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Performance of RIS-empowered communication networks over symmetric/asymmetric fading channels

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Dedications

To those who planted hope in my heart and were the light along my path. To my dear parents, you are the greatest blessing in my life and the secret behind every success I've achieved. You taught me that perseverance creates miracles and that prayer paves the way. Thank you for your patience, your love, and your unwavering support at every step of this journey. And to my beloved siblings, you are my true support, the laughter that eases heavy days, and the shoulder I lean on in times of fatigue. Your presence by my side has been one of the main sources of my strength. I dedicate this humble achievement to you—it is not mine alone, but yours as well. Through you, I became who I am.

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To my dear family, thank you for your constant support and encouragement throughout my studies.

I would like to especially thank my supervisor, Mr. BENMAHMOUD Slimane, for his valuable guidance and advice that helped me complete this work.

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Thank you all.

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List of abbreviations

(RIS) Reconfigurable Intelligent Surfaces.

(IoT) Internet of Things.

(CNs) Cellular networks

(WCs) wireless communications

(WSNs) Wireless sensor networks

(RF) Radio frequency

(LoS) line-of-sight

(FM) frequency modulation

(AM) amplitude modulation

(GPS) global positioning system

(GSM) Global System for Mobile communications

(UHF) ultrahigh frequency

(VHF) very high frequency

(QoS) quality-of-service

(HD) half-duplex

(FD) full duplex

(WLANs) Wireless local networks

(FDMA) Frequency division multiple-access

(TDMA) Time division multiple-access

(CDMA) Code division multiple-access

(OFDMA) Orthogonal frequency division multiple-access

(EM) electromagnetic

(MEMS) micro electromechanical system

General introduction

Modern wireless communication is essential to our daily lives, enabling everything from mobile phone use and video streaming to smart home devices and industrial automation. However, it faces significant challenges, including high energy consumption and the unpredictable, often uncontrollable nature of the wireless environment. These issues can lead to signal degradation, increased latency, and reduced reliability especially in densely populated urban areas or complex indoor environments. As wireless networks continue to grow in size and complexity to meet rising demand, researchers are exploring innovative technologies to improve performance and efficiency. One such promising solution is Reconfigurable Intelligent Surfaces (RIS)**.** RIS technology consists of engineered surfaces embedded with passive or semi-passive elements that can dynamically reflect, refract, or absorb radio signals in a controlled manner. By actively shaping the propagation of wireless signals, RIS has the potential to transform traditionally hostile wireless environments into more manageable, predictable spaces. This could lead to substantial improvements in coverage, signal quality, and energy efficiency, paving the way for more sustainable and reliable communication networks.

The concept

By eliminating the need for physical cables, wireless communication offers enhanced mobility and flexibility. This reduction in physical infrastructure not only lowers installation and maintenance costs but has also paved the way for the vast ecosystem of mobile devices and the Internet of Things (IoT) that we see today.

The aim of the thesis

This research analyzes the performance of Reconfigurable Intelligent Surface (RIS)-assisted wireless networks by evaluating their outage probability and data rates. We study how RIS can reduce connection dropouts and improve overall performance, paving the way for its use in 5G and future networks.

Content and organization of this thesis:

This thesis is organized into four chapters. In **the first chapter** we give an overview of cellular networks.

In **the second chapter**, we deal with Relay-aided cooperative communications and the key technologies enabling their applications.

In **the third chapter**, the secrets of IRS-assisted communications networks are revealed.

In **the last chapter**, we present the simulation results of the performance of an RIS aided wireless network

Finally, the conclusion summarizes our work and presents new research perspectives in the field of IRS

Chapter 1: Fundamentals of cellular networks

Cellular networks represent a major breakthrough in modern communication, transforming how we connect over distances. What began as a basic concept for providing localized wireless signals has quickly become a sophisticated system that efficiently delivers widespread mobile services like voice, data, and wireless internet. The success of these networks depends on smart use of wireless frequencies and broad service areas. This field is constantly evolving, driven by the increasing need to boost performance and extend coverage to meet the rising demands for wireless connectivity in our digital age.

1.1 Introduction

Cellular networks (CNs) are the invisible links that connect us all to make digital communication, to share information, and to use many services as easily as possible. Making a phone call, streaming a video, or sending a text message is all done via a CN. CNs are essentially the infrastructure that allows our personal wireless devices to communicate with each other and simultaneously access a vast global network, through the radio waves. Carrier networks function on several key parameters, such as inefficient use of wireless frequencies and adequate coverage of services. This goes into effect because there has been continuous development in this field over the years with increasing demand to improve and extend the performance and coverage to meet the increasing needs for wireless communications (WCs) in our modern society.

1.2 Wireless communication

WC is one of the big engineering success stories of the last 25 years - not only from a scientific point of view, where the progress has been phenomenal but also in terms of market size and impact on society. Companies that were completely unknown 25 years ago are now household names all over the world, due to their wireless products. Furthermore, in several countries the wireless industry is dominating the whole economy. Working habits, and even more generally the ways we all communicate, have been changed by the possibility of talking "anywhere, anytime”. For a long time, WC has been associated with cellular telephony, as this is the biggest market segment, and has had the highest impact on everyday lives. In recent times, wireless computer networks have also led to a significant change in working habits and mobility of workers. For instance, answering emails in a coffee shop has become an everyday occurrence. In addition to these widely publicized cases, a large number of less obvious applications have been developed, and are starting to change our lives. Wireless sensor networks (WSNs) monitor factories, wireless links replace the cables between computers and keyboards, and wireless positioning systems monitor the location of trucks that have goods identified by wireless radio frequency (RF) tags. This variety of new applications causes the technical challenges for the wireless engineers to become bigger with each day **[1].**

Communication is the process of exchanging information, ideas, thoughts, feelings, or messages between two or more entities. It can be classified into two main categories: wired communication and wireless communication. Wired communication utilizes a physical connection or aguided medium. Instead of relying on electromagnetic waves traveling through the air, wired communication uses typically a cable or wire, to carry the signals. However, there are challenges associated with its infrastructure setup and cable installation, which can be both costly and time consuming to address. In remote areas, the establishment of wired communication can be particularly challenging. In order to overcome the problems encountered by wired communication, wireless communication has been used. WC is a specific type of communication where the transmission of information occurs without the use of physical connections like wires, cables, or optical fibers Instead, it relies on the transmission of electromagnetic waves (such as radio waves, microwaves, infrared, or light) through the air or space. WC eliminates the possibility of communication failure, unlike in wired communication where cables can be susceptible to damage from environmental conditions. In scenarios such as floods or other disasters, WC incurs minimal loss to the communication infrastructure compared to wired communication **[2].**

1.3 History of wireless communication

When looking at the history of communications, we find that WC is actually the oldest form - shouts and jungle drums did not require any wires or cables to function. Even the oldest "electromagnetic" (optical) communications are wireless: smoke signals are based on propagation of optical signals along a line-of-sight (LoS). In1880, Alexander Graham Bell invented and obtained a patent for his telephone. Together with his assistant Charles Sumner Tainter, they achieved a significant milestone by transmitting the first wireless telephone message using the photo phone. Unlike traditional telephones that relied on electricity, (CNs) are among the most significant developments in modern communications, revolutionizing the way we communicate and connect over long distances. Starting as a simple idea to provide wireless signal coverage in areas, CNs rapidly evolved into a complex system capable of efficiently delivering mobile communication services with comprehensive coverage. CNs are widely used in everyday life, whether for voice calls, data transmission, or even wireless internet technologies **[3].** In 1873, James Clerk Maxwell formulated the theory of electromagnetism, laying the foundation for our understanding of the relationship between electricity and magnetism. Building upon Maxwell's theory, Heinrich Hertz conducted experiments in 1886 that provided empirical evidence for the existence of radio waves. Hertz's discoveries marked a significant milestone in the field of WC **[4].** The exact inventor of the radio is a topic of debate, but in 1891, Nikola Tesla successfully showcased a functional wireless radio during a lecture. Tesla's demonstration played a significant role in the development of radio technology **[1].** In 1897, Guglielmo Marconi obtained a patent for his wireless telegraph, which he had developed. By 1901, people started exploring various aspects of radio technology. Broadcasting stations were established, and on November 2nd, 1920, Pittsburgh's KDKA station made the first ever commercial broadcast. This significant event occurred on Election Day, allowing people to hear the presidential race results before reading about them in newspapers. In 1922, the British Broadcasting Company (BBC) made its inaugural public broadcast from a London studio owned by Marconi. In the same year, The Toronto STAR initiated its own radio station and became the first station to broadcast a hockey game a year later, featuring Foster Hewitt. However, radio encountered challenges such as poor audio quality caused by static and interference from sky waves. The issues with radio interference were addressed in 1933 with the development of frequency modulation (FM) by Edwin Armstrong. FM technology offered improved sound quality compared to amplitude modulation (AM). Initially, radio stations operated within the 42-to-50-megahertz band, but eventually shifted to the higher frequency range of 88 to 108 megahertz **[5].** The numerous advancements in wireless transmissions have made it an integral part of the information age we live in today. Satellites, intentionally launched into Earth's orbit, are among the commonly used objects that play a significant role in facilitating various services such a television, radio, internet, and navigation systems like the global positioning system (GPS). Other wireless technologies include Wi-Fi, enabling wireless internet access on mobile devices without the need for Ethernet or USB cables; Bluetooth, which facilitates wireless connections between devices; and infrared, which transmits information wirelessly through infrared radiation **[2].** The primary advantage often associated with wireless transmission is its ability to provide mobility, allowing users to stay connected and access information on the go.

1.4 Overview of Cellular networks

The vision of WCs supporting information exchange between people or devices is the communications frontier of the next few decades, and much of it already **[1].**

1.4.1 Analog Cellular Systems

The 1970s saw a revived interest in cellular communications. In scientific research, these years saw the formulation of models for path loss, Doppler spectra, fading statistics, and other quantities that determine performance type of analog telephone systems. A highlight of that work was Jakes' book Microwave Mobile Radio that summed up the state of the art in this area. The 1960s and 1970s also saw a lot of basic research that was originally intended for landline communications, but later also proved to be instrumental for WCs. For example, the basics of adaptive equalizers, as well as multicarrier communications, were developed during that time. For the practical use of wireless telephony, the progress in device miniaturization made the vision of "portable" devices more realistic. Companies like Motorola and AT&T vied for leadership in this area and made vital contributions. Nippon Telephone and Telegraph (NTT) established a commercial cell phone system in Tokyo in 1979. However, it was a Swedish company that built up the first system with large coverage and automated switching: up to that point, Ericsson AB had been mostly known for telephone switches while radio communications was of limited interest to them. However, it was just that expertise in switching technology and the decision to use digital switching technology that allowed them to combine different cells in a large area into a single network, and establish the Nordic Mobile Telephone (NMT) system. Note that while the switching technology was digital, the radio transmission technology was still analog, and the systems became therefore known as analog systems. Subsequently, other countries developed their own analog phone standards. The system in the USA, e.g., was called Advanced Mobile Phone System (AMPS). An investigation of NMT also established an interesting method for estimating market size: business consultants equated the possible number of mobile phone users with the number of Mercedes 600 in Sweden. The analog systems paved the way for the wireless revolution. During the 1980s, they grew at a frenetic pace and reached market penetrations of up to 10% in Europe, though their impact was somewhat less in the U.S.A. In the beginning of the 1980s, the phones were "portable," but definitely not handheld. In most languages, they were just called "carphones," because the battery and transmitter were stored in the trunk of the car and were too heavy to be carried around. But at the end of the 1980s, handheld phones with good speech quality and quite acceptable battery lifetime abounded. The quality had become so good that in some markets digital phones had difficulty establishing themselves - there just did not seem to be a need for further improvements **[1].**

