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Theme

Performance Analysis for NOMA Energy Harvesting: PS Protocol

In front of the jury composed of:

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وَأَن لَّيۡسَ لِلۡإِنسَٰنِ إِلَّا مَا سَعَىٰ ٣٩

and that each person will only have what they endeavoured towards,

وَأَنَّ سَعۡيَهُۥ سَوۡفَ يُرَىٰ ٤٠

and that ˹the outcome of˺ their endeavours will be seen ˹in their record˺,

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First of all, Al hammed li ALLAH,

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Dedication

This dissertation is dedicated to my family for their endless love, and unwavering support for me. Who always believe in me with their unwavering encouragement and treasured support unconditionally all through my studies, especially during my difficult times.

Gherbi Manar

Dedication

To the eternal support and eternal source, to the one who gives before taking and prioritizes others over herself, to my beloved mother.

To my stronghold in times of hardship and my delight in times of prosperity, to the one whose support contributed to my journey until the very end, my dear father.

To the loved ones of my heart, to those without whom I wouldn't have completed this journey, my sisters and brother.

And finally, to everyone who contributed, even if it was a little, to reaching the end of this work, I dedicate the fruit of my academic efforts represented in this graduation thesis, asking Allah to make it sincerely for His noble face.

Thank you from the bottom of my heart.

Lissioued Joumana

Abstract

Abstract

Non-Orthogonal Multiple Access (NOMA) is a promised technology for next-generation networks to increase capacity, user fairness, spectrum efficiency and mass connectivity where NOMA permits several users to share the same resources. In order to improve system performance and increase coverage area, NOMA can be combined easily with several technologies, such as cooperative communication technology. Moreover, when the relay has no power in cooperative NOMA network, the energy harvesting (EH) technology is one of the technologies proposed to combat this problem, which uses two protocols: Time Switching (TS) protocol or Power Splitting (PS) protocol. In our work, we use the PS protocol to evaluate the performance of the downlink cooperative NOMA. We simulate the performance of the considered system in terms of capacity, Bit Error Rate (BER) and Outage Probability (OP) using MATLAB. The simulation results show that the performance of the downlink cooperative NOMA system with PS outperforms that of the cooperative NOMA without PS. To achieve better performance, the optimal gain can obtain according to EH and power allocation parameters.

Keywords: NOMA, Cooperative, PS, Capacity, BER, OP.

Résumé

L'accès multiple non orthogonal (NOMA) est une technologie promise pour les réseaux de nouvelle génération afin d'augmenter la capacité, l'équité pour les utilisateurs, l'efficacité spectrale et la connectivité de masse, car NOMA permet à plusieurs utilisateurs de partager les mêmes ressources. Afin d'améliorer les performances du système et d'augmenter la zone de couverture, NOMA peut être combiné facilement avec plusieurs technologies, telles que la technologie de communication coopérative. De plus, lorsque le relais n'est pas alimenté dans le réseau coopératif NOMA, la technologie de récupération d'énergie (EH) est l'une des technologies proposées pour lutter contre ce problème, qui utilise deux protocoles : le protocole Time Switching (TS) ou le protocole Power Splitting (PS). Dans notre travail, nous utilisons le protocole PS pour évaluer les performances de la liaison descendante coopérative NOMA. Nous simulons les performances du système considéré en termes de capacité, le taux d'erreur sur les bits (BER) et la probabilité d'indisponibilité (OP) à l'aide de MATLAB. Les résultats de la simulation montrent que les performances du système NOMA coopératif de liaison descendante avec PS surpassent celles du NOMA coopératif sans PS. Pour obtenir de meilleures performances, le gain optimal peut être obtenu en fonction des paramètres EH et d'allocation de puissance.

Mots clés: NOMA, Coopératif, PS, Capacité, BER, OP.

ملخص

الوصول المتعدد غير المتعامد (NOMA) هو تقنية موعودة لشبكات الجيل التالي لزيادة السعة وعدالة المستخدم وكفاءة الطيف والاتصال الجماعي، حيث تسمح NOMA للعديد من المستخدمين بمشاركة نفس الموارد. يمكن دمج NOMA بسهولة مع العديد من التقنيات، مثل تكنولوجيا الاتصالات التعاونية من أجل تحسين أداء النظام وزيادة منطقة التغطية. علاوة على ذلك، عندما لا يكون للترحيل قوة في شبكة NOMA التعاونية، فإن تقنية حصاد الطاقة (EH) هي إحدى التقنيات المقترحة لمكافحة هذه المشكلة، والتي تستخدم بروتوكولين: بروتوكول تبديل الوقت (TS) أو بروتوكول تقسيم الطاقة (PS). في عملنا، نستخدم بروتوكول PS لتقييم أداء الوصلة الهابطة التعاونية NOMA. نقوم بمحاكاة أداء النظام المدروس من حيث السعة ومعدل الخطأ في البت (BER) واحتمال الانقطاع (OP) باستخدام برنامج MATLAB. تظهر نتائج المحاكاة أن أداء نظام NOMA التعاوني للوصلة الهابطة مع PS يتفوق على أداء NOMA التعاوني بدون PS. ولتحقيق أداء أفضل، يمكن الحصول على الكسب الأمثل وفقًا لمعايير EH وتخصيص الطاقة.

الكلمات المفتاحية: NOMA، التعاونية، PS، السعة، OP، BER

Summary

Summary

Figures list

Tables list

Abbreviations list

1G	First Generation
2G	Second Generation
3D	3-dimensional
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
AF	Amplify-and-forward
AGWN	Additive Gaussian white noise
AI	Artificial intelligence
AP	Access points
AR	Augmented reality
AUV	Autonomous underwater vehicles
AWGN	Additive white Gaussian noise
B5G	Beyond fifth generation
BackCom	Backscatter communication
BER	Bit error ratio
BS	Base station
CC	Cooperative communication
CDMA	Code division multiple access
C-NOMA	Cooperative NOMA
C-RAN	Centralized radio access network
CSI	Strong channel state information
CU	Central unit
DC	Direct current
DF	Decode-and-forward
DL	Downlink
DU	Distributed units
E2E	End-to-end
EH	Energy harvesting
eMBB	Enhanced Mobile Broadband

FDMA	Frequency division multiple access
HAP	High platforms
IGAS	Integrated ground-air-space
IMT	International mobile telecommunication
IOT	Internet of things
ISI	Inter-symbol interference
ITU	International telecommunication union
KPI	Key performance indicators
LAP	Low platforms
LDS-CDMA	Low-density spreading CDMA
MA	Multiple access
MAI	Multiple access interference
MIMO	Multiple inputs multiple outputs
ML	Machine learning
mMTC	Massive machine type communication
mmW	Millimeter waves
MPA	Message passing algorithm
NFV	Networking function virtualization
NGMA	Generation multiple access
NOMA	Non-orthogonal multiple access
OMA	Orthogonal multiple access
OP	Outage probability
PS	Power splitting
QOS	Quality of service
RAN	Radio access network
RAT	Radio access technology
RE	Renewable energy
RE	Renewable energies
RF	Radio frequency
RIS	Reconfigurable intelligent surfaces
RU	radio units
SAGIN	Network space-air-ground-integrated

SC	Superimposition coding
SCMA	Sparse code multiple access
SDN	Software defined networking
SIC	Successive interference cancellation
SINR	Signal to interference plus noise ratio
SNR	Signal-to-noise ratio
SUD	Single User Detection
TDMA	Time division multiple access
THz	Terahertz
THz Com	THz communication
TS	Time switching
TST	Terrestrial space terminals
U1	User 1
U2	User 2
UAV	Unmanned aerial vehicles
UE	User equipment
UL	Uplink
URLLC	Ultra reliable low latency communication
VR	Virtual reality
WSN	Wireless sensor network

Symbols list

P, P_{total}, P_S	The total transmit power.
α_i	The fraction of the power attributed to the user.
X_i	The transmitted signal from BS to the user.
X	The superimposed transmitted signal.
h_i	The complex channel coefficient between users and the BS.
w_i	The Additive Gaussian white noise and interference received by user.
y_i	The received signal at user.
$E[\|h_i\|^2]$	The channel gain.
σ	The variance.
γ_i	The signal-to-noise ratio.
R_i	The user throughput.
W	The total bandwidth.
N_0	The noise power spectral density.
δ_i	The signal to interference plus noise ratio.
w	The Additive Gaussian white noise.
P_i	The user power.
R_T	The sum rate of the users.
SE	The spectral efficiency.
EE	The energy efficiency.
w_R	The noise at the relay.
h	The complex channel coefficient between BS and relay.
y_R	The received information signal at the relay.
σ_R	The variance at relay.
P_R	The power total of relay.
C_i	The capacity of user.
P_{out}^i	The outage probability of BS-relay-User.
β	The amplification coefficient.
γ	The SNR at the base station.
E_h	The energy harvesting at the relay.
β	The TS factor.
T	The total communication time duration.

η	The energy conversion efficiency factor.
h_{r}	The Rayleigh fading channel between BS-relay.
P_r	The transmission power of relay.
ρ	The PS factor.
w_r	The additive white Gaussian noise at the relay.
σ_r	The variance at relay.
$\mathrm{d_r}$	The distances between the BS-relay.
d_i	The distances between BS and user.
BER	The Bit Error Rate.

General Introduction

General Introduction

Over the previous decades, the generations of cellular communication networks from the first to the fifth generation have supported various multiple access technologies, including FDMA, TDMA, CDMA, and OFDMA [1]. Where these technologies generate an orthogonal signal where only one resource can allocate to a single user due to the limitations of orthogonally. As research efforts continue, the sixth generation (6G) has entered the interest stage. In contrast to earlier generations of systems, which concentrated on device-to-device communication services, the 6G network aims to integrate device-to-device communication networks and satellite networks to provide comprehensive worldwide coverage of mobile communications [2]. Where these services increase network demands such as massive connectivity, spectral efficiency, low latency, etc. Recently, Non-Orthogonal Multiple Access (NOMA) technology has attracted researchers due to its ability to increase spectral efficiency, improve user fairness and serve multiple users in the same resources for upgrading networks towards the 6G.

Currently, NOMA is considered as a promising solution for 6G networks due to its ability to promote ultra-low latency, more resource sharing, and higher spectral efficiency. In this context, NOMA technology allows to share the same resources with users via the same channel, which enhances the cell-edge throughput. Also, NOMA can serve multiple devices in the network, which was limited previously by orthogonal multiple access (OMA) technologies. Furthermore, NOMA has combined with other assistive technologies as cooperative communication, which enhances network coverage, reliability, and transmission. On the other hand, NOMA cooperative nodes use all their power to process or transmit signals in the second phase. Thus, may they will suffer from low batteries. The researchers thought of using the energy harvesting (EH) technology from radio frequency sources to exploit the energies surrounding the environment for charging nodes and achieving the principle of green communication. To harvest energy, radio EH techniques use two protocols: The time switching (TS) protocol and the power splitting (PS) protocol.

The dissertation objective is to analyze the performance of cooperative NOMA using energy harvesting with PS protocol. To achieve this objective, the work has been divided into four chapters:

- **First Chapter**

In the first chapter, we will present a study on the development of technologies and the requirements of the new generations 5G, B5G, and 6G networks. We will focus more on 6G enabling technologies, with the most promising ones.

- **Second Chapter**

In the second chapter, we will focus on the basics of two technologies: NOMA and cooperative NOMA. The study will be about the detail of their principle working, transmission models, network types, the used techniques and protocols.

- **Third Chapter**

In the third chapter, we will explore EH technology from all its aspects in general. In particular, we will discuss the radio-EH and its protocols TS and PS in the context of cooperative NOMA network.

- **Fourth Chapter**

In the last chapter, we will simulate the considered system based on downlink cooperative NOMA using PS protocol by MATLAB software. We will evaluate the performance in terms of capacity, BER and OP. To validate our work, we will consider the system based on downlink cooperative NOMA without PS protocol as a benchmark for comparison.

In the end, we will conclude this dissertation with a general conclusion.

Chapter 1:

5G, B5G & 6G Requirements and Technologies

1.1. Introduction

The fifth generation (5G) of networks' technology emerged as a result of the need to improve communication between mobile phones, where it ensures a greater increase in the number of connected users and a higher spectral density than earlier generations. However, like any technology, 5G revealed several limitations and defects, requiring it to be extended to beyond 5G (B5G), which removes these limitations and improves network services. With the rapid growth of connected devices in the network and the increase in the uses and coverage levels of communications, B5G becomes insufficient for all network requirements. Where that technology will promote to the sixth generation (6G). It will enable complete coverage (air-land-sea) and sharing the greatest amount of resources between those devices with high frequency spectrum that reaches up to terahertz.

In this chapter, we will present the evolution of the requirements and the technologies of the new generations of networks (5G, B5G and 6G) until to the promising multiple access technology of the 6G.

1.2. Evolution in Generations of Wireless Communication Networks by Multiple Access Technologies

The evolutionary background can be traced back to the 1980s, multiple access (MA) scheme has been regarded as a key technology to distinguish each generation of wireless communication systems in the past decades [1]. In the existing wireless systems, orthogonal multiple access (OMA) has been widely used from first-generation (1G) mobile communication system to 4G [2].

Well-known frequency division multiple access (FDMA) for 1G, Second Generation (2G) in the year 1990’s it used digital modulation technologies such as Time Division Multiple Access (TDMA), code division multiple access (CDMA) for third Generation (3G) which available in the year the 2000s has a major transformation with a high data rate that available for video communication (video call). In the year 2010’s the orthogonal frequency division multiple access (OFDMA) for the fourth Generation (4G) introduced with the capability of high-speed data communication, not only video calling but be able to do a video conference with many peoples up to a few hundred of peoples [3], [4]. In these OMA schemes, users are multiplexed orthogonally in either the frequency, time, or code domain so that mixed signal can be separated at receiver with low complexity [2].

While OMA can effectively minimize inter-user interference with a relatively low implementation complexity, its spectral efficiency needs to be further improved in order to meet the requirements in next-generations. Fifth Generation (5G) and Beyond 5G (B5G or 5G+) are technologies that are currently being commercialized since the year 2020 some countries introduced 5G technology with the capability of transfer data up to Gigabits communication. Sixth Generation (6G) is a technology for the future with the target of data communication up to Terabits per second expected available in the year 2030. To accommodate all elevated network requirements, researchers proposed a non-orthogonal multiple access (NOMA) scheme, it is a multiple access method proposed for the future generations mobile network. NOMA is a type of non-orthogonal multiplexing where users are multiplexed in the power domain, which is not sufficiently utilized by previous wireless mobile systems [5], [6]. The following figure 1.1 shows the evolution of network generations and each technology:

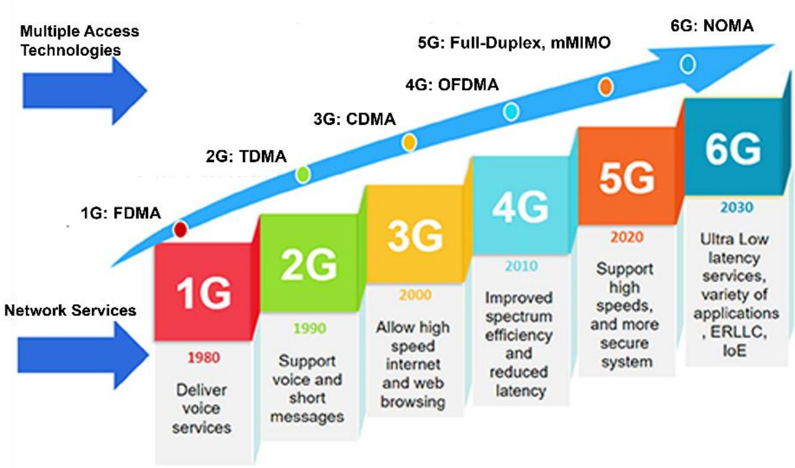

Figure 1.1: Evolution in generations of wireless communication networks [7].

1.3. Fifth Generation

Since the launch of 2G, 3G and 4G networks the volume of mobile and wireless data traffic has increased exponentially. It is estimated that between 2010 and 2020, data traffic on the network has increased 1,000 times. The significant increase in traffic is due to the increase in the number of subscribers and the number of connected objects (IoT: Internet of Things) because the use of mobile networks is no longer limited to telephony, SMS and web browsing only. All of these uses increase traffic and therefore require high data transfer rates and low latency. To achieve these goals, telecom researchers have launched a new network: 5G [8], [9].

Fifth-generation networks not only aim to provide higher data rate, lower latency, greater capacity and better customer experience than other generations, but also commit to filling the Internet of Things (IoT) with reliable and secure services at low cost.

In general, the frequency range of 6 to 100 GHz is assigned to 5G wireless system [10] provides big bandwidth. Hence, 5G is eminently suitable for high-density device communication in IoT applications, Machine Learning (ML) and other uses.

To better reflect on the wireless generation networks for an evolution of key performance indicators (KPIs), the ITU (International Telecommunication Union) has defined the 5G standard through its organization IMT (International Mobile Telecommunications) [11] to generally achieve some requirements, which are indicated in the following figure 1.2:

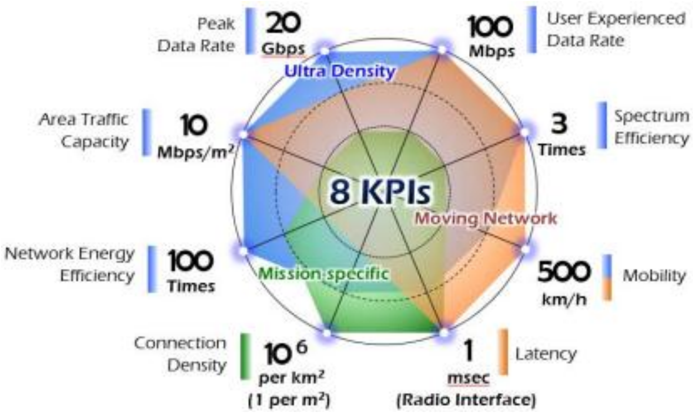

Figure 1.2: KPIs for 5G [12].

1.3.1. Architecture of 5G

The increase in the number of users and devices connected to the Internet prompted 5G to form an advanced architecture, which are mainly concentrated in three layers, as shown in figure 1.3. These layers are called, respectively: « Applications », « Virtualization » and « Forwarding ».

- ✓ **Applications:** It is the upper layer that includes various innovative services such as controlling robots remotely and virtual user experiences while ensuring maximum reliability.
- ✓ **Virtualization:** It is the middle layer has a network underlying a service-oriented infrastructure. It consists of two key enablers that represent the future of telecommunication, to perform this task Software Defined Networking (SDN) and Network Function Virtualization (NFV) [13].
- ✓ **Forwarding:** It is the lower layer that provides a large amount of data to the middle layer "activation platform", in an efficient and transparent way. Due to huge traffic and strict latency requirements, contains the following technologies: Millimeter waves, Full-duplex communications, Massive MIMO (multiple inputs multiple outputs) [9].

