *ith* user.
- x_i → Transmitted signal from the *ith* user.
- $w \sim \mathcal{CN}(0,\sigma^2)$ → Additive white Gaussian noise (AWGN).

Since different users experience different channel gains, SIC is applied at the base station to decode signals in descending order of received power.

b- Achievable Data Rates in Uplink NOMA

Using Shannon's capacity formula, the achievable data rates for each user are:

- Rate of User 1 (strong user) before SIC:

$$R_1 = \log_2\left(1 + \frac{|h_1|^2 P_1}{|h_2|^2 P_2 + \sigma^2}\right) \qquad \text{(II.12)}$$

- Rate of User 2 (weak user) after SIC:

$$R_2 = \log_2\left(1 + \frac{|h_2|^2 P_2}{\sigma^2}\right) \qquad \text{(II.13)}$$

- Total system sum rate:

$$R_{\text{sum}} = R_1 + R_2$$

c- Outage Probability in Uplink NOMA

A user experiences an outage if its SINR falls below a predefined threshold γ_{th} Outage probability of User 1 (strong user):

$$P_{\text{out},1} = P\left(\frac{|h_1|^2 P_1}{|h_2|^2 P_2 + \sigma^2} < \gamma_{\text{th},1}\right) \quad \text{(II.14)}$$

- Outage probability of User 2 (weak user):

$$P_{\text{out},2} = P\left(\frac{|h_2|^2 P_2}{\sigma^2} < \gamma_{\text{th},2}\right) \quad \text{(II.15)}$$

d- Energy Efficiency in Uplink NOMA

Energy efficiency (E) is defined as:

$$E = \frac{R_{\text{sum}}}{P_{\text{total}}} \quad \text{(II.16)}$$

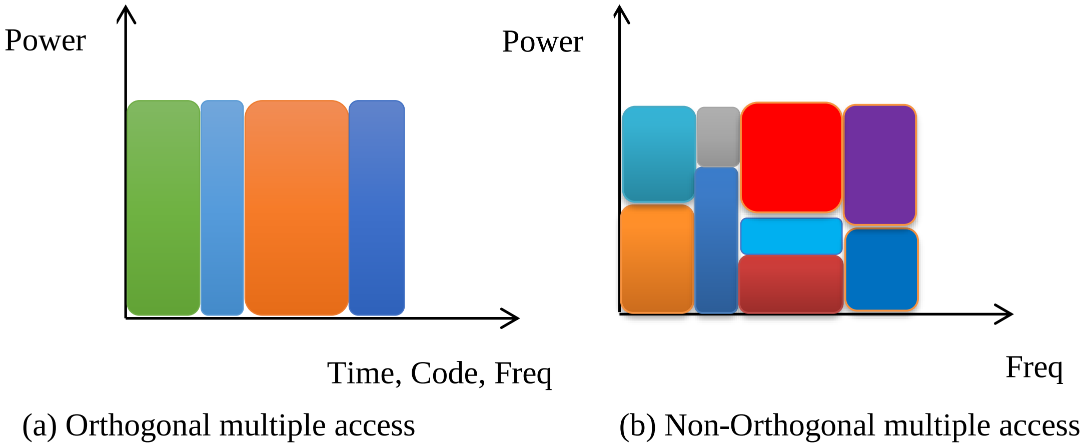
Where:

$$P_{\text{total}} = P_1 + P$$

measures the total system throughput per unit of power consumption.

II.7 COMPARISON OF OMA AND NOMA SYSTEMS

The comparison between OMA and NOMA systems is essential to understand their respective strengths, limitations, and suitability for different wireless communication scenarios. Below, we evaluate both systems based on key performance metrics and discuss their advantages and disadvantages.



(a) Orthogonal multiple access (b) Non-Orthogonal multiple access

Figure II 13: Difference between OMA and NOMA

In this section, we compare the simulation results for downlink NOMA and OMA (OFDMA, TDMA) systems.

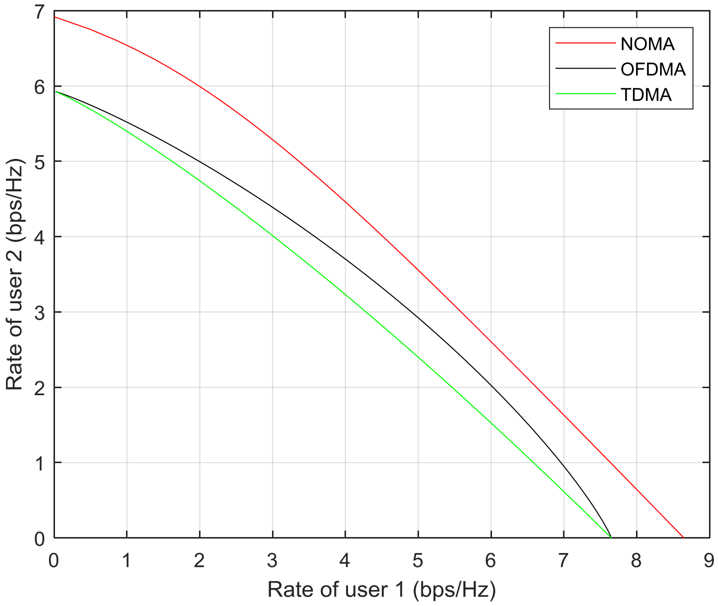


Figure II 14: Simulation results of TDMA and OFDMA system with NOMA

Figure II. 14 provides a comparison between OMA and NOMA systems. So from this figure, we can found that a sum rate of the capacity in the case of NOMA is high compared than the sum rate of the capacity in the TDMA system. Furthermore, we show that the value of the sum rate of the capacity is augment progressively with the increase of the number of users and the transmitted power.

II.7 .1 Key Performance Metrics

- Spectral Efficiency
- Energy Efficiency
- System Capacity and Throughput
- User Fairness and Latency

➢ **A Comprehensive table of OMA and NOMA Systems**

The dynamic progression of wireless communication technologies necessitates a thorough comparison between traditional orthogonal multiple access (OMA) methods and advanced NOMA techniques[86], the latter offering substantial improvements in system capacity. This table systematically contrasts their core characteristics:

Table II 1:A COMPREHENSIVE TABLE OF OMA AND NOMA

Metric	OMA	NOMA
Spectral Efficiency	Moderate, limited by orthogonal resource allocation.	High, due to non-orthogonal resource sharing and advanced techniques.
Energy Efficiency	Efficient in low-density networks; decreases in dense networks.	Improved in dense networks, but with higher processing overhead.
System Capacity	Limited by fixed resource allocation.	Significantly higher, supporting more users simultaneously.
User Fairness	Fair but static resource allocation.	Dynamic allocation ensures better fairness for users with weak signals.
Latency	Can increase in dense networks due to resource contention.	Reduced latency due to simultaneous transmission.
Complexity	Low complexity, easy to implement.	High complexity due to advanced processing and power control.

II.7.2 Advantages and Disadvantages

By studying these aspects, you'll gain a comprehensive understanding of why NOMA is a promising technology despite its challenges, and where OMA remains relevant.

The table below shows the advantages and disadvantages of OMA and NOMA.

Table II 2: ADVANTAGES AND DISADVANTAGES OF NOMA AND OMA

Aspect	**OMA**	**NOMA**
Advantages	- Simplicity in implementation and resource allocation.	- Higher spectral efficiency and system capacity.
	- Low computational complexity at the receiver.	- Improved user fairness and support for massive connectivity.
	- Proven reliability in traditional cellular networks.	- Better performance in high-density and interference-prone environments.
Disadvantages	- Limited spectral efficiency and scalability in dense networks.	- Higher computational complexity (e.g., SIC at the receiver).
	- Inefficient resource utilization in scenarios with varying user demands.	- Requires precise power control and channel state information.
	- Struggles with interference management in high-density scenarios.	- Increased system complexity and implementation challenges.

II.7.3 Challenges and Limitations

Both Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) systems face unique challenges and limitations that impact their performance, scalability, and practical implementation. Understanding these challenges is crucial for optimizing their use in modern and future wireless communication networks[87].

Power Control Requirements

– NOMA requires accurate power allocation to ensure that users with weaker signals can be decoded successfully.

- The near-far problem (where nearby users overpower distant users) poses a significant challenge, necessitating dynamic and real-time power control mechanisms.

Channel State Information (CSI) Dependency

- NOMA performance heavily depends on accurate and timely CSI for effective user pairing and power allocation.
- In fast-changing environments, obtaining reliable CSI can be challenging, leading to suboptimal performance.

In this table II.3, below we present a Summary of the Challenges between OMA and NOMA**:**

Table II 3:A SUMMARY OF THE CHALLENGES BETWEEN OMA AND

Aspect	OMA	NOMA
Spectral Efficiency	Limited by fixed resource allocation.	High but challenged by multi-user interference.
Scalability	Struggles in high-density networks.	Scalable but requires advanced interference management.
Complexity	Low complexity, easy to implement.	High complexity due to SIC and power control.
Interference	Inter-cell interference is a challenge.	Multi-user interference requires precise management.
Implementation	Well-established but less flexible.	Emerging technology with standardization and hardware challenges.

II.7.4 Future Directions to Address Challenges

- **Hybrid OMA-NOMA Systems:** Combining the strengths of both techniques to improve scalability and efficiency.
- **Advanced Interference Cancellation:** Developing robust algorithms to manage interference in NOMA systems.
- **Resource Management:** Leveraging machine learning for dynamic resource allocation and power control.
- **Energy-Efficient Designs:** Reducing the computational overhead of NOMA through hardware and software optimizations.

- **Standardization Efforts:** Promoting global standards for NOMA to ensure compatibility and widespread adoption.

II.8 CONCLUSION

In this chapter, we study Performance Analysis and Optimization. We comprehensively Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) systems have provided valuable insights into their respective architectures, performance metrics, advantages, and challenges. With its simplicity and reliability, OMA remains a cornerstone of traditional wireless networks. At the same time, NOMA emerges as a transformative technology capable of addressing the demands of modern and future networks through higher spectral efficiency, massive connectivity, and improved user fairness. The comparative analysis highlights the trade-offs between the two techniques, emphasizing the importance of selecting the appropriate multiple-access scheme based on specific network requirements and use cases.

The findings underscore NOMA's potential to revolutionize wireless communication systems, particularly in high-density scenarios such as 5G and IoT networks. However, challenges such as computational complexity, interference management, and implementation barriers must be addressed to realize its full potential. As wireless communication continues to evolve, integrating OMA and NOMA, along with emerging technologies like beamforming and energy harvesting, will play a pivotal role in shaping next-generation networks. The evolution of multiple access techniques reflects the ongoing quest for higher efficiency, scalability, and adaptability, paving the way for a connected world that meets the diverse needs of users and applications

Chapter III

Downlink NOMA; Performance Analysis and Optimization

III.1 INTRODUCTION

In downlink NOMA, power-domain multiplexing assigns different power levels to users based on their channel conditions. Users with weaker channel conditions (e.g., those farther from the base station) are allocated higher power, while users with stronger channel conditions receive lower power. At the receiver end, SIC is employed to decode signals. The user with the stronger channel condition decodes and removes the interference caused by the weaker user's signal before decoding its signal. This hierarchical decoding process ensures efficient resource utilization and improved spectral efficiency.

The importance of downlink NOMA in modern wireless networks, such as 5G and the Internet of Things, cannot be overstated. With the exponential growth in connected devices and the demand for higher data rates, NOMA addresses critical challenges like network congestion, latency, and energy efficiency[88]. In 5G and beyond, NOMA enhances system capacity and supports massive connectivity, making it a cornerstone for enabling ultra-reliable low-latency communication and massive machine-type communication[89].

Despite its many positives, it still needs many improvements to solve its problems, like

- User Pairing and Clustering
- Power Allocation Optimization
- Receiver Complexity and Energy Consumption
- Successive Interference Cancellation (SIC) Complexity and Error Propagation
- Inter-User Interference Management
- Channel State Information (CSI) Accuracy
- Fairness vs. Trade-off

For that, in this chapter, we invested in User Pairing and Clustering Power Allocation Optimization in NOMA downlink and got a positive result. Depending on the algorithms we suggested.

III.2 MOTIVATION FOR PERFORMANCE ANALYSIS AND OPTIMIZATION IN DOWNLINK NOMA

Non-Orthogonal Multiple Access (NOMA) has emerged as a promising technology for improving spectral efficiency and supporting massive connectivity in next-generation wireless networks[90]. Unlike traditional orthogonal access schemes, NOMA enables multiple users to share the same time-frequency resources by utilizing power-domain multiplexing and successive interference cancellation (SIC) [91]. However, the practical deployment of downlink NOMA faces several challenges that necessitate rigorous performance analysis and optimization.

III.2.1Challenges in Downlink NOMA

III.2.1.1 Interference Management

- NOMA relies on superposition coding at the transmitter and SIC at the receiver, making it highly susceptible to inter-user interference.
- Imperfect SIC can lead to error propagation, degrading overall system performance.