1.4.2 Digital Cellular Systems

Even though the public did not see a need for changing from analog to digital, the network operators knew better. Analog phones have a bad spectral efficiency, and due to the rapid growth of the cellular market, operators had a high interest in making room for more customers. Also, research in communications had started its inexorable turn to digital communications, and that included digital wireless communications as well. In the late 1970s and the 1980s, research into spectrally efficient modulation formats, the impact of channel distortions, and temporal variations on digital signals, as well as multiple access schemes and much more, were explored in research labs throughout the world. It thus became clear to the cognoscenti that the real-world systems would soon follow the research. Again, it was Europe that led the way. The European Telecommunications Standards Institute (ETSI) group started the development of a digital cellular standard that would become mandatory throughout Europe and was later adopted in most parts of the world: Global System for Mobile communications (GSM). The system was developed throughout the 1980s; deployment started in the early 1990s and user acceptance was swift. Due to additional features, better speech quality, and the possibility for secure communications, GSM-based services overtook analog services typically within 2 years of their introduction. In the U.S.A., the change to digital systems was somewhat slower, but by the end of the 1990s, this country also was overwhelmingly digital. Digital phones turned cellular communications, which was already on the road to success, into a blockbuster. By the year 2000, market penetration in Western Europe and Japan had exceeded 50% and though the U.S.A. showed a somewhat delayed development, growth rates were spectacular as well **[1].**

1.4.3 Cellular Telephone Systems

Cellular telephone systems are extremely popular and lucrative worldwide: these are the systems that ignited the wireless resolution. Cellular systems provide two-way voice and data communication with regional, national, or international coverage. Cellular systems were initially designed for mobile terminals inside vehicles with antennas mounted on the vehicle roof. Today these systems have evolved to support lightweight handheld mobile terminals operating inside and outside buildings at both pedestrian and vehicle speeds **[2].**

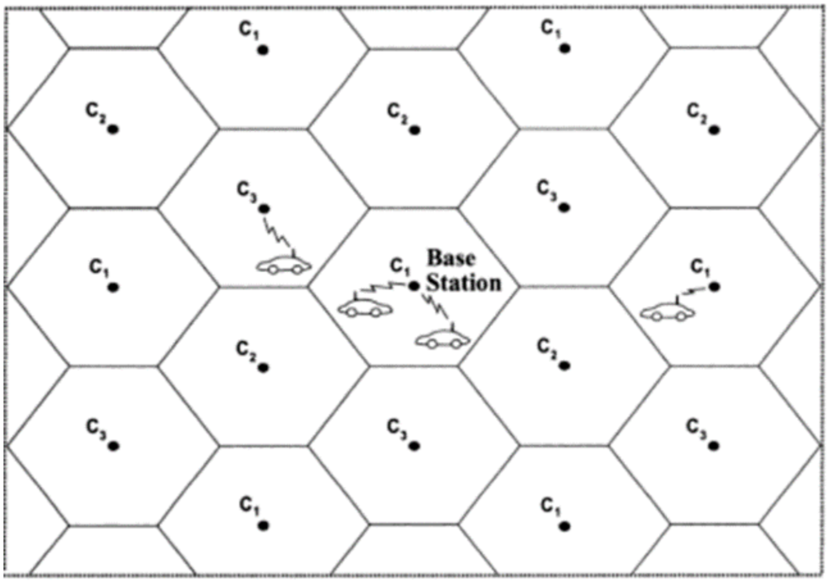

Figure 1.1. Cellular system **[2].**

The basic premise behind cellular system design is frequency reuse, which exploits the fact that signal power falls off with distance to reuse the same frequency spectrum at spatially separated locations. Specifically, the coverage area of a cellular system is divided into non overlapping cells, where some set of channels is assigned to each cell. This same channel set is used in another cell some distance away, as shown in Figure 1.1, where C, denotes the channel set used in a particular cell. Operation within a cell is controlled by a centralized base station, as described in more detail below. The interference caused by users in different cells operating on the same channel set is called inter cell interference. The spatial separation of cells that reuse the same channel set, the reuse distance, should be as small as possible so that frequencies are reused as often as possible, thereby maximizing spectral efficiency. However, as the reuse distance decreases, inter cell interference increases owing to the smaller propagation distance between interfering cells. Since inter cell interference must remain below a given threshold for acceptable system performance, reuse distance cannot be reduced below some minimum value. In practice it is quite difficult to determine this minimum value, since both the transmitting and interfering signals experience random power variations due to the characteristics of wireless signal propagation. In order to determine the best reuse distance and base station placement, an accurate characterization of signal propagation within the cells is needed **[2].**

1.5 Antennas in cellular networks

Antennas are crucial devices in wireless technology. Essentially, they are structures designed to send and receive radio waves. When transmitting, an antenna takes electrical signals from a device (like a radio or phone) and radiates them out as electromagnetic waves. When receiving, it does the opposite: it captures these waves from the air and converts them back into electrical signals that the device can understand. The shape and size of an antenna are very important as they determine how well it works at different frequencies and in different directions.

1.5.1 Antenna parameters

Antennas are essential components in any wireless communication system. They play a critical role in transmitting and receiving electromagnetic signals, and their characteristics determine the quality of wireless communication. Here are some of the most important characteristics of antennas **[6]**:

- ✓ *Frequency range*: The frequency range is the range of frequencies over which an antenna is designed to operate. Antennas Activate Windows as ultrahigh frequency (UHF), very high frequency (VHF), or GHz, depending on the application.

- ✓ *Gain*: Gain is a measure of the ability of an antenna to direct and concentrate energy in a specific direction. It is usually measured in decibels (dB) and is relative to an isotropic radiator (an ideal antenna that radiates energy uniformly in all directions).
- ✓ *Directivity*: Directivity is a measure of the ability of an antenna to concentrate energy in a particular direction. It is the ratio of the maximum radiation intensity in a specific direction to the average radiation intensity over all directions.
- ✓ *Radiation pattern*: The radiation pattern is a graphical representation of the directionality of an antenna's radiation. It shows the distribution of energy in space around the antenna.
- ✓ *Polarization*: Polarization is the orientation of the electric field of the electromagnetic wave with respect to the antenna. It can be either linear or circular, and different types of antennas are designed to work with different polarizations.
- ✓ *Impedance*: Impedance is the measure of opposition to the flow of an alternating current in an electrical circuit. The impedance of an antenna must match the impedance of the impedance of an antenna must match the impedance of the transmission line to ensure maximum power transfer and efficient operation.
- ✓ *Bandwidth*: Bandwidth is the range of frequencies over which an antenna can operate without significant loss of performance. The broader the bandwidth, the better the antenna is at receiving and transmitting

Gain and directivity are the two main characteristics that characterize antennas. The directionality of a beam of radiation describes how strongly it is focused in one direction. Therefore, directional antennas have smaller radiation patterns than omnidirectional ones while omnidirectional antennas are rather uniformly focused in all three dimensions. Figure 1.3 shows the directional antenna patterns with specific antenna gains. This is typically achieved by mixing several different types of radiating pieces. The gain of an antenna is a common metric listed in technical documents, and it is used to rate the amount of power emit-ted by the antenna. For the (IoT) to operate in the unlicensed industrial, scientific, and medical (ISM) bands, the equivalent (or effective) isotropic radiated power (EIRP) must be less than or equal to that of a licensed digital transmitter, reducing the potential for interference in the increasingly crowded radio spectrum. To achieve the same signal intensity as the antenna under test (AUT) in the direction of its strongest beam, the ideal isotropic antenna would have to emit a total power equal to the

EIRP. This metric gives a more complete picture of the transceiver module because it considers not only gain but also transmitter output power and antenna feed loss **[6].**

1.5.2 Antennas for (IoT)

Internet everywhere and Internet of things (IoT) everywhere! This time frame and future ones are all about connecting with everyone via whatever method. Communication is always at the tip of a digital noodle. The technology is being developed at an exponential rate right now, much faster than humanity as a whole ever dreamed of. The connectivity option, IoT, contains several heterogeneous end systems, such as smart homes, the industrial IoT, smart agriculture, and smart cities. And the smart grid can connect to them all. Developing a wireless product involves more unknowns than market fit and returns on investment. Some unknowns are more physics-based, but still affect the economics of a product. And so there are only a few things that you have to consider during the design and production process. The difficult balance between physical size, performance, and cost that antenna designers often face is heavily influenced by a bunch of factors and (IoT) specifics **[6]**.

1.5.3 Applications and frequencies

IoT applications use a wide range of frequencies depending on the type of device and the application requirements. Here are a few examples of IoT applications and the frequencies they typically use **[6]:**

- ✓ *Smart home devices*: Many smart home devices, such as smart thermostats, security cameras, and smart lighting systems, use Wi-Fi frequencies (2.4 GHz and 5 GHz) for connectivity. However, some devices may also use other frequencies such as Bluetooth (2.4 GHz) or Zigbee (2.4 GHz).

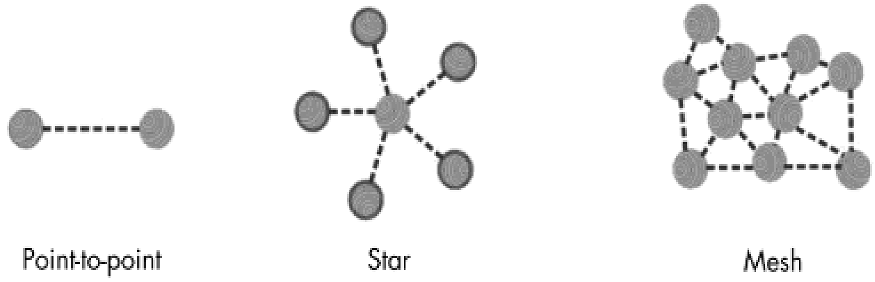

Figure1.2. IoT network communication topologies **[6]**.

- ✓ *Industrial automation*: IoT devices used in industrial automation applications often use sub-GHz frequencies such as 900 MHz or 2.4 GHz to avoid interference from other wireless devices in the environment.
- ✓ *Healthcare devices*: IoT devices used in healthcare applications often use Bluetooth (2.4 GHz) or Zigbee (2.4 GHz) for connectivity. However, some devices may also use cellular frequencies such as LTE-M (Cat-M1) or NB-IoT for remote monitoring applications.
- ✓ *Smart cities*: IoT devices used in smart city applications may use a range of frequencies depending on the specific application. For example, smart traffic lights may use 900-MHz frequencies for long-range communication, while smart parking systems may use Bluetooth (2.4 GHz) for short-range communication
- ✓ *Agriculture*: IoT devices used in agriculture applications may use a range of frequencies depending on the specific application. For example, soil moisture sensors may use sub-GHz frequencies to achieve longer range and better penetration through soil, while drones used for crop monitoring may use Wi-Fi (2.4 GHz or 5 GHz) frequencies for remote control and data transmission.

Overall, the frequency that an IoT device chooses will depend on the requirements of the specific application (e. g. range, data rate and power consumption). Over time as IoT technology continues to develop it is likely that new frequencies and wireless protocols will be developed to support the new IoT applications **[6].**

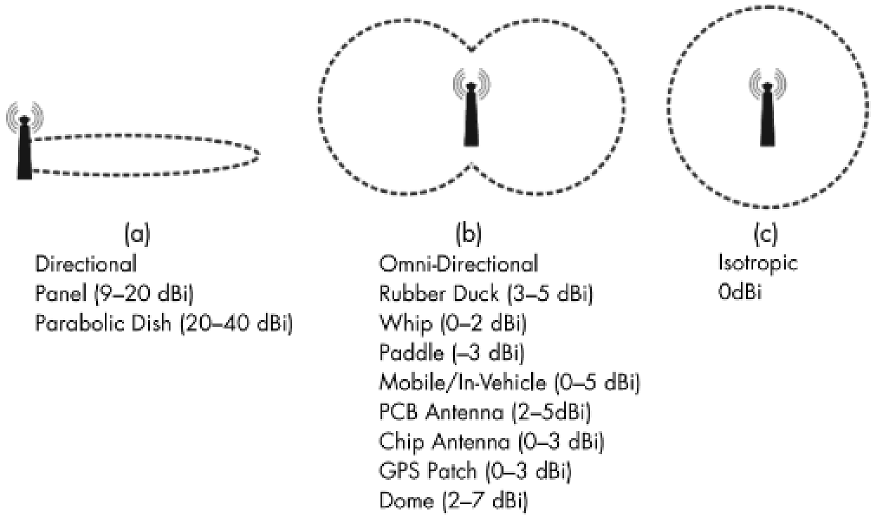

Figure 1.3. Patterns of radiating antenna depending on the type of gain **[6]**.