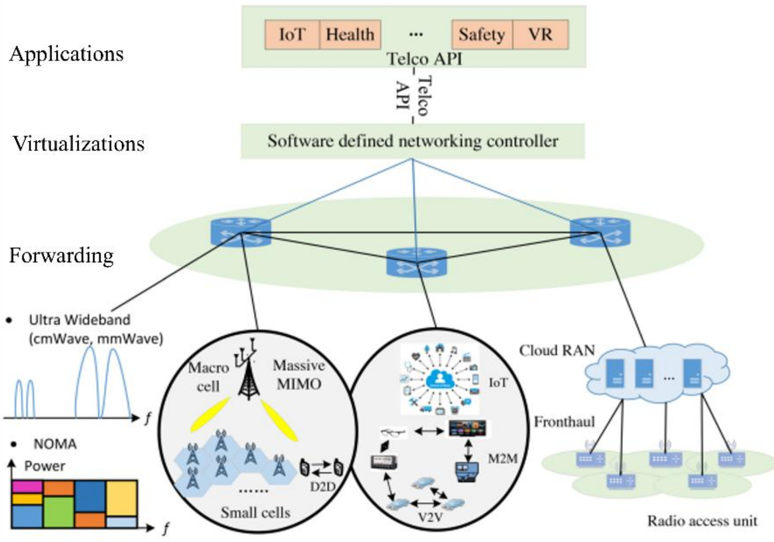

Figure 1.3: Architecture of 5G [14].

1.3.2. The 5G Technologies

5G includes three main technologies, which are indicated in figure 1.4, and they are as follows: Millimeter waves (mmW), Massive MIMO, Full-Duplex. These technologies were also used in 4G, but they differ in many important aspects [10]. Where in 5G they become able to meet the challenges posed by the growth of data traffic as well as they will help improve energy efficiency and increase capacity with network scalability and reliability. The principles of these technologies are briefly described in the following:

- **Millimeter waves (mmW):** Millimeter waves are all waves whose frequency is between 30 and 300 GHz with a languor of 1 up to 10m. They are used in 5G technology because of their large bandwidth. Millimeter waves provide secure communication and high-speed transmission up to 10 Gbps; with a reduced size of the radiating elements. They have low interference compared to other systems [14].
- **Massive MIMO:** Massive MIMO technology is one of the major keys to unlocking these 5G user experiences. This technology is characterized by the use of a high number of "Smart" micro antennas on a single device (from 8 to 128 currently) [15].
- **Full-Duplex:** Full-Duplex is a serial or network connection that allows. simultaneous reception and transmission of data. Full-duplex mode was tested in the first phase of the 5G test. This technology can double the capacity of the most basic physical layer of a wireless network [14].

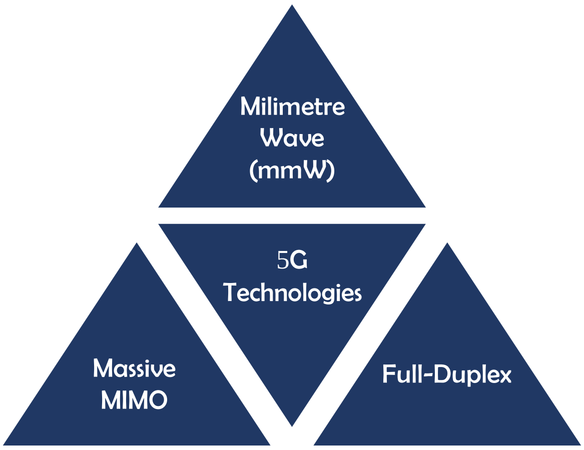

Figure 1.4: 5G enabling technologies.

1.3.3. Problems of 5G

- mmW cannot fully meet the needs of mobile communication, and has shortcomings such as insufficient coverage and unstable performance.
- Massive MIMO for fixed wireless access is not ideal.
- The power consumption of the terminal device is too high. Telecom operators recommend using the 4G network as much as possible to save consumption on the 5G mobile phone.
- At present, eMBB (enhanced Mobile Broadband) is mainly used for data transmission, but immersive eMBB applications have not been practically realized [16].

1.4. Technology Development from 5G to B5G

The fifth generation (5G) wireless systems have been begun to be widely deployed over the world in recent years. It has reached transmission levels with a peak rate of 10 Gbps and a low latency of 1 millisecond. However, there are still technical limitations in the application of 5G [15]. As this technology will not be able to meet the demands of the huge data traffic growth from massively interconnected devices that is forecasted for future years.

The huge number of technologies used and subscribers increased the need to request a speed of more than 100 Gbps, which is much faster than the current 5G speeds. These terabyte-approaching speeds can only be achieved at ultra-high frequencies exceeding 100 GHz and above [17]. Therefore, the attention of the research community was shifting toward what would be the next innovations in wireless communication architectures and technologies for the Beyond 5G (B5G). the researchers have developed B5G that works in the range of 0.1~0.3 THz, and this frequency band is called the Terahertz frequency band [16].

1.4.1. Beyond 5G

Beyond 5G is the next generation of mobile communication systems after 5G, with features that contribute to the creation of sustainable and new value, such as ultra-low power consumption, ultra-security and reliability, autonomy, and scalability, in addition to the further advancement of 5G's characteristic features such as high speed and high capacity, low latency, and multiple simultaneous connections. Research indicates that B5G will be applied in practice from 2025 onwards, given the increased network requirements that will be met by the embodiment of this technology in many applications [18].

B5G pushes radio spectrum utilization to the next level for enables the virtualization technologies that you rely on the most [17], [16]. B5G networks promise delivering optimized services in three main usage scenarios: Enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC), are being pushed against stricter requirements giving rise to new KPI [14]. The following figure 1.5 shows these improvements:

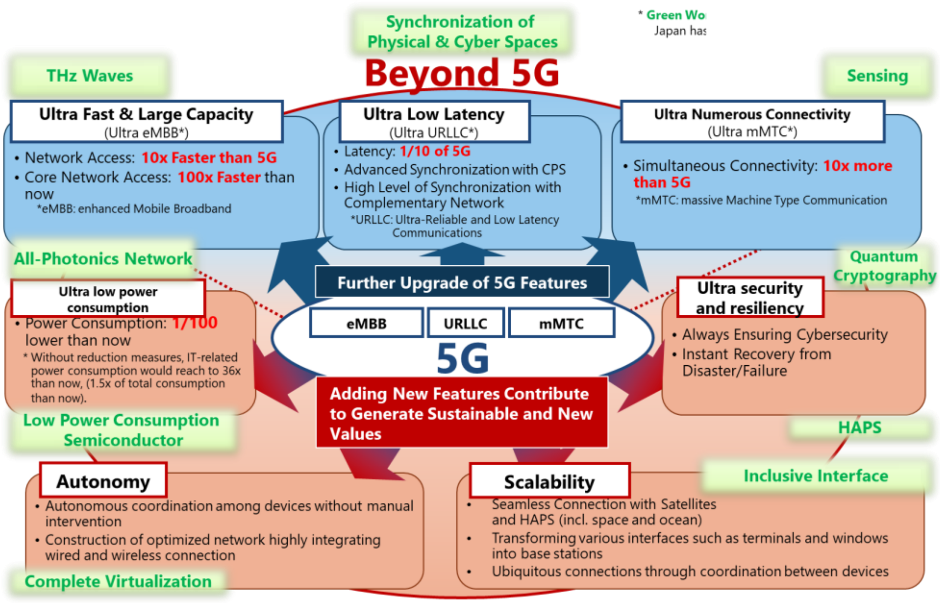

Figure 1.5: Optimization of B5G vs 5G (in Japan) [14].

1.4.2. Beyond 5G Features

Mobile communication technologies have experienced great success since their inception for the current Fifth Generation (5G). 5G technologies continue their evolutionary path after 2020 (beyond 5G, B5G) to extend the service scenarios and features, where the next five years will see B5G networks enable use cases mobile broadband to increase industrial productivity. finally converging to the Sixth Generation (6G) by 2030 [15].

In this evolutionary path, B5G contain a wide variety of features in all key areas of communication networks:

- Improvements of radio spectrum usage, novel strategies for coverage/service extension, support of novel use cases and mobile edge cloud applications, usability of the current unexplored spectrum.
- Enhancements of mobile network architectures aiming at significantly reducing energy consumption [15].
- AI (Artificial intelligence) based E2E (End-to-end) network slicing solutions to combine optimization of RAN (Radio Access Network), Transport, Core and cloud resources [13].
- Machine learning techniques to optimize time and frequency slot allocation and minimize interference between devices in ultra-dense environments [14].
- Power consumption optimization of terminal devices has been widely discussed in 3GPP (3rd Generation Partnership Project), and several technical standards have been formulated [12].
- Massive MIMO propagation is become even more unrestricted than in 5G, With the assistance of terminal devices, the devices are interconnected to form a small network to enables the realization of a Cell-Free network architecture [17].

1.4.3. Further Evolution towards 6G: A Step Beyond 5G

Originally, great expectations were set on 5G to become a universal network that connects everything to everything and allows almost limitless real-time applications, However, due to the limitations of the 5G architecture, available components and software solutions, requirements of the most challenging applications will not yet be met in the near future. Thus, many of the exciting opportunities will have to wait for the B5G technology and some will not see the day light until 6G with its futuristic features is here [18]. The evolution of mobile communication will continue and will eventually enter a 6G era in around the 2030.

The 6G communication networks will meet the lag of 5G system by introducing new synthesis of future services such as ambient sensing intelligence and new humanity and human-machine interaction, a pervasive introduction of AI and the incorporation of other new technologies [19]. The table 1.1 below shows a comparison between the three new generations 5G, B5G and 6G:

Description	5G	B5G	6G
Frequency bands	• Sub-6Ghz • mmWave for fixed access	• Sub-6Ghz • mmWave for fixed access	• Sub-6Ghz • mmWave for fixed access • Exploraction of higher frecuency and THz Bands
Rates requirement	20 Gb/s	100Gb/s	1 Tb/s
Radio only delay requirement	100 ns	10 ns	10 ns
End-to-End delay (latency)requirement	5 ms	1 ms	1 ms
Processing delay	100 ns	50 ns	10 ns

Table 1.1: A comparative analysis of 5G, B5G, and 6G [19].

1.5. Sixth Generation

The vision of 6G can be summarized by the phrase ubiquitous wireless intelligence, where ubiquitous refers to omnipresent coverage and seamless accessibility to services. 6G wireless technology envisions to make the network and the smart devices cognizant and content-aware for all the users by exploiting the concepts of new techniques [20].

Because of living in the era of sustainability. 6G networks would support sustainability while will being stable, scalable, efficient, reliable, and agile [19]. Therefore, future wireless networks (6G) are taking on new standards of key performance requirements than the networks used to be, as showing in the following figure 1.6:

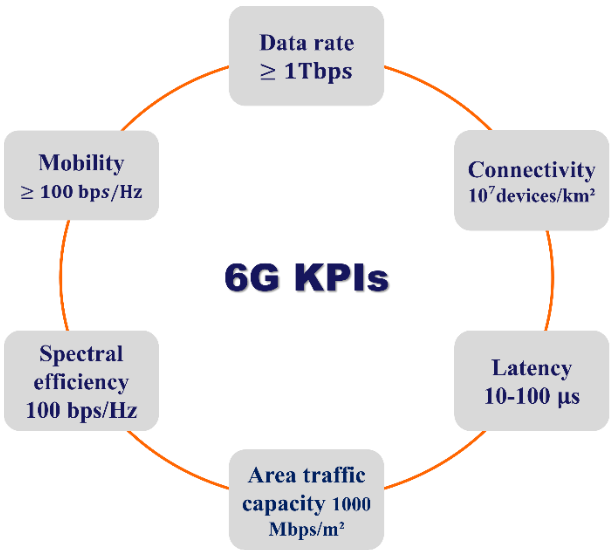

Figure 1.6: The KPIs of 6G.

➢ **Advantages of 6G:**

As with any new technology, there are several advantages to 6G:

- 6G networks will provide faster speeds, lower latency, and more reliable connections than 5G networks: This means that users will be able to access data faster, with fewer delays with big applicant frequency band will be in the range of 0.1~10 THz [17].
- 6G will also enable a larger number of connected devices and users, allowing for more efficient communication and data transfer.
- With 6G, it would be possible to connect up to 10 million connected objects per km² with massive data rate for successfully handle of services simultaneously over both uplink and downlink [20].
- The increased speed and reliability of 6G networks will enable a variety of new applications that are not possible with current networks. For example, 6G will enable the development of new augmented reality and virtual reality applications, as well as the ability to control robots and other machines remotely [20].

1.5.1. Architecture of 6G

Sixth generation (6G) wireless communication network is expected to evolve beyond the conventional terrestrial cellular network [21]. The 6G promise to integrate land, air and maritime communications forming a vertical 3D network (so-called 3DNet or SkyNet) [19] as seen in the figure 1.7, for a robust network that is more reliable, faster, and can support a large number of devices with ultra-low latency requirements.

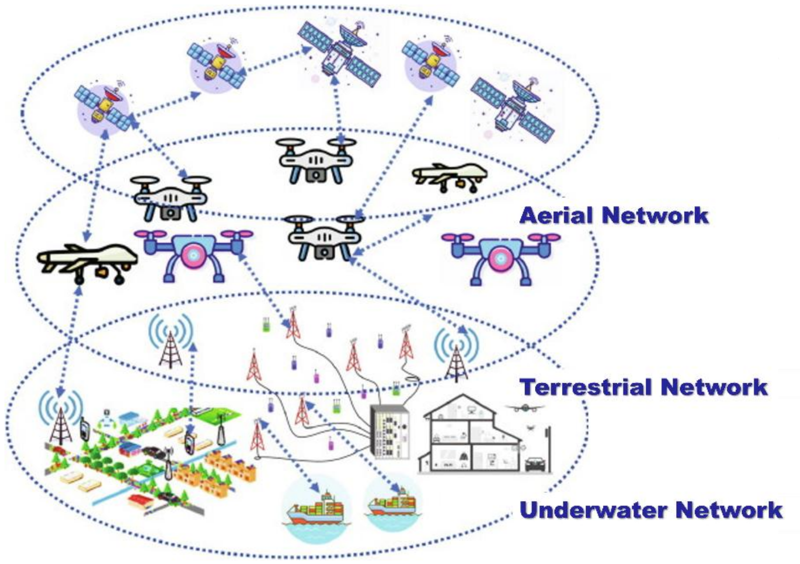

Figure 1.7: The architecture of 6G includes next generation wireless communications for aerial, terrestrial and underwater networks [22].

- **Terrestrial network:** 6G terrestrial communication networks partition the traditional base stations (BSs) of the C-RAN (Centralized Radio Access Network) into the central unit (CU), distributed units (DUs), and radio units (RUs). This partitioning requires flexible radio access technology (RAT) [22]. The powerful CU in the cloud has substantial computation and data storage capabilities managed by the higher network layers, whereas the network functions of the lower layers are deployed within multiple DUs at the edge. The RUs are responsible for signal transmission and reception, whereas the networking policy is formulated at the DUs and CU. Furthermore, instead of using traditional costly wired links, the fronthaul and backhaul of flexible CU/DU/RU architectures may rely on high-speed millimeter wave (mmWave) and terahertz (THz) techniques [21]. Similarly, both the user equipment (UE) and sensors are supported by high-speed mmWave THz radio links.
- **Underwater network:** The 6G architecture of underwater communication networks has the task of supporting autonomous underwater vehicles (AUVs) and AUV controllers, which can be harnessed in diverse scenarios [20], including underwater air crash investigations, military applications, and deep-sea exploration. The AUV-based network supports multiple AUVs and multiple AUV controllers equipped with sensors and sonar/camera systems for collaborative navigation, localization, and object tracking [19].
- **Aerial network:** Aerial communications in 6G rely on drones or unmanned aerial vehicles (UAVs) and low/high altitude platforms (LAPs/HAPs) [22]. Furthermore, the 6G satellite network contains several layers and due to the long transmission distance from the satellite to ground, high transmit power is required for mitigating the pathloss and specialized terrestrial-space terminals (TSTs) have to be used [18]. For efficiently collecting information, multiple UAVs and multiple satellites may cooperatively transfer their data forming a heterogeneous integrated ground-air-space (IGAS) network [20].

As an evolution from conventional BS-centric networking, user-centric cell-free networks have become popular [19], which judiciously allocate the network's resources according to the specific quality of service (QoS) requirements of the UE. As a benefit of this user-centric method, amorphous coverage areas are created by assigning the access points (APs) in homogeneously by matching their density to the non-uniform user density. Hence, they exhibit excellent load-balancing capability [22]. The network determines its resource allocation strictly based on the QoS requirements [21].

1.5.2. The 6G Technologies

In order to meet the requirements of future 6G network, new key technologies should be introduced such as: 3-dimensional (3D) networking, quantum communications, holographic beamforming, backscatter communication, reconfigurable intelligent surfaces (RISs), and proactive caching [18].

Currently, the enabling technologies of 6G are the most frequently investigated mainly include wireless access solutions, new spectrum resources and the new coverage methods of air-space-earth-sea integration. The corresponding these technologies include as showing in the figure 1.8: Non-Orthogonal Multiple Access (NOMA), Cooperative Communications (CC), Terahertz (THz), Backscatter Communications (BackCom), Energy Harvesting (EH) or Simultaneous Wireless Information and Power Transfer (SWIPT), AI.

- **NOMA:** In the most popular NOMA domain for new solutions of network, the 6G will design advanced NOMA techniques in terms of integrating the diverse resource domains of mmWave/THz systems or enhancing the coverage area of UAV and satellite networks.
- **CC:** Core communications technologies with CC are further studied to significantly improve communication quality and develop new communications scenarios for 6G ubiquitous networks. CC is integrated as foundation theory in future multiple 6G network such as, UAVs communications, air-space-ground of integrated networks, underwater acoustic communication, besides it is closely combined with other key technologies, for examples, Massive MIMO, NOMA, Full-duplex transmission [23].
- **THz:** The unprecedented increase in wireless data traffic, predicted to occur within the next decade, is motivating academia and industries for recognition THz communications (THzCom) as a highly promising technology for the 6G era, due to its unique potential to support terabit-per-second transmission in emerging applications [17].
- **BackCom:** Backscatter Communication (BackCom), which is based on passive reflection and modulation of an incident radio-frequency (RF) wave, has emerged as a cutting-edge technological paradigm for self-sustainable Internet-of-things (IoT). Targeting the sixth-generation (6G) horizon, we anticipate the integration of different techniques into BackCom systems as a new frontier for enabling 6G IoT networks [23]. In addition, owing to the unrivaled effectiveness of non-orthogonal multiple access (NOMA), the 6G will create NOMA-enhanced BackCom system.

- **EH/SWIPT:** Green communications have always been a target for the alleviate energy overhead. EH and SWIPT came as solutions to this problem, they will be adopted widely in 6G for alleviate energy demand, improve energy efficiency, especially in some technologies such as NOMA.
- **AI:** The mobile network operators demand the 6G network to be intelligent and self-organizing. The AI is the answer to many of these challenges, which can entirely change the future of wireless network technologies [21]. AI can cooperate with some techniques like Machine Learning (ML) to reduce the algorithm complexity and optimize the accuracy rate to accelerate the applications in 6G.