III.2.1.2 Power Allocation Complexity

- Efficient power allocation is crucial to balance the trade-off between strong and weak users while ensuring reliability.
- Suboptimal power allocation can lead to poor signal quality and reduced system performance.

III.2.1.3 User Fairness and QoS Constraints

- Prioritizing certain users in power allocation can lead to unfair resource distribution.
- Guaranteeing quality of service (QoS) for all users requires adaptive strategies that consider varying channel conditions.

III.2.2 Need for Optimization

Given these challenges, optimization techniques are essential to enhance the performance of downlink NOMA by:

- Maximizing Spectral Efficiency: Efficient power and resource allocation strategies are needed to fully exploit NOMA’s spectral advantages.
- Improving Energy Efficiency: Optimization frameworks must balance power consumption with throughput to ensure sustainable network operation.
- Enhancing System Capacity: Advanced algorithms can help maximize the number of supported users while maintaining reliable communication.

III.2.3 Key Areas of Focus in Analysis and Optimization

To address these motivations, research typically concentrates on:

- Power Allocation: Determining the optimal power split between users to maximize capacity or ensure fairness[92],[84],[93],[6].

- User Pairing/Clustering: Grouping users efficiently to minimize interference and enhance SIC performance[94].
- Hybrid Approaches: Combining NOMA with MIMO, beamforming, or OMA for enhanced performance[7],[95].

III.3 PERFORMANCE ANALYSIS AND EVALUATION SCENARIOS FOR DOWNLINK NOMA

III.3.1 System Model

In this chapter, we examine a downlink transmission scenario within a multi-user single-input single-output H-NOMA system (see Figure III.1),[95]. In this hybrid setup, a lone antenna BS communicates with K single-antenna users, grouped into M clusters. Each cluster, labeled as (G_i), is assigned a distinct time-slot t_i , ∀ i ={1, 2, 3,...., M}, where *i* ranges from 1 to M. Notably, the overall transmission time (T) is partitioned into M sub-time slots, as depicted in FigureIII.2, such that $T = \sum_{i=1}^{M} t_i$ Furthermore, the users in each sub-time slot are served using a power-domain NOMA technique.

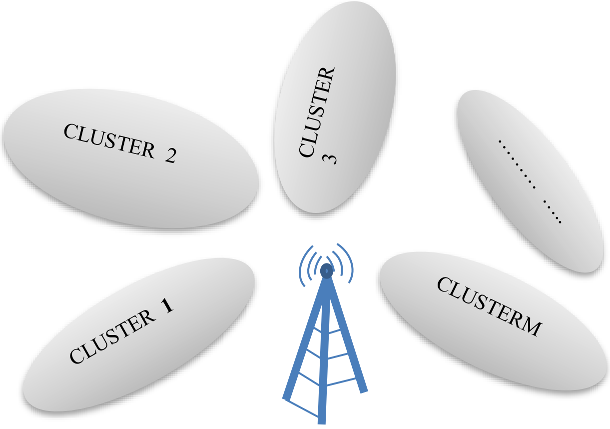


Figure III. 1: A hybrid TDMA-NOMA system [91].

.

On the other hand, $u_{j,i}$ represents the *j* user in the *i* clusters. Considering that the user grouping strategy significantly influences the system's performance, we shed some light on the proposed user grouping strategy later in this paper.

The signal transmitted from the BS during this period can be formulated as:

$$x_i = \sum_{j=1}^{M_i} p_{j,i} x_{j,i} \tag{III.1}$$

Where $x_{j,i}$ and $p_{j,i}$ represent the symbol designed for user $u_{j,i}$ and the corresponding power allocation, respectively. Note that the channel coefficients between the BS and the user $u_{j,i}$ are denoted by $h_{j,i}$ i =1, 2, ..., M. j =1, 2, ..., K_i. Additionally, it is assumed that both the BS and the users possess perfect channel state information. The received signal at $u_{j,i}$ can be defined as follows:

$$y_{j,i} = h_{j,i} x_{j,i} + w_{j,i} \tag{III.2}$$

Where $w_{j,i}$ denotes the AWGN with zero-mean and variance $\sigma^2_{j,i}$ dBm/Hz at receiver. Generally, it is supposed that each cluster users are ordered based on their channel strengths, such that,

$$|h_{1,i}|^2 \geq |h_{2,i}|^2 \geq \ldots\ldots\ldots \geq |h_{k,i}|^2, \ \forall i \in M \tag{III.3}$$

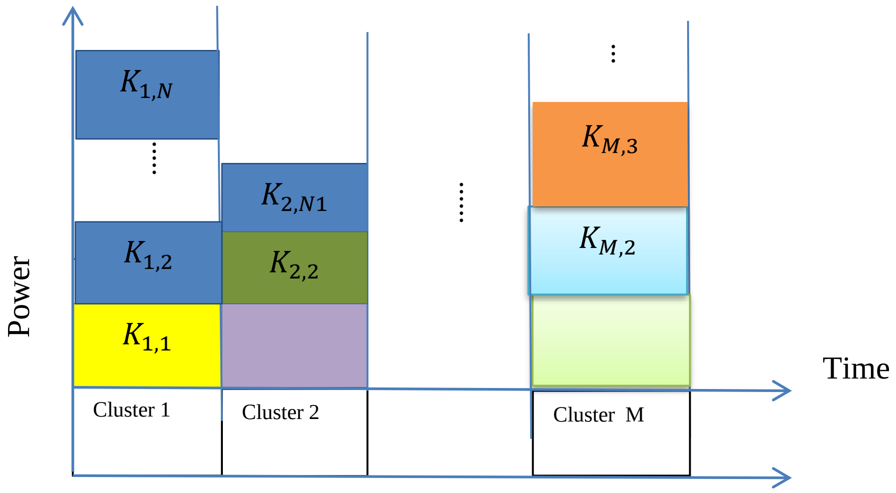


Figure III. 2: Multi-User H-NOMA System Downlink Transmission

Specifically, the SIC process is performed by the stronger users, wherein user $u_{j,i}$ employs SIC to decode and remove the signals intended for users from $u_{i+1,i}$ to $u_{kj,i}$ before decoding its own signal. It is presupposed in this paper that SIC operates flawlessly, devoid of errors.

Thus, the signal received by $u_{j,i}$ post the application of SIC can be expressed by:

$$r_{j,i} = h_{j,i} p_{j,i} x_{j,i} + h_{j,i} \sum_{s=1}^{j-1} p_{j,i} x_{j,i} + w_{j,i} \; \forall i \in M, \forall \in Ki \qquad \text{(III.4)}$$

The SNR at which $u_{j,i}$, decodes the message of weaker users $u_{d,i}$ ∀d ∈ { j+1, j+ 2, ..., K_i } can be written as:

$$\mathrm{SNR}_{\mathrm{j,i}} = \frac{\left|\mathrm{h}_{\mathrm{j,i}}\right|^2 p_{d,i}^2}{w_{j,i} + \Sigma_{\mathrm{s}=1}^{\mathrm{d}-1} p_{j,i}^2 \left|\mathrm{h}_{j,i}\right|^2}, \forall i \in M, \forall j \in K_i, \forall d \in \left\{ j+1, j+2, ..., K_i \right\} \qquad \text{(III.5)}$$

Specifically, the stronger user $u_{j,i}$ possesses the ability to execute SIC only if the messages designated for the weaker users, i.e., $u_{d,i}$, ∀d ∈{j +1,j +2, ..., K_i }, are received at $u_{j,i}$ with a higher SINR compared to users with stronger channel conditions. In fact, this can only be achieved by incorporating the following constraint into the design [91]:

$$p_{k,i}^2 \geq p_{k-1,i}^2 \geq \ldots \geq p_{1,i}^2, \forall i \in M \qquad \text{(III.6)}$$

The constraint mentioned in equation (III.6) is termed the SIC constraint in this paper. Hence, the SINR of $u_{j,i}$ can be defined as:

$$\mathrm{SINR}_{j,i} = \min\left\{\mathrm{SINR}_{j,i}^1, \mathrm{SINR}_{j,i}^2, \ldots.., \mathrm{SINR}_{j,i}^j\right\} \forall i \in M \;, \forall j \in \mathrm{K}_i \qquad \text{(III.7)}$$

Therefore, according to the definition provided above, the attained rate at $u_{j,i}$ can be expressed by:

$$R_{j,i} = t_i \log_2\left(1 + \mathrm{SINR}_{j,i}\right), \; \forall \mathrm{i} \in \mathrm{M}, \; \forall \mathrm{j} \in \mathrm{K}_i \qquad \text{(III.8)}$$

The total required transmit power at the BS is as follows:

$$\sum_{i=1}^{M} \sum_{j=1}^{\mathrm{K}_i} p_{j,i}^2 \qquad \text{(III.9)}$$

This is restricted by an upper limit of $p_{\max}$. The total transmitted power constraint is expressed as:

$$p_t = \sum_{i=1}^{M} \sum_{j=1}^{K_i} p_{j,i}^{2} \leq p_{\max} \tag{III.10}$$

The sum power allocation coefficient for the u_i can be given by the following equation:

$$\alpha_i = \sum_{i=1}^{n} P_i \leq 1 \tag{III.11}$$

In which, $\sum_{i=1}^{i} P_i \leq P_t, P_i \geq 0, \forall i$ Where P_t is the total powers transmitted by the BS:

$$\boldsymbol{\alpha}_1 + \boldsymbol{\alpha}_2 + \ldots + \boldsymbol{\alpha}_i = 1,\ \boldsymbol{\alpha}_i > \ldots \boldsymbol{\alpha}_2 > \boldsymbol{\alpha}_1 \tag{III.12}$$

Given the context provided, adjusting the power splitting factor (α) to allocate time and transmit power among users within a hybrid TDMA-NOMA system, all the while ensuring fairness in terms of achieved rates. The specific solution methodology will be detailed in the following section.

In this system model, the BS superimposes information signals for its M serviced users, each user equipment utilizes successive cancellation interference algorithm (SIC) to detect its respective signal. It is assumed in this network that user 1 is the furthest from the BS, while user M is the closest. In NOMA system, greater power is allocated to users located farther from the BS, with the least power allocated to the closest user. Each user initially deciphers the strongest signal and subsequently subtracts the decoded signal from the composite received signal. The receiver employing SIC iteratively subtracts until it isolates its own signal.

The sum capacity can be written as:

$$R_t = \sum_{i=1}^{i} R_{j,i} \tag{III.13}$$

III.3.2 Problem Formulation:

As previously highlighted in the introduction, ensuring user fairness is a pivotal necessity for the advancement of wireless networks, including 5G and beyond. Consequently, our focus revolves around distributing the accessible resources namely, time and transmit power among users to uphold fairness in terms of achieved rates within the hybrid TDMA-NOMA system[95].

Specifically, our goal is to maximize the minimum attained rate for each individual user. This objective is pursued through the resolution of the subsequent max-min optimization problem:

$$\underset{p_{j,i}t_i\,,}{\text{Max}} \quad \underset{1\le j\le k_i}{\min} \quad \underset{,1\le i\le M}{\mathrm{R}_{\mathrm{j,i}}}$$

Maximize the minimum achieved rate $\mathrm{R}_{\mathrm{j,i}}$ over users (j) and time slots (i) within the specified limits $1\le j\le k_i$ and $1\le i\le M$ while considering the variables $p_{j,i}$ and t_i .

$$\sum_{1}^{c} t_i \le T$$

$$P_t \le P_{max} \tag{III.14}$$

$$p_{k,i}^2 \ge p_{(k-1,i)}^2 \ge .....\ge p_{(1,i)}^2 \forall i \in M$$

The constraint guarantees that the cumulative allocated time does not surpass the available transmission time T. Additionally, the constraint promotes the effective implementation of (SIC). Nevertheless, increased complexity arises from the concurrent allocation of both time and transmits power to all users served in the system. Furthermore, the non-convex nature of the objective function intensifies the difficulty of solving the original problem outlined in. Consequently, we introduce an iterative algorithm to achieve a solution, as elaborated in the subsequent section.

III.3.3 PROPOSED METHODOLOGY AND DISCUSSIONS

III.3.3.1 User grouping based approach

In this section, we present an iterative approach developed for jointly solving inherently non-convex optimization problems. Then, in this section, we focus on the selection of initial parameters and the convergence aspects of the proposed iterative method. In the following subsections, we first provide a brief discussion of the proposed grouping strategy.

The selection of a suitable grouping strategy is crucial for the performance of the H-NOMA system, given that the optimal solution to the OPP relies on formulating optimal groups. Specifically, determining the ideal transmit power necessitates an exhaustive search for the optimal solution to OPP across all possible sets of groups. However, this approach is computationally complex and economically unfeasible for practical systems, including those in future wireless networks with (IoT) applications.