1.6 The fifth generation (5G)

5G wireless technology is more than just faster download speeds on our smart phones. It's an important breakthrough and leap forward in the ability and potential of wireless communications. Through near real-time responsiveness and the ability to support a dense ecosystem of connected devices, 5G will revolutionize our digital world and dominate future technological breakthroughs. The purpose of this introduction will be to explore the wide scope and impact of 5G technology, exploring the possibilities it can unlock in areas such as smart infrastructure, industrial automation, and virtual and augmented reality scenarios. Becoming familiar with the fundamentals of 5G technology and its major impact on society is crucial to understanding the next phase of technological advancement and the profound changes it will have on the lives of both individuals and their communities **[7].**

1.6.1 Evolution of Mobile Radio

After a brief introduction to 5th generation wireless systems, this section briefly outlines the evolution of mobile communication technology from 1G to 5Gthe first generation cellular system (1G) were analog telecommunications standards introduced in the 1970s. Here the voice channel used frequency modulation, and they used frequency division multiple access (FDMA) techniques. The major disadvantages of 1st generation wireless systems are poor voice quality, poor battery quality and large phone size. 2G was introduced in 1980s.The 2G systems were digital and were oriented to voice with low-speed data services. 2G used GSM technology and GSM stands for global system for mobile communication. It is a circuit switched, connection-based technology, where the end systems are devoted for the entire call period. Therefore, it causes low efficiency in usage of bandwidth and resources. Generally, GSM enabled systems don't support high data rates and they are generally unable to handle complex data like video. Next comes 2.5G. 2.5G is not an officially defined term rather it was invented for marketing purpose. 3G stands for 3rd generation wireless system. It has the capability to handle complex data like video and also it supports high data rates. Generally, 3G wireless systems use Code Division Multiple Access Technique (CDMA). The 3G technology adds multimedia facilities to 2G phones by allowing video, audio, and graphics applications. Apart from that, 3G promises increased bandwidth, 384 kbps when the device holder is walking, 128 kbps in a car and 2 Mbps in a fixed application. 4G stands for 4th generation wireless system. It has been lunched in many countries. In 2009 IMT-A specified the requirements for 4G standards. A 4G system is expected to provide a comprehensive and secure based solution to laptop and mobile devices. Such as internet access, gaming services and streamed multimedia may be provided to users. The technologies like Coded Orthogonal Frequency Division Multiplexing (COFDM), Multiple Input Multiple Output (MIMO) and link adaptation are used in 4th generation wireless system. Now research is going on 5th generation wireless system (5G). It is expected that, it will fulfill the entire requirement that has not been fulfilled by 4G. 5G technology has changed the means to use cell phones within very high bandwidth. User never encountered ever before such a high value technology. All kind of advanced features which makes 5G technology most powerful and in huge demand in near future.5th generation technologies which are on hand held telephone offering more power and features than at least 1000 lunar modules. Users can also attach their 5G technology cell-phones with their laptops to get broadband internet access **[8].**

1.6.2 Features of 5G

1. *Fast Network*: The user data-rate of 4G wireless communication system is 100 Mbps which is fast but not so—fast that satisfies the ever-increasing demands of subscribers, industries, etc. The user in the year 2020 will experience a data-rate greater or equal to 1 Gbps.

2. *Reliable service in crowd areas*: Due to a huge traffic, Users experiences denial of service due to overloading of network. Hence, 5G aimed to give a better service and connectivity in crowd place such as shopping malls, metro station.

3. *Service in Remote Place*: Some of the application for remote place includes remote meter reading for billing purpose, e-health like telemedicine, smart city, and video surveillance. 5G aimed to improve these services in remote place

4. *Integration of numbers of low power devices*: Already 4G supports huge numbers of low power devices but still for some application 4G does not meet the requirements. Hence 5G aimed to supports huge number devices consuming low power and such devices will be seamlessly integrated in commercial 5G mobile

5. *Intelligent Handover*: Handover means a switching of call from one network to network or switching within the cell of same network. Present scenario of handover is quite complicated since the delay occurs during handover is large which results in call dropping. Hence in 5G, an intelligent handover is expected with a least delay during the switching of the network.

6. *Pseudo Outdoor Communication*: Research has proved that more than 50% of voice traffic and 70% of data traffic originate from indoor areas but network coverage and service in indoor area are not so good as compared to outdoor area. Hence, the fifth generation of mobile communication system is aimed at pseudo- outdoor communication where network coverage, data-rate and other services in indoor area are equivalent to outdoor area **[7].**

1.7 Conclusion

With cellular networks evolving and maturing in tandem with the promise of 5G, our goal was clear: They had finally created a foundation for the Internet of Things. Cellular networks are based on the same principles as traditional wireless technology. The overall structure of a cell network and its frequency management helps provide broadband connectivity to devices within a wide area. 5G represents a major evolutionary event, delivering faster connectivity, low latency and significantly improved device performance with which the Internet of Things can flourish. Antennas are the perfect complement and core component to this entire ecosystem, connecting the network infrastructure to the devices connected to it. From advanced antenna arrays that enable 5G to deliver the best possible capabilities through communication to a diverse range of antennas that make it easier for IoT devices to function efficiently, these are essential parts of a robust wireless solution. 5G networks will have their way as they continue to evolve and become more powerful. Over time, they will serve as the heart and soul of an unprecedented and connected world of IoT devices contributing greatly to new ideas, innovative solutions, and transforming how we live our lives as consumers, entrepreneurs, innovators, and citizens.

1.8 References

[1] Molisch, Andreas F. Wireless communications. Vol. 34. John Wiley & Sons, 2012.

[2] Goldsmith, Andrea. Wireless communications. Cambridge university press, 2005.

[3] Rappaport, Theodore S. Wireless communications: principles and practice. Cambridge University Press, 2024.

[4] Lakshmanan, M.K., & Nikookar, H. (2006). A Review of Wavelets for Digital Wireless Communication. Wireless Personal Communications, 37, 387-420.

[5] Engelmann, R. H. "The origins of radio." IEEE Potentials 19, no. 4 (2000): 41-44

[6] Kulkarni, Prutha P. Antennas for IoT. Artech House, 2023.

[7] Kumar, A., & Gupta, M. (2018). A review on activities of fifth generation mobile communication system. Alexandria Engineering Journal, 57(2), 1125-1135.

[8] Agarwal, A., Misra, G., & Agarwal, K. (2015). The 5th generation mobile wireless networks-key concepts, network architecture and challenges. American Journal of Electrical and Electronic Engineering, 3(2), 22-28.

Chapter 2: Relay-aided cooperative communication

This chapter explores communication systems that use relays. It covers the fundamentals of cooperative communications, including their applications, pros and cons, and various relaying protocols.

2.1 Introduction

Cooperative communications and networking represent a new paradigm which uses both transmission and distributed processing to significantly increase the capacity in wireless communication networks. Current wireless networks face challenges in fulfilling users' ever-increasing expectations and needs. This is mainly due to the following reasons: lack of available radio spectrum, the unreliable wireless radio link, and the limited battery capacity of wireless devices. The evolving cooperative wireless networking paradigm can tackle these challenges. The basic idea of cooperative wireless networking is that wireless devices work together to achieve their individual goals or one common goal following a common strategy. Wireless devices share their resources (i.e., radio link, antenna, etc.) during cooperation using short-range communications. The advantages of cooperation are as follows:

- ✓ *First*, the communications capability, reliability, coverage and quality-of-service (QoS) of wireless devices, which can be enhanced by cooperation.
- ✓ *Second*, the cost of information exchange (i.e., transmission power, transmission time, spectrum, etc.), which can be reduced by cooperation.

Cooperative communication and networking will be a key component in next generation wireless networks [1]. Additionally, the network spectral efficiency offered by relay-assisted systems depends on the duplexing protocol used for transmission. If a half-duplex (HD) relay protocol is used, transmitters and relays are not allowed to function simultaneously on the same physical resource. This problem can be solved using a full duplex (FD) relay protocol **[2].**

2.2 Brief overview of cooperative communication network

2.2.1 Base station cooperation

Base station cooperation can take multiple forms. The simplest form of base station cooperation, especially with multi-antenna base stations, involves the exchange of information among neighboring cells regarding their cell-edge nodes and remote-cell aware processing at each of the base stations. Then, each of the base stations can put a null on the channel gain vector of the nodes that generate and/or are harmed by the most co-channel interference. This and other simple scenarios like it are in the realm of interference management, and are possible without fully coordinated action from base stations. Specifically, this form of action does not require the base stations to know the traffic for other base stations (therefore the issue of a wideband backbone and its delay does not come into play), nor is it required to know the codebooks used by the other base station, and nor does it require the base stations to be synchronized **[1].**

2.2.2 Downlink cooperation

For downlink base station cooperation, base stations can generate a virtual multi-antenna array with zero-forcing beamforming. There are a variety of ways to exploit this general idea. Somekh *et al*. used the circular Wyner cellular model **[4]** to find expressions for downlink (and uplink) capacities with base station cooperation, which is also sometimes called multi-cell processing. In **[5]** the same model and a zero-forcing beamforming approach were used for data transmission in multiple cells. In particular, the approach is to transmit to the best user in each cell, and the high-load asymptotic are derived in an information theoretic approach. Mundarath *et al*. considered the scheduling aspects of distributed downlink zero-forcing beamformers under finite loads. Such downlink strategies require certain assumptions about sharing of information among cells. To begin with, the data must be shared among the base stations. Secondly, the base station transmitters must be synchronized. Finally, the channel state information of the users must be shared among the base stations, and must be kept up-to-date, so that beamforming vectors can be reliably determined **[1].**

2.2.3 Uplink cooperation

The problem of uplink cooperation is rather different from its downlink counter-part. In the uplink cooperation scenario, a mobile might be in a situation where no single base station can decode its data alone. However, the signals received at two or more base stations may be sufficient to decode the mobile data. The collection of information at various base stations and their combination present new issues. In particular, since each of the base stations cannot decode the received signal alone, these signals must be sampled and exchanged among base stations, which requires significantly larger bandwidth than the data do. Thus, considering the effect of base station cooperation on the backhaul capacity becomes an important issue. The capacity of the uplink linear cellular networks with base station cooperation via finite capacity links was broached in, and bounds on the rate of the system under the Wyner model were obtained from an information theoretic viewpoint. This work generated broad insights into the general capabilities of uplink base station cooperation, but the specifics of coding and signal design for such systems remain open problems. Thankfully, the uplink does not suffer in quite the same way from the timing problem that plagues the downlink distributed beamforming The varying propagation times from the mobiles to base stations can be compensated in the algorithm that combines the data from multiple base stations, since the signal of each of the mobiles can be extracted separately **[1].**

2.2.4 Dedicated wireless relays

Traditional cellular networks provide fixed throughput for all subscribers where a basic voice service can be supported. Unlike such networks, broadband wireless cellular networks promise a high data rate throughout the coverage area. While such promise is feasible for the inner coverage area, at the cell-edge data rates are limited for various reasons. Decreasing the cell-size is one way to satisfy the required data rate; however, it is a costly solution because it requires the installation of additional base stations. In contrast, deploying relay stations provides a cost-effective solution. Compared with a full-scale base station, a relay can save on equipment costs, backhaul link, and deployment. Relay station assists the main base station to improve its coverage or through-put. A relay station can be used to extend the coverage area of a base station, or to provide coverage in so-called holes. In addition, thanks to the advances in antenna array techniques, relays can also be used to improve throughput and capacity **[1].**

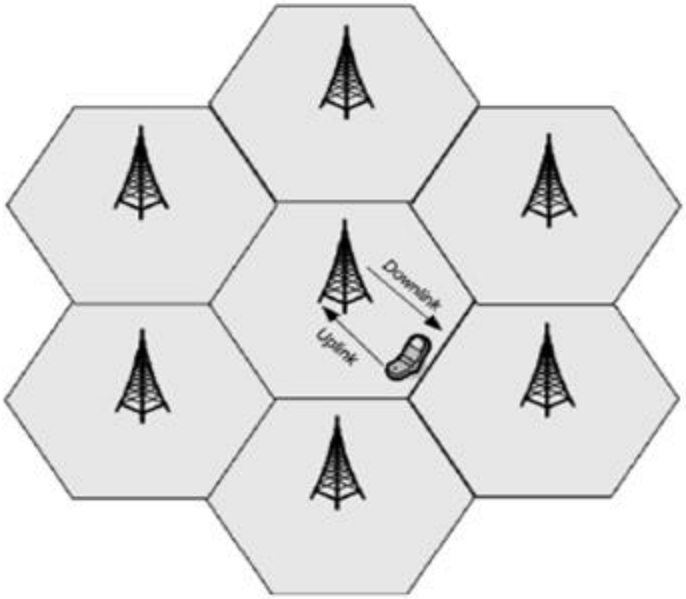

Figure2.1. Example of a traditional infrastructure network

[2].