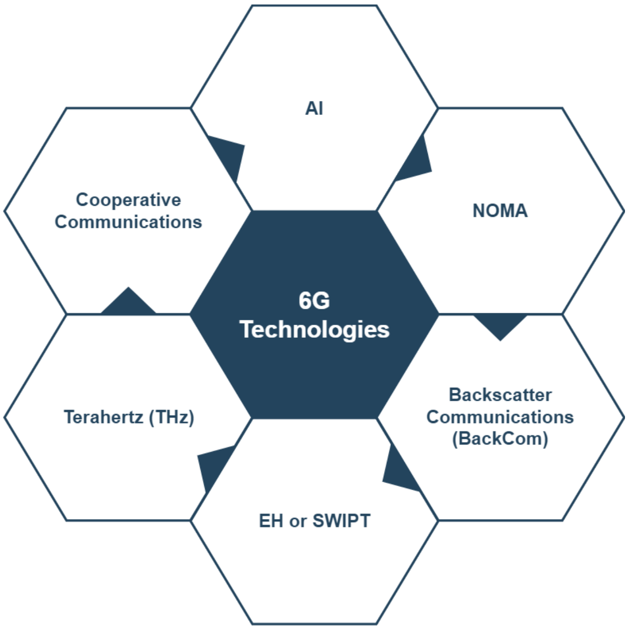

Figure 1.8: The 6G enabling technologies.

The three techniques NOMA, CC, EH are the main focuses of this thesis.

1.5.3. NOMA Advances for 6G Networks

As a prominent member of the next generation multiple access (NGMA) family, non-orthogonal multiple access (NOMA) has been recognized as a promising multiple access candidate for the sixth-generation (6G) networks, after it was promoted for use in the fifth generation, and due to the presence of obstacles that restricted its use in 5G [24]. NOMA has been recognized as an essential enabling technology for the forthcoming 6G networks to meet the heterogeneous demands on low latency, high reliability, massive connectivity, improved fairness, high throughput and introducing an additional degree of freedom in the power domain. His schemes have been proposed in several wireless network topologies, including cooperative networks, device-to-device networks and unmanned-aerial vehicle (UAV)-based networks. In addition to the emerging applications, e.g., space-air-ground-integrated-networks (SAGINs), virtual reality (VR), augmented reality (AR), etc., for optimized quality-of-service (QoS) [25], [24].

The role of NOMA technique in sixth generation networks becomes as follows:

- New requirements: Supporting massive connectivity by considering various QoS requirements including latency and reliability.
- New techniques: Integrating NOMA with other 6G physical layer techniques.
- New applications: Application in heterogeneous scenarios to support emerging 6G applications.
- New tools: Integration with artificial intelligence (AI) to design an adaptive resource allocation [25].

1.6. New Development: NOMA

The non-orthogonal multiple access (NOMA) is a novel multiple access (MA) technology for mobile networks in which more than one user are allowed to utilize a designated sub-frequency resource simultaneously over a given time period [26]. This is unlike the orthogonal multiple access (OMA) technology traditionally used in previous generations of mobile networks (1G to 4G) in a form of time division multiple access (TDMA), frequency-division multiple access (FDMA), or orthogonal-FDMA (OFDMA), in which only one user is allowed to utilize a designated sub-frequency resource [2], and figures (1.9 and 1.10) illustrates two scenarios of an transmission by BS, one with OMA technology where each user is served by different frequency slot, and the other with NOMA technology where two users are served simultaneously using the same frequency slot [27].

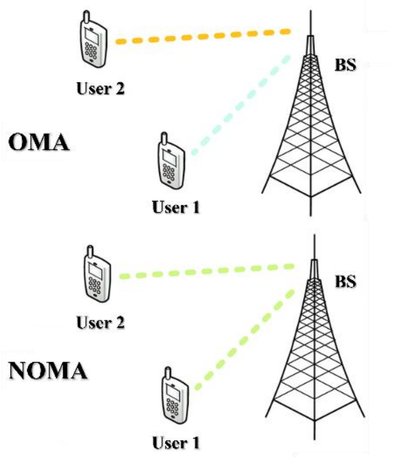

Figure 1.9: BS illustration with OMA and NOMA.

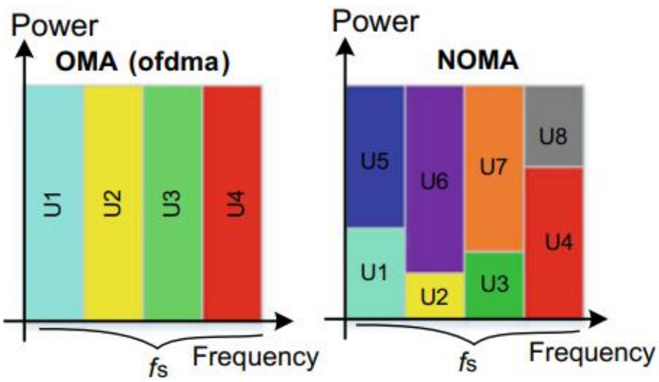

Figure 1.10: Illustration of power-domain diagram OMA vs NOMA [27].

1.7. Conclusion

Through the rapid development in each new generation of 5G, B5G and 6G networks, 6G is expected to make a great leap towards an interconnected digital world from space to the depths. In this chapter, we have provided an overview of the evolution of all generations of networks. Then we detailed the new generations only as 5G, B5G and 6G in terms of the architecture and used technologies. According to the chain of development of each generation, we mentioned the problems and reasons for the transition from one generation to the next. Finally, down to the promising multiple access technology of 6G, which will contribute to its emergence as the most advanced generation.

In the next chapter, we will discuss two of the enabling 6G technologies integrated into a single technology which is NOMA under cooperative communications.

Chapter 2:

Cooperative NOMA

2.1. Introduction

Non-orthogonal multiple access (NOMA) is considered one of the promising technologies of the 6G, since it is able to achieve the requirements of this generation. NOMA has the ability to share the same resources between users without any interference, which increases the users' number and coverage in the network compared to OMA that offers limited coverage and access. In order to increase NOMA performance, it combines with several technologies, including cooperative communications, to develop cooperative NOMA, which provides many features to users away from the transmission nodes.

In this chapter, we will study the concept working of NOMA technology according to its key techniques, transmission models and its applications, after introducing its domains. Then, explore the basics of cooperative NOMA technology from cooperation network types and its protocols.

2.2. Non-orthogonal Multiple Access

Recently, non-orthogonal multiple access (NOMA) has emerged as a very promising technology to enable massive connectivity which is highly demanded in Beyond 5G (B5G) and Sixth Generation (6G) future networks. This access is performed in a non-orthogonal manner where multiple users are served on the same resource block such as frequency band, time slot, etc.

The fundamental idea of NOMA is to exploit the power domain as a new dimension to achieve multiplexing. To enable the application of NOMA, two main techniques, namely superimposition coding (SC) and successive interference cancellation (SIC) are introduced [28]. In particular, SC must simultaneously communicate two messages by encoding them into a single two-layer message, and SIC must decode the desired message from the overlapped message as showing in figure 2.1, it can separate users in both uplink and downlink channels [29]. With the development and maturity of these two techniques, NOMA can be applied regardless of the difficulty of implementation.

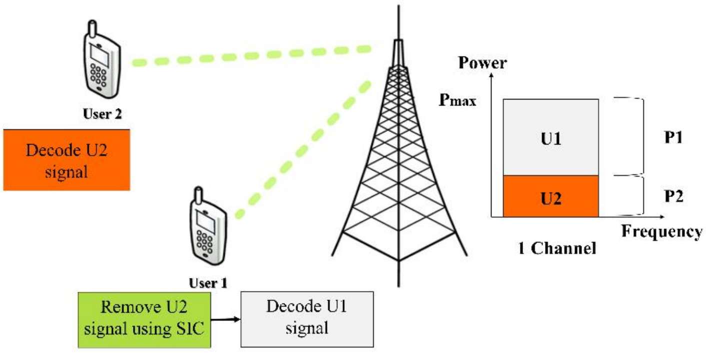

Figure 2.1: Concept of non-orthogonal multiple access (NOMA).

The family of NOMA schemes as showing in figure 2.2 can be basically divided into two categories: power domain NOMA and code domain NOMA. The first assigns a unique power level to a user and multiple users transmit their signals sharing the same time-frequency code resources, each using its allocated power [30]. The second relies on codebooks, spreading sequences, interleaving patterns, or scrambling sequences to allocate resources to users non-orthogonally [9].

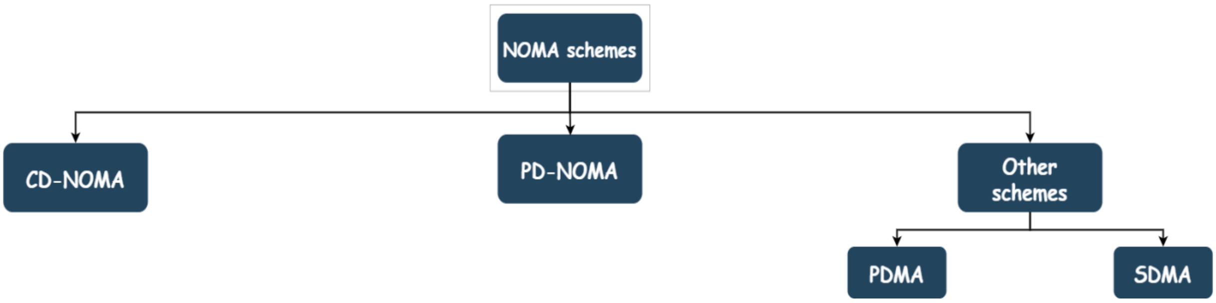

Figure 2.2: Classification of the main NOMA schemes.

2.2.1. Code-Domain NOMA

NOMA in the code domain is based on CDMA which allows multiple users to share the same radio resources, while using their unique codes. These codes are well designed to provide orthogonality between users [9]. The codes used for NOMA are chosen in such a way as to have good inter-correlation and auto-correlation values to minimize multiple access interference (MAI) and inter-symbol interference (ISI) without being orthogonal. Code domain NOMA further classified in to different categories: Message passing algorithm (MPA) based multiuser detection scheme is employed in Low-density spreading CDMA (LDS-CDMA) [31], to improve the system performance. In LDS-OFDM, the multiple subcarriers of OFDM are mapped by the signature matrix parameters unlike the time samples in CDMA. In Sparse code multiple access (SCMA), the receiver complexity and spectral efficiency are improved by using the sparse spreading as well as multidimensional constellations [27].

2.2.2. Power-Domain NOMA

PD-NOMA technology allows multiple users to access all frequency and time resources. According to the code stacking (SC) mechanism, this will improve the spectral efficiency [30]. All the users are allotted with different power levels based on their distances from the base station such as the near user (strong channel state information: CSI) is with low power and far user (poor CSI) with high power. All these users are superimposed and transmitted in to the air [9]. The data of users in the superimposed signal is decoded at the receiver based on their power level by mitigating the noise successively called successive interference cancellation (SIC) technique [31]. Hence, power domain NOMA requires high complexity transmitter and receiver to avoid the noise completely.

2.3. Key technologies of NOMA

The basic principles of NOMA techniques are based on the use of superposition coding (SC) at the transmitter and successive interference cancellation (SIC) techniques at the receiver.

2.3.1. Superposition coding

The superposition coding (SC) technique processes the information at the transmitter by a single parallelly source transmits the information of many users to guarantee higher detection reliability by superimposing several users at the same RE (renewable energy) with a power allocation among users based on the near-far propriety [12], [32]. SC allocates different power coefficients to different users, thereby guarantees the required preferences of the system. In the downlink, signals of different users are added linearly at the base station (BS) using SC [28]. The fundamental concept of superposition coding is that it is able to encode a message for a user associated with poor channel conditions with low bit rate and then superposition it on the signal of a user with better channel conditions, the following figure 2.3 shows the basic concept of SC technique:

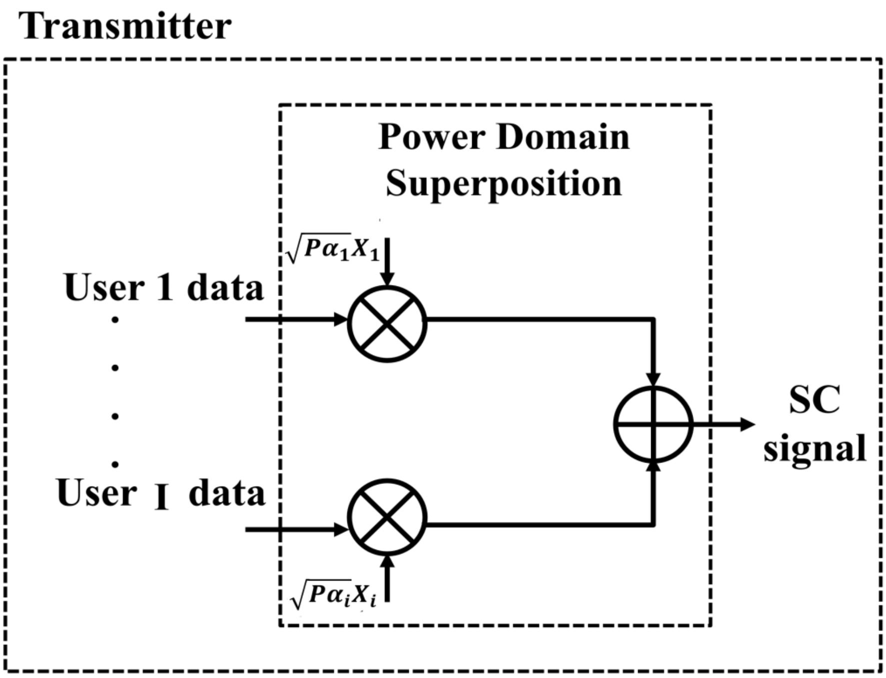

Figure 2.3: The concept of SC technique.

SC allows the transmitter (base station: BS) to transmit signals from multiple users at the same time. Each user's signal is encoded and modulated independently. Then the BS assigns a power level to each user based on their channel status. Users close to the base station are assigned low power levels because their channel conditions are better than users farther away [9]. However, all signals from different users will be added together and form a signal represented by the following formula:

$$X = \sum \sqrt{P\alpha_i} X_i \tag{2.1}$$

The simple PD-NOMA system as the figure 2.1 consists of a BS and two users. Suppose x_1 and x_2 are signals to be transmitted from BS to users 1 and 2, respectively. The base station transmits the following signal:

$$X = \sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2 \tag{2.2}$$

Where α_i represents a fraction of the power attributed to the user, subject to the constraint of $\alpha_1 + \alpha_2 = 1$ and $\alpha_1 > \alpha_2$. P is the total transmitting power.

2.3.2. Successive interference cancellation

It has been widely exploited that network capacity can be significantly improved with the help of effective interference management, so SIC is considered a promising IC technique in wireless networks [33]. SIC at the receiver detects multi-user's information. Because of the near-far effect, significant variations in channel conditions of different users are present. SIC decodes the message of each user [34].

The basic idea of SIC is that one of the user's signals is decoded, treating the other user's signal as a noise, but the latter is then decoded in favor of the former's signal having already been suppressed as present in the figure 2.4, but before SIC, users are ranked according to their signal power. SIC technique has better performance, which is more suitable for power domain NOMA supporting users through different power levels.

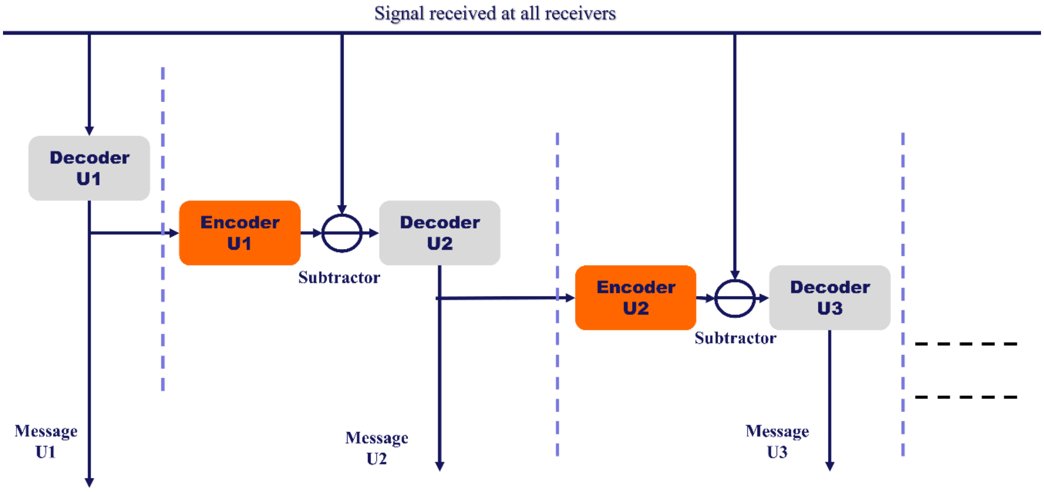

Figure 2.4: Basic principle of SIC.

The signal received by UEI (User Equipment I) will have the following form:

$$y_i = h_i X + w_i \tag{2.3}$$

Where X is the transmitted superimposed signal. h_i is the complex channel coefficient between UEI and the base station (BS). w_i is the Gaussian noise (additive Gaussian white noise: AGWN) and interference received by users.

The best order to decode the received signal in NOMA is to increase the channel gain, which is normalized by noise and interference power between cells $E[|h_i|^2]$ [35]. Assuming that, user 1 has better channel conditions than user 2:

$$E[|h_1|^2] > E[|h_2|^2] \tag{2.4}$$

Then the signal from user 2 will be the first in the decoding order. Therefore, user 2 can use a linear receiver to decode its message from the superimposed signal and treat user 1's signal in y_2 as additional interference. For user 1, the decoding process consists of the following steps: first decode and reconstruct the user 2 signal, then subtract from y_1 [35]. According to this principle, its signal-to-noise ratio (SNR) is expressed as follows:

$$\gamma_i = \frac{|h_i|^2 P\alpha_1}{|h_i|^2 P\alpha_2 + \sigma^2} \tag{2.5}$$

Where σ is the variance. P is the power allocated to the i-th user.

Therefore, the throughput of each user in the PD-NOMA system is expressed as:

$$R_i = \log_2(1 + \gamma_i) \tag{2.6}$$

Users who receive revenue from h_1 and h_2 channels, among which h_1 is the highest and h_2 is the lowest. The base station will assign the higher power to the farthest user 2. The lowest power will be allocated to user 1 because it is closest to the station. This ensures that remote users with low channel gains will receive lower levels of interference from users with high channel gains [12].

User 1 uses the SIC detector to first decode the signal of user 2, then subtract it from the received signal [36]. User 2 considers the signal of user 1 as noise and easily decodes his own signal:

- **User 1**

$$y_1 = h_1 X + w_1 \tag{2.7}$$

$$y_1 = h_1(\sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2) + w_1 \tag{2.8}$$

$$y_1 = h_1\sqrt{P\alpha_1}X_1 + h_1\sqrt{P\alpha_2}X_2 + w_1 \tag{2.9}$$

Where X is the transmitted superimposed signal $X = \sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2$. $h_1\sqrt{P\alpha_1}X_1$ is the dominant desired signal. $h_1\sqrt{P\alpha_2}X_2$ is the low power interference. w_1 is the noise.

Since we have $\alpha_1 > \alpha_2$ so the signal containing α_2 is directly treated as interference, Its SNR is:

$$\gamma_1 = \frac{|h_1|^2 P\alpha_1}{|h_1|^2 P\alpha_2 + \sigma^2} \tag{2.10}$$

Where P is the total allocated power to the nearest user.