Moreover, the disparity in channel strengths among users within the same group emerges as another critical factor influencing the overall system performance. As NOMA serves users within each group, effective implementation of (SIC) technique requires maximizing the difference in channel strengths among users. Conversely, grouping users with similar channel strengths can introduce errors in the SIC implementation, leading to a degradation in the overall system performance. In light of this key consideration, we organize users to maximize the difference between their channel strengths. For instance, with two users in each group (i.e., Ki = 2), the user groups based on the proposed grouping strategy can be defined as:

$$(\{U_{1,1},U_{2,1}\},\{U_{1,2},U_{2,2}\},\cdots\{U_{1,c},U_{2,c}\})\equiv\{U_1,U_k\},\ \{U_2,U_{k-1}\},\cdots\{U_{k/2},U_{k/2+1}\} \tag{III.15}$$

The essential stages of simulation and validation in a real-world setting are important for confirming the effectiveness of the proposed methodology. This involves validating that the attained rates align with fairness objectives and evaluating the impact of dynamically adapting α on the overall efficiency of the system. Precision in adjusting parameters, such as the rate of variation in the power splitting factor, initial values, and convergence criteria, is imperative for achieving optimal system performance.

III.3.3.2 Application strategy

The proposed strategy focuses on a single-cell downlink NOMA network comprising a (BS) and a group of N users distributed uniformly within the cell., and; $u_n = \{1, 2, 3, \ldots, N\}$ Generally, in NOMA matching schemes, users are divided into two groups. High and low channel gain is based on the distances at the BS. In our system, we will be divided in to two groups. That is to say: the nearest near (NN) group, the Farthest Far (FF) group, and the Near Far (NF) group, as shown in Fig. 3 and Fig. 4 are the respective groups of NN, FF and NF. To optimize the overall system performance, we propose a new user pairing strategy based on the k-means clustering algorithm. The idea is to group users with similar channel conditions to minimize intra-group interference and improve overall NOMA performance.

- Use k-means clustering to group users into M clusters based on their channel gains.
- Assign users in each cluster to either the PD-NOMA group based on their QoS requirements.

- Adjust the cluster size to balance the trade-off between interference and resource allocation efficiency.

To ensure fairness in power allocation among users, we propose a three-step approach:

- **Step 1:** Determine the minimum power required to satisfy each user's QoS requirements estimation fairness power allocation, denoted as P_min_i for user i.
- **Step 2:** Allocate the remaining power budget (after satisfying the minimum requirements) among users using the proportional fairness criterion. The allocated power for user *i* is denoted as Pi.
- **Step 3:** Adjust the power allocation of each user based on their group (PD-NOMA) to minimize the intra-group interference.

To evaluate the performance of our proposed pairing strategy and fair power allocation, perform simulations and compare the results with other existing NOMA schemes, such as traditional PD-NOMA, in terms of metrics like sum-rate, fairness, and user satisfaction.

By combining the benefits of both PD-NOMA, and incorporating a fair power allocation mechanism, our proposed H-NOMA algorithm with the new pairing strategy can significantly improve the overall system performance while ensuring fairness among users.

Comprehensive documentation of the proposed methodology, regarding its implementation intricacies and the results acquired, holds significant importance. Providing transparent communication regarding the approach's strengths, limitations, and practical considerations enhances a holistic comprehension of its applicability and influence on optimizing the H-NOMA system.

a- Near-far pairing (N-F)

In this strategy, the user who is closest to the BS is paired with the user who is farthest away from the BS. The next closest user gets matched with the next furthest user, and so on. In a case of 4 users, U_1 is the closest user, while U_4 is the farthest user. As a result, N-F pairing will pair U_1 and U_4 in the same resource block. In the following resource block , U_2 will be matched with U_3.

In the first pair of users, U_1 is the near user and U_4 is the far user. Therefore, we have to choose the power allocation coefficients as $\alpha_1 < \alpha_4$. So, U_1 should perform (SIC), while U_4 will perform direct decoding. Similarly, in the second pair of users, U_2 is the near user and α_1

is the far user. Therefore, we have to choose $\alpha_2 < \alpha_3$. Here, U_2 should perform SIC while U_3 will perform direct decoding.

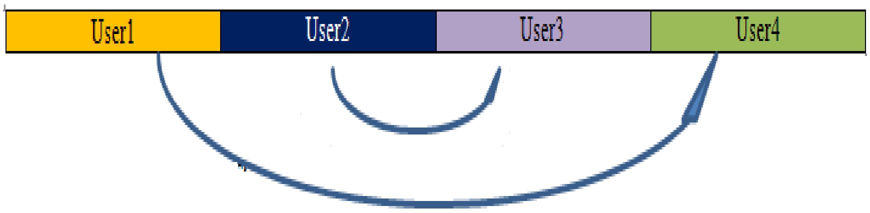


Figure III. 3: Pairing strategies in downlink communication scenario with Near- Near ,far- Far pairing (N-F)

The achievable rates for the users in the first pair are

$$R_1 = 1/2\ log_2(1+\frac{P_{\alpha 1}|h_1|^2}{\sigma^2}) \tag{III.16}$$

$$R_4 = 1/2\ log_2\left(1+\frac{P_{\alpha 4}|h_4|^2}{P_{\alpha 1}|h_4|^2+\sigma^2}\right) \tag{III.17}$$

The achievable rates for the users in similarly, for the second pair.

$$R_2 = 1/2\ log_2(1+\frac{P_{\alpha 2}|h_2|^2}{\sigma^2}) \tag{III.18}$$

$$R_3 = 1/2\ log_2\left(1+\frac{P_{\alpha 3}|h_3|^2}{P_{\alpha 2}|h_3|^2+\sigma^2}\right) \tag{III.19}$$

b- Near-near, far-far pairing (N-N, F-F)

An alternative user pairing approach involves linking the nearest user with the subsequent nearest user. Similarly, the farthest user is matched with the subsequent farthest user. In our instance, if we adopt this approach, U_1 will be paired with U_2 in one resource block. In the subsequent resource block, U_3 will be paired with U_4.

In the initial user pair, U_1 is closer to the BS than U_2. Hence, we need to select $\alpha_1 < \alpha_2$ U_1 to conduct SIC, where U_2 will engage in direct decoding. Likewise, U_3 is nearer to the BS than U_4. Therefore, we must opt for $\alpha_3 < \alpha_4$ where U_3 will undertake SIC, while U_4 will pursue direct decoding.

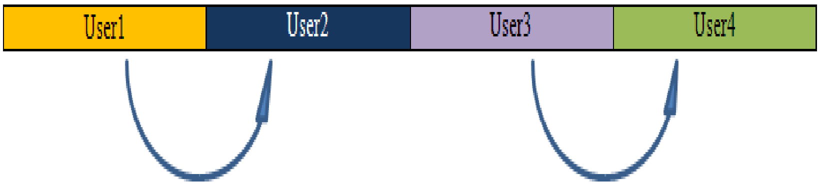


Figure III. 4: Pairing strategies in downlink communication scenario with Near-far pairing (N-F)

The achievable rates for the users in the first pair

$$R_1 = 1/2\ log_2\left(1+\frac{P_{\alpha 1}|h_1|^2}{\sigma^2}\right) \tag{III.20}$$

$$R_2 = 1/2\ log_2\left(1+\frac{P_{\alpha 2}|h_2|^2}{P_{\alpha 2}|h_2|^2}\right) \tag{III.21}$$

The achievable rates for the users in similarly, for the second pair

$$R_3 = 1/2\ log_2\left(1+\frac{P_{\alpha 3}|h_3|^2}{\sigma^2}\right) \tag{III.22}$$

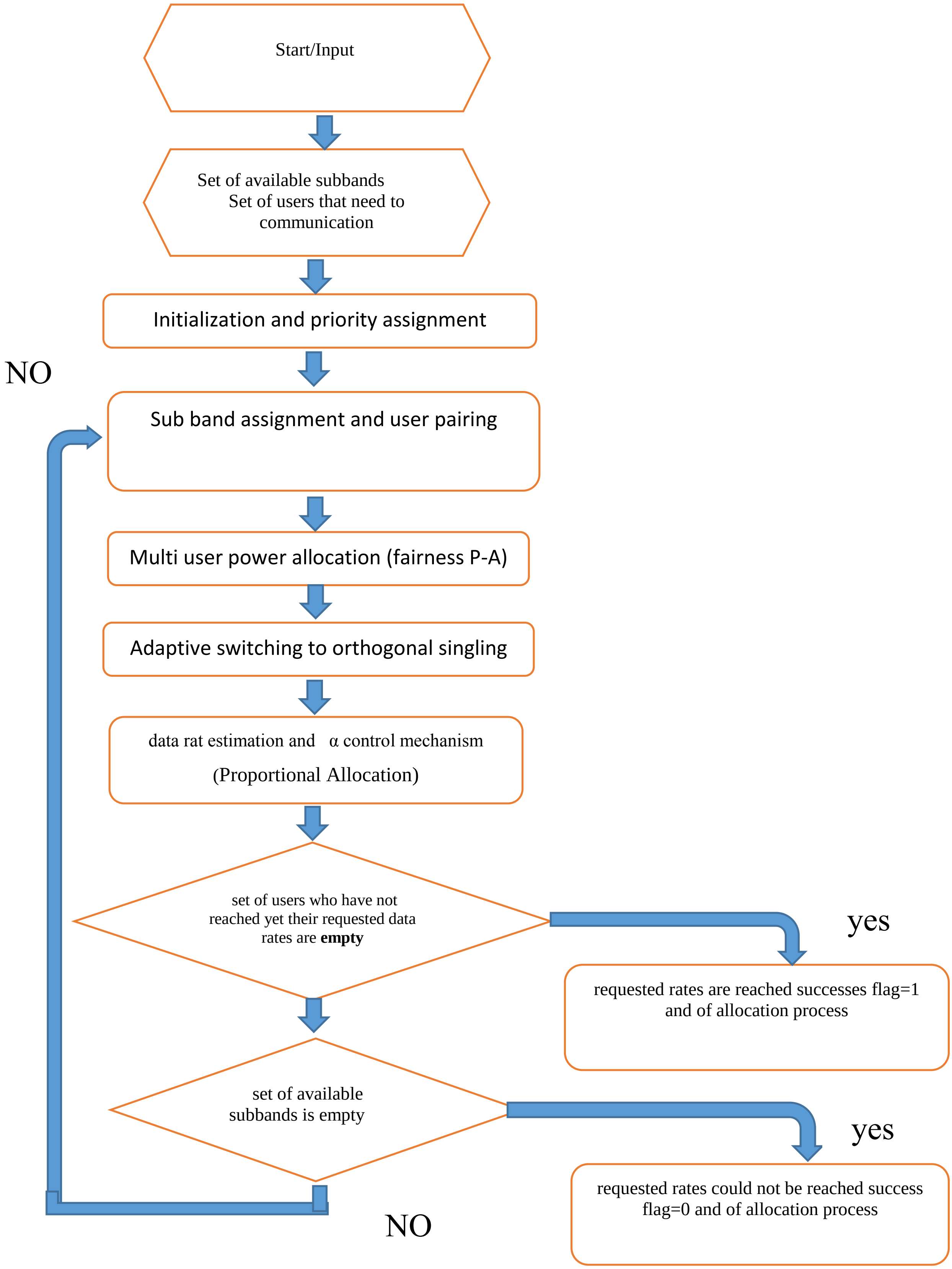
$$R_4 = 1/2\ log_2(1+\frac{P_{\alpha 4}|h_4|^2}{P_{\alpha 3}|h_4|^2}) \tag{III.23}$$

- **User Pairing via Fairness Power Allocation Algorithm**

In wireless systems (e.g., NOMA), user pairing groups near-users (strong channel) with far-users (weak channel) to maximize spectral efficiency. The Fairness Power Allocation Algorithm ensures equity by:

1. **Assigning higher power** to weak-channel users,
2. **Balancing achievable rates** across pairs,
3. **Using metrics** like max-min fairness to dynamically adjust power. This maintains QoS equality without sacrificing throughput, making it essential for 5G networks.

Visual Representation (Organigram)

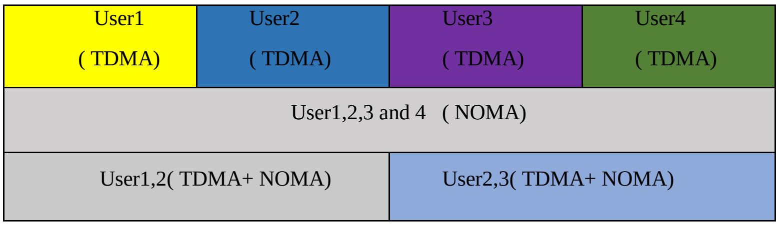


III.4 RESULTS OF SIMULATIONS AND DISCUSSION

To assess the performance of the H-NOMA scheme using the proposed method, we conduct a comparative analysis with the performance of the conventional scheme, which involves equal time allocations. In the simulations performed using matlab software, the users are uniformly distributed over a random radius around the BS.