2.3 Cooperative relay networks

Wireless networks can be classified into two major categories: traditional infrastructure networks and multi-hop networks. In traditional networks, the communication is performed directly between the BS and the MS and vice versa, so, there is only one hop. Though obstacles may degrade the line-of-sight (LoS) S-D link quality in this scheme, the source makes no use of the cooperation potential of other terminals in the network to compensate for the impairments (Figure 2.1) **[1].**

2.3.1 Strategies of relay-assisted transmission

The paradigm of the conventional S-D communication is now changed to S-R-D, and the role played by the relay can be selected from different modes of operation influencing the total achievable rate of the system. Additionally, when there is a half-duplex relay, the resources allocated for each phase of the relay-assisted transmission also have an important impact on the achievable rate. Therefore, the strategies of relay-assisted transmission have to consider the decoding mode at the relay and the resource allocation. Basically, the three decoding modes analyzed in the literature are: amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward (CF) **[1].**

Amplify-and-forward (AF)

This is the simplest strategy that can be used at the relay. The relay amplifies the received signal from the source and transmits it to the destination without doing any decoding. For this reason, it is also called non-regenerative relaying. The main drawback of this strategy is that the relay terminal amplifies the received noise at the same time. Applying this strategy to cooperative communication leads to a better bit error rate (BER) than direct transmission. The outage probability of the cooperative communication was derived in, demonstrating that a diversity order of 2 is obtained for two cooperative users. When the relay is equipped with multiple antennas and there is channel state information available for the S-R/R-D links, the AF strategy can attain significant gains over the direct transmission by means of optimum linear filtering of the data to be forwarded **[1].**

Decode-and-forward (DF)

In this strategy the complexity at the receiver increases in comparison to that in the AF strategy. Now the relay terminal has to estimate the message received from the source, therefore the total performance depends on the success of this message decoding. Depending on the type of symbols retransmitted, the strategy at the relay is repetition coding (RC) or unconstrained coding (UC). In RC, the relay retransmits the same symbols previously estimated, while in UC the symbols transmitted are not the same as the received ones, but are related to the same information sent by the source (source and relay are using different codebooks). Hence, this protocol is also called regenerative relaying **[1].**

Compress-and-forward (CF)

In this strategy, the relay does not decode the data but uses Wyner-Ziv lossy source coding on the estimated symbols of the received signal. Then, the compressed signal is transmitted to the destination by the relay. This strategy was suggested Depending on the channel gains of the different links, the CF strategy can be superior to the DF strategy. However, it adds more complexity to the system **[1].**

2.3.2 Relaying techniques

a) Half Duplex Relaying

HD relaying is a process when signals travel in both directions, but one at a time. One example is walkie-talkie. Both transmitter and receiver can send signals, but they must take turns. The two walkie-talkies have to take turns when they send data to each other. A person has to press a button if they want to talk to transmit their voice to the other person. They have to release the button in order to receive other person transmission **[3].**

b) Full Duplex Relaying

FD relaying is defined as a process in which the transmission and reception happens simultaneously. In 5G Networks, FD relaying technique has become popular in the recent years. FD relaying became more flexible with the advancement of antenna technologies and signal processing. However, it experiences residual-loop self-interference. FD relaying mainly consists of two types. Namely, FD AF and FD DF relaying. In FD relaying, a user can transmit and receive the data at the same time. Due to this, it has become more significant for enabling high spectral efficiency and better outage probability **[3].**

2.4 Relay Transmission Topologies

- ✓ *Serial relay transmission*: it is used for long distance communication and range extension in shadowy region. It provides power gain. In this topology, signal propagates from one relay to another relay and the channels of neighboring hop are orthogonal to avoid any interference. Figure 2.2 shows the serial relay transmission topology **[7].**

Figure 2.2. Serial relay transmission topology **[7].**

- ✓ *Parallel relay transmission*: The serial relay transmission suffers from multi-path fading. For outdoors and non-line of sight communication, signal wavelength may be large and installation of multiple antennas is not possible. To increase the robustness against multipath fading, parallel relay transmission can be used. In this topology, signal propagates through multiple relay paths in same hop and destination combines the signals received with the help of various combining schemes. It provides power gain and diversity gain simultaneously. Figure 2.3 shows the parallel relay transmission topology **[7].**

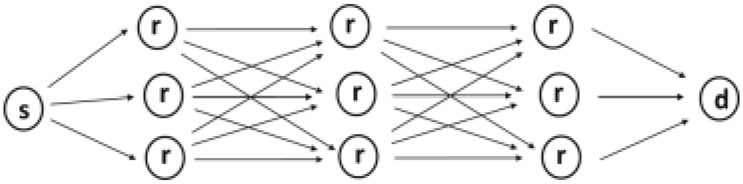

Figure 2.3: Parallel relay transmission topology [7].

2.5 Fundamentals of cooperative wireless communications

This type of communication differs from p-2-p communications based on collaboration between their points of communication in the use of a new element, called a relay. The basic diagram of relay-assisted communication involves three nodes, as shown in Fig. 2.4. The source node S wishes transmit information to the destination node D and the relay node R assists Communication **[8].**

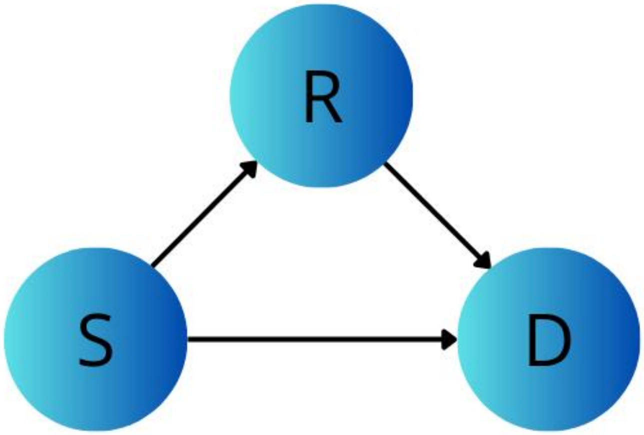

Figure 2.4: Relay-assisted communication scheme **[8].**

Unlike MIMO systems, additional channel resources are needed in communications assisted by relays due to the limitations of radio technology. Therefore, the relay is forced to operate in half-duplex mode and communication is split in two orthogonal duplexing phases, namely the receiving relay phase and the phase of the transmitter relay. Phase separation can be carried out by access time division multiple access (TDMA) or frequency division multiple access (FDMA). In TDMA mode, information received and transmitted at the level of the relay are divided into different time slots and share the same frequency channel, this separation is used by regenerative relay protocols. In FDMA, information received and transmitted at the relay are separated into different frequency bands and share the same slots schedules, this division is used by regenerative relay protocols and non-regenerative. The possible transmission combinations lead to four transmission protocols. Half-duplex relay between three nodes, as shown in Figure 2.5 where the solid lines refer to the relay reception phase and dotted lines correspond to the relay transmission phase. These four protocols can be classified as follows:

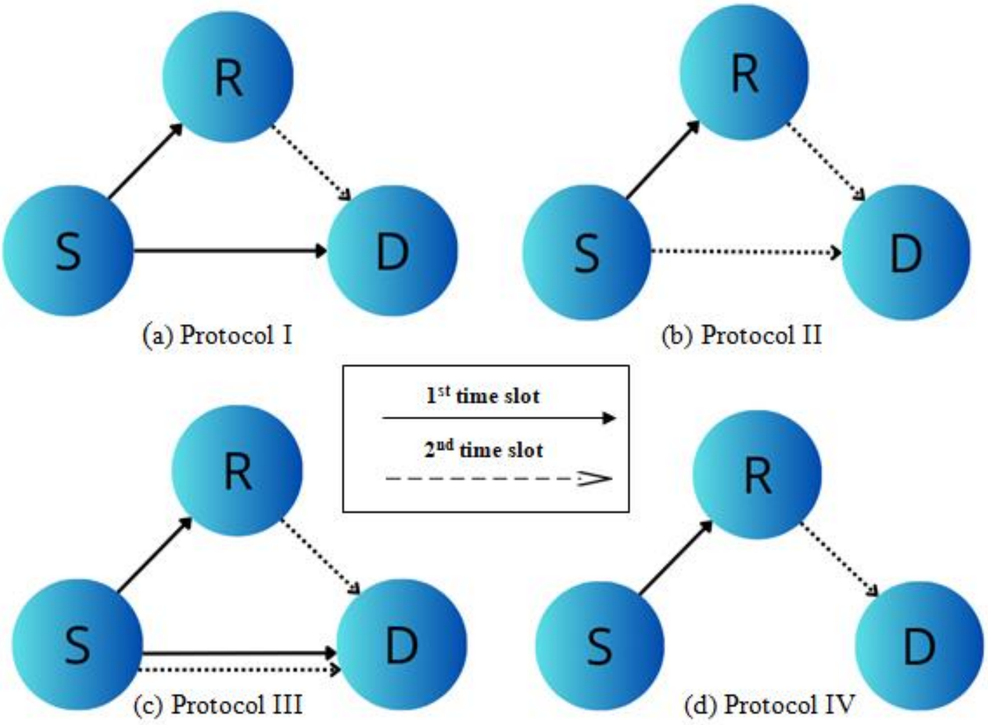

Figure 2.5: Semi-duplex relay protocols in three-node scenarios **[8].**

2.5.1 Relaying protocols

- ✓ ***Protocol I***. In the receiver relay phase, the source broadcasts the information towards the destination and the relay; in the transmitter relay phase, the relay communicates with the destination, as shown in Figure 2.5(a).