And its data rate has the form:

$$R_1 = \log_2(1 + \gamma_1) \tag{2.11}$$

- **User 2**

$$y_2 = h_2 X + w_2 \tag{2.12}$$

$$y_2 = h_2(\sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2) + w_2 \tag{2.13}$$

$$y_2 = h_2\sqrt{P\alpha_1}X_1 + h_2\sqrt{P\alpha_2}X_2 + w_2 \tag{2.14}$$

Where $h_2\sqrt{P\alpha_1}X_1$ is the dominant desired signal. $h_2\sqrt{P\alpha_2}X_2$ is the low power interference. w_2 is the noise.

Since we have $\alpha_1 > \alpha_2$ so the signal containing α_2 is directly treated as interference, The SNR of user 2 after decoding X_1 is:

$$\gamma_{1,2} = \frac{|h_2|^2 P\alpha_1}{|h_2|^2 P\alpha_2 + \sigma^2} \tag{2.15}$$

And its data rate has the form:

$$R_{1,2} = \log_2(1 + \gamma_{1,2}) \tag{2.16}$$

The SNR of user 2 after decoding X_2 is:

$$\gamma_2 = \frac{|h_2|^2 P\alpha_2}{\sigma^2} \tag{2.17}$$

And its data rate has the form:

$$R_2 = \log_2(1 + \gamma_2) \tag{2.18}$$

2.4. NOMA Transmission Models

As the previous generations of mobile communication are failed to transmit signals if the power of users is unbalanced, by using NOMA we can overcome this drawback. The key idea of NOMA is transmitting information between the users even though users are at a long distance from the base station and having unbalanced powers [37]. The transmission model of this technique, which is like all transmission models as showing in the figure 2.5, consists of three parts: transmitter (BS), channel and receiver (UE). Through two main links: downlink (DL) and uplink (UL).

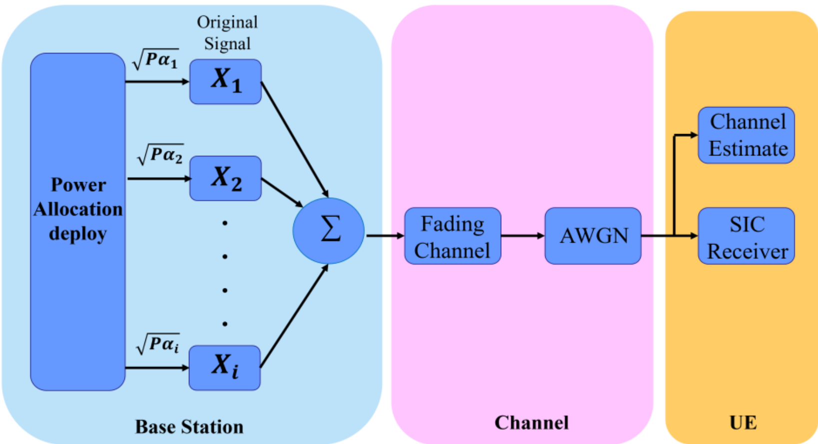

Figure 2.5: NOMA transmission structure [37].

2.4.1. Downlink NOMA

Downlink NOMA transmission employs the SC technique at the BS for sending a combination of the signals and the SIC technique may be invoked by the users for interference cancelation and the Single User Detection (SUD) for decoding, as shown in figure 3.6:

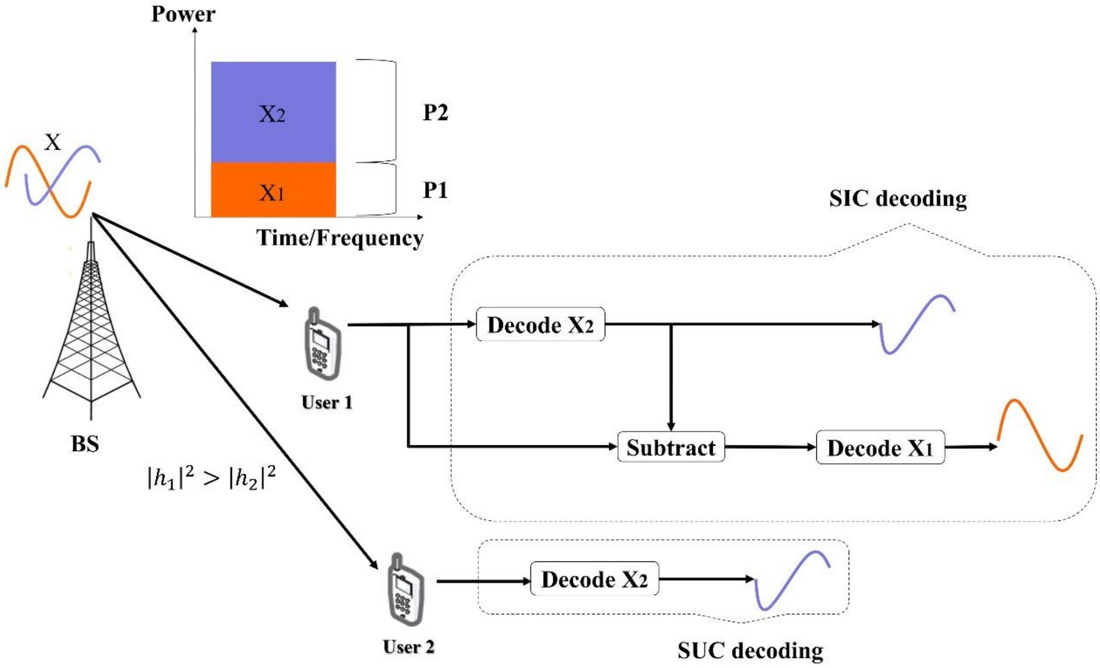

Figure 2.6: Downlink NOMA in a simple two-user system.

In this DL scheme, we have two users who communicate with the same BS. Users simultaneously share the same resources served by the BS. The BS sends message to every user. User 1 is near user, user 2 is far user. User 1 has better channel state than user 2, i.e., |h1|>|h2| [38]. BS allocates appropriate power coefficient to the messages of all users.

The BS transmits over the bandwidth W the superimposed signal $\sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2$. The received signal y_1 and y_2 from each user is therefore a superposition of X_1 and X_2:

$$y_1 = h_1(\sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2) + w_1 \quad (2.19)$$

$$y_2 = h_2(\sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2) + w_2 \quad (2.20)$$

User 2 is considered as the weak user and user 1 as the strong user, i.e., $|h_1|^2 > |h_2|^2$. It has been proven that optimal data rates can only be achieved by first decoding weak user 2, before performing the SIC and decoding strong user 1 [35].

According to the optimal decoding order on the receiver side of user 2, X_2 is decoded considering X_1 as noise. Therefore, its signal to interference plus noise ratio (SINR) is:

$$\delta_2 = \frac{|h_2|^2 P\alpha_2}{WN_0 + |h_2|^2 P\alpha_1} \quad (2.21)$$

Where W is the total bandwidth. N_0 is the noise power spectral density.

On the receiver side of user 1, x1 is also decoded to x2 as noise. Then user 1 subtracts x2 from the superimposed signal y1 before decoding its own signal x1 [38], [35]. The signal to interference plus noise ratio of x1 after SIC is:

$$\delta_1 = \frac{|h_1|^2 P\alpha_1}{WN_0} \quad (2.22)$$

The data rates for NOMA are:

$$R_2 = W \log_2(1 + \frac{|h_2|^2 P\alpha_2}{WN_0 + |h_2|^2 P\alpha_1}) \quad (2.23)$$

$$R_1 = W \log_2(1 + \frac{|h_1|^2 P\alpha_1}{WN_0}) \quad (2.24)$$

2.4.2. Uplink NOMA

In the uplink, the BS sends control signals to the transmitting users to determine power allocation. Once the transmit power is determined, each transmitting user sends its message. The BS in this case receives a signal constituted by the superposition of the signals of transmitting users [39]. Using SIC, the BS decodes the messages of the users according to the decreasing order of channel gains [40]. The signal of the user having the highest channel gain is first decoded, while considering the signals of all other users as interference. It is then subtracted from the total received signal before decoding the signals of the remaining users [38]. Secondly, the signal of the user with the lowest channel gain is decoded without interference. The uplink NOMA system is showing in figure 2.7:

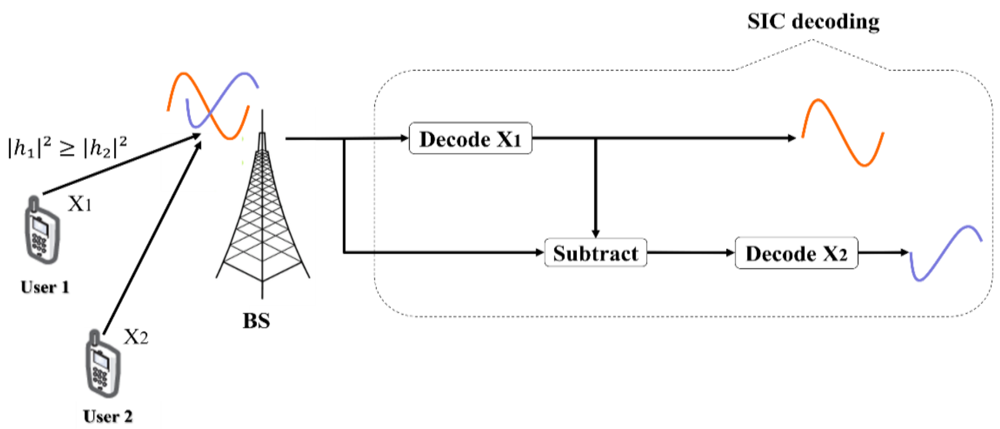

Figure 2.7: Uplink NOMA in a simple two-user system.

Both users transmit on the same bandwidth W. The signal received at the BS is therefore a superposition of X_1 and X_2:

$$y = h_1\sqrt{P_1\alpha_1}X_1 + h_2\sqrt{P_2\alpha_2}X_2 + w \quad (2.25)$$

Where w is a Gaussian noise (additive Gaussian white noise: AGWN). P_1, P_2 are the power of each user 1 and 2.

2.5. Spectral Efficiency and Energy Efficiency

In new multiple access networks, it is essential to seek the best performance for spectral efficiency and energy efficiency.

2.5.1. Spectral Efficiency

Spectral efficiency is defined as the number of bits per second per unit bandwidth that can be transmitted in a communication system [41]. It is then written as follows:

$$SE = \frac{R_T}{W}\ (bps/Hz) \quad (2.26)$$

Where R_T is the sum rate of the users.

2.5.2. Energy Efficiency

Energy efficiency is the ratio between the maximum number of bits that can be transmitted by the network and the total necessary energy consumed [41]. It can be defined as follows:

$$EE = \frac{R_T}{P_{total}} = SE\frac{W}{P_{total}}\ (bits/joule) \quad (2.27)$$

Where P_{total} is the total power used by the BS.

→ According to Shannon's theory, the dependence of energy efficiency on spectral efficiency is monotonic [37], where a minimum EE is guaranteed in the case of high SE and when SE tends towards zero, the EE is maximal.

2.6. Key Applications

Due to compatibility, NOMA can be combined with many communication technologies, including cooperative communication so-called cooperative NOMA (C-NOMA), multiple input and multiple output (MIMO), energy harvesting (EH), visible light communication (VLC), software-defined multiple access (SoDeMA) and Internet of Things (IOT) for developing many applications and to further improve network performance.

2.7. Cooperative NOMA

Based on the principle of NOMA, the far user shares the radio channel and the transmit power with the near user. Compared to OMA, the achievable performance of the far user is degraded [42]. As the near user has to decode the signal intended for the far user before decoding its own signal, the near user can act as a relay and help forward the signal to the far user, which can effectively enhance the reception reliability of the far user. This technique combinates the cooperative communications with NOMA and it is named cooperative NOMA [43]. The key idea behind C-NOMA is to rely on strong NOMA users acting as relays to assist weak NOMA users, therefore C-NOMA fully benefits from SIC decoding.

Compared to conventional NOMA, the key advantages of cooperative NOMA transmissions can be summarized as follows:

- **Low system redundance:** Upon applying SIC techniques in NOMA, the message of the weak user has already been decoded at the strong user, hence it is natural to consider the employment of new protocol for weak signal [44]. Explicitly, the weak signal can be remodulated and retransmitted from a position closer to the destination.
- **Better fairness:** A beneficial feature of cooperative NOMA is that the reliability of the weak user is significantly improved. As a consequence, the fairness of NOMA transmission can be improved, particularly in the scenarios when the weak user is at the edge of the cell illustrated by the BS [45].
- **Higher diversity gain:** C-NOMA is capable of achieving an improved diversity gain for the weak NOMA user, which is an effective technique of overcoming multi-path fading [45]. It was analytically demonstrated that the diversity gains of the weak users in cooperative NOMA are the same as those of the conventional cooperative networks, even for using EH (Energy-Harvesting) relays [43], which is the focus of our study, more details will be provided about it.

2.8. Cooperative NOMA Networks

Cooperative communication is an outstanding solution to improve system performance and extend coverage areas for wireless networks [45], his fundamental idea is to introduce a certain number of intermediate nodes by many types to assist the communication between the source and the users [46]. Depending on the cooperation types, current works on cooperative NOMA networks can be classified into two categories: Relay cooperation and user cooperation, as shown in figure 3.9:

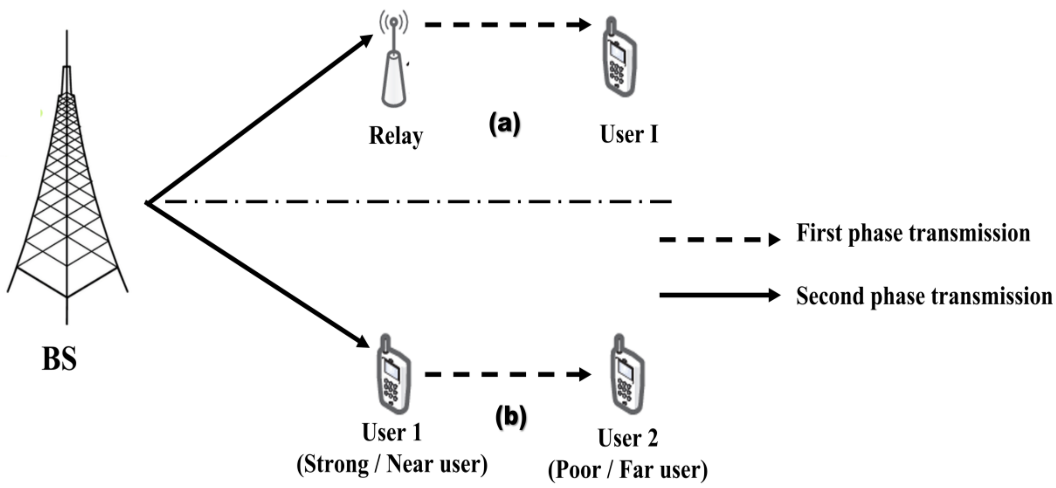

Figure 2.9: Cooperative NOMA networks schemes (a) Relay cooperation scheme (b) User cooperation scheme.

2.8.1. Relay Cooperation

It also called "the fixed relay", where dedicated relays are deployed to relaying packets for the users [46]. In his network, as shown in figure 3.9 (a) there is a single transmitter, one or more receiver and a fixed node which cooperates with the BS over two phases, where in the first phase the BS transmits the information to relay, in the second phase the relay performs the retransmission to users.

2.8.2. User Cooperation

The users act as relays for one another in the cooperative network [46], they are primarily interested in transmitting their own data, where as shown in figure 2.9 (b) in the first phase the BS transmits the SC signal to the strong user, which decodes and separates its own signal then performs retransmission the signal to the poor user having weak connection to the BS in the second phase.

2.9. Cooperative Relaying Protocols

The cooperative relaying is an important paradigm of wireless standards, especially when it applied to NOMA, it improved the system performance. It works according to different protocols where exist two well-known relaying protocols: Decode-and-forward (DF) and amplify-and-forward (AF) protocols [47]. The DF relaying first decodes the received information at the relay and then retransmits it after encoding again to the destination, while the AF relaying first scaled up the received information by a gain factor and then retransmits it to the destination [48]. The figure 2.10 below represented scheme of cooperative relaying works in the DF/AF protocols:

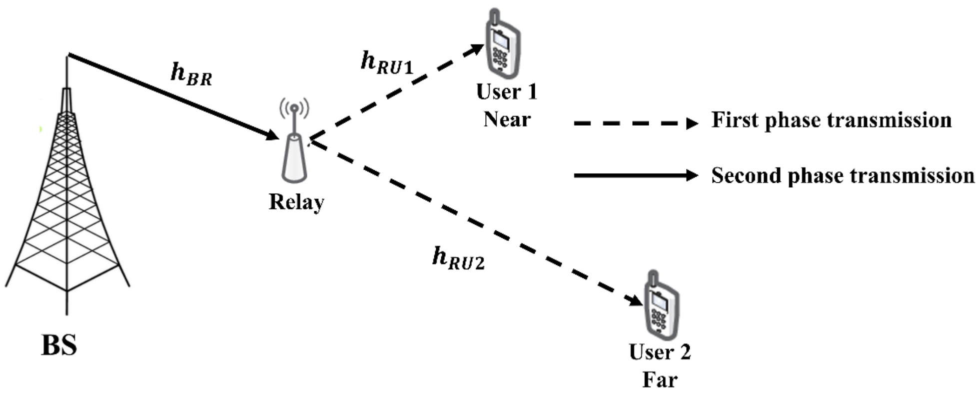

Figure 2.10: Cooperative relaying scheme.

2.9.1. Decode and Forward

The DF protocol works to decoding the received information SC from the BS in the relay, which encoding again this information SC and transmit it to users [49].

According to our scheme:

- **First phase:**

The signal of the received information at the relay can be given as [50]:

$$y_R = h(\sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2) + w_R \tag{2.28}$$

Where y_R is the signal at the relay. h is the complex channel coefficient between BS and relay. w_R is the noise at the relay.

The SINRs to detect X_1 and X_2 at the relay node become [50]:

$$\delta_R^2 = \frac{|h|^2 P\alpha_2}{|h|^2 P\alpha_1 \sigma_R^2} \tag{2.29}$$

$$\delta_R^1 = \frac{|h|^2 P\alpha_1}{\sigma_R^2} \tag{2.30}$$

Where σ_R^2 is the variance at relay.

- **Second phase:**

The relay re-encodes the signal has been decoding in the first phase and forwards it to the users [50]. The far user decodes its own signal directly and the near user uses the SIC to decode its own signal:

$$y_2 = h_2(\sqrt{P_R\alpha_1}X_1 + \sqrt{P_R\alpha_2}X_2) + w_2 \tag{2.31}$$

$$y_1 = h_1(\sqrt{P_R\alpha_1}X_1 + \sqrt{P_R\alpha_2}X_2) + w_1 \tag{2.32}$$

Where P_R is the power total of relay.

User 2 decode its signal directly without a SIC, so the SINR at User 2 is:

$$\delta_{DF,2} = \frac{|h_2|^2 P_R \alpha_2}{|h_2|^2 P_R \alpha_1 + \sigma_2^2} \tag{2.33}$$

The User 1 decode User 2 signal, then using the SIC decode its own signal. The SINRs at User 1 can be written as:

$$\delta_{DF,1}^2 = \frac{|h_1|^2 P_R \alpha_2}{|h_1|^2 P_R \alpha_1 + \sigma_1^2} \tag{2.34}$$

$$\delta_{DF,1}^1 = \frac{|h_1|^2 P_R \alpha_1}{\sigma_1^2} \tag{2.35}$$

The capacity of users can be [51]:

$$C_{DF,2} = \frac{1}{2}\log_2(1 + min\{\delta_R^2, \delta_{DF,2}\}) \tag{2.36}$$

$$C_{DF,1} = \frac{1}{2}\log_2(1 + min\{\delta_R^1, \delta_{DF,1}^1\}) \tag{2.37}$$

The outage occurs in the BS-relay-User 2 path when [51]:

$$C_{DF,2} < R \tag{2.38}$$

Where R is the data rate.