As illustrated in Table III.1, let's consider a time slot of 4 m_s within this duration, there are four users to be accommodated. Using TDMA, the 4 m_s slot is divided into four 1 m_s slots, each allocated to a single user. In contrast, NOMA allocates the entire 4 m_s slot to users, which inevitably escalates SIC complexity and processing time. Conversely, H-NOMA divides the 4 m_s slot into two 2 m_s slots, assigning two NOMA users to each slot, as depicted in the subsequent table:

Table III 1:ASSIGNMENT OF USERS ACROSS VARIOUS MULTIPLE ACCESS SCHEMES



<table>
<tr><td>User1
(TDMA)</td><td>User2
(TDMA)</td><td>User3
(TDMA)</td><td>User4
(TDMA)</td></tr>
<tr><td colspan="4">User1,2,3 and 4 (NOMA)</td></tr>
<tr><td colspan="2">User1,2(TDMA+ NOMA)</td><td colspan="2">User2,3(TDMA+ NOMA)</td></tr>
</table>

In this simulation, we consider N = 4 users. The network's sum rate employed for each studied user pairing scheme is plotted. In addition, we compare the network's sum rate performance with just SC-NOMA and TDMA.

The following two figures show the performance evaluation in Downlink NOMA N-F paring with fair power allocation. In fig III.5 the algorithm calculates and compares the sum rates of TDMA, OFDMA, NOMA, and H-NOMA as the power splitting factor alpha varies. In fig III.6 the calculated rates for this scenario use the proportional allocation algorithm based on the estimated channel qualities of the users. The plot illustrates how the sum rates of these techniques change with different power allocation strategies.

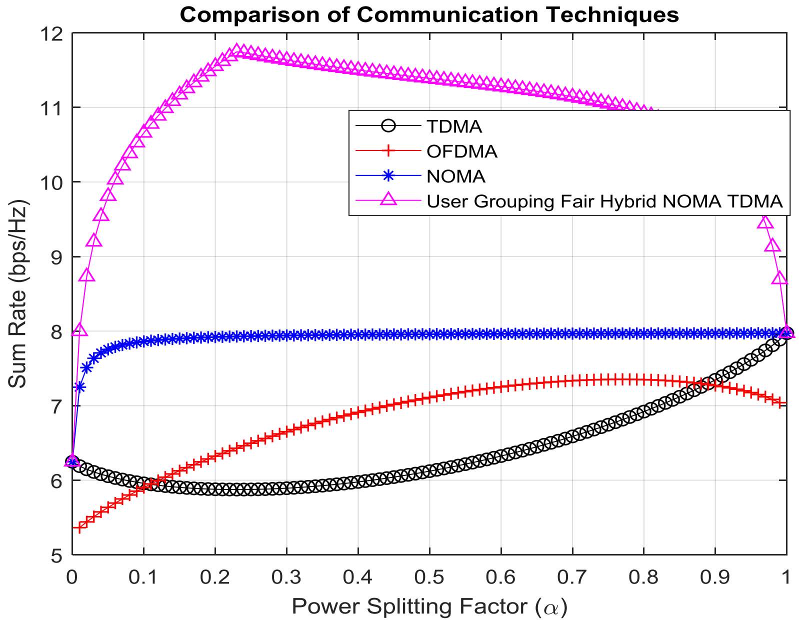


Figure III. 5: Comparative Rates of TDMA, OFDMA, NOMA, and H- NOMA Employing Power Splitting Factor Algorithm.

In this section, we aim to evaluate the performance of the H-NOMA scheme compared to conventional schemes in wireless communication systems. By conducting simulations in Matlab with users uniformly distributed around a BS (as detailed in table II), we can analyze the effectiveness of different time allocation methods. The comparison between traditional methods like TDMA and the more advanced NOMA and H- NOMA schemes will provide valuable insights into improving system efficiency and capacity.

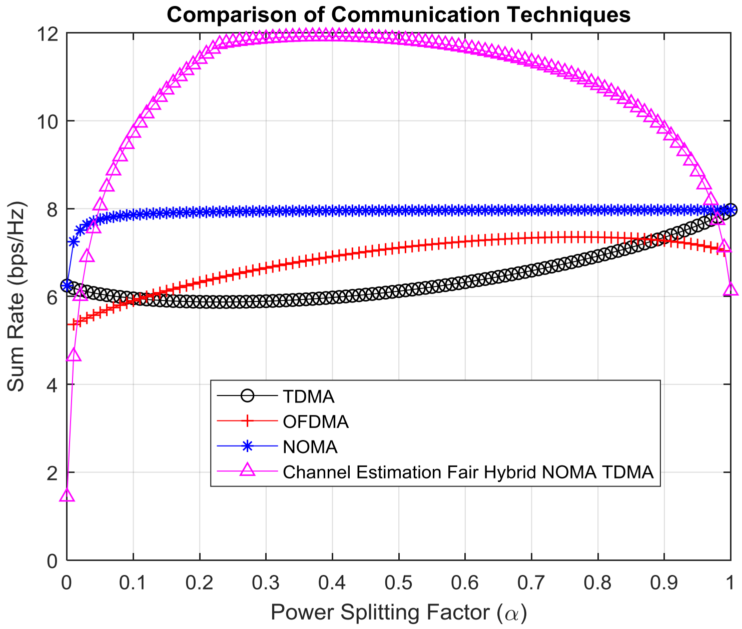


Figure III. 6: Rate Comparison of TDMA, OFDMA, NOMA, and H- NOMA Utilizing the Proportional Allocation Algorithm.

These algorithms use user pairing methods to group users based on their channel conditions and allocate power to each group. The three pairing strategies used are:

- Near-Near (N-N) Pairing: This strategy pairs users with similar channel conditions, typically those close to the BS. This pairing allows for more efficient power allocation, as the users have similar channel conditions and can be allocated similar amounts of power.
- Far-Far (F-F) Pairing: This strategy pairs users with similar channel conditions, typically those far from the BS. This pairing also allows for more efficient power allocation, as the users have similar channel conditions and can be allocated similar amounts of power.
- Near-Far (N-F) Pairing: This strategy pairs users with different channel conditions, typically pairing a user close to the BS with a user far from the BS. This pairing allows for more efficient resource utilization, as the users have different channel conditions and can be allocated different amounts of power.

This modified simulation applies the user grouping fairness power allocation to the Hybrid NOMA TDMA scenario. The users are grouped based on channel conditions, and power allocation is adjusted accordingly.

Table III 2:USERS PARAMETERS

User distance	**Value (m)**	**P-A coefficients**
D_{u1}	10	0.6
D_{u2}	9	0.3
D_{u3}	4	0.08
D_{u4}	3	0.02

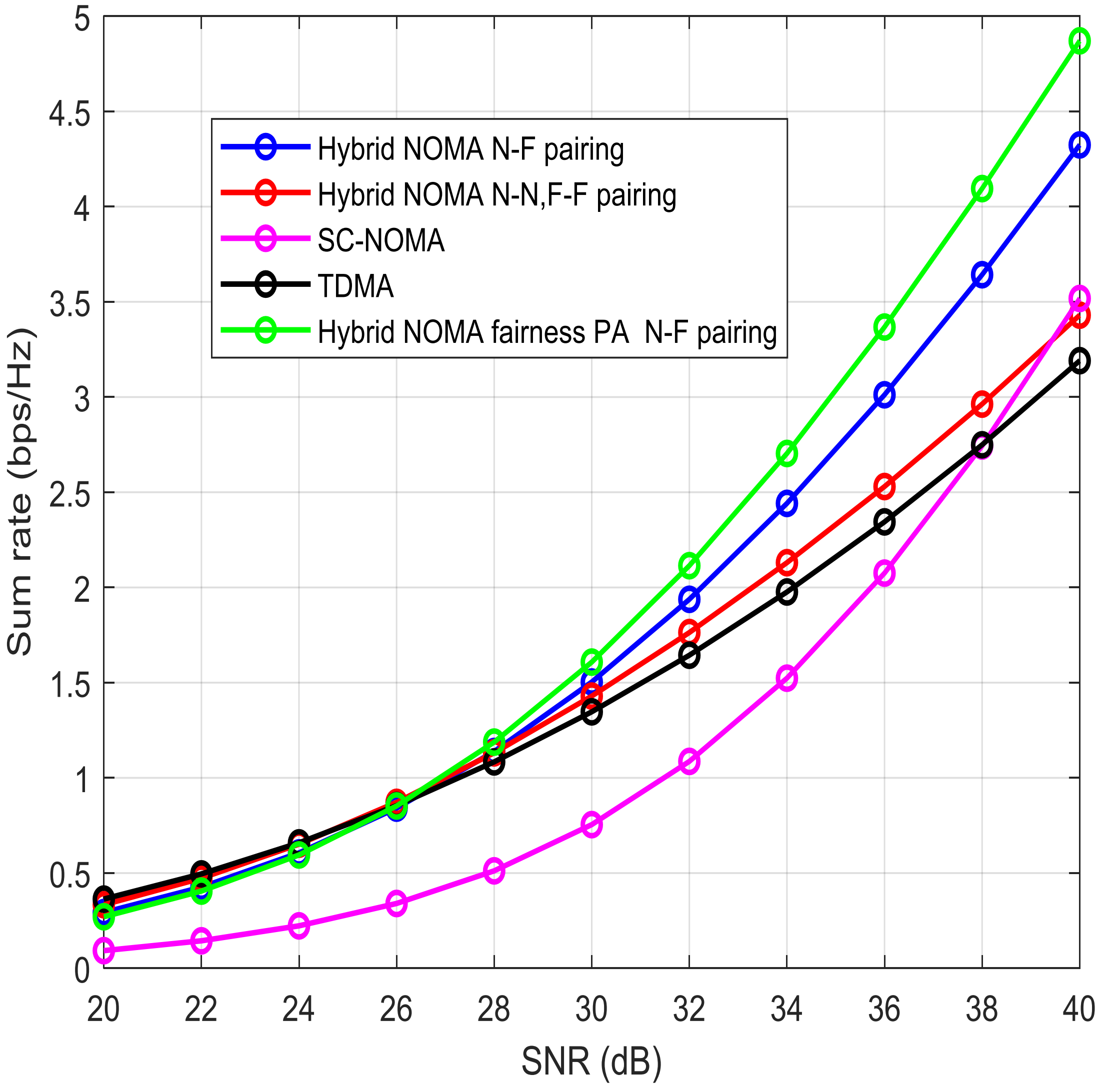


Figure III. 7: pairing strategy with fair power allocation SNR ratio

Table III 3:COMPARATIVES ANALYSIS OF THE PROPOSED H-NOMA AND OTHERS RESULTS

Comparison (40 db)	**Sum rate (bit/sec/Hz)**
H-NOMA fairness PA	4.8662
H-NOMA N-F pairing	4.3271
H-NOMA N-N,F-F pairing	3.4278
NOMA	3.5228
TDMA	3.1938

As illustrated in table III.3; the performance of NOMA fares poorly in comparison to TDMA due to the overloading of all users onto the same carrier, leading to interference issues. This observation underscores the fact that increasing the number of users sharing the same carrier comes at a cost, as highlighted in this fig III.8.