- ✓ **Protocol II**. In the receiver relay phase, the source only transmits its message to the relay and the destination is unable to receive the information; in the transmitter relay phase, the source and the relay communicate simultaneously with the destination, as presented in Figure. 2.5(b). This protocol corresponds to a multiple access channel (MAC) solution.
- ✓ ***Protocol III***. In the receiver relay phase, the source broadcasts the information towards the destination and the relay; in the transmitter relay phase, the source and the relay communicate simultaneously with the destination. This protocol combines protocol I and protocol II, as shown in Figure. 2.5(c).
- ✓ ***Protocol IV***, also known as transfer protocol. In the receiver relay phase, the source only transmits its message to the relay, in the transmitter relay phase, the relay only communicates with the destination, as shown in Figure. 2.5(d). Unlike traditional transfer protocols, the first three protocols also use the source destination link. However, if the quality of source-destination link drops below a certain threshold, performance obtained from the first three protocols converge towards those of the protocols routing. Depending on the type of relay-assisted system considered and the status information of the channel (Channel state information (CSI)) at the source, the duration of the relay phase receiver and transmitter relay can be previously assigned or not **[9].**

2.5.2 Resource allocation

The Static resource allocation relay is assumed when transmission is carried out in two time slots with a fixed duration. Possible examples applications are a centralized cellular scenario based on TDMA or a system where the channel model is characterized by statistical information. On the contrary, the dynamic resource allocation relay requires that the source knows all the qualities of the links. With this knowledge, the allocation adaptive resources on each phase maximize spectral efficiency relay-assisted communication. The static resource allocation relay can evaluate knowledge about the successful transmission to the destination or relay and involves multiple schemes retransmission at the relay level to increase spectral efficiency. The different types of static resource allocation strategies, illustrated on Figure 2.6, can be summarized as follows **[8].**

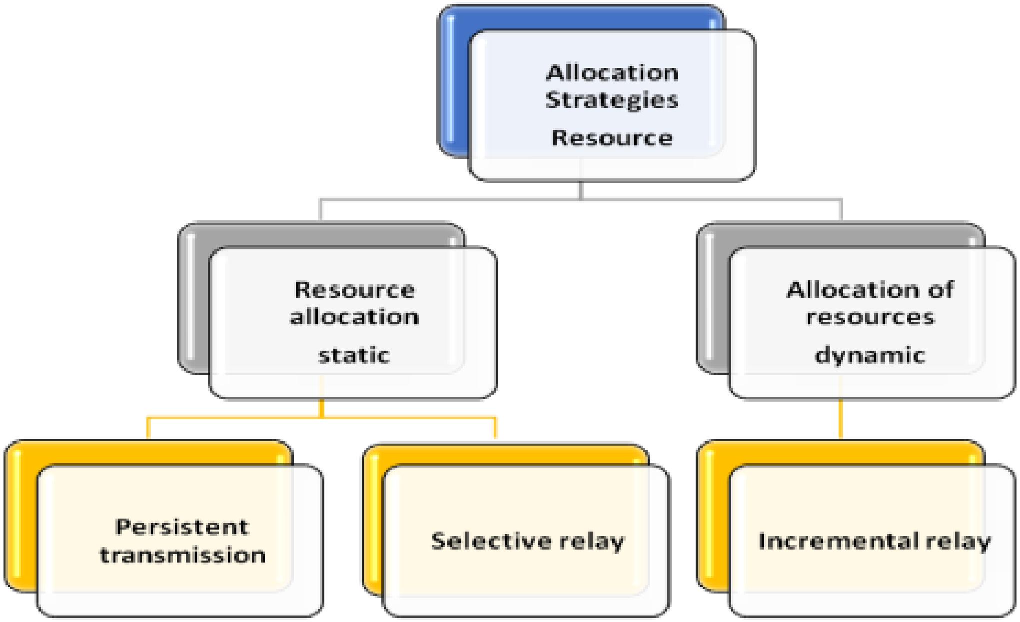

Figure 2.6 Resource allocation strategies in assisted communication by relay [8].

- ✓ **Persistent transmission:** In this retransmission scheme, the relay terminal can still transmit.
- ✓ **Selective relay**: This retransmission scheme is applied to the retransmission strategy decoding and transfer (DF), because it considers the success or failure of the source-relay connection. If the relay is not receiving the signal correctly or if the state of the channel of the source-relay link is less than a threshold, the source retransmits the message while the relay remains silent. Otherwise, if the relay correctly receives the signal from the source, the relay retransmits the message to the destination**.**
- ✓ **Incremental relay**: This retransmission scheme considers success or the failure of the source-destination link during the receiver relay phase. The relay transmits the information when the message to the destination received by mistake**.**

2.6 Some application scenarios

Relay-aided cooperative techniques are proving to be a versatile solution for a multitude of application scenarios. By strategically deploying intermediary nodes to facilitate and enhance signal transmission, these cooperative strategies address critical challenges in diverse environments. From extending coverage in rural and remote areas to bolstering reliability in dense urban settings, and from improving data rates in cellular networks to enabling robust communication in vehicular ad-hoc networks, relay-aided cooperation offers a powerful toolkit to optimize wireless connectivity across a wide spectrum of use cases. Its ability to overcome path loss, mitigate fading, and enhance network capacity makes it a key enabler for next-generation wireless systems and emerging applications **[10].** This section highlights some of the areas where the cooperative relaying strategies can be applied:

2.6.1 Virtual antenna array

The field of high-data-rate, spectrally efficient and reliable wireless communication, is currently receiving much attention. It is a well-known fact that the use of MIMO antennas improves the diversity gain of wireless systems. However multi-antenna technique is not attractive for tiny wireless nodes due to limited hardware and signal processing capability. Diversity can be achieved through user cooperation, whereby mobile users share their physical resources to create a virtual array, which removes the burden of multiple antennas on wireless terminals **[7].**

2.6.2 Wireless ad-hoc network

Ad hoc network is an autonomous and self-organizing network without any centralized controller or pre-established infrastructure. In this network, randomly distributed nodes form a temporary functional network and support seamless leaving or joining of nodes. Such network has been successfully deployed for military communication and has a lot of potential for civilian applications including commercial and educational use, disaster management, road vehicle network etc **[7].**

2.6.3 Wireless sensor network

Cooperative relaying can be used to reduce the energy consumption in sensor nodes. Hence, lifetime of sensor network can be increased. Due to nature of wireless medium, communication through weaker channels requires huge energy as compared to relatively stronger channels. Careful incorporation of relay nodes which cooperate with each other into routing process can select better communication links and precious battery power can be saved **[7].**

2.6.4 Cooperative sensing for cognitive radio

In cognitive radio system, unlicensed secondary users can use the resources which are licensed for primary users. When primary users want to use their licensed resources, secondary users have to vacant these resources. Hence, secondary users have to constantly sense the channel for detecting the presence of primary user. It is very challenging to sense the activity of spatially distributed primary users in wireless channel. Spatially distributed nodes can improve the channel sensing reliability by sharing the information and reduce the probability of false alarming **[7].**

2.6.5 Wireless local networks (WLANs)

Wireless Local Area Networks (WLANs) take support network communication overshot distances in any scenario urban, where interference can significantly affect performance. The low cost and high bandwidth of these networks have enabled an increase of their use. Continuous data rate requirements for Real-time and non-real-time web applications require new strategies to improve the performance of WLAN technologies. A method to improve network capacity is based on the use of relay nodes intermediaries to increase the strength of the wireless signal. As for the cellular networks, cooperative communication is able to also mitigate problems in terms of coverage and interference in the WLAN **[7].**

2.7 Multiple Access Techniques

Multiple users access network using multiplexing. Multiplexing is a process of combining multiple signals and transmitting over a common channel when multiplexing is used to allow multiple users to communicate over a single common channel we call it as multiple access. In other words, Multiple Access is nothing but the application of multiplexing. Wi-Fi hotspot sharing its internet connection among multiple users by providing them a frequency block which they transmit and receive data. The greater is the size of block greater is throughput. Multiple Accesses can be divided into two types Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) which utilizes power domain/code domain **[3].** Multiple Access techniques are mainly divided into 4 types:

- ✓ Frequency division multiple-access (FDMA)

- ✓ Time division multiple-access (TDMA)
- ✓ Code division multiple-access (CDMA)
- ✓ Orthogonal frequency division multiple-access (OFDMA)

2.7.1 Frequency division multiple-access

In Frequency division multiple-access the frequency spectrum is divided into different slots. Each slot is allocated to a device present in the wireless network so we have seen various devices operating in different ranges we have the wireless personal area network wireless metropolitan area network wide area network the ZigBee protocol Bluetooth, WiMAX and many other devices so each device is assigned different frequency depending on division they have been given **[3].**

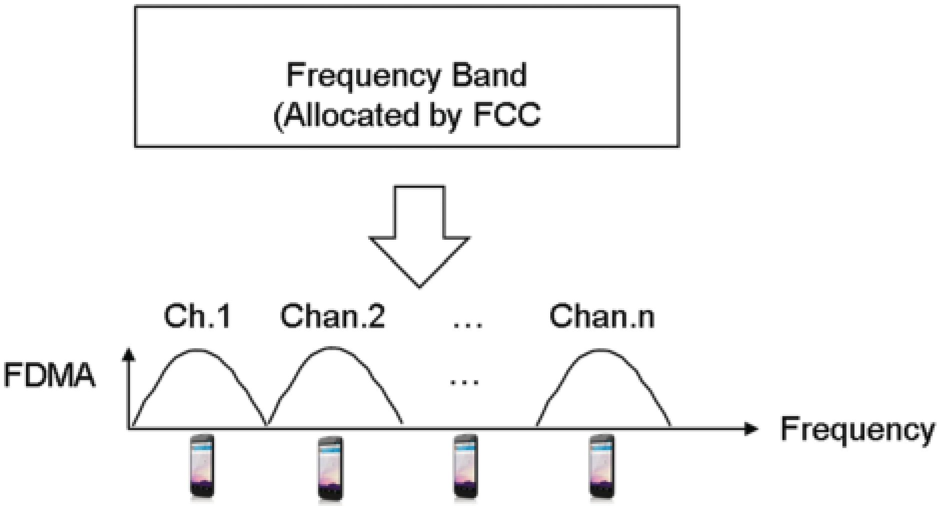

Figure 2.7: Frequency Division Multiple Access **[3].**

2.7.2 Time division multiple-access

In order to overcome the limitations of this band un-allocation what we have is we put the devices into different time slots. If device 1 is given time t1 then I can only do the data transfer or any activities within that time Frequency spectrum is given for a short duration. Period for transmission of data is called as Time Frame (TF). Wait for each (TF) assignment. If (TF) is short then propagation delay exists. If (TF) is large waiting time increases **[3].**

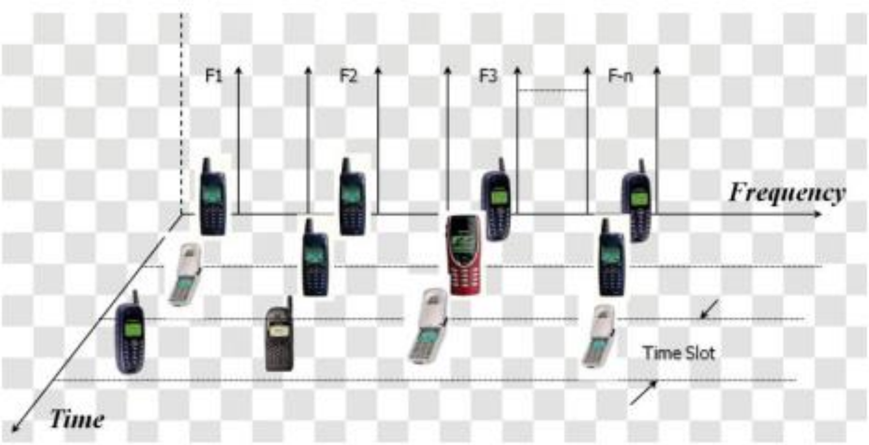

Figure 2.8: Time Division Multiple Access **[3].**

2.7.3 Code division multiple-access

In order to overcome the limitations of TDMA, Code division multiple-access has been found. In CDMA the signal is sent in a Unicode format and so you don't have any kind of interference in this kind of technique so you have the available frequency and all devices can transmit the data at one particular time. So, it assumes all devices should receive with same power. Solution by means of power controlling technique controls the transmission power **[3]**.