So, the outage probability of BS-relay-User 2 is obtained by [51]:

$$P_{out,DF}^{UE2} = P(C_{DF,2} < R) \tag{2.39}$$

The outage occurs in the BS-relay-User 1 path when [51]:

$$C_{DF,1} < R \tag{2.40}$$

So, the outage probability of BS-relay-User 1 is obtained by [51]:

$$P_{out,DF}^{UE1} = P(C_{DF,1} < R) \tag{2.41}$$

2.9.2. Amplify and Forward

The AF protocol works to amplify the received information SC from the BS by the gain factor in the relay without decoding, then retransmits it to the destination [49].

- **First phase:**

The received signal at the relay can be given as [50]:

$$y_R = h(\sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2) + w_R \tag{2.42}$$

The coefficient of amplification (the gain factor) β in AF protocol given by [47]:

$$\beta = \frac{1}{\sqrt{P|h|^2+\sigma^2}} \tag{2.43}$$

- **Second phase:**

The received signal at the user 2 after the amplification from the relay for the signal y_R can be written as [47]:

$$y_2 = \beta\sqrt{P}h_2\left[h(\sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2) + w_R\right] + w_2 \tag{2.44}$$

And we write the signal received at the user 1 as [47]:

$$y_1 = \beta\sqrt{P}h_1h(\sqrt{P\alpha_1}X_1 + \sqrt{P\alpha_2}X_2) + \beta\sqrt{P}h_1w_R + w_1 \tag{2.45}$$

The received signal interferes with the noise ratio (SINR) of user 2 to detect X_2 is given by [47]:

$$\delta_{AF,2} = \frac{\beta^2\gamma^2\alpha_2|h|^2|h_2|^2}{\beta^2\gamma^2|h|^2|h_2|^2\alpha_1+\beta^2\gamma|h_2|^2+1} \tag{2.46}$$

Where γ is the signal-to-noise ratio at the base station as $\gamma = \frac{P}{\sigma^2}$.

In user 1, the SIC is implemented and the received SINR at UE1 to detect X_2 can be written by [47]:

$$\delta_{AF,1,X_2} = \frac{\beta^2\gamma^2\alpha_2|h|^2|h_2|^2}{\beta^2\gamma^2|h|^2|h_1|^2\alpha_1+\beta^2\gamma|h_2|^2+1} \tag{2.47}$$

The received SINR at UE1 to detect its own signal is given by [47]:

$$\delta_{AF,1,X_1} = \frac{\beta^2\gamma^2\alpha_1|h|^2|h_1|^2}{\beta^2\gamma|h_1|^2+1} \tag{2.48}$$

The capacity of at UE2 and at UE1 can written by [51]:

$$C_{AF,2} = \frac{1}{2}\log_2(1 + \delta_{AF,2}) \tag{2.49}$$

$$C_{AF,1} = \frac{1}{2}\log_2(1 + \delta_{AF,1,X_1}) \tag{2.50}$$

The outage occurs in the BS-relay-User 2 path when [51]:

$$\frac{1}{2}\log_2(1 + \delta_{AF,2}) < R \tag{2.51}$$

$$\delta_{AF,2} < 2^{2R} - 1 \tag{2.52}$$

So, the outage probability of BS-relay-User 2 is obtained by [51]:

$$P_{out,AF}^{UE2} = P(\frac{1}{2}\log_2(1+\delta_{AF,2}) < R) = P(\delta_{AF,2} < 2^{2R} - 1) \tag{2.53}$$

The outage occurs in the BS-relay-User 1 path when [51]:

$$\frac{1}{2}\log_2(1+\delta_{AF,1,X_1}) < R \tag{2.54}$$

$$\delta_{AF,1,X_1} < 2^{2R} - 1 \tag{2.55}$$

So, the outage probability of BS-relay-User 1 is obtained by [51]:

$$P_{out,AF}^{UE1} = P(\frac{1}{2}\log_2(1+\delta_{AF,1,X_1}) < R) = P(\delta_{AF,1,X_1} < 2^{2R} - 1) \tag{2.56}$$

2.10. Conclusion

Cooperative communication significantly contributes to improving the performance of NOMA, as well as their continuity and avoiding their outage. In this chapter, we have studied NOMA about its domains, key technologies, types of transmission models, spectral efficiency, energy efficiency and key applications. Then, in particular, we have studied also the cooperative NOMA about its network types and relaying protocols. During our study, the relay of cooperative NOMA was in an ideal state that it has power to process and forward information. But with the time, the relay power will decrease and it will need a power source to charge and continue to work. Therefore, the energy harvesting (EH) technology comes to self-charge the relay.

In the next chapter, we will study EH technology, its sources, and how the relay collects energy by studying the used EH protocols.

Chapter 3:

Energy Harvesting
for wireless communications

3.1. Introduction

In wireless networks, devices, especially relays, suffer from weakness and lack of power after a period of operating time, as they need to charge their batteries for power supply, but it is difficult in their case, especially when they are in high or remote places. Energy harvesting technology is a solution to this problem by exploiting the energies surrounding the environment to obtain self-utilized energy.

In this chapter, we will study EH technology, especially the importance, the applications, the sources, advantages and disadvantages. In particular, we will present the radio EH techniques and their protocols: Time Switching protocol (TS) and Power Splitting protocol (PS).

3.2. Energy Harvesting

Energy harvesting is the collecting and exploiting of many ambient energies in the environment, thus promoting a cleaner and more sustainable ecosystem. EH is considered as green energy, where it uses diverse external mediums to tap into previously untapped energy reserves and also for capturing and converting a latent energy form into usable electrical power, as shown in figure 3.1:

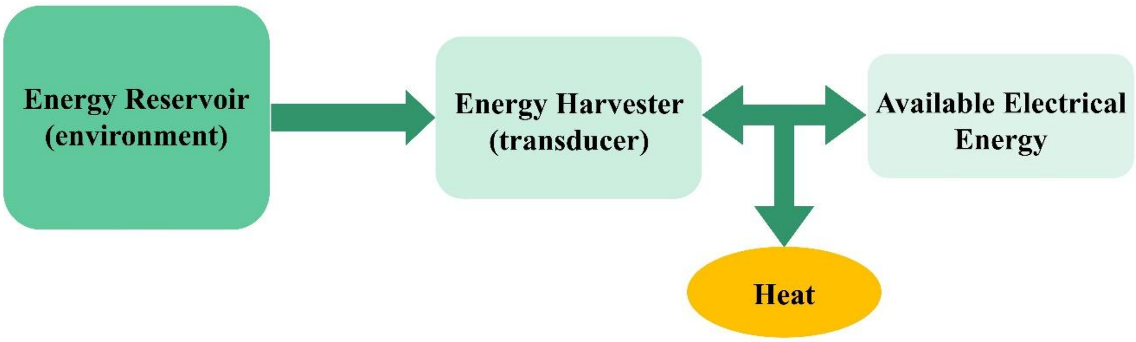

Figure 3.1: Scheme of harvested energy from environment.

The EH is particularly valuable when traditional power sources are impractical or inaccessible such as remote locations, rough terrains and areas with limited infrastructure [52]. Where in traditional energy-constrained wireless networks, the wireless devices normally use batteries as energy source and require periodically recharging or replacing the batteries, which is difficult for a large number of wireless devices, that resulting limited lifetime of the many wireless devices and the networks [53], [54]. EH allows these energy-limited wireless devices to harvests energy from the renewable energies (REs) in environment for extending the lifetime of energy-constrained wireless networks. Thus, the EH opens the way to self-sustaining systems of low-energy consumption users to realizes green communication [55]. The bellowing figure 3.2 present KPIs comparison between EH and batteries:

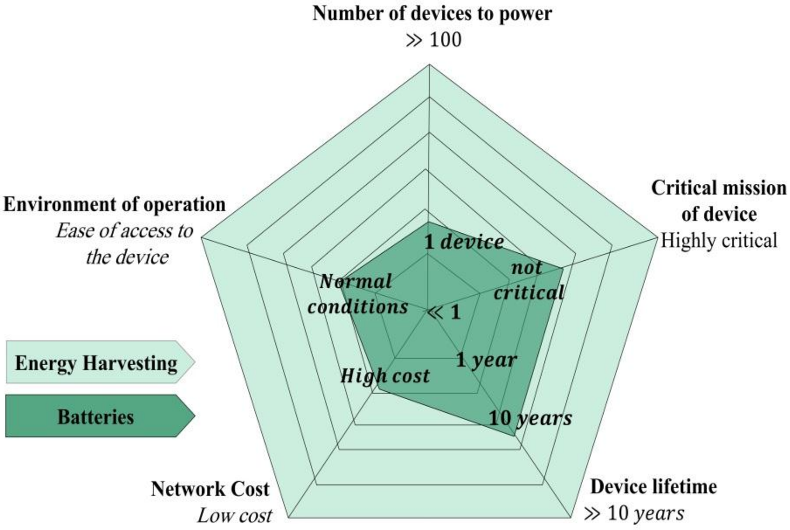

Figure 3.2: KPIs of EH vs Batteries.

3.3. Energy Harvesting Importance

Energy harvesting is of great importance in all uses for many reasons, as follows:

- EH allows the implementing and deployment thousands of sensors in remote locations that ensure greater coverage [56].
- Using EH avoids throwing millions of toxic batteries each year into the environment, and helps to reduce the carbon and radiation emissions.
- EH reduces the size and weight of equipment used so that the EH is proportional to the mass of the harvester.
- EH allows unlimited lifetime for comfortable sensor nodes without a battery that augments the autonomy of wireless sensor networks (WSNs) [55].

3.4. Energy Harvesting Applications

The harvested energy has many diverse applications in various fields such as:

- **Industrial:** Control sensors that are used in IoT and other sensor networks, in industrial environments need reliable long life power supplies [54]. EH can provide power to these sensors, which can operate without the need for external power or battery replacement.
- **Telecommunication:** EH charges the wireless devices in networks such as relays and drones, which are difficult to charge or replace their batteries. The researchers seek to apply energy harvesting to charge phones and computers directly and anywhere

without the need for a direct electrical supply, by taking advantage of the surrounding electromagnetic energy.

- **Transportation:** EH is provided power to devices in vehicles, such as those used for monitoring engine performance and tire pressure. Additionally, EH can used power to charging stations for electric vehicles [55].
- **Building:** EH can help in powering light switches in large buildings with many switches, it eliminates the trouble of constantly charging and replacing batteries, and reduces the maintenance cost [57].
- **Automation:** EH allows in powering automatic devices, such as smart watches, fitness trackers, engine control device [57], and where it increases the convenience of these devices and reduces the need for users to recharge or replace their batteries.
- **Medical:** Researchers have developed a device that harvests energy from the reverberation of heartbeats through the chest and converts it to electricity to run a pacemaker or an implanted defibrillator, hopefully obviating the need for periodic battery replacement. they have developed also a chip that can be implanted into the inner ear, with power provided by harvesting the energy in sound waves to monitor biological activity in the ears of people with hearing or balance impairments [58],[56].

3.5. Energy Harvesting Sources

Energy Harvesting or also known as Energy Extraction is the process of collecting and storing ambient energy for future uses. As shown in the figure 3.3, the energy can be harvested from a lot of sources in the environment, such as solar, thermal, vibration, tidal, wind power and radio frequency (RF) [59].

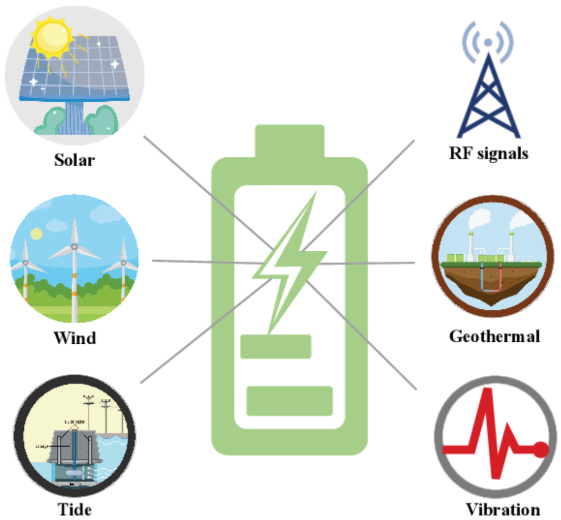

Figure 3.3: Various energy harvesting sources [60].

3.5.1. Solar Energy

Of all energy harvesting sources, solar energy is a convenient source and most popular. Where the solar light is everywhere, which makes it an ideal source of energy harvesting for use in multiple systems [59]. Energy is harvested from the light using photovoltaic cells, which provide power when exposed to light.

3.5.2. Thermal Energy

Thermal energy produces electricity when there is a temperature difference by Seebeck effect, where it converts the heat of power plants, factories, motor vehicles, computers or even human bodies into electricity [61]. In comparison with other sources of energy, the thermoelectric energy source provides relatively low electrical power levels.

3.5.3. Vibration Energy

A vibration energy harvesting system uses the mechanical vibration to apply a force to a transducer or to displace an electromagnetic coil [61]. In general, the energy generated by mechanical vibration as the vibration of the surroundings around the harvesting device is usually used as the energy source and then converted into electrical energy.

3.5.4. Tidal Energy

Tidal energy is harvested by using turbines that are related to kinetic energy and its rotational force underwater. In order to produce electricity, generators are introduced into the water, specifically where there is a high tide or current flow. There are various ways to optimize the amount of electricity that is harvested from tidal energy [62]. A few of the most popular methods include exposing turbine blades to the surface of water or submerged blades in slightly deeper water.

3.5.5. Wind Energy

Wind power has been harvested for thousands of years. It is extracted by using wind turbine that converts circular motion into electrical energy. Wind turbines are well known for their use in large scale electricity production, but they can also be used to power network node [59]. Wind turbines can easily deliver tens of megawatts, which is interesting to quickly recharge the node battery or power devices that require more energy.

3.5.6. RF Energy

The RF energy harvesting is a "Green" self-sustainable operation which can potentially provide unlimited energy supply that can be used to remotely power up low power devices. The RF energy is broadcasted by all kinds of radio transmitters such as mobile telephones, BS, and television/radio broadcast stations. EH process is handled by receivers which are captures the RF energy, then convert it into a Direct Current (DC) power [61], [59]. Its detail is explained in the following.

3.6. Impact of EH on RF Networks

Recently, the RF harvesters offer exceptional advantages from multiple characteristics and categories over other sources, where the RF-EH technique has been used as an alternative method for operating the new generation multiple access networks [63]. This technique is considered a potential solution to the constraints of wireless networks, where it enables self-sustaining to systems for network lifetime maximization, which can be improved to a few decades, while also reducing the cost of their maintenance [64], [65]. This feature has made that technique as the preferable option for certain areas and applications. In RF-EH systems as in figure 3.4 below, wireless devices can harvest energy from an RF signal and convert it into electricity for information processing and transmission.

As an extension of EH technologies in the RF, the simultaneous wireless information and power transfer (SWIPT) technique comes for transmitting both the information and power to concerned devices in networks [66]. Therefore, SWIPT is a solution to optimize transmission nodes and power allocation of the RF-EH system.

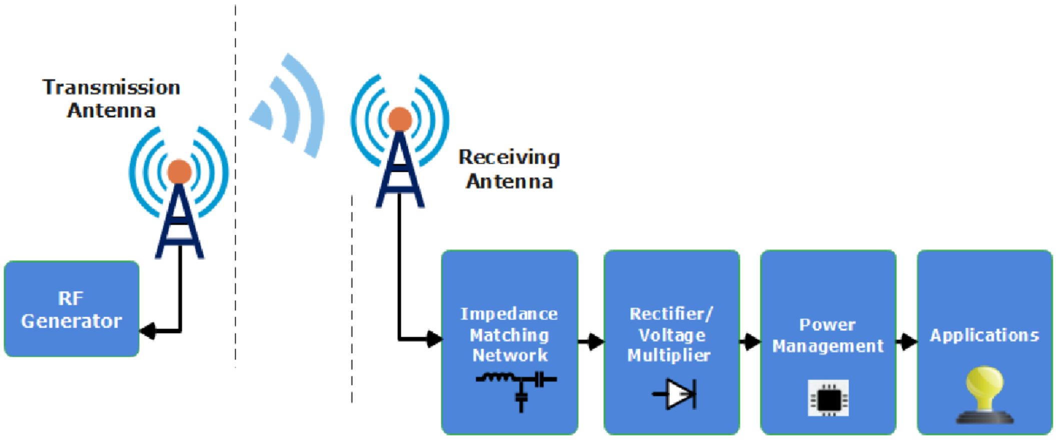

Figure 3.4: An RF energy harvesting systems conceptual block diagram [66].

3.6.1. RF-EH Characteristics

Contrary to other energy-harvesting sources, the RF-EH is characterized as following:

- **Simultaneous Ability:** RF-EH have an ability to regulate and provide constant energy transfer over a long distance, simultaneously [67].
- **Stability:** The harvested power is relatively stable and predictable for long-term performance to fixed distance in an RF-EH network setup [67].
- **Node Location:** The different locations of network nodes have a big importance, where in the total RF-EH relies on how far the dedicated RF source is from the ambient RF source [68].

3.6.2. RF-EH Categories

The RF-EH source type is divided into two categories:

- **Static Sources:** They are represented the stable-power transmitters, where the sensor device's power is supplied by modulating the signal in the frequency or in the transmitted power. They are existed in the broadcast radio, BS and television [69].
- **Dynamic Sources:** They are represented the transmitters of regularly broadcast which are not monitored by the internet of things' system as Wi-Fi access points, microwave radio links and police radios. These sources produce an energy, where the system research a harvesting opportunity for it [69].

3.7. EH Techniques

In RF networks, energy harvesting is used in many different technologies and fields, and among these techniques is cooperative NOMA as an approach to save power and extend the lifetime of a relay because when it continues to receive signals and forward them to users, it loses its power, since wireless batteries cannot be replaced or recharged [70]. The relay using the EH method collects RF signals from the surrounding environment or from a signal coming to it from the BS to harvest power, as shown in figure 3.5:

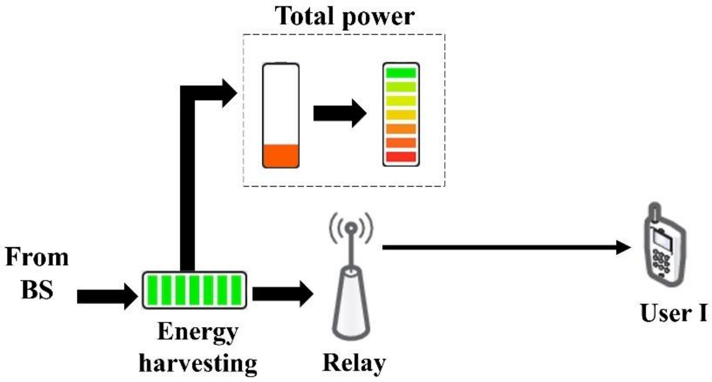

Figure 3.5: The transmission of relay with EH.