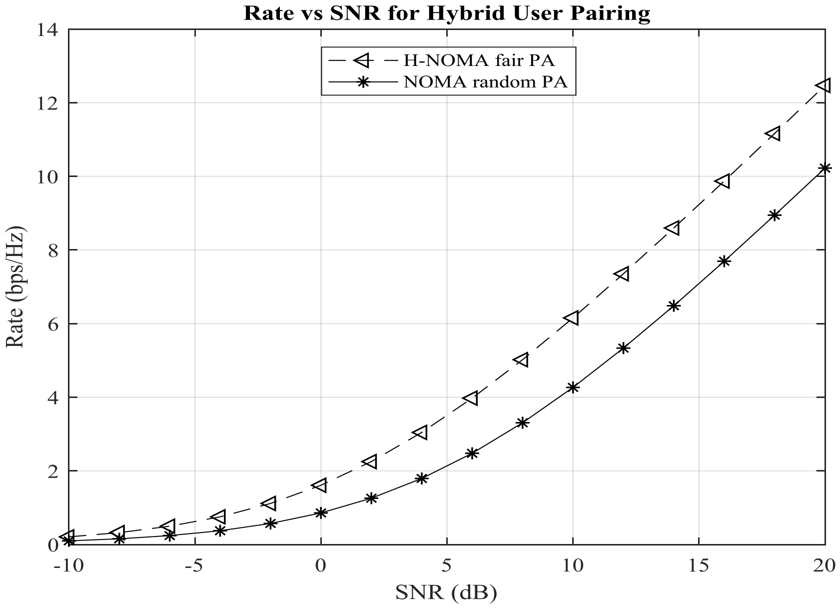


Figure III. 8: Comparison of the sum capacity between fair PA H-NOMA and NOMA with optimal user pairing, where uses N = 8

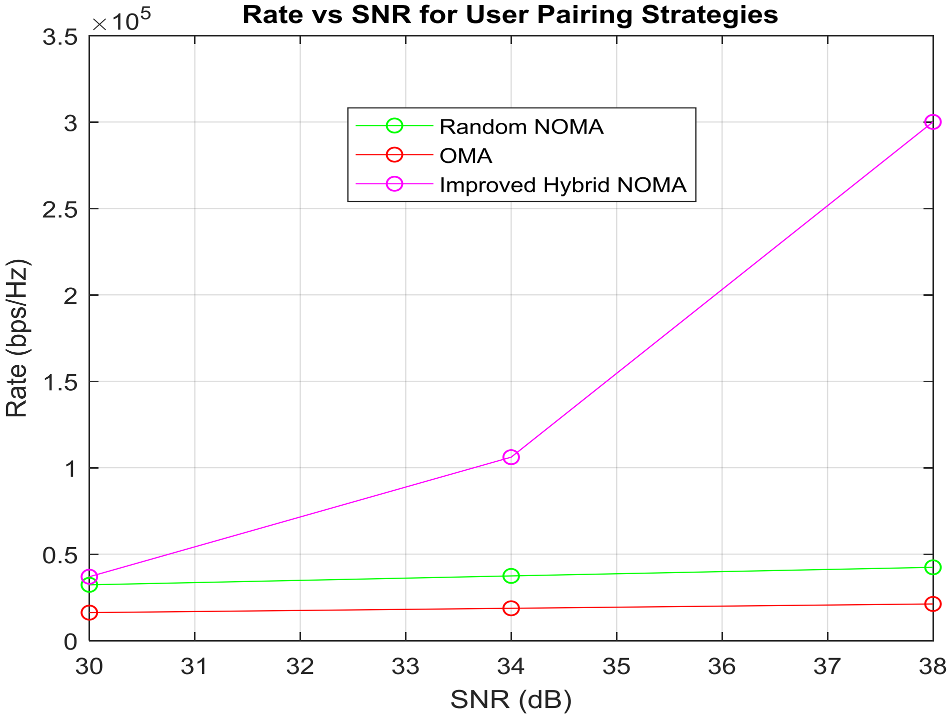


Figure III. 9: Comparison between NOMA, OMA user pairing, and H-NOMA with fair PA user pairing, where uses N =1132.

The simulations show that the sum of the H-NOMA with n-f pairing achieves the highest rates, followed by SC-NOMA and TDMA. The performance difference between the schemes becomes more significant as the SNR increases. Overall, the simulation results show that hybrid NOMA schemes can achieve higher sum rates than SC-NOMA and TDMA and that the choice of pairing can significantly affect the performance of the hybrid NOMA scheme

III.5 CONCLUSION

In this chapter, we propose a novel pairing strategy for hybrid NOMA systems that integrates fair power allocation to enhance system performance and user satisfaction. This strategy leverages the advantages of traditional NOMA schemes, such as power-domain NOMA (PD-NOMA), while ensuring equitable power distribution among users.

The proposed hybrid NOMA-OMA algorithm for downlink networks (Proportional Allocation Algorithm, Power Splitting Factor Algorithm.) achieves a more efficient user pairing approach compared to random user pairing. Simulation results demonstrate that NOMA-based user pairing algorithms, when integrated with hybrid NOMA-OMA schemes, significantly improve system performance, leading to increased radio capacity and enhanced network efficiency.

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Chapter IV

Performance Analysis of the Downlink NOMA System with Energy Harvesting

IV.1 INTRODUCTION

Integrating energy harvesting with downlink NOMA systems presents a promising avenue to enhance network performance. In such configurations, base stations with energy harvesting capabilities can sustainably power their operations, while user devices can harvest energy to support their communication needs. This synergy improves energy efficiency and aligns with the global shift towards green communications[96].

A critical aspect of optimizing downlink NOMA systems with energy harvesting is the development of fair power allocation algorithms. These algorithms aim to distribute power among users to maximize system throughput while ensuring fairness, particularly for users with weaker channel conditions. Achieving this balance is essential to prevent performance degradation for certain users and to maintain overall network efficiency. Recent studies have proposed various strategies to address this challenge, including optimization techniques and artificial intelligence-based approaches.

This chapter aims to conduct a comprehensive performance analysis of downlink NOMA systems incorporating energy harvesting mechanisms, focusing on resource allocation strategies that ensure fair power distribution among users. The specific objectives include:

System Modeling: Developing a detailed model of a downlink NOMA system integrated with energy harvesting capabilities, encompassing both the base station and user devices.

Performance Metrics Evaluation: Analyzing key performance indicators such as outage probability, throughput, and energy efficiency in the context of the integrated system.

Fair Power Allocation Algorithm Development: Designing and implementing a power allocation algorithm that ensures fairness among users, particularly addressing the challenges faced by users with weaker channel conditions.

Comparative Analysis: Benchmarking the proposed algorithm against existing power allocation schemes to assess fairness and overall system performance improvements.

Through this analysis, the chapter seeks to advance fair and efficient resource allocation in energy-harvesting-enabled downlink NOMA systems, thereby supporting the development of sustainable and high-performance wireless networks.

IV.2 OPTIMIZATION STRATEGIES

In downlink Non-Orthogonal Multiple Access (NOMA) systems, power allocation strategies play a pivotal role in determining overall system performance. Two primary approaches are often considered: fixed power allocation and fair (dynamic) power allocation[97].

- **Fixed Power Allocation** assigns predetermined power levels to users, typically based on their channel conditions or predefined policies. While this method is straightforward and easy to implement, it may not adapt efficiently to varying network conditions, potentially leading to suboptimal performance, especially for users with weaker channel conditions[98].
- **Fair Power Allocation**, on the other hand, dynamically adjusts the power distribution among users to ensure a balance between system throughput and user fairness[99]. This approach considers real-time factors such as user demand, channel variations, and quality of service requirements, aiming to optimize the sum rate while maintaining equitable resource distribution.

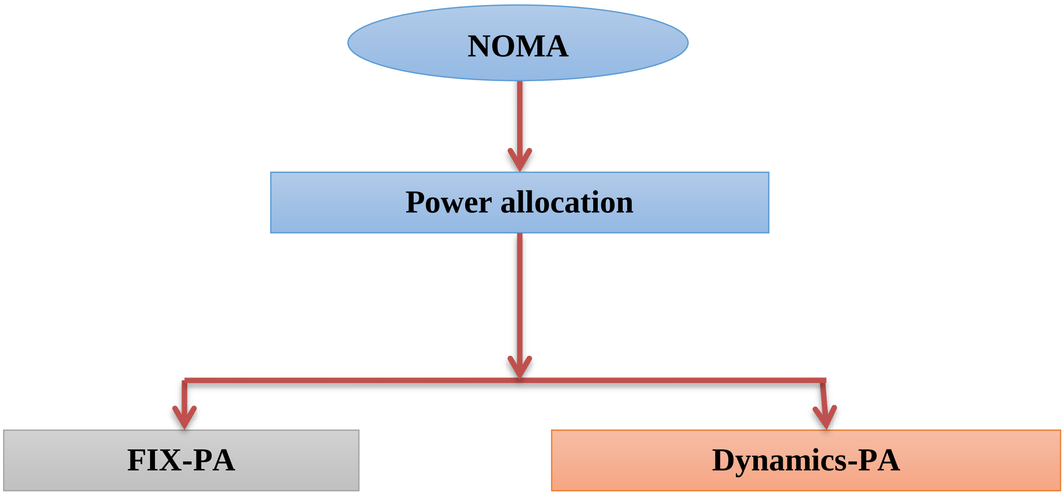

Figure IV. 1: Diagram of NOMA Downlink System: Fixed and Fair Power Allocation Strategies

IV.3 BASIC CONCEPT OF NOMA SYSTEM

IV.3.1 SYSTEM MODEL DOWNLINK OF NOMA

In this section, we present the block diagram and the NOMA system which are present in the Fig IV.2 and Fig IV.3 respectively. The block diagram is composed by the transmitter and the receiver, each equipped with a single antenna. Suppose that x_1 and x_2 are the signals to be transmitted from the BS to users 1 and 2, respectively. The superposition coded signal transmitted by the BS is given by:

$$y = \sum_{i=1}^{i} \sqrt{P_i}\, x_i \qquad \text{(IV.1)}$$

Where P_i, i=1, 2, is the transmit power for user i and the message signal x_i. The total transmit power of users 1 and 2 can then be written as $P=P_1+P_2\ldots+P_i$.

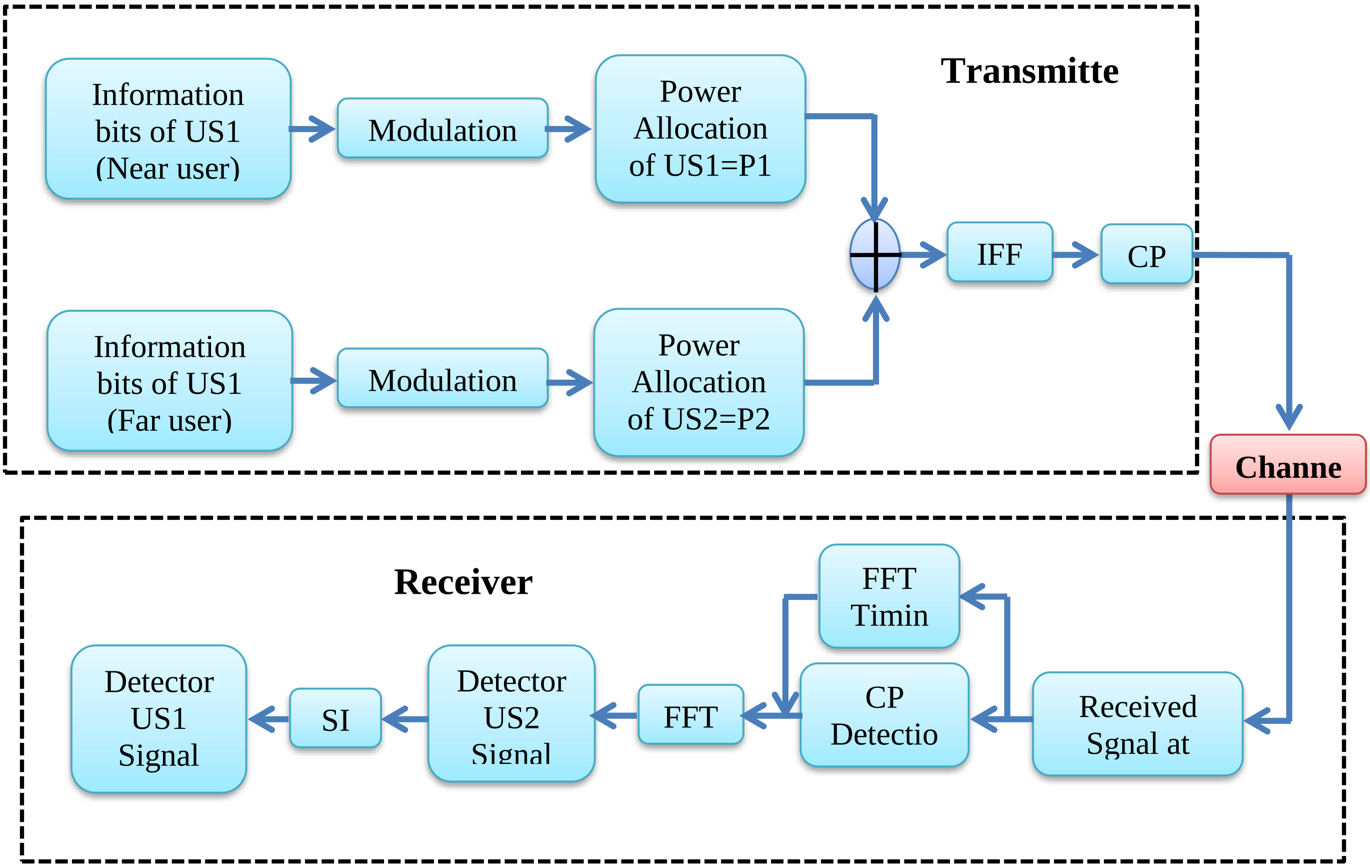

Figure IV. 2: The block diagram of the transmitter and the receiver for downlink NOMA system with using successive interference cancellation technique

The signal transmitted by the base station for two users is represented by:

$$y = \sum_{i=1}^{i} \sqrt{P(\alpha_1 x_1 + \alpha_2 x_2)} \qquad \text{(IV.2)}$$

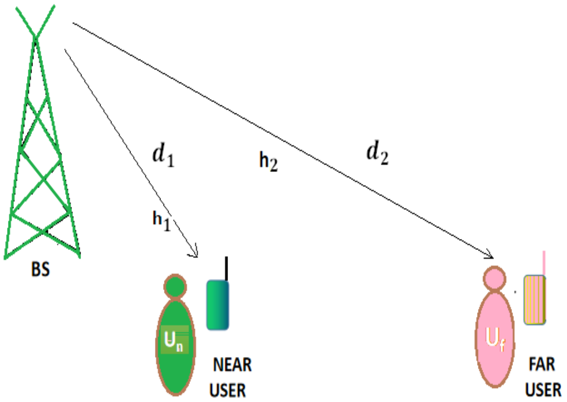

Figure IV. 3: Downlink NOMA

The sum power allocation coefficient for the UE_i can be given by the following equation:

$$\alpha_i = \sum_{i=1}^{n} \leq 1 \tag{IV.3}$$

In which, $\sum_{i=1}^{i} P_i \leq P_t, P_i \geq 0, \forall i$

Where P_t is the total powers transmitted by the BS.