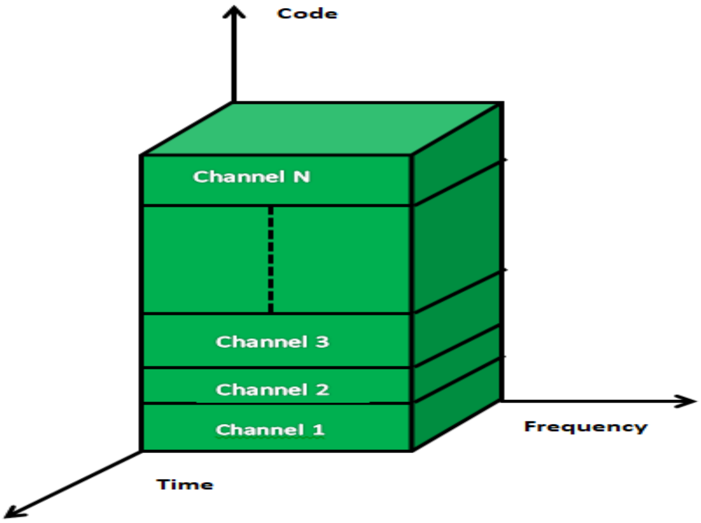

Figure 2.9 Code Division Multiple Access **[3].**

2.7.4 Orthogonal frequency division multiple-access

In Orthogonal frequency division multiple-access we have this frequency allocation so in this what you are basically at the right angles the data is being given and so n number of users can use the data at same time without any kind of interference's or any other kind of jamming our signal so what basically this technique employs it has the multi-user version of OFDMA scheme that it employs a orthogonal frequency-division multiple multiplexing scheme it uses in order to implement this multiple-access technique and it assigns a subset of carriers to individual users so every user has been give some time and so he can do n number of activities within that particular time and then similarly user2 can come within that time and he can use so there is no kind of interference or any kind of jamming due to vicinity signals or data transfer can takes place in a very good manner as compared to other techniques so it allows simultaneous low date transmission which are low power consuming. The main advantage this so there is an overlapping kind of activity which happens at the right angles so you can see only user is allocated at right angle and division is done at right angles **[3].**

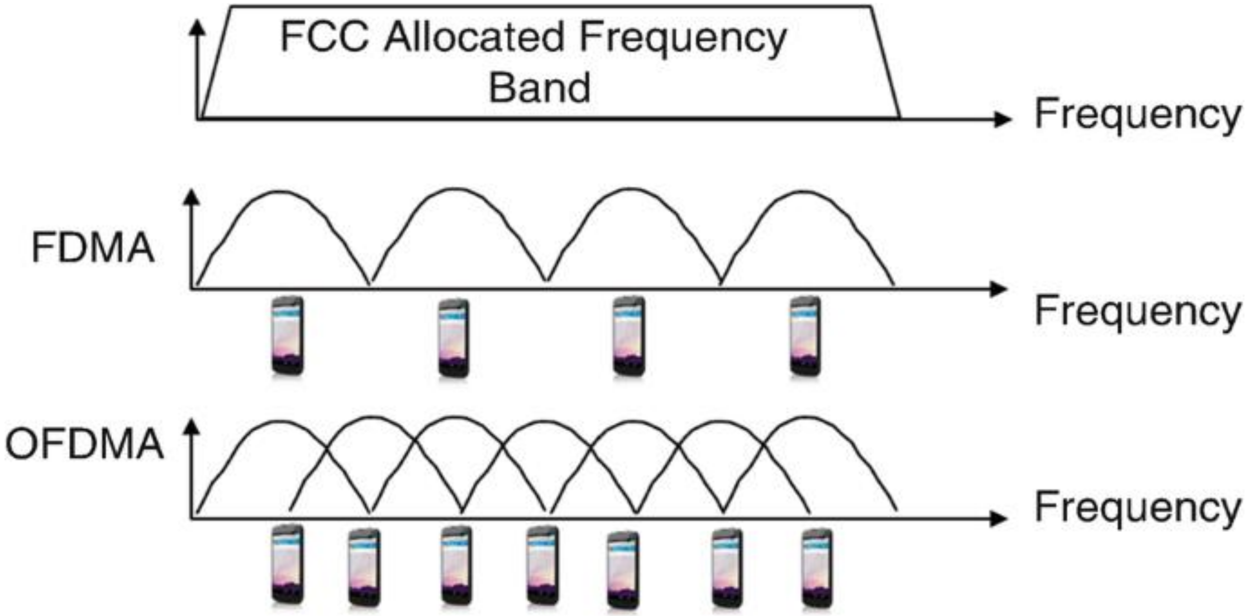

Figure 2.10 Orthogonal Frequency Division Multiple Access **[11].**

2.8 Benefits of cooperative transmission

From the perspective of the network, cooperation can benefit not only the nodes involved, but the whole network in many different aspects. For illustration purposes, we choose to explain only a few potential benefits below **[12].**

2.8.1 Higher spatial diversity

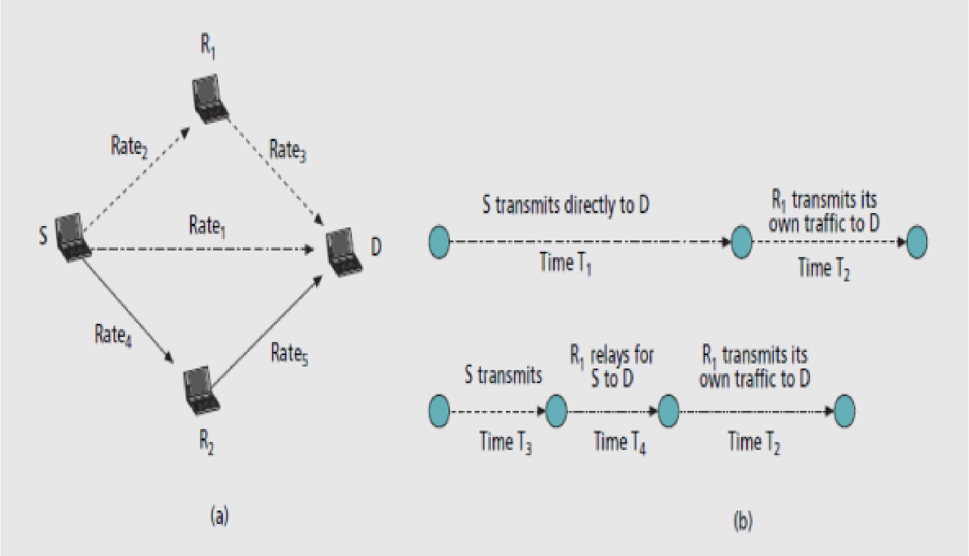

Figure 2.11 a) Cooperation in a network; b) illustration of the delay and throughput improvement achieved by cooperation in the time domain **[12].**

In this example, Figure 2.11 shows a small network of four nodes. If the channel quality between nodes *S* and *D* degrades severely (e.g., due to shadow or small-scale fading), a direct transmission between these two nodes may have an intolerable error rate, which in turn leads to retransmissions. Alternatively, *S* can use *spatial diversity* by having a relay*R*1 overhear the transmissions and then forward the packet to *D* as discussed above. The source *S* may resort to yet another terminal *R*2 for help in forwarding the information, or use *R*1 and *R*2 concurrently. Similar ideas apply to larger networks as well. Therefore, compared with direct transmission, the cooperative approach enjoys a higher successful transmission probability. We note here that cooperative communications have the ability to adapt and to mitigate the effects of shadow fading better than MIMO since, unlike MIMO, antenna elements of a cooperative virtual antenna array are separated in space and experience different shadow fading **[12].**

2.8.2 Higher throughput-lower delay

At the physical layer, rate adaptation is achieved through adaptive modulation and adaptive channel coding. Many MAC protocols have introduced rate adaptation to combat adverse channel conditions. For instance, when a high channel error rate is encountered due to a low average SNR, the wireless LAN standard IEEE 802.11 switches to a lower transmission rate so as to guarantee a certain error rate. The power of cooperation is evident when it is applied in conjunction with any rate adaptation algorithm. In Figure 2.11a, specifically, if Rate2 and Rate3 are higher than Rate1 such that the total transmission time for the two-hop case through *R*2 is smaller than that of the direct transmission, cooperation readily outperforms the legacy direct transmission, in terms of both throughput and delay perceived by the source *S*. Furthermore, for relays such as *R*1 and *R*2, it turns out that their own individual self-interest can be best served by helping others. As further illustrated in Figure 2.11b, the intermediate node *R*1 that cooperates enjoys the benefit of lower channel-access delay, which in turn can be translated into higher throughput. It is worthwhile to note that Figure 2.11b also draws a rough analogy with the cooperative scheme discussed above and illustrates that rate adaptation can further improve the benefits of cooperation in a network setting **12].**

2.8.3 Lower power consumption and lower interference

The diversity, error rate, and throughput gains obtained through cooperation can be traded in for power savings at the terminals. Alternatively, cooperation leads to an extended coverage area when the performance metric (error rate, throughput, etc.) is fixed. The advantage of cooperation also leads to reduced interference when the network is deployed in a cellular fashion to reuse a limited bandwidth. With the improvement of throughput, we can reduce the average channel time used by each station to transfer a certain amount of traffic over the network. Therefore, the signal-to-interference ratio (SIR) between proximal cells using the same channel can be reduced, and a more uniform coverage can be achieved. As wireless network deployments become ever denser, a reduction of SIR will directly lead to a boost in network capacity. Indeed, the problem of dense deployment has already been reported for IEEE 802.11 b/g networks, which have only three no overlapping channels **[12]**.

2.8.4 Adaptability to network conditions

The cooperative communication paradigm allows wireless terminals to seamlessly adapt to changing channel and interference conditions. The choice of relays, cooperation strategy, and the amount of resources available for cooperation can be opportunistically decided. For example, in Figure 2.10 a, if the source *S* has some information about the current channel gains, packet-loss rates, traffic conditions, interference, or remaining battery energy of nodes in the network, it may choose to transmit its information directly to its destination *D*, using *R*1 or *R*2 or both in a cooperative fashion, depending on which transmission mode results in better performance (in terms of error rates, throughput, or power). This way, a surplus of resources such as battery energy or bandwidth at a particular node can be utilized by other nodes in the network in a manner that will benefits everyone, including the relay node itself. Although originating from physical layer cooperation, all the after mentioned benefits cannot be fully realized until proper mechanisms have been incorporated at higher protocol layers (e.g., MAC, network) and the necessary information is made available from the lower layer (e.g., PHY). Indeed, across-layer approach has to be followed to reap all the benefits of cooperation **[12].**

2.9 The advantages and disadvantages of cooperation

Cooperative communications offer several reliability advantages of the link, energy consumption, coverage and capacity in wireless systems, attracting widespread interest in academic circles and industrial **[13].** In order to achieve practical systems, the choice of parameters system design must take into account the advantages and disadvantages the most important disadvantages of cooperative systems. In the wide range of scenarios, the most favorable aspects of cooperation are:

2.9.1 Advantages of cooperation

- ✓ *Reduced signal attenuation*: The wireless channel is affected by the effects of loss of path, shadow and fainting. This implies a decrease exponential of signal strength with distance from source and the destination. Increasing distance results in greater attenuation of the signal, resulting in a lack of communication between the source and destination. On the contrary, in communication assisted by relay, the distance between the source and the relay and the distance between the relay and the destination are shortened. As a result, the signal strength improves and the source can use more modulation symbol alphabets high to transmit more data in each channel. This circumstance increases the data rate transmitted to the user, resulting in an increase in system performance**.**

- ✓ *Reduction of shading effects*: Large cities are characterized by many obstacles, such as hills or tall buildings, which obscure the main path between the source and destination and affect the signal propagation. Relay-assisted communication creates a route alternative to avoid obstacles
- ✓ *Reduced fading effects*: By exploiting the independently orthogonal phases, cooperative diversity communications also fight signal fluctuations caused by fading effects
- ✓ *Quality of Service (QoS)*: Relay-assisted communications balance capacity and coverage issues and provide quality of service equal for all users.
- ✓ *Low cost*: Cooperative communication is a cheaper solution than the cellular scenario, where the cost of building base stations is very high.
- ✓ *Deployment without infrastructure*: The use of relays provides the lack infrastructure. In disaster areas, cooperation can be used to communicate in a simple way.