During transmission, a problem arose where the power and information carrying the same signal could not be processed at the same time, which performs SWIPT applications to come up with a way to solve this problem by dividing the signal into two parts: a part for power transfer or energy harvesting, and the other part to transmit messages or information decoding. For this process, energy harvesting has two protocols: Time switching protocol (TS) and power splitting protocol (PS). TS splits the signal in the time domain, while PS splits the signal in the power domain [71]. Their principles are explained in detail in the following.

3.7.1. Time Switching

With TS, a receiver switches between energy harvester and data decoder [72]. The time slot is divided into two components: In the first time slot, the devices or relays harvest energy from RF signals and the harvested energy is used for information transmission in the second time slot [73]. The following figure 3.6 present the TS scheme:

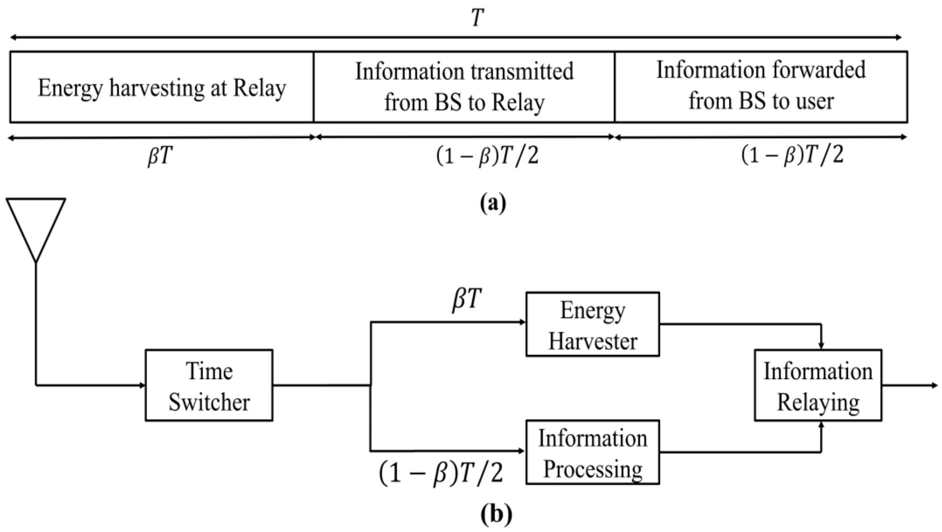

Figure 3.6: TS protocol schematic diagram: (a) Phase times. (b) Information processing at Relay.

The TS principle working when using DF-relay cooperation: In the first time slot, the BS first transmits a signal in βT seconds to relay which harvests energy during this time. Then in the second time slot, the time is divided into two parts, one $(1-\beta)T/2$ for transmission the information signal from BS to relay, the other $(1-\beta)T/2$ for forwarding the signal from the relay to user [74], by using the harvested energy.

The EH formula at the relay in TS protocol is given by [74]:

$$E_h = \beta T \eta P_S |h_r|^2 \quad (3.1)$$

Where β is the TS factor and T is the total communication time duration. η $(0 < \eta < 1)$ is the energy conversion efficiency factor. P_S is the total transmitting power. h_r is the Rayleigh fading channel between BS-relay.

The transmission power of relay during second $(1-\beta)T/2$ of time can be given as [74]:

$$P_r = \frac{E_h}{(1-\beta)T\,/\,2} = \frac{\eta P_S |h_r|^2 \beta T}{(1-\beta)T\,/\,2} = \frac{2\eta P_S |h_r|^2 \beta}{(1-\beta)} \quad (3.2)$$

3.7.2. Power Splitting

With PS, a receiver separates the RF signals into two parts by a PS coefficient [72]. The received signal power is divided into two parts according to the power splitting ratio, one for energy harvesting and the remaining for information processing [73]. The following figure 3.7 present the PS scheme:

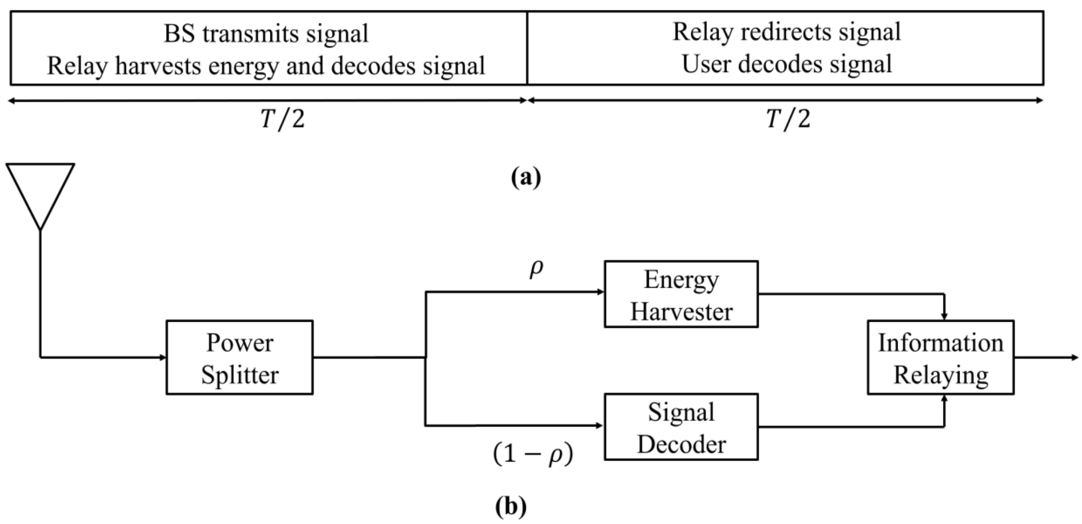

Figure 3.7: PS protocol schematic diagram: (a) Phase times. (b) Information processing at Relay.

The PS principle working when using DF-relay cooperation: The received signal at relay is split into two parts. The first part $T/2$ is divided into two operations, one for harvesting energy with (ρ) factor, and the other for decoding the information with $(1-\rho)$. In the second part $T/2$, the relay is recoded the information and forwarded it to users [75]. For more detail on the principle working of this protocol, we present in figure 3.8 a simple CR-NOMA network consisting of a BS, DF-relay and two users, where U1 is far and U2 is near to relay:

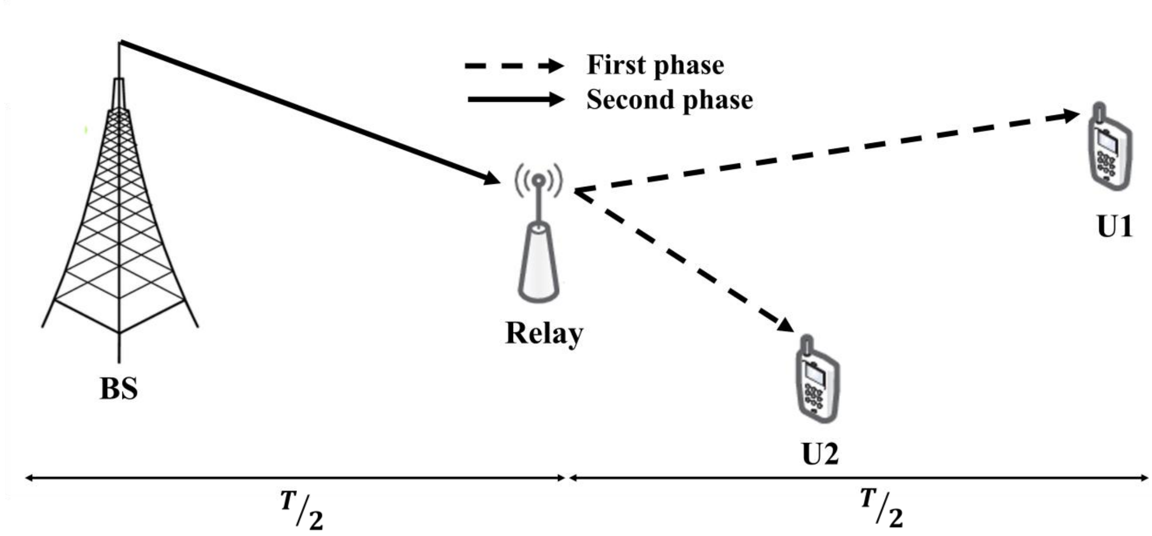

Figure 3.8: Simple CR-NOMA network with EH-PS.

- **Before harvested the energy:**

The SC received signal at relay from BS is given by:

$$y_r = \sqrt{P_S}\left(\sqrt{\alpha_1 X_1} + \sqrt{\alpha_2 X_2}\right)h_r + w_r \tag{3.3}$$

Where P_S is the total transmitting power by BS. α_1 and α_2 are the power allocation coefficients of U1 and U2, respectively, and $\alpha_1 > \alpha_2$, $\alpha_1 + \alpha_2 = 1$. X_1 and X_2 are the signals of the U1 and U2, respectively. h_r is the Rayleigh fading channel between BS-relay. w_r is the additive white Gaussian noise (AWGN) at the relay.

- **During harvested the energy:**

The $(1-\rho)$ signal decoded at the relay is given by [75]:

$$y_r = \sqrt{P_S(1-\rho)}\left(\sqrt{\alpha_1 X_1} + \sqrt{\alpha_2 X_2}\right)h_r + w_r \tag{3.4}$$

Where ρ is the PS factor, $0 < \rho < 1$.

The energy harvested from the ρ signal at relay is given by [75]:

$$E_h = \rho T \eta P_S |h_r|^2/2 \tag{3.5}$$

The transmission power of relay can be given as [75]:

$$P_r = \frac{E_h}{T\,/\,2} = \rho \eta P_S |h_r|^2 \tag{3.6}$$

- **After harvested the energy:**

The received signal at the users from relay is given by:

$$y_i = \sqrt{P_r}\left(\sqrt{\alpha_1 X_1} + \sqrt{\alpha_2 X_2}\right) h_i + w_i \tag{3.7}$$

Where h_i is the Rayleigh fading channel between relay and users. w_i is the AWGN at users.

3.8. EH Advantages and Disadvantages

As any technique, the EH offers several advantages and disadvantages, including:

3.8.1. EH Advantages

The EH has many advantages as follows:

- **Environmentally Friendly:** EH is a clean and renewable energy form of generating electrical power, where it is helps reduce our reliance on non-renewable sources of energy like fossil fuels, where it is the only environmental and economical way to power an electronic system for a long time [76].
- **Green Communication Source:** There is no wastage produced by this technique and hence it is one of the viable alternatives for green energy generation.
- **Lower Cost:** EH reduces the need for batteries, which can be expensive and require replacement. The uses of EH technologies can perform to significant cost savings over the long term. Where it offers saving of electric bills due to less usage of mains power for consumer electronic devices [76].
- **Low Maintenance:** EH devices have not many moving parts, which means they require a little maintenance [77].
- **Increased Reliability:** EH is worked to increase the reliability of electronic devices to enhance wireless communications [77].

3.8.2. EH Disadvantages

The EH has also some disadvantages as follows:

- **Limited Output Power:** EH systems typically provide low-level electrical power output and also varies in time, which means they are only suitable for certain low-power applications [78].
- **Initial Cost:** The initial cost of implementing the EH can be high, which can be a significant deterrent for some applications [79].
- **Dependent on External Factors:** EH systems are dependent on external factors like light or wind. where they are affected due to atmospheric changes and other factors such as obstacles, weather etc. [79].
- **Accreditation Performance:** EH uses electronic components and equipment, hence its efficiency largely depends on performance of these components [78].

3.9. Conclusion

The radio EH becomes the closest technology to green communications. It is a solution to the problem of depletion of batteries or relays, as it reduces the malfunction and losses that result.

In this chapter, we have examined EH technology in all its aspects, importance, applications, sources, advantages and disadvantages. The focus of this chapter was on the protocols TS and PS of the radio EH techniques and its schemes. In particular, the scheme of the PS protocol with a cooperative NOMA network, whose performance will be analyzed by MATLAB simulation in the next chapter.

Chapter 4:

Simulation of Downlink Cooperative NOMA using PS Protocol

4.1. Introduction

In this chapter, we will focus on downlink cooperative NOMA using PS protocol. We will study and evaluate the performance of the downlink cooperative NOMA using PS protocol. We will evaluate especially the capacity of the system, the outage probability (OP) and the bit error rate (BER) through simulation by MATLAB software. For a comprehensive analysis, we will compare our results with those of downlink cooperative NOMA without PS protocol.

4.2. System Model

Figure 4.1 represents the basic cooperative NOMA system model in the downlink. It consists of a base station (BS), one DF-relay and two users, namely the far user (U1) and the near user (U2). In this system is assumed that the relay has no power to forward the signals in the second phase to users. Therefore, to obtain power, we assume that the relay uses the energy-harvesting technology from the BS with using the PS protocol. The Rayleigh fading channel is assumed also to be between nodes.

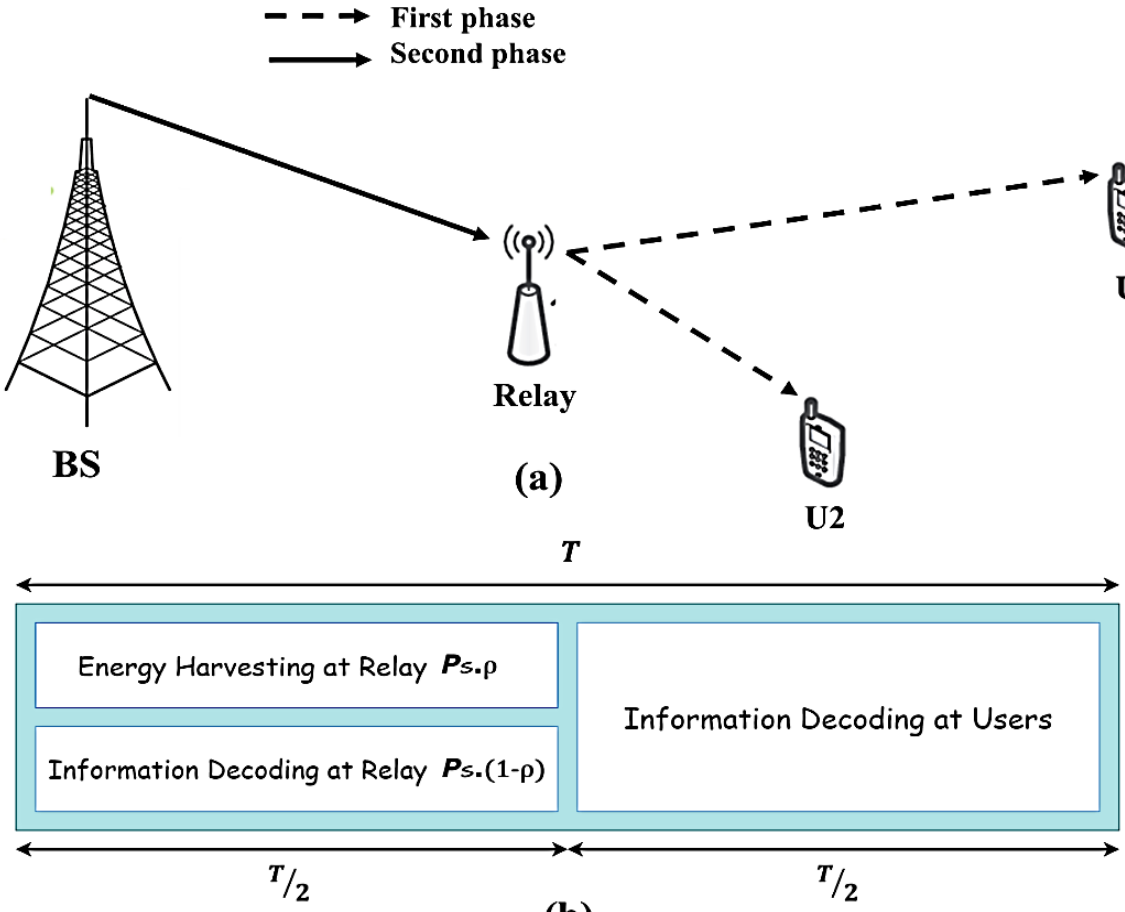

Figure 4.1: CR-NOMA assisted EH (PS protocol) scheme. (a): System model of the PS aided DF-relay C-NOMA. (b): Structure of PS protocol at the relay.

By assuming T is a total communication time duration which is divided into two halves. During the first halve (T/2), the power of the received signal from BS at the relay with different power levels based on the channel gain $|h_2|^2 > |h_1|^2$, it is split also into two parts: One (ρ) for using EH, and the other $(1 - \rho)$ for decoding the superimposed coding (SC) of the users' signals in the decoder. At remaining halve (T/2), the SC signal is forwarded to the users by the relay.

- **The first T/2:**

The signal received (SC) from BS is given by:

$$y_r = \sqrt{P_S}\left(\sqrt{\alpha_1 X_1} + \sqrt{\alpha_2 X_2}\right)h_r + w_r \tag{4.1}$$

Where P_S is the total transmitting power by BS. $\alpha_1 + \alpha_2 = 1$. $\alpha_1 > \alpha_2$. α_1 and α_2 are the power allocation coefficients of U1 and U2, respectively. X_1 and X_2 are the signals of the U1 and U2, respectively. h_r is the Rayleigh fading channel between BS-relay, where $\mathrm{h_r} \sim \mathrm{CN}(0, \sigma_r^2)$. $\sigma_r^2 = \mathrm{d_r}^{-\alpha}$, where $\mathrm{d_r}$ denote the distances between the BS-relay, respectively and α is the path loss exponent. w_r is the additive white Gaussian noise (AWGN) at the relay, where $w_r \sim \mathrm{CN}(0, \sigma_r^2)$.

The part of the signal that is supplied in the decoder at the relay is given by:

$$y_r = \sqrt{P_S(1-\rho)}\left(\sqrt{\alpha_1 X_1} + \sqrt{\alpha_2 X_2}\right)h_r + w_r \tag{4.2}$$

Where ρ is the PS factor, $0 < \rho < 1$.

The relay decodes X_1 first without SIC. Then, it uses the SIC to decoding X_2. The SINR at the relay is given by:

$$\delta_r^1 = \frac{(1-\rho)a_1 P_S |h_r|^2}{(1-\rho)a_2 P_S |h_r|^2 + \sigma_r^2} \tag{4.3}$$

$$\delta_r^2 = \frac{(1-\rho)a_2 P_S |h_r|^2}{\sigma_r^2} \tag{4.4}$$

The energy harvested at relay is given by:

$$E_h = \eta P_S |h_r|^2 \rho \frac{T}{2} \tag{4.5}$$

Where η is the energy conversion efficiency factor, $0 < \eta < 1$.

The relay transmission power through the harvested energy is given by:

$$P_r = \frac{E_h}{T/2} = \frac{\eta P_S |h_r|^2 \rho \frac{T}{2}}{T/2} = \eta P_S |h_r|^2 \rho \tag{4.6}$$

- **The second T/2:**

By using the harvested power, the relay configures the received signals as a new SC signal and forward it to the users. The received signal at the users is given by:

$$y_i = \sqrt{P_r}\left(\sqrt{\alpha_1 X_1} + \sqrt{\alpha_2 X_2}\right) h_i + w_i \tag{4.7}$$

Where h_i is the Rayleigh fading channel between BS and users, $h_i \sim \mathrm{CN}(0, \sigma_i^2)$. $w_i \sim \mathrm{CN}(0, \sigma_i^2)$ is the AWGN at the users.