The received signal the user1 is given by:

$$y_1 = h_1\sqrt{P_T \alpha_1 x_1} + h_2\sqrt{P_T \alpha_2 x_2} + w_1 \tag{IV.4}$$

Where:

- $\boldsymbol{h_1}$ Is the Rayleigh fading coefficient between the BS near user
- $\boldsymbol{\alpha_1}$ And $\boldsymbol{\alpha_2}$ are the fraction of power allocated to near user and the far user respectively.
- **P** is the transmitter power.
- $\boldsymbol{x_1}$ And $\boldsymbol{x_2}$ are the messages to be transmitted to near user and the far user respectively.
- $\boldsymbol{w}$ Is the Gaussian noise.

The received signal by the user2 is given by:

$$y_2 = h_1\sqrt{P_T \alpha_1 x_1} + h_2\sqrt{P_T \alpha_2 x_2} + w_2 \tag{IV.5}$$

Where:

- **h2** - Rayleigh fading coefficient between the BS and far user.
- $\boldsymbol{\alpha_1}$ and $\boldsymbol{\alpha_2}$ are the fraction of power allocated to near user and the far user respectively
- **P** is the Transmit power.
- $\boldsymbol{x_1}$ And $\boldsymbol{x_2}$ are the messages to be transmitted to near user and the far user respectively.
- $\boldsymbol{w}$ −Is the Gaussian noise.
- $\boldsymbol{\alpha_1} + \boldsymbol{\alpha_2} + \dots + \boldsymbol{\alpha_i} = 1$
- $\boldsymbol{\alpha_i} > \dots \boldsymbol{\alpha_2} > \boldsymbol{\alpha 1}$

The capacity equations of the NOMA for far and near user can be written as follows:

$$R_i = w \log_2(1 + SNR_i) \tag{IV.6}$$

$$SNR_i = \frac{P_i |h_2|^2}{N + \sum_{k=1}^{i-1} P_k |h_2|^2} \tag{IV.7}$$

$$R_i = W \log_2\left(1 + \frac{P_i |h_2|^2}{N + \sum_{k=1}^{i-1} P_k |h_2|^2}\right) \tag{IV.8}$$

The sum capacity of the NOMA can be written as:

$$\boldsymbol{R_t = \sum_{i=1}^{i} R_i} \tag{IV.9}$$

IV.3.2. SIMULATION RESULTS AND DISCUSSION

In this section, we study and compare the theoretical and the simulation results for downlink NOMA and TDMA systems in the case of fixed and dynamic fairness power allocation. For a fair comparison, we assumed that the transmitted power is varied between 0 and 40 dB for both systems. The power allocation coefficients for two, three, four, five users are presented respectively in table IV.1 In addition, we consider a different number of users (Two, three, four and five users) are distributed and communicated with the Base Station, when these users are positioned at different distance from the BS.

Table IV 1:THE DIFFERENT VALUES OF THE FIX POWER ALLOCATION COEFFICIIENTS WITH THE VARIATION OF THE NMBER OF USEERS

	α_1	α_2	α_3	α_4	α_5
Tow users	0.75	0.25			
Three users	0.75	0.1825	0.0675		
Four users	0.65	0.20	0.12	0.003	
Five user	0.75	0.20	0.02	0.018	0.012

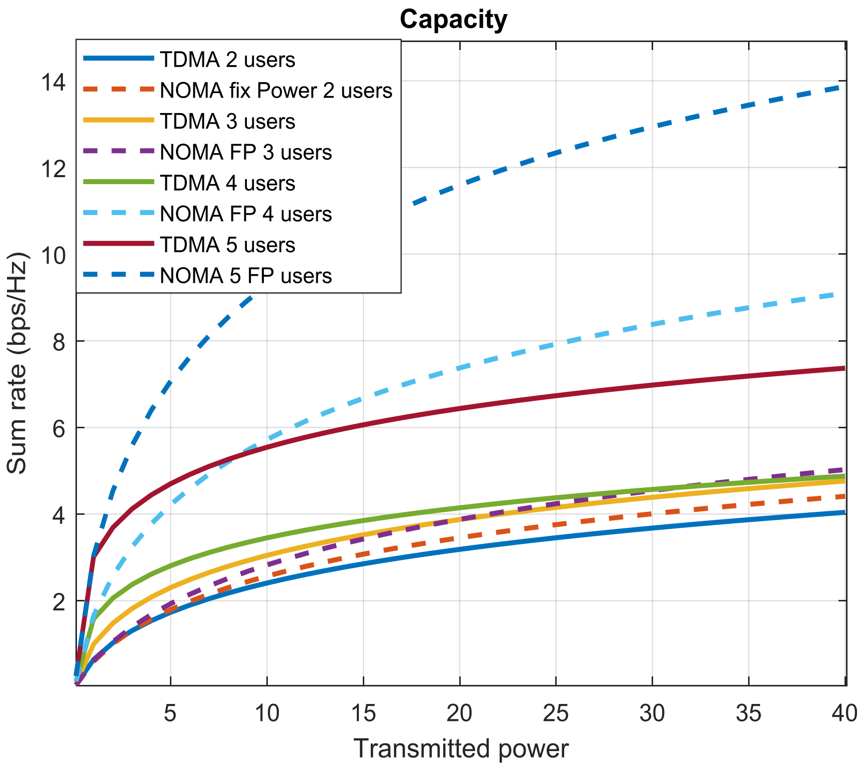

Figure IV. 4: Simulation results of TDMA system using fixed PA and Fairness PA

Fig IV.4 provides a comparison between TDMA and NOMA systems by using a dynamic fairness power allocation technique. So from this figure, we can found that a sum rate of the capacity in the case of NOMA with dynamic fairness algorithm is high compared than the sum rate of the capacity in the TDMA system. Furthermore, we show that the value of the sum rate of the capacity is augment progressively with the increase of the number of users and the transmitted power.

Fig IV.5 shows the performance evaluation of in Downlink NOMA system, which is used the superposed code and successive interference cancellation techniques for two scenarios such as: a fixed and a fairness power allocation with different number of users. So from this figure, it is clear that the value of the capacity obtained by the second scenario is high than the first scenario.

From the numerical simulations results, which is presented in the table 2, we have shown that the improvement of the capacity with the use a dynamic fairness power allocation technique is very significant compared with the use a fixed power allocation.

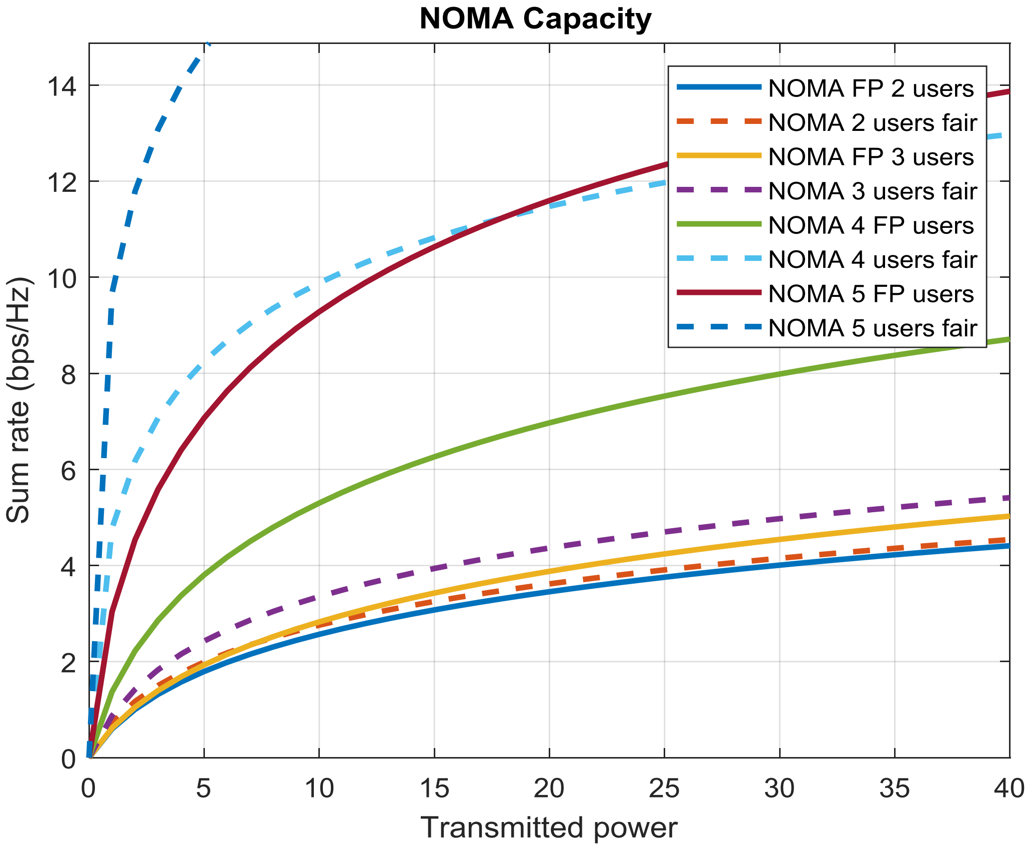

Figure IV. 5: Simulation results of downlink NOMA system using fixed PA and Fairness PA

Table IV 2:THE VARIATIONS OF THE SUM RAT OF THE CAPACITY IN THE CASE OF THE FIXED WITH THE FAIRNESS POWER ALLOCTION IN DIFFERENT NUMBER OF USERS.

Transmitted Power (dB)	**40**			
users	**2**	**3**	**4**	**5**
Fix PA Sum rate(bps/Hz)	4.421	5.0137	9.1037	13.8891
Fairness PA Sum rate(bps/Hz)	4.5188	5.3967	11. 872	18.0947
Transmitted Power	**30**			
Fix PA Sum rate(bps/Hz)	4.0085	4.5218	8.3878	12.9557
Fairness PA Sum rate(bps/Hz)	4.1162	4.9495	11.2293	17.3266
Transmitted Power	**20**			
Fix PA Sum rate(bps/Hz)	3.4545	3.8602	7.3834	11.6115
Fairness PA Sum rate(bps/Hz)	3.5766	4.3406	10.2834	16.1765
Transmitted Power	**10**			
Fix PA Sum rate(bps/Hz)	2.5669	2.8125	5.7319	9.2945
Fairness PA Sum rate(bps/Hz)	2.707	3.3335	9.5903	14.0465

IV.4.CONCLUSION

In this chapter, we have investigated the critical role of power allocation in enhancing the performance of non-Orthogonal Multiple Access (NOMA) systems within advanced wireless frameworks, such as 5G and energy-harvesting cellular networks. We explored both fixed and dynamic fairness power allocation techniques in the power domain, revealing through simulation results that dynamic fairness power allocation enables the NOMA system to achieve a higher sum-rate capacity compared to traditional methods like TDMA. Additionally, by integrating energy harvesting capabilities and leveraging a stochastic geometry model for analytical rigor, our findings demonstrate that NOMA significantly outperforms Orthogonal Multiple Access (OMA) counterparts, emphasizing its potential for efficient spectrum and energy utilization. These insights highlight the importance of carefully selecting power allocation strategies to optimize system performance without dissipation. Looking ahead, our future research will focus on advancing NOMA systems by exploring user grouping with power splitting and extending the framework to energy harvesting-enabled cooperative NOMA systems, where network nodes equipped with multiple antennas could further boost capacity, reliability, and sustainability in next-generation wireless networks.

General conclusion

GENERAL CONCLUSION

In this thesis, we have undertaken a thorough and structured exploration of multiple-access wireless networks, with a specific emphasis on the transformative potential of Non-Orthogonal Multiple Access (NOMA) systems as a next-generation solution compared to the conventional Orthogonal Multiple Access (OMA) paradigm. The study is organized across four comprehensive chapters, each building upon the previous to provide a holistic understanding of NOMA's capabilities, challenges, and future prospects in wireless communication systems.