2.9.2 Disadvantages of cooperative

Despite all these advantages, relay-assisted communications present also certain disadvantages, summarized below:

- ✓ *Increased overhead costs*: Each link introduces overheads, such as synchronization and channel estimation. In some scenarios, CSI is required at each node, resulting in consumption significant amount of resources.
- ✓ *Resource consumption*: Relay-assisted communications establish additional links between nodes, which consume additional resources, such as battery, frequency, or time.
- ✓ *Increased interference and traffic*: Data transmitted from of each node may cause interference and may increase traffic for the entire system.
- ✓ *Loss of spectral efficiency*: Relay-assisted communication is based on a half-duplex protocol, which results in a loss of spectral efficiency compared to direct transmission **[13].**

The advantages and disadvantages of cooperative networks lead to choosing suitably the system design parameters, because the increase of one parameter implies a reduction of another parameter. Therefore, a good decision can be obtained with a compromise solution, which finds the right compromises between the different aspects involved. Figure 2.12 shows these tradeoffs and provides at-a-glance system design parameters to optimize **[14].**

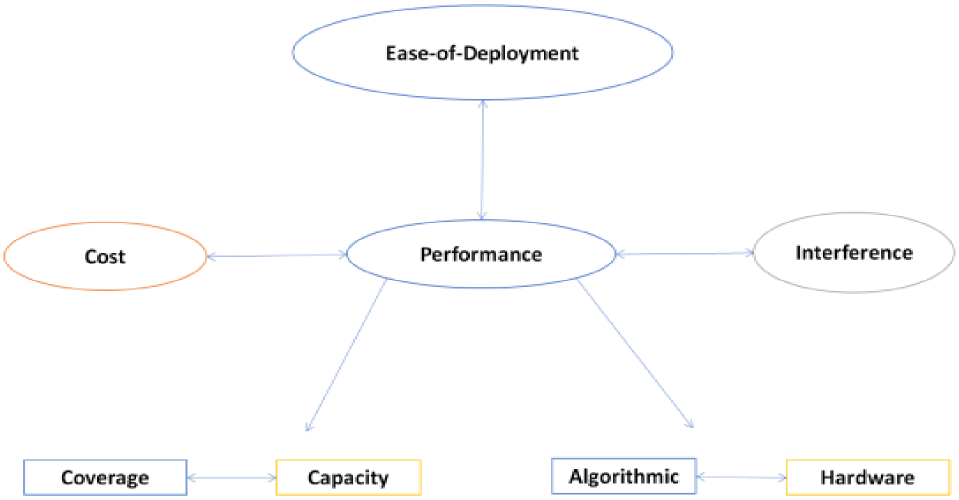

Figure 2.12. System design parameters **[14].**

Coverage versus capacity:

The designer must choose to increase the radius cell to provide greater coverage or increase capacity of the system.

Algorithmic complexity versus hardware complexity*:*

The relay has complexity relatively low equipment compared to base stations. The low hardware complexity implies an increase in complexity algorithmic due to sorting, synchronization and transfer.

Interference against performance*:*

Relay-assisted communications ensure the reduction of transmission power and the improvement of performance in terms of coverage and capacity. On the other hand, the relay causes additional traffic, which produces additional interference.

***Ease of deployment relative to performance**:*

The designers of network can deploy relays in a planned and unplanned manner. In the first case, the placement and parameterization of the relay node static are optimized, providing a complex task with performance higher. In the latter case, the costs are considerable.

2.10 Conclusion

Ultimately, by taking advantage of distributed nodes, relay-aided cooperative communication helps in overcoming basic signal propagation issues, it is a major step forward in wireless networking. Relays that work together to pass information achieves significant improvements in coverage area, link reliability, and network capacity. Although actual implementation requires meticulous attention to synchronization, resource management, and protocol development, the benefits of exploiting spatial diversity with cooperative tactics are enough to make this technology especially useful for the growing needs of the next generation of wireless systems and an array of new emerging technologies, thus providing advanced wireless networks that are more powerful and efficient.

2.11 References

[1] Hossain E, Kim DI, Bhargava VK, editors. Cooperative cellular wireless networks. Cambridge University Press; 2011 Mar 10.

[2] Lu, Wei, and Marco Di Renzo. "Stochastic geometry modeling and system-level analysis & optimization of relay-aided downlink cellular networks." IEEE Transactions on Communications 63, no. 11 (2015): 4063-4085.

[3] Rahul Chowdary Erpina, Viswakanth Reddy Gopireddy. Performance of a Non-Orthogonal Multiple Access System with Full-duplex relaying over Nakagami-m Fading, Faculty of Computing, Blekinge Institute of Technology, 371 79 Karlskrona, Sweden.

[4] I. E. Telatar, "Capacity of multi-antenna Gaussian channels," Eur. Trans. Telecommun. (ETT), vol. 10, pp. 585-595, Nov.-Dec. 1999.

[5] A. Goldsmith, "Capacity limits of MIMO Channels, IEEE J. Selected Areas in Commun, vol. 21, no. 5, June 2003.

[6] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," IEEE Trans. Theory, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[7] Himanshu Katiyar, Ashutosh Rastogi and Rupali Agarwal: Cooperative Communication – A Review Department of Electronics and Communication Engineering, Babu Banarasi Das National Institute Technology and Management, Lucknow, Uttar Pradesh, India.

[8] Glisic, Savo G. Advanced wireless communications and internet: Future evolving technologies. John Wiley & Sons, 2011.

[9] Shen, Yuan, Henk Wymeersch, and Moe Z. Win. "Fundamental limits of wideband cooperative localization via Fisher information." In 2007 IEEE Wireless Communications and Networking Conference, pp. 3951-3955. IEEE, 2007.

[10] Pejanovic-Djurisic, M. & Kocan, Enis. (2011). Relaying techniques for cooperative communication systems. 10.1109/TELFOR.2011.6143577.

[11] Saleh Faruque *Radio Frequency Multiple Access Techniques Made Easy Book © 2019*

[12] Yıldız Technical University. Department of Electronics and Communications Engineering. A. F. M. Shahen Shah. Thesis cooperative communication in wireless networks (2010)

[13] Zimmermann, E., Herhold, P. and Fettweis, G., 2003, October. On the performance of cooperative diversity protocols in practical wireless systems. In 2003 IEEE 58th Vehicular Technology Conference.
[14] Dohler, Mischa, and Yonghui Li. Cooperative communications: hardware, channel and PHY. John Wiley & Sons, 2010.

Chapter 3: RIS-assisted communication networks

This chapter introduces reconfigurable intelligent surfaces (RISs), a promising technology for wireless networks known for being low-cost, easy to deploy, and efficient with spectrum and power, covering the features and applications of RISs.

3.1 Introduction

Reconfigurable intelligent surface (RIS) is recently arising as a promising technology to meet numerous requirements of emerging wireless applications in the sixth-generation (6G) networks. It is commonly easy to integrate an RIS into wireless environment to establish favorable reflecting links, e.g., via RIS deployment into an indoor ceiling, a building facade, and an unmanned aerial vehicle. Comprising of a vast amount of cost-efficient reflecting elements, RIS is capable of dynamically manipulating the propagation environment by adjusting the phase shift of each reflecting element in real time via a smart controller. Alternatively, extra information can also be carried via phase shift modulation methods by RIS. Serving as either a reflector or a transmitter, RIS has shown great potentials in improving spectral efficiency, energy efficiency, coverage, and security. Typically, RIS is acknowledged with the ability of constructing supplementary links from the transmitter towards the desired receiver to strengthen the received signal power. These supplementary links play an important role in assisting wireless communications especially when the direct line-of-sight (LoS) path between the transceivers is blocked by obstacles such as buildings, trees, and human bodies. In order to fully reap the benefits of RIS, intensive efforts have been invested to the optimization of phase shift design to maximize multifarious performance metrics under various constraints **[1].**

3.2 Overview

In the first five generations of wireless communication, the propagation environment has been seen as an uncontrollable component in the whole communication process. The propagation environment is naturally imposed from the physical objects surrounded by the transmitter and receiver which form the wireless channel by altering the electromagnetic (EM) waves between them. During the entire evolution of wireless communication technologies, the main interest was in developing sophisticated techniques at the transmitter and receiver just to compensate for the effects of the propagation environment such as attenuation, shadowing, fading, etc. The concept of turning the propagation environment itself into an optimization variable, same as the transmitter and receiver, creates a smart radio environment as shown in Figure 1.1. This may emerge cutting-edge solutions for the fundamental limitations in wireless communication **[2].**

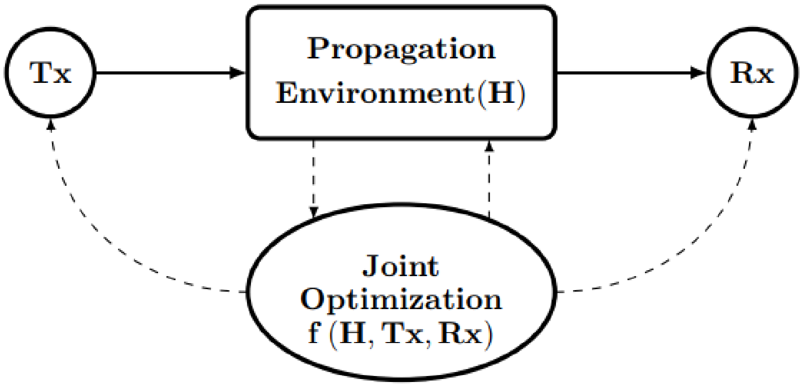

Figure 3.1. Smart radio environment **[2].**

A RIS is introduced as the key enabler for creating smart radio environments. It is an inexpensive planar surface that is composed of multiple identical elements whose EM properties can be independently reconfigured. These elements are based on low power tunable electronic circuits which are capable of reengineering the impinging radio waves in real-time by manipulating their characteristics to fulfill particular functions. The RIS can create different operations for the EM waves such as wave steering, blocking, splitting, polarizing, and many others. Furthermore, a RIS is a highly energy-efficient unit as it doesn't consume any power for transmission, but it solely leverages the impinging radio waves to achieve a specific need. Moreover, it requires minimal signal processing capabilities to configure the tunable elements. The RIS is introduced as a new player to the whole communication process, which may provide several solutions for the limitations that exist in the wireless channel and emerge new applications, which have never existed with classical wireless communication systems **[2].**

3.3 Fundamentals of RIS

3.3.1 Architecture

The architecture of a RIS is as shown in Figure 3.2, where a thin planar surface of multiple unit cells is connected to a smart controller **[2]**.

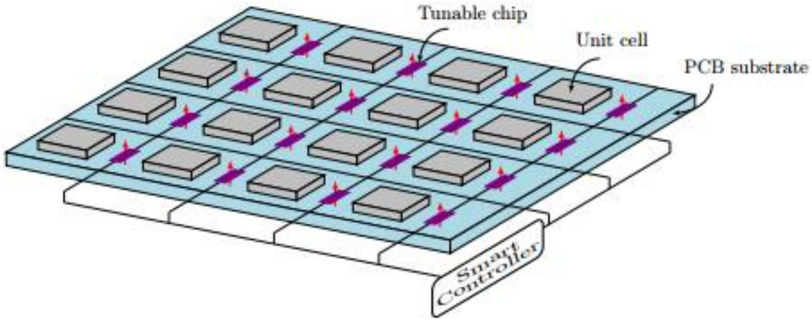

Figure 3.2. The architecture of RIS **[2]**.