The U1 decodes its signal X_1 without SIC and U2 uses the SIC for decoding its signal X_2. The SINR of users are given by:

$$\delta_{U1}^1 = \frac{a_1 P_r |h_1|^2}{a_2 P_r |h_1|^2 + \sigma_1^2} \tag{4.8}$$

$$\delta_{U2}^1 = \frac{a_1 P_r |h_2|^2}{a_2 P_r |h_2|^2 + \sigma_2^2} \tag{4.9}$$

$$\delta_{U2}^2 = \frac{a_2 P_r |h_2|^2}{\sigma_2^2} \tag{4.10}$$

Where $\sigma_i^2 = d_i^{-\alpha}$, d_i denote the distances between BS and users.

4.3. Simulation and Results

In this section, we simulate the system presented in figure (4.1) in order to illustrate the effect of energy harvesting with PS protocol at the downlink cooperative NOMA system for two users. The metrics used for the simulation: the capacity of system, outage probability (OP) and bit error rate (BER).

4.3.1. Simulation Parameters

In the simulations, we use the following parameters:

Parameters	*Notions*	*Values*
Distance between BS and relay	d_r	$0.5\ m$
Distance between relay and U1	d_1	$2\ m$
Distance between relay and U2	d_2	$1\ m$
PS factor	ρ	0.4
Energy conversion	η	0.95
Exponent of the path loss	PL	4
Power allocation coeff of U1	α_1	0.8
Power allocation coeff of U2	α_2	0.2
Transmission rate of U1	R_1	$0.1\ bps/Hz$
Transmission rate of U2	R_2	$0.5\ bps/Hz$
Channel	*Rayleigh*	

Table 4.1: Simulation Parameters.

4.3.2. Capacity of System

In this subsection, we perform the capacity simulation of downlink cooperative NOMA using EH-PS protocol for the following parameters: $SNR, \rho,\ \eta$ and α_2. we compare the capacity of our system with downlink cooperative NOMA without EH-PS protocol.

The capacity is the quantity of information that the channel can transmit, according to our system it is given by the following forms:

The capacity of U1 and U2 for DL C-NOMA using PS protocol are given by:

$$C_{U1}^{PS} = \frac{1}{2}\log_2(1 + \min(\delta_r^1, \delta_{U1}^1)) \tag{4.11}$$

$$C_{U2}^{PS} = \frac{1}{2}\log_2(1 + \min(\delta_r^2, \delta_{U2}^2)) \tag{4.12}$$

The capacity of U1 and U2 for DL C-NOMA without PS protocol are given by:

$$C_{U1} = \frac{1}{2}\log_2\left(1 + \min(\frac{a_1 P_S |h_r|^2}{a_2 P_S |h_r|^2 + \sigma_r^2}, \frac{a_1 P_r |h_1|^2}{a_2 P_r |h_1|^2 + \sigma_1^2})\right) \tag{4.13}$$

$$C_{U2} = \frac{1}{2}\log_2\left(1 + \min(\frac{a_2 P_S |h_r|^2}{\sigma_r^2}, \frac{a_2 P_r |h_2|^2}{\sigma_2^2})\right) \tag{4.14}$$

Note: In the DL cooperative NOMA without PS protocol, we assume that $P_s = P_r$.

- **SNR:**

Figure 4.2 presents the changes of capacity for two users of downlink cooperative NOMA, using PS protocol compared to without PS protocol with SNR. The capacity of U2 is better than U1 with or without PS protocol because U2 is close to relay/BS. It is observed also that the capacity of users with PS has better performance gain than the case of without PS protocol. Therefore, the PS improves channel capacity.

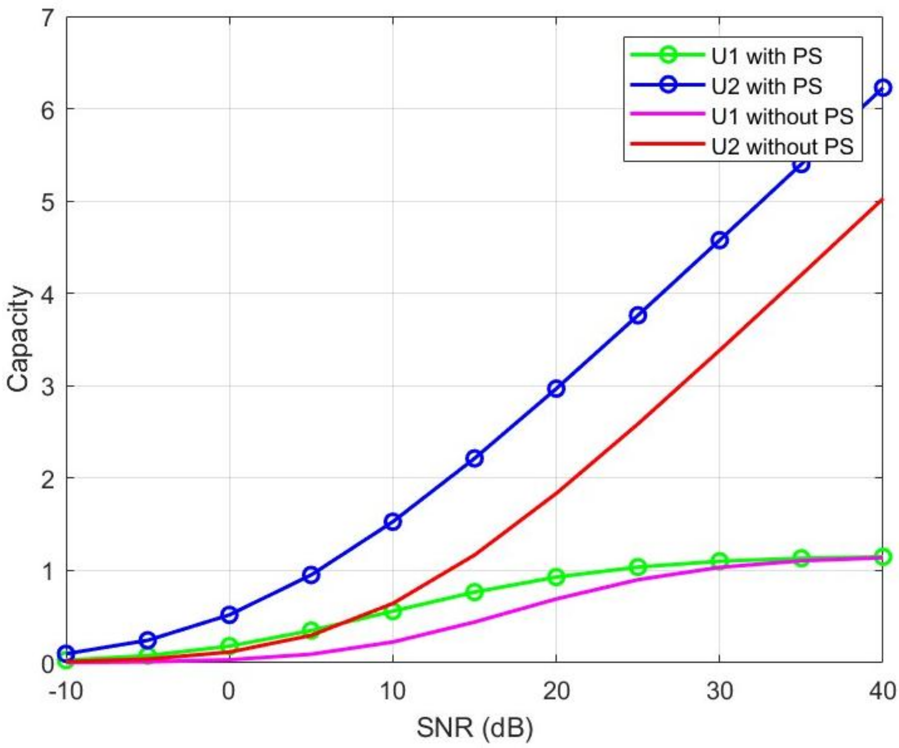

Figure 4.2: Capacity of U1 and U2 for DL C-NOMA using PS protocol compared to without PS protocol.

- ***ρ* Factor and *η* Conversion:**

Figure 4.3 presents the capacity for two users of downlink cooperative NOMA with/without PS vs ρ, when SNR=20dB. The augmentation of ρ in lower values increase the capacity of users, and in the high values of ρ, the capacity performance degrades. It seen also the maximum performance is achieved based on ρ. Therefore, the capacity of downlink cooperative NOMA using PS protocol is not always better than downlink cooperative NOMA without PS protocol.

Figure 4.4 presents the capacity for two users of downlink cooperative NOMA with/without PS vs η, when SNR=20dB. The augmentation of η increase the capacity of users. The capacity of downlink cooperative NOMA using PS protocol is better as the values of η

increase than the capacity of downlink cooperative NOMA without PS protocol remained stationary.

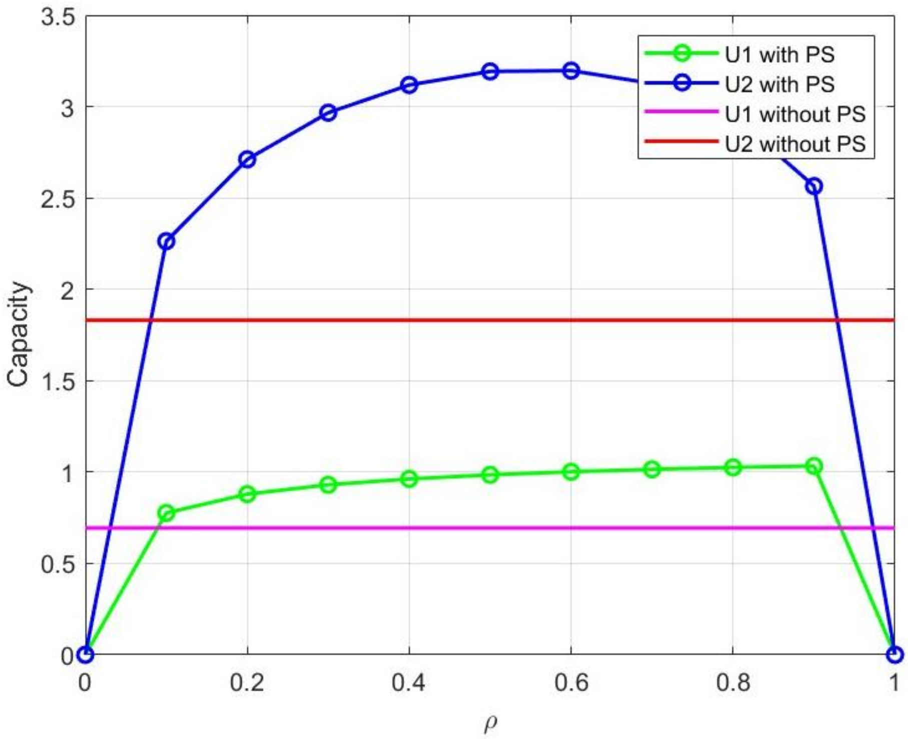

Figure 4.3: Capacity of U1 and U2 for DL C-NOMA using PS protocol vs ρ.

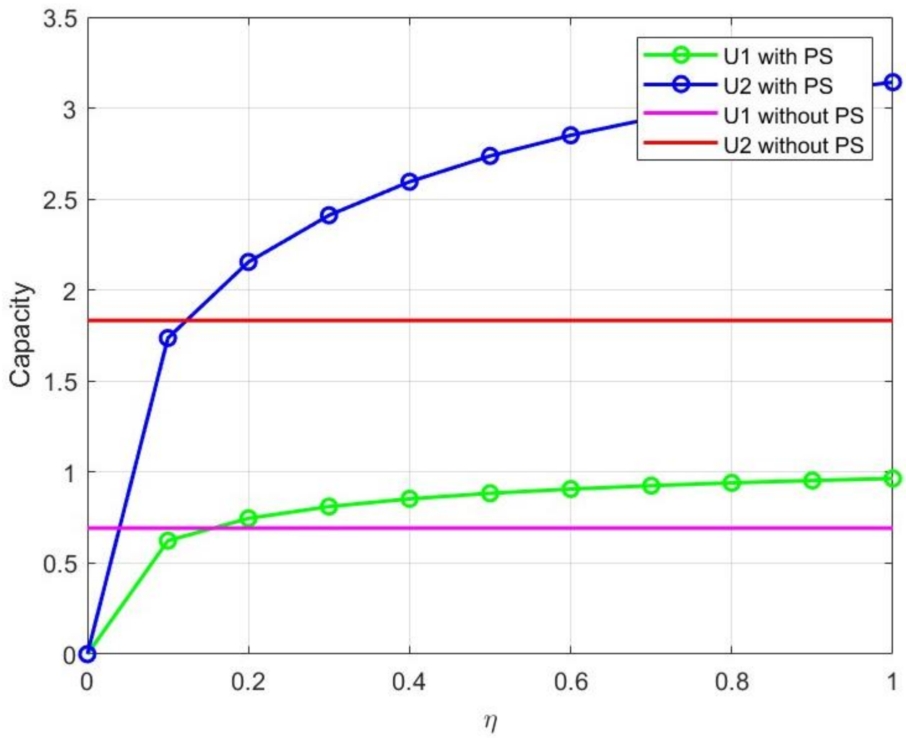

Figure 4.4: Capacity of U1 and U2 for DL C-NOMA using PS protocol vs η.

- **α_2 Coeff:**

Figure 4.5 presents the capacity for two users of downlink cooperative NOMA with/without PS vs α_2, when SNR=20dB. The changes of α_2 change the capacity of the two users. The changes of α_2 effect the SIC and the detection of the users. Again, the capacity of downlink cooperative NOMA using PS protocol is better than downlink cooperative NOMA without PS protocol in all α_2 values.

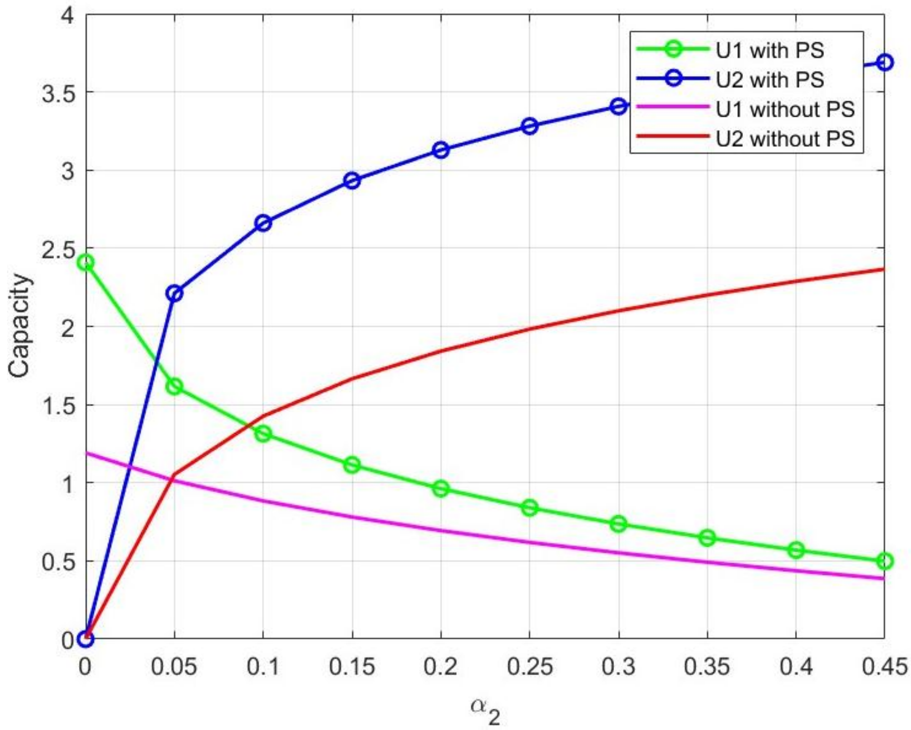

Figure 4.5: Capacity of U1 and U2 for DL C-NOMA using PS protocol vs α_2.

4.3.3. Outage Probability

The outage defined the action that happened when the receiver cannot successfully decode the received signal. The outage is expressed when the capacity is less than the transmission rate. In this subsection, we perform the outage probability simulation of downlink cooperative NOMA using EH-PS protocol for the following parameters: SNR, ρ, η and α_2. We compare the outage probability of our system with downlink cooperative NOMA without PS protocol.

The OP of U1 is defined as own capacity C_{U1} , which is less than the rate R_1:

$$P_{out}^{U1} = P(C_{U1}^{PS} < R_1) \tag{4.15}$$

The OP of U2 is defined as the sum of: When x_1 is detected erroneously and correctly. Then, the OP of U2 signal can be expressed by:

$$P_{out}^{U2} = P(C_{U1}^{PS} < R_1, C_{U2}^{PS} < R_2) \quad (4.16)$$

Likewise, in the system without PS protocol, the outage probability of U1 and U2 are defined as:

$$P_{out}^{U1} = P(C_{U1} < R_1) \quad (4.17)$$

$$P_{out}^{U2} = P(C_{U1} < R_1, C_{U2} < R_2) \quad (4.18)$$

- **SNR:**

Figure 4.6 presents the changes of outage probability for two users of downlink cooperative NOMA, using PS protocol compared to without PS protocol with SNR. The U2 achieve better performance gain compared to U1. It is observed also the users of downlink cooperative NOMA using PS protocol achieve better performance than users of downlink cooperative NOMA without PS protocol.

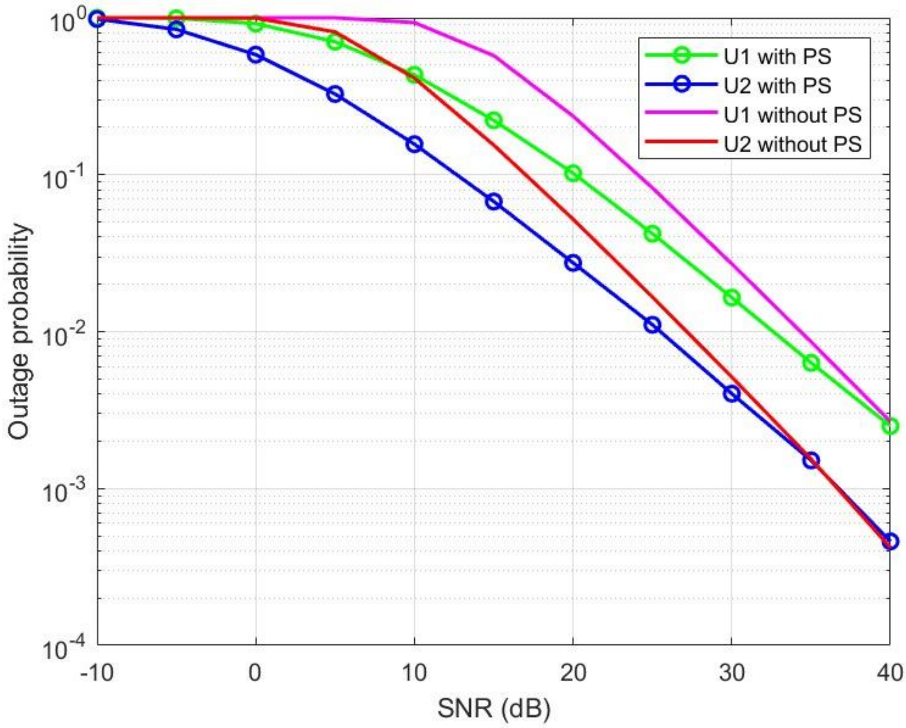

Figure 4.6: OP of U1 and U2 for DL C-NOMA using PS protocol compared to without PS protocol.

- **ρ Factor and η Conversion:**

Figure 4.7 presents the outage probability for two users of downlink cooperative NOMA with/without PS vs ρ, when SNR=20dB. The augmentation of ρ decrease the outage probability of users. Again, the outage probability of the two users of downlink cooperative NOMA using PS protocol has better performance gain compared to outage probability of downlink cooperative NOMA without PS protocol.

Figure 4.8 presents the outage probability for two users of downlink cooperative NOMA with/without PS vs η, when SNR=20dB. The augmentation of η values, reduces the outage probability of the two users of downlink cooperative NOMA using PS protocol and improves it. The outage probability of downlink cooperative NOMA using PS protocol outperforms the downlink cooperative NOMA without PS protocol.

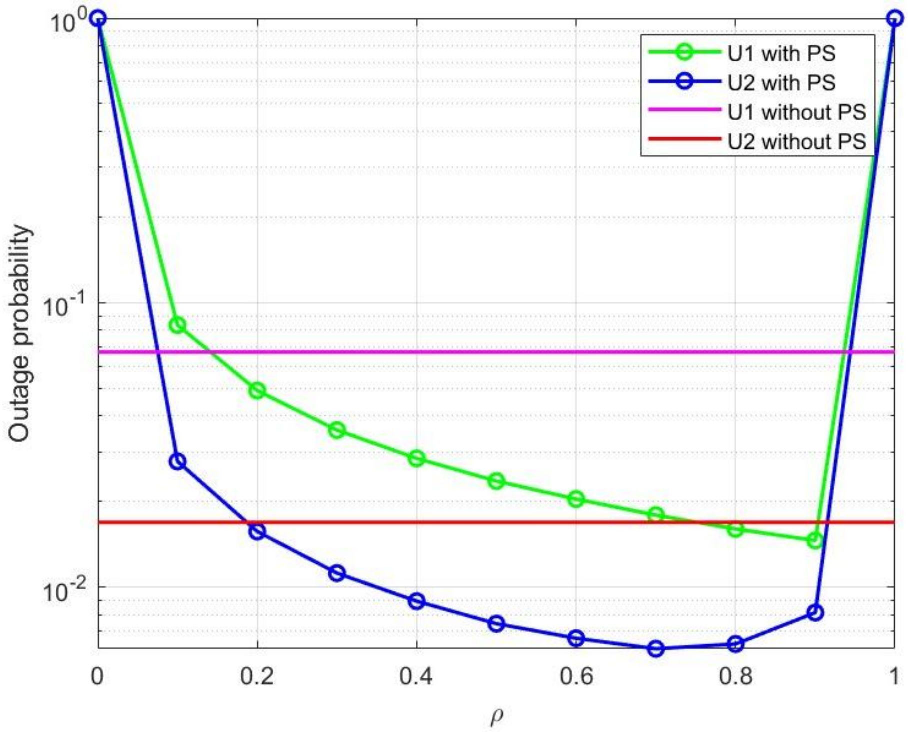

Figure 4.7: OP of U1 and U2 for DL C-NOMA using PS protocol vs ρ.