The journey began in Chapter 1 with a broad overview of multiple-access wireless networks, establishing the historical context, technological evolution, and foundational principles that underpin modern wireless communication systems. This introductory discussion set the stage for understanding the critical role of resource allocation and user multiplexing in meeting the ever-growing demands of connectivity, bandwidth, and efficiency in wireless networks. Building on this foundation, Chapter 2 presented a detailed comparative analysis of OMA and NOMA systems, dissecting their operational mechanisms, strengths, and limitations. This investigation revealed NOMA's superior spectral efficiency and capacity to support a higher number of simultaneous users, positioning it as a compelling alternative to OMA in the face of increasing network congestion and data demands.

In Chapter 3, the focus shifted to a deeper exploration of downlink NOMA systems, where we analyzed their underlying principles, operational advantages, and inherent challenges. Through rigorous performance evaluations and optimization techniques, this chapter illuminated how NOMA leverages power domain multiplexing to enhance throughput and fairness among users, while also addressing practical issues such as interference management and system complexity. The findings underscored NOMA's potential to outperform OMA in diverse scenarios, although not without the need for careful design and adaptation to real-world conditions. Finally, Chapter 4 extended the scope of this research by integrating energy harvesting into the downlink NOMA framework—an innovative step toward sustainable wireless networks. This chapter provided an in-depth performance analysis, supported by simulation results, which demonstrated how energy harvesting can mitigate power constraints and enhance the efficiency of NOMA systems. The synergy between NOMA and energy harvesting was shown to not only improve system reliability but also align with the growing emphasis on green communication technologies, offering a pathway to environmentally conscious and scalable network designs.

Taken together, the contributions of this thesis offer a comprehensive performance analysis that bridges theoretical insights with practical implications. By systematically evaluating NOMA's advantages over OMA, optimizing its downlink performance, and exploring its integration with energy harvesting, this study highlights NOMA's transformative potential for the future of wireless communication. The results suggest that NOMA, particularly when enhanced with sustainable energy solutions, can significantly improve spectral and energy efficiency, accommodate the escalating demands of connected devices, and pave the way for more resilient and adaptable network architectures. Beyond its technical findings, this work contributes to the broader discourse on next-generation wireless systems, providing a robust foundation for researchers, engineers, and policymakers to consider in the pursuit of more efficient, scalable, and environmentally sustainable communication technologies. As wireless networks continue to evolve, the insights and methodologies presented herein serve as a stepping stone toward realizing the full potential of H-NOMA-based systems in shaping the future of global connectivity.

FUTURE RESEARCH DIRECTIONS

This work opens several promising research directions.

First, we plan to develop an optimized resource allocation algorithm for hybrid NOMA in vehicular systems, dynamically adapting to varying channel conditions while ensuring robust security against emerging threats. By integrating power-domain and OMA features, this algorithm will establish a more flexible and secure multiple-access framework tailored to the high mobility of vehicular networks.

Building on our current analysis of OMA and NOMA, we will expand our investigation to more sophisticated hybrid NOMA techniques, with a particular focus on vehicle-to-vehicle (V2V) communications.

Furthermore, we propose enhancing our framework with advanced signal processing methods, such as interference alignment, to further optimize resource allocation in hybrid NOMA vehicular systems. This includes developing adaptive algorithms capable of handling the highly dynamic channel conditions inherent in vehicular environments.

From a practical perspective, while our simulations have demonstrated the effectiveness of NOMA-based solutions, future work will validate their performance in real-world vehicular scenarios. Comprehensive testing will cover diverse environments, including urban intersections, highway platooning, and vehicle-to-infrastructure (V2I) applications. Rigorous evaluations will ensure compatibility with emerging automotive technologies, such as connected autonomous vehicle (CAV) standards.

Finally, we recognize that our NOMA framework has broader applicability beyond vehicular networks. Future research should explore its adaptation to other critical communication systems—such as industrial IoT, UAV networks, and emergency response systems—where similar demands for reliability and security exist. The versatility of our approach suggests significant potential for deployment across next-generation wireless systems.

[1] U. Ghafoor et al., "Energy efficiency optimization for hybrid NOMA based beyond 5G heterogeneous networks," IEEE Vehicular Technology Conference (VTC2021-Fall), pp. 1-5, 2021.

[2] Y. Sanada, "Non-orthogonal multiple access with joint maximum likelihood detection in heterogeneous network," in Proc. IEEE 87th Vehicular Technology Conference (VTC-Spring), Porto, Portugal, pp. 1-5, 2018.

[3] M. Aldababsa, M. Toka, S. Gökçeli, G. K. Kurt, and O. Kucur, "A tutorial on nonorthogonal multiple access for 5G and beyond," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 2, pp. 1574-1604, Secondquarter 2018.

[4] P. Siano, "Future generation 5G wireless networks for smart grid: A comprehensive review," *Energies*, vol. 12, no. 22, p. 4360, Nov. 2019.

[5] M. Mohammadi, B. K. Chalise, H. A. Suraweera, C. Zhong, G. Zheng, and I. Krikidis, "Full-duplex non-orthogonal multiple access for next generation wireless systems," *IEEE Communications Magazine*, vol. 57, no. 5, pp. 110-116, May 2019.

[6] M. Liaqat and K. Ariffin, "Power-domain non orthogonal multiple access (PD-NOMA) in cooperative networks : an overview," *Wirel. Networks*, vol. 26, no. 1, pp. 181–203, 2020.

[7] Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura, "System-level performance evaluation of downlink non-orthogonal multiple access (NOMA)," in *Proc. IEEE 24th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, London, UK, 2013, pp. 611-615, doi: 10.1109/PIMRC.2013.6666209.

[8] H. You, Y. Hu, Z. Pan, and N. Liu, "Density-based user clustering in downlink NOMA systems," *IEEE Transactions on Wireless Communications*, vol. 21, no. 5, pp. 3029-3041, May 2022.

[9] K. Selvam and K. Kumar, "Energy and spectrum efficiency trade-off of non-orthogonal multiple access (NOMA) over OFDMA for machine-to-machine communication," in 2020 International Conference on Emerging Trends in Information Technology and Engineering (ic-ETITE), 2020, pp. 1–6.

[10] M. Basharat *et al.*, "Non-Orthogonal Radio Resource Management for RF Energy Harvested 5G Networks," *IEEE Access*, vol. 7, pp. 46550–46561, 2019, doi: 10.1109/ACCESS.2019.2908947.

[11] S. M. R. Islam, N. Avazov, O. A. Dobre, and K. S. Kwak, “Power-Domain Non-Orthogonal Multiple Access (NOMA) in 5G Systems: Potentials and Challenges,” *IEEE Commun. Surv. Tutorials*, vol. 19, no. 2, pp. 721–742, 2017, doi: 10.1109/COMST.2016.2621116.

[12] Z. Ding, M. Peng, and H. V. Poor, "Cooperative non-orthogonal multiple access in 5G systems," IEEE Communications Letters, vol. 19, no. 8, pp. 1462–1465, Aug. 2015, doi: 10.1109/LCOMM.2015.2441064.

[13] Z. Sheng, X. Su, and X. Zhang, "A novel power allocation method for non-orthogonal multiple access in cellular uplink network," in *2017 13th International Conference on Natural Computation, Fuzzy Systems and Knowledge Discovery (ICNC-FSKD)*, Guilin, China, 2017, pp. 5–7, doi: 10.1109/FSKD.2017.8393029.

[14] I. Transmission and R. Systems, "RF energy harvesting and information transmission based on NOMA for wireless powered IoT," Sensors, vol. 18, no. 10, p. 3254, Oct. 2018, doi: 10.3390/s18103254.

[15] F. Mukhlif, K. Ariffin, B. Nooridin, Y. A. Al-gumaei, and A. S. Al-rassas, “ENERGY HARVESTING FOR EFFICIENT 5G,” *2018 Int. Conf. Smart Comput. Electron. Enterp.*, pp. 1–5, 2018.

[16] S. Mohammad, O. Omarov, G. Nauryzbayev, S. Arzykulov, M. S. Hashmi, and A. M. Eltawil, "Capacity analysis of wireless powered cooperative NOMA networks over generalized fading," in 2021 IEEE Wireless Communications and Networking Conference (WCNC), Nanjing, China, 2021, pp. 1-6, doi: 10.1109/WCNC49053.2021.9417356.

[17] R. Lei, D. Xu, and I. Ahmad, "Secrecy outage performance analysis of cooperative NOMA networks with SWIPT," IEEE Wireless Communications Letters, vol. 10, no. 7, pp. 1495-1499, July 2021, doi: 10.1109/LWC.2021.3070429.

[18] M. A. Germien, G. S. E. M. E. Mohamed, and M. Abd-elnaby, “NOMA for 5G and beyond : literature review and novel trends,” *Wirel. Networks*, vol. 29, no. 4, pp. 1629–1653, 2023, doi: 10.1007/s11276-022-03175-7.

[19] J. Li, C. W. Sung, and C. S. Chen, “Performance Study of Cooperative Non-orthogonal Multiple Access with Energy Harvesting,” *2019 2nd Int. Conf. Commun. Eng. Technol.*, pp. 30–34, 2019.

[20] J. Xu and Z. Liang, "Energy efficiency optimization of NOMA IoT communication for 5G," IEEE Internet of Things Journal, vol. 9, no. 1, pp. 862-873, Jan. 2022, doi:

10.1109/JIOT.2021.3091234.

[21] J. He and S. Shi, “User grouping and power allocation in NOMA-based internet of things,” *Wirel. Networks*, vol. 6, 2023, doi: 10.1007/s11276-023-03251-6.

[22] M. A. K. and P. Kumar, “The Role of Wireless Communication in the Internet of Things (IoT): Applications, Challenges, and Future Trends,” *J. Netw. Comput. Appl.*, vol. 161, p. 102630, 2020.

[23] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge, UK: Cambridge University Press, 2005.

[24] M. Hussien, M. Nerma, N. Kamel, Y. K. Min, and V. Jeoti, "Pre-coding based multi-user OFDM system," in *Proc. IEEE International Conference on Telecommunications and Malaysia International Conference on Communications*, Penang, Malaysia, 2007, pp. 447-450, doi: 10.1109/ICTMICC.2007.4448656.

[25] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2002.

[26] W. Stallings, *Wireless Communications and Networks*, 2nd ed. Upper Saddle River, NJ: Pearson, 2016.

[27] A. Goldsmith, *Wireless Communications*. Cambridge, UK: Cambridge University Press, 2005.

[28] V. K. Bhargava and A. Goldsmith, *Wireless Communication Systems: From RF Subsystems to 4G Enabling Technologies*. Cambridge, UK: Cambridge University Press, 2007.

[29] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2002.

[30] J. G. Proakis and M. Salehi, *Digital Communications*, 5th ed. New York, NY: McGraw-Hill, 2008.

[31] K. Sayood, *Introduction to Data Compression*, 5th ed. Burlington, MA: Morgan Kaufmann, 2017.

[32] W. Stallings, *Cryptography and Network Security: Principles and Practice*, 7th ed. Upper Saddle River, NJ: Pearson, 2017.

[33] S. Lin and D. J. Costello, Jr., *Error Control Coding*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2004.

[34] B. P. Lathi and Z. Ding, *Modern Digital and Analog Communication Systems*, 5th ed.

Oxford, UK: Oxford University Press, 2018.

[35] A. S. Tanenbaum and D. J. Wetherall, *Computer Networks*, 5th ed. Upper Saddle River, NJ: Pearson, 2011.

[36] F. K. and S. Talha, “A survey of channel models for 5G wireless communication systems,” *Phys. Commun*, vol. 17, pp. 208–218, 2016.

[37] and A. G. K. P. S. Bithas, N. Nomikos, A. Antonopoulos, “A survey on multiple-antenna techniques for 5G wireless communication systems,” *IEEE Access,* vol. 7, pp. 145244–145267, 2019.

[38] and H. V. P. H. Wang, Z. Ding, “‘Multiple access in the Internet of Things: A survey,’” *IEEE Internet Things*, vol. 4, pp. 1229–1243, 2017.

[39] A. Goldsmith, *Wireless Communications*. Cambridge, UK: Cambridge University Press, 2005.

[40] T. S. Rappaport, "Millimeter wave wireless communications," *IEEE Transactions on Communications*, vol. 64, no. 1, pp. 232-278, Jan. 2016, doi: 10.1109/TCOMM.2015.2514119.

[41] D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ: Wiley, 2011.

[42] J. C. Maxwell, “‘A dynamical theory of the electromagnetic field,’” *Phil. Trans. Roy. Soc. Lond.*, vol. 155, pp. 459–512, 1865.

[43] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2002.

[44] M. A. Alim et al., "Line-of-sight propagation modeling for 5G millimeter-wave networks," *IEEE Transactions on Wireless Communications*, vol. 19, no. 2, pp. 1159-1173, Feb. 2020, doi: 10.1109/TWC.2019.2953073.

[45] H. L. Bertoni, "Fresnel zones for wireless links: Theory and experiments," *IEEE Antennas and Propagation Magazine*, vol. 56, no. 4, pp. 12-26, Aug. 2014, doi: 10.1109/MAP.2014.6931648.

[46] T. Kürner and A. F. Molisch, "Radio wave propagation in urban scenarios," *Proceedings of the IEEE*, vol. 107, no. 11, pp. 2154-2189, Nov. 2019, doi: 10.1109/JPROC.2019.2935714.

[47] S. Sun et al., "Friis equation revisited: Millimeter-wave path loss modeling," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 9, pp. 1937-1947, Sep. 2020, doi: 10.1109/JSAC.2020.3000887.

[48] J. M. Jornet and I. F. Akyildiz, "Channel modeling for terahertz band communication," *IEEE Communications Magazine*, vol. 57, no. 6, pp. 102-108, Jun. 2019, doi: 10.1109/MCOM.2019.1800790.

[49] A. F. Molisch et al., "Hybrid beamforming for massive MIMO: A survey," *IEEE Communications Magazine*, vol. 55, no. 9, pp. 134-141, Sep. 2017, doi: 10.1109/MCOM.2017.1600400.

[50] H. L. Bertoni, "Radio propagation for urban wireless communications," *Proc. IEEE*, vol. 107, no. 11, pp. 2109-2129, Nov. 2019, doi: 10.1109/JPROC.2019.2935712.

[51] T. S. Rappaport et al., "Millimeter-wave mobile communications for 5G: Challenges and opportunities," *IEEE Trans. Veh. Technol.*, vol. 67, no. 7, pp. 6162-6176, Jul. 2018, doi: 10.1109/TVT.2018.2843363.

[52] K. Haneda et al., "Indoor 5G 3GPP-like channel models for office and shopping mall environments," *Proc. IEEE ICC*, 2016, pp. 694-699, doi: 10.1109/ICC.2016.7510861.

[53] M. K. Samimi et al., "28 GHz millimeter-wave ultrawideband small-scale fading models in wireless channels," *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1300-1312, Mar. 2016, doi: 10.1109/TVT.2015.2431731.

[54] T. S. Rappaport et al., "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," *IEEE Access*, vol. 7, pp. 78729-78757, 2019, doi: 10.1109/ACCESS.2019.2921522.

[55] A. F. Molisch, "Ultrawideband propagation channels: Theory, measurement, and modeling," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 12, pp. 3158-3166, Dec. 2005.

[56] S. P. Weber, J. G. Andrews, and X. Yang, "Interference in wireless networks: Trends and solutions," IEEE Communications Surveys & Tutorials, vol. 19, no. 1, pp. 469-492, 1st Quart. 2017, doi: 10.1109/COMST.2016.2615984.

[57] M. Patzold, B. O. Hogstad, and N. Youssef, "A new shadowed fading model for land mobile satellite channels," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2720-2731, May 2016, doi: 10.1109/TVT.2015.2444389.

[58] A. F. Molisch, “Ultrawideband Propagation Channels,” *IEEE Trans. Antennas Propag*, vol. 53, no. 12, pp. 3158–3166, Dec. 2005.

[59] M. Z. Shakir et al., "Green heterogeneous networks for 5G," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 12, pp. 3369-3390, Dec. 2016, doi:

10.1109/JSAC.2016.2615269.

[60] N. B. et Al, “5G Ultra-Dense Networks: Architecture and Technologies,” *IEEE Access*, vol. 8, pp. 140895–140924, 2020.

[61] E. Lutz et al., "5G broadcast: A scalable replacement for DVB-T2," *IEEE Transactions on Broadcasting*, vol. 67, no. 2, pp. 321-330, Jun. 2021, doi: 10.1109/TBC.2021.3069435.

[62] M. G. and M. Zorzi, “Non-Terrestrial Networks in 5G & Beyond,” *IEEE Commun. Surv. Tutor*, vol. 23, no. 3, pp. 2224–2287, 2021.

[63] J. A. Farrell, "GNSS aided navigation & tracking," *IEEE Aerospace and Electronic Systems Magazine*, vol. 35, no. 12, pp. 16-29, Dec. 2020, doi: 10.1109/MAES.2020.3012521.

[64] S. Garg, K. Kaur, and G. Kaddoum, "BLE 5.2 for medical IoT: Performance evaluation and improvements," *IEEE Internet of Things Journal*, vol. 8, no. 7, pp. 5119-5133, Apr. 2021, doi: 10.1109/JIOT.2020.3037342.

[65] M. Chen et al., "Emergency paging systems in hospitals: Reliability analysis and design considerations," *IEEE Transactions on Biomedical Engineering*, vol. 68, no. 4, pp. 1123-1135, Apr. 2021, doi: 10.1109/TBME.2020.3026541.

[66] H. Haas et al., "Li-Fi for vehicle-to-everything (V2X) communications," *IEEE Photonics Journal*, vol. 13, no. 5, Oct. 2021, Art no. 7900113, doi: 10.1109/JPHOT.2021.3118284.

[67] F. Liu et al., "Automotive radar interference mitigation: A review," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 1, pp. 49-62, Jan. 2021, doi: 10.1109/TITS.2019.2957623.

[68] M. Agiwal, N. Saxena, and A. Roy, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Wireless Communications*, vol. 28, no. 2, pp. 156-162, Apr. 2021, doi: 10.1109/MWC.001.2000400.

[69] S. Garg, K. Kaur, and G. Kaddoum, "Productivity impact of wireless office networks in modern workplaces," *IEEE Access*, vol. 9, pp. 134512-134525, 2021, doi: 10.1109/ACCESS.2021.3116478.

[70] L. Da Xu, W. He, and S. Li, "Internet of Things in industries: From M2M to human-centered design," *IEEE Internet of Things Journal*, vol. 8, no. 7, pp. 5189-5201, Apr. 2021, doi: 10.1109/JIOT.2020.3033664.

[71] D. Goodman, "3G cellular standards and patents," *IEEE Wireless Communications*, vol. 12, no. 2, pp. 22-25, Apr. 2005, doi: 10.1109/MWC.2005.1421925.

[72] E. Dahlman et al., "4G: LTE/LTE-Advanced for mobile broadband," *IEEE Communications Magazine*, vol. 49, no. 2, pp. 62-69, Feb. 2011, doi: 10.1109/MCOM.2011.5706315.

[73] M. Agiwal et al., "Next generation 5G wireless networks: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1617-1655, Thirdquarter 2016, doi: 10.1109/COMST.2016.2532458.

[74] Y. Liu, M. Elkashlan, and Z. Qin, "Nonorthogonal multiple access for 5G and beyond," *Proceedings of the IEEE*, vol. 105, no. 12, pp. 2347-2381, Dec. 2017, doi: 10.1109/JPROC.2017.2768666.

[75] A. Mahmood, M. Zeeshan, and T. Ashraf, “A new hybrid CDMA – NOMA scheme with power allocation and user clustering for capacity improvement,” *Telecommun. Syst.*, vol. 78, no. 2, pp. 225–237, 2021, doi: 10.1007/s11235-021-00805-x.

[76] W. Saad, M. Bennis, and M. Chen, "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems," *IEEE Network*, vol. 34, no. 3, pp. 134-142, May/Jun. 2020, doi: 10.1109/MNET.001.1900287.

[77] C. Perera et al., "Internet of Things in smart cities: Wireless communication technologies and standards," *IEEE Internet of Things Journal*, vol. 7, no. 9, pp. 8025-8045, Sep. 2020, doi: 10.1109/JIOT.2020.3006846.

[78] A. Gupta and R. K. Jha, "5G-based V2X communications for autonomous vehicles: Standardization, challenges, and opportunities," *IEEE Vehicular Technology Magazine*, vol. 15, no. 4, pp. 82-92, Dec. 2020, doi: 10.1109/MVT.2020.3018451.

[79] L. Chettri and R. Bera, "5G-enabled IIoT: A comprehensive survey on resource allocation for URLLC," *IEEE Transactions on Industrial Informatics*, vol. 18, no. 5, pp. 3008-3022, May 2022, doi: 10.1109/TII.2021.3116813.

[80] H. Marzetta, T. L. Marzetta, and J. Zhang, "Non-orthogonal multiple access (NOMA): A new paradigm for 5G wireless networks," *IEEE Communications Magazine*, vol. 54, no. 2, pp. 35-41, Feb. 2016, doi: 10.1109/MCOM.2016.7402259.

[81] E. S. El-mokadem and A. M. El-kassas, "BER performance evaluation for the downlink NOMA system over different fading channels with different modulation schemes," in *Proc. 36th National Radio Science Conference (NRSC)*, Port Said, Egypt, 2019, pp. 3-8, doi: 10.1109/NRSC.2019.8734179.

[82] E. H. Dinan and B. Jabbari, "Spreading codes for TDMA systems," *IEEE Transactions on Communications*, vol. 46, no. 4, pp. 577-583, Apr. 1998, doi: 10.1109/26.664317.

[83] Y. Saito et al., "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *Proc. IEEE 77th Vehicular Technology Conference (VTC Spring),* Dresden, Germany, pp. 1-5,2013.

[84] W. F. Alghasmari and L. Nassef, “Power Allocation Evaluation for Downlink Non-Orthogonal Multiple Access (NOMA),” vol. 11, no. 4, pp. 126–132, 2020.

[85] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. K. Bhargava, "Application of non-orthogonal multiple access in 5G and beyond networks," *IEEE Journal on Selected Areas in Communications,* vol. 35, no. 10, pp. 2181-2195, Oct. 2017.

[86] R. Alhamad,"Adaptive NOMA/OMA for wireless communications," *Signal, Image and Video Processing*, vol. 15, no. 7, pp. 1469-1475, Oct. 2021.

[87] Z. Ding *et al.*, “A Survey on Non-Orthogonal Multiple Access for 5G Networks : Research Challenges and Future Trends,” vol. 8716, no. c, pp. 1–15, 2017.

[88] H. B. Salameh, A. Al-ajlouni, and A. Al-ajlouni, “A two-dimensional OMA-NOMA user-pairing and power-minimization approach for opportunistic B5G-enabled IoT networks,” *Cluster Comput.*, vol. 26, no. 2, pp. 1113–1124, 2023.

[89] M. Belattar, C. Soumali, and M. Atrouche, “Non-Orthogonal Multiple Access Technique Performance Characterization in Downlink Network,” International Journal on Communications Antenna and Propagation ,vol. 12, no. October, pp. 356–364, 2022.

[90] A. Khazali, M. G. Shayesteh, and H. Kalbkhani, “User grouping and power allocation for energy efficiency maximization in mmWave-NOMA heterogeneous networks,” *Wirel. Networks*, vol. 28, no. 6, pp. 2403–2420, 2022.

[91] M. Atrouche, M. Belattar, and R. Bouchebbat, “Optimized User Pairing and Fairness-Driven Power Allocation for Enhanced Hybrid NOMA Downlink Performance,” International Journal on Communications Antenna and Propagation ,vol. 14, no. August, pp. 193–202, 2024.

[92] E. Erturk, O. Yildiz, S. Shahsavari, and N. Akar, “Power allocation and temporal fair user group scheduling for downlink,” *Telecommun. Syst.*, vol. 77, no. 4, pp. 753–766, 2021.

[93] M. Atrouche, S. Ayad, and B. Mounir, "Comparative study of fairness and fixed power allocation algorithms in non-orthogonal multiple access system," in 2022 2nd International Conference on Advanced Electrical Engineering (ICAEE), Algiers, Algeria, 2022, pp. 1-5, doi: 10.1109/ICAEE53772.2022.9961966.

[94] W. P. Communications, N. G. Jeshvaghani, N. Movahhedinia, and M. R. Khayyambashi, "A novel user grouping algorithm for downlink NOMA systems," *IEEE Transactions on Wireless Communications*, vol. 21, no. 3, pp. 1587-1602, Mar. 2022 .

[95] K. Deka and S. Sharma, “Hybrid NOMA for Future Radio Access : Design , Potentials and Limitations,” *Wirel. Pers. Commun.*, vol. 123, no. 4, pp. 3755–3770, 2022.

[96] W. Sun and J. Li, “Power allocation optimization for hybrid information and energy transfer with massive MIMO downlink,” *IET Commun.*, 2023.

[97] M. Belattar, C. Soumali, and M. Atrouche, “Analysis of Fair-NOMA Power Allocation : a Comparative Study Between NOMA and OMA Systems,” International Journal on Communications Antenna and Propagation ,vol. 12, no. December, pp. 385–393, 2022.

[98] M.-R. Hojeij, "Resource allocation techniques for non-orthogonal multiple access systems," Ph.D. dissertation, CentraleSupélec, Université Paris-Saclay, France, 2019.

[99] M. Basharat, S. A. R. Zaidi, and D. C. McLernon, "Joint user grouping and time allocation for NOMA with wireless power transfer," in *Proc. IEEE International Conference on Communications (ICC)*, Paris, France, pp. 1-6,2017.