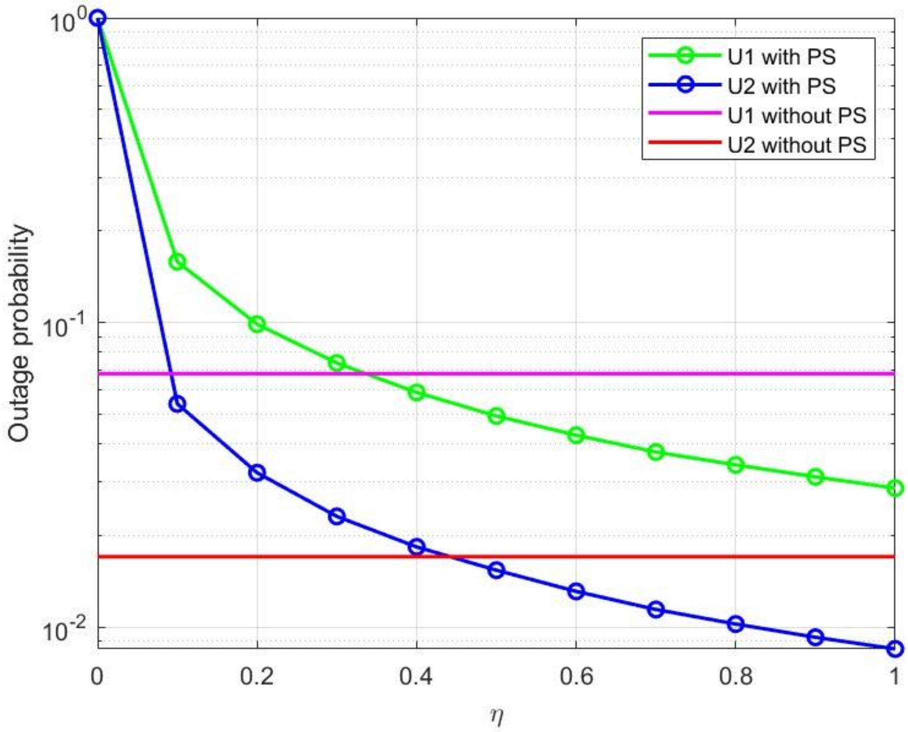

Figure 4.8: OP of U1 and U2 for DL C-NOMA using PS protocol vs η.

➢ **α_2 Coeff:**

Figure 4.9 presents the outage probability for the two users of downlink cooperative NOMA with/without PS vs α_2, when SNR=20dB. The change of α_2 effect the SIC the detection of users' signals. The outage probability of downlink cooperative NOMA using PS protocol outperforms the downlink cooperative NOMA without PS protocol.

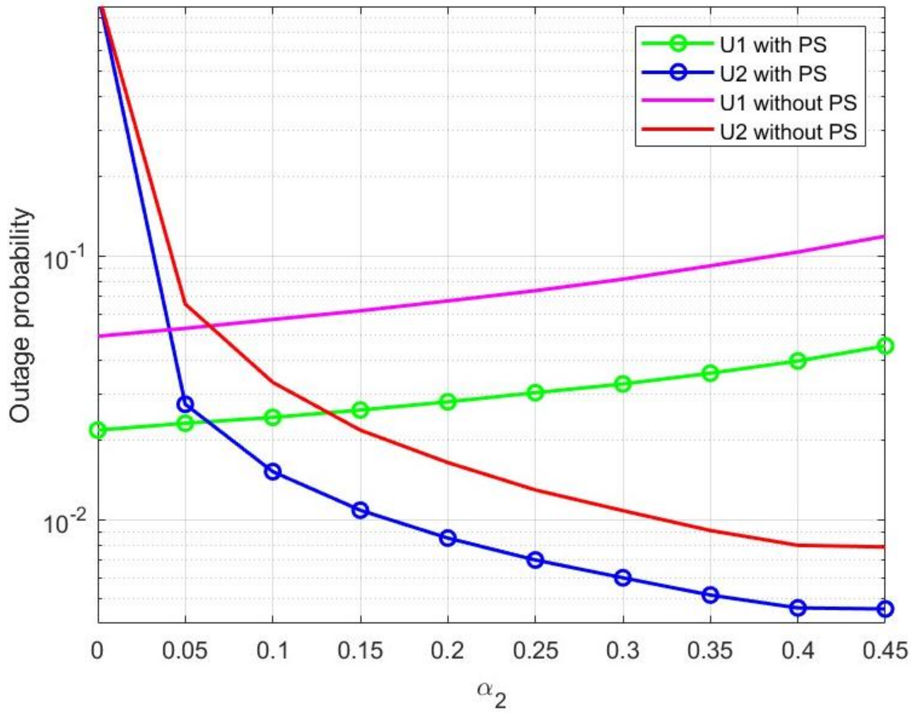

Figure 4.9: OP of U1 and U2 for DL C-NOMA using PS protocol vs α_2.

4.3.4. Bit Error Rate:

BER is used to calculate errors that occur in a transmission system, BER is a key parameter used to evaluate systems that transmit digital data from one location to another. In this subsection, we perform the BER simulation of downlink cooperative NOMA using EH-PS protocol for the following parameters: SNR, ρ, η and α_2. we compare the BER of our system with downlink cooperative NOMA without EH-PS protocol.

The BER is obtained by the following formula:

$$BER = \frac{\text{Number of erroneous bits}}{\text{Number of total bits transmitted}} \tag{4.19}$$

- **SNR:**

Figure 4.10 presents the changes of BER for the two users of downlink cooperative NOMA, using PS protocol compared to without PS protocol with SNR. The augmentation of SNR increases the BER performance, therefore the U2 achieve better performance than U1. The BER of downlink cooperative NOMA using PS protocol achieve better performance gain compared to downlink cooperative NOMA without PS protocol.

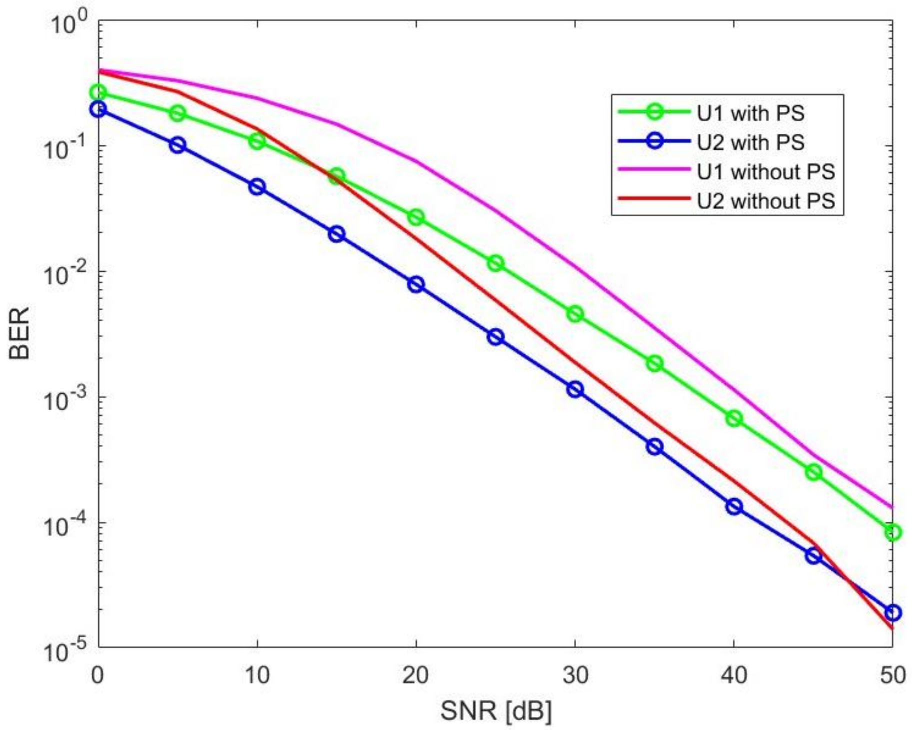

Figure 4.10: BER of U1 and U2 for DL C-NOMA using PS protocol compared to without PS protocol.

- ***ρ*** **Factor and** ***η*** **Conversion:**

Figure 4.11 presents the BER for two users of downlink cooperative NOMA with/without PS vs ρ, when SNR=20dB. The augmentation of ρ decrease the BER of users and improves it. Again, the downlink cooperative NOMA using PS protocol has higher performance gain compared to downlink cooperative NOMA without PS protocol.

Figure 4.12 presents the BER for two users of downlink cooperative NOMA with/without PS vs η, when SNR=20dB. The augmentation of η improves the BER performance of users. The change of η values has an effect on the performance of the downlink cooperative NOMA using PS protocol. Increasing η improves the performance of downlink cooperative NOMA using PS protocol compared to downlink cooperative NOMA without PS protocol.

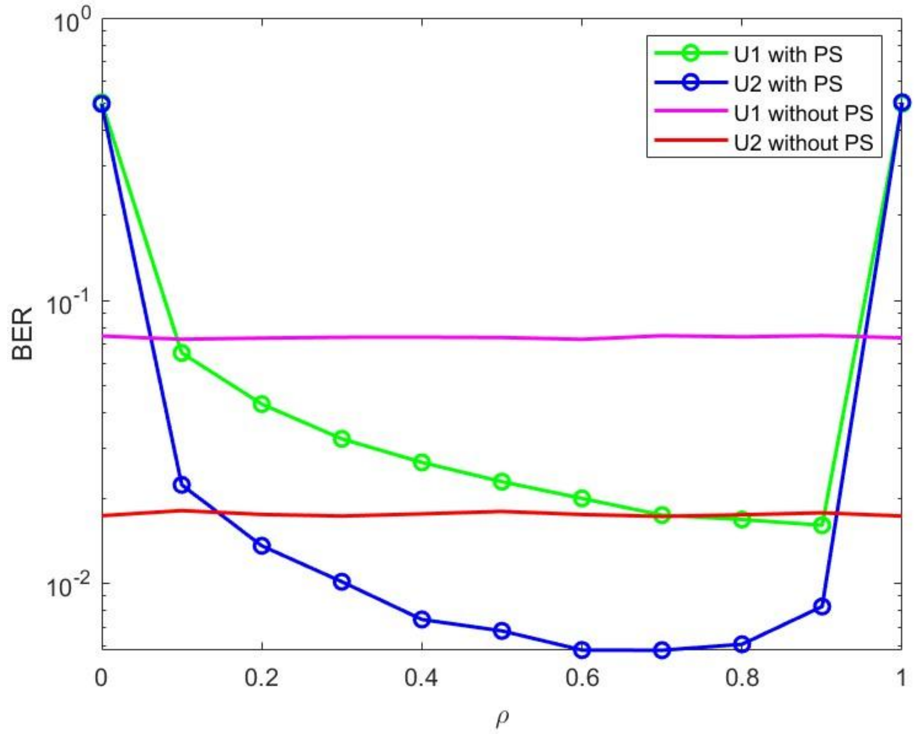

Figure 4.11: BER of U1 and U2 for DL C-NOMA using PS protocol vs ρ.

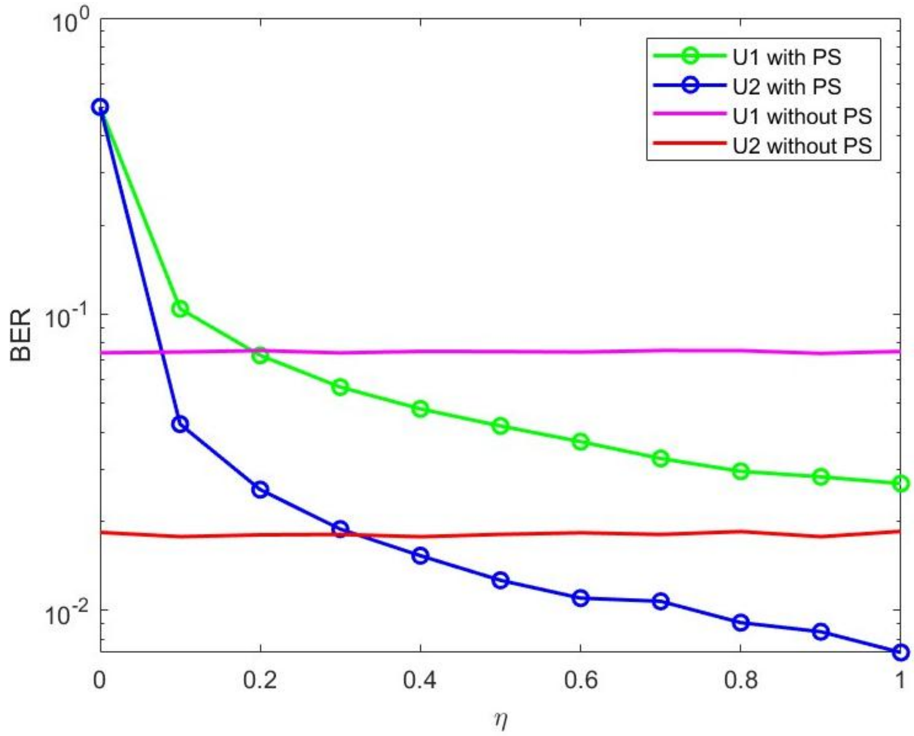

Figure 4.12: BER of U1 and U2 for DL C-NOMA using PS protocol vs η.

- **α_2 Coeff:**

Figure 4.13 presents the BER for the two users of downlink cooperative NOMA with/without PS vs α_2, when SNR=20dB. The increasing of α_2 effect the BER of the two users. The change of α_2 effect the SIC and the detection of the users' signals. Also, the downlink cooperative NOMA using PS protocol has better performance than without PS protocol.

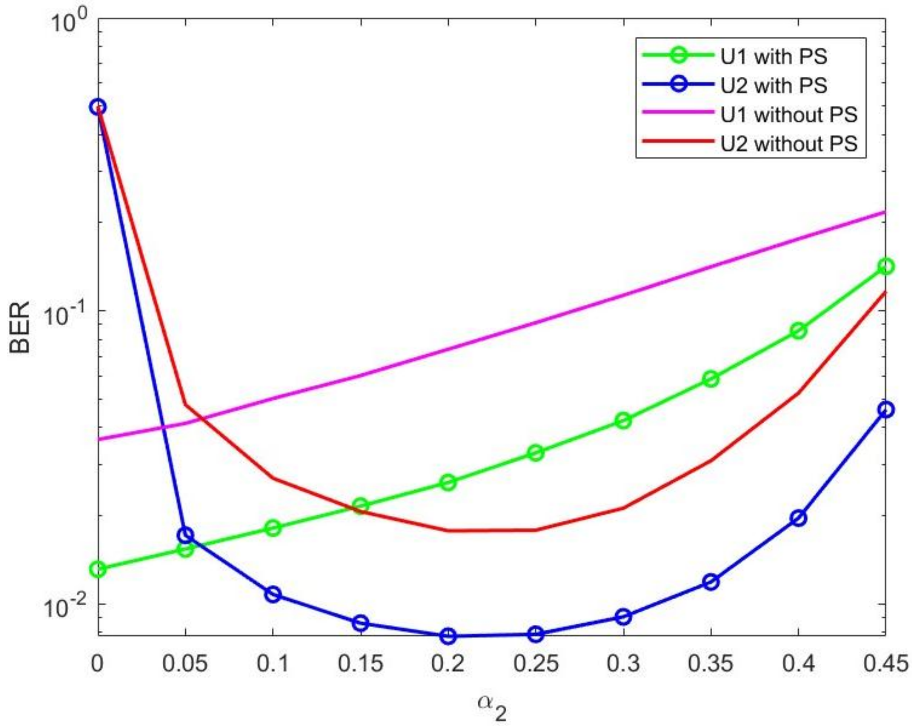

Figure 4.13: BER of U1 and U2 for DL C-NOMA using PS protocol vs α_2.

4.4. Conclusion

In this last chapter, we have focused on our system based on downlink cooperative NOMA using the PS protocol. We have evaluated the performance of our studied system in terms of capacity, OP and BER. For comparison, we have used the system based on downlink cooperative NOMA without PS protocol as a benchmark.

The simulation results show that the BER, OP and capacity of downlink cooperative NOMA using the PS protocol achieve better performance than without PS protocol. Furthermore, the change in power allocation affects the SIC process and the detection of users. Finally, we conclude that the improvement of the system performance depends on the values of the PS parameters. Thus, for a best performance of our studied system, we have to find the best parameters of PS protocol.

General Conclusion

General Conclusion

The growth of multi-access technologies has contributed to the evolution of wireless network generations. While the OMA techniques confirmed the network limitations in the previous generations, the NOMA technology would be a way to get beyond these limits in the future 6G network. As a promising solution, NOMA has gotten more attention due to its ability to meet many requirements of networks and share the same resources with multiple users. In order to improve spectral efficiency and increase coverage area, NOMA has combined with a variety of techniques, including cooperative communication.

Although, the cooperative NOMA networks achieve a better performance than the traditional NOMA networks. But their nodes may suffer from running out or recharging batteries. As promised solution of this problem, these nodes can continuously obtain power from surrounding RF sources by the EH technology used. Thus, the EH is employed to enhance the energy sustainability of wireless devices without replacing or recharging batteries. For this reason, cooperative relay NOMA is supported by EH as a powerful solution for green wireless networks. EH techniques work with two basic protocols: TS protocol and PS protocol. The objective of this dissertation was to analyze the performance of downlink cooperative NOMA using PS protocol, which compared to its counterpart cooperative NOMA system without EH. We have presented many key performance indicators such as capacity, OP, and BER of the proposed system.

In this dissertation, we have presented at the beginning a study about the development of technologies and requirements of networks form the new generations to 6G. Next, we studied NOMA technology from its domains, main techniques, transmission links, spectral and energy efficiency to its technologies. We also studied the cooperative NOMA technology with its famous schemes. After that, we presented the energy harvesting technology from many aspects and focused on radio EH with their protocols TS and PS. Finally, we have analyzed the performance of the cooperative NOMA system using PS protocol based on capacity, OP and BER.

The results obtained by simulation (MATLAB software) showed that the performance of the downlink cooperative NOMA using the PS protocol outperforms that of without EH in terms of capacity, OP, and BER. Therefore, we conclude that the PS protocol improves the system performance and achieves optimal performance according to the EH and power allocation parameters.

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