The unit cells are the main constructing component of the RIS, whereas the role of the smart controller is to adapt the interaction of the unit cells to the impinging waves. In general, the concept of meta-material is the key enabler for building the RIS. The research field of meta-material is interested in building materials of reconfigurable EM properties that don't exist in natural materials **[3].** That is why the RIS is widely known as a meta-surface, in addition to other names such as intelligent reflecting surface, large intelligent surface, digitally controllable scatterers, and software controllable surface. On the other hand, the unit-cell is known as a meta-atom, reflecting element, and scattering element. The unit cell can be conceptually realized as a sub-wavelength metallic or dielectric scattering particle such as a small antenna that is connected to tunable electronics circuits as positive intrinsic negative (PIN) diodes, varactors, or micro electromechanical system (MEMS) switches **[4].** The tunable electronic circuits are responsible for the configuration of the unit cell's response towards the incident EM waves. The EM wave manipulation capability of the RIS resides mainly in controlling the reflection coefficient of each unit cell to the impinging waves. The reflection coefficient of the unit cell is commonly alternated by controlling the load impedance connected to the reflecting element **[5].** For instance, in the case of having a PIN diode as a tunable chip for each element. Then the PIN diode can be switched between on and off states by controlling its bias voltage which will vary the load impedance connected to the element between short-circuit and open-circuit. Thus, generating a $\boldsymbol{\pi}$ phase shift difference for the reflection coefficient between the on and off. Furthermore, for the sake of full phase shift control, multiple PIN diodes or varactors can be connected to each unit cell which will allow multiple choices or continuous configuration for the connected load impedance. Moreover, the amplitude of the reflection coefficient can be configured by attaching a variable resistor load to each unit cell which will control the energy dissipated portion of the incident wave in the unit cell **[6].** Moreover, a major advantage of the RIS is that it is a highly energy-efficient unit as it doesn't have any power amplifier, radio frequency (RF) chain, or complex signal processing capabilities. That is why the RIS is widely known for nearly-passive RIS as it doesn't consume any power for transmission and the main energy is used in the control process of the tunable circuits to alternate the impinging wave. However, active RIS which can additionally amplify the impinging radio waves are possible by integrating amplifiers to the unit cells which may be practically costly and energy inefficient **[7]**.

3.3.2 Electromagnetic functions

The RIS can be configured to support multiple functions for the incident EM waves. In Figure 3.3, we discuss some of the possible functions of the RIS **[2]**:

- ✓ *Reflection*: The RIS is configured such that the incident EM wave is reflected towards a specified direction where the angle of reflection doesn't necessarily be equal to the angle of incidence according to the generalized Snell's law.
- ✓ *Refraction*: The RIS refracts the impinging waves towards a specified direction. However, in this scenario, the RIS is commonly manufactured from unobstructed material towards EM waves such as a glass substrate.
- ✓ *Focusing*: The RIS focuses all the scattered waves from the unit cells at a certain location to maximize the received signal strength there. This function can be achieved by adjusting the phase shifts induced from all the unit cells in the RIS such that the scattered paths are added constructively at a certain location.
- ✓ *Splitting*: The RIS creates multiple reflected and refracted waves for a single impinging wave. This function can be satisfied by dividing the RIS into several sub-surfaces and configuring them independently to split the incident wave.

- ✓ *Absorption*: The RIS ensures minimum reflection and refraction power of the impinging waves which may be possible by controlling the amplitude reflection coefficients of the unit cells.
- ✓ *Polarization*: The RIS is utilized to change the polarization state between the incident and reflected/refracted waves. This function usually relies on dual polarized unit cells which could excite two orthogonal polarization states and induce independent phase shifts per each polarization state whenever a wave is incident on them.

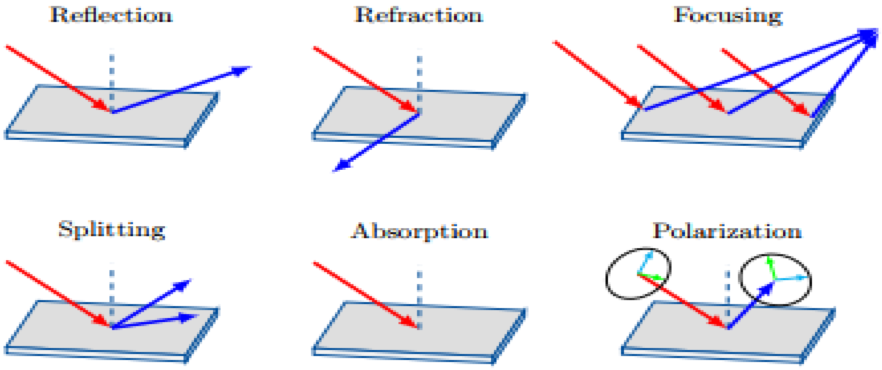

Figure 3.3. Electromagnetic functions of RIS **[2]**.

3.3.3 Typical features of RIS

By judiciously tuning the phase shifts of the reflecting elements of the RIS, the reflected signals can be constructively superimposed with those from the direct paths for enhancing the desired signal power, or destructively combined for mitigating deleterious effects of multiuser interference. Hence, RISs provide additional degrees of freedom to further improve the system performance. In the following, we list some typical RIS applications in various emerging systems **[10].**

A. RIS-aided mm-Wave Systems

Mm-Wave techniques have the potential of supporting high data rates given their high bandwidth. However, communication at Mm-Wave frequency also has some drawbacks, such as its severe path loss. Fortunately, this can be mitigated by its huge array gain provided by a large antenna array within a compact space, given its short wavelength. Another impediment is that it is vulnerable to blockages by cars, pedestrians, and trees. The readily penetration loss is also high, which cannot be readily addressed by using a large antenna array. Instead, RISs can be deployed to construct an auxiliary transmission link even when the direct link is blocked.

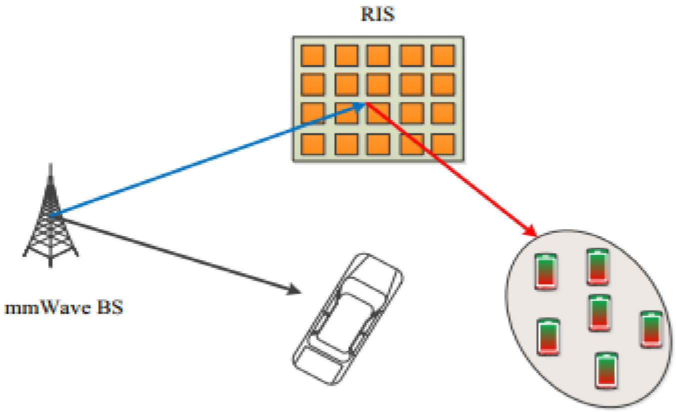

Figure 3.4.RIS-aided mm-Wave systems **[10].**

B. *RIS-aided Multi-cell Networks*

To maximize spectrum efficiency (SE), multiple BSs indifferent cells reuse the same scarce frequency resources, which leads to inter-cell interference, especially for the cell-edge users. Specifically, the desired signal power received by the cell-edge user from its serving BS is comparable to the interference received from its neighboring cells. Hence, the cell-edge users suffer from a low signal-to-interference-plus-noise ratio (SINR). To address this issue, it is

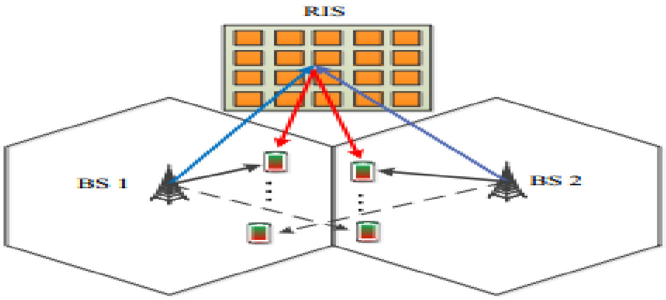

Figure 3.5.RIS-aided multi-cell networks **[10].**

proposed to deploy an RIS at the cell boundary as shown in Figure. 3.5. In such a setting, the RIS is able to simultaneously enhance the signal gleaned from the serving BS, and mitigate the interference from the other.

C. *RIS-aided Simultaneous Wireless Information and Power Transfer (SWIPT) Networks*

SWIPT is a promising technique of providing cost-effective-power delivery to energy-limited internet of things (IoT) networks, where a BS with constant power supply broadcasts wireless signal to information receivers (IRs) and energy receivers (ERs) simultaneously. The key challenge in SWIPT systems is that the ERs and IRs operate under different power supply requirements. Explicitly, ERs require a received power on the order much higher than IRs. As a result, ERs should be deployed in closer proximity to the BS than IRs to harvest sufficient power, since the signal attenuation limits the ERs' practical operational range. To deal with this problem, it is proposed to deploy an RIS in the proximity of the ERs, as shown in Figure 3.6.

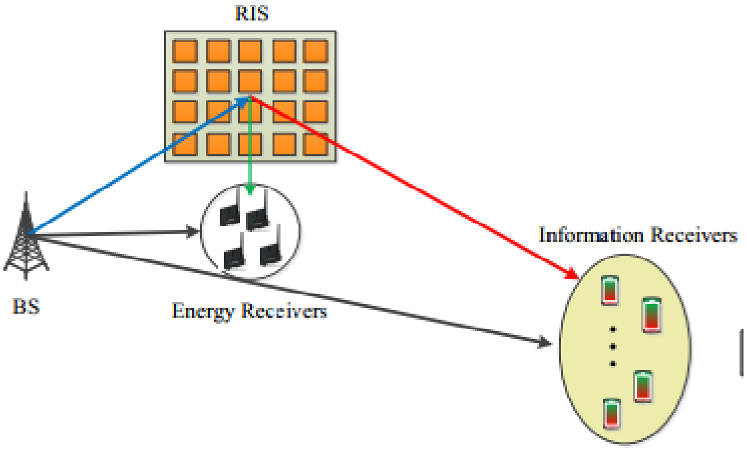

Figure 3.6.RIS-aided SWIPT systems **[10].**

D. *RIS-aided Mobile Edge Computing (MEC) Networks*

In novel future applications such as virtual reality (VR), computation-intensive image and video processing tasks must be executed in real time. However, due to the limited power supply and hardware capabilities of typical VR devices, these tasks cannot be accomplished locally. To tackle this issue, these computationally intensive tasks can be offloaded to powerful computing nodes that are usually deployed at the edge of the network. However, for some special cases where these devices are far from the MEC node, they can suffer from a low data offloading rate due to the severe path loss, which leads to excessive offloading delays. To overcome this impediment, a novel RIS-aided MEC framework was proposed as shown in Figure 3.7.

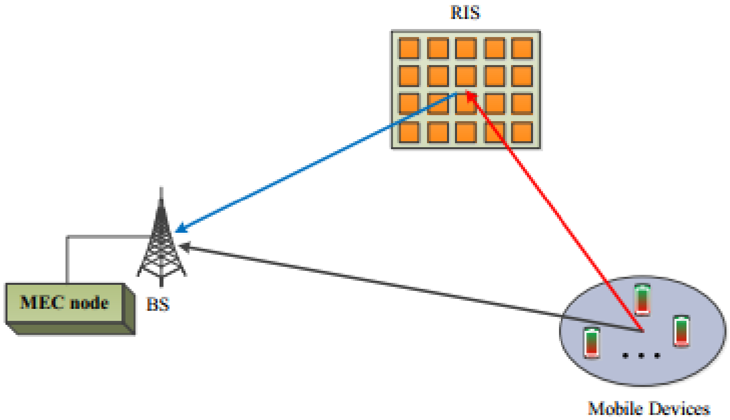

Figure 3.7.RIS-aided (MEC) Networks

E. RIS-aided Non-orthogonal Multiple Access (NOMA)

NOMA constitutes a promising future multiple access technique in future wireless networks, in which each orthogonal resource block is shared by multiple simultaneous users. This significantly enhances the spectral efficiency of conventional orthogonal multiple access (OMA). However, in some special cases when the users' channel vectors are orthogonal to each other, NOMA may not be a good option. The ideal implementation scenario for NOMA is when all the users' channel vectors represent the same angular direction. To broaden the application of NOMA, RIS can be introduced into the system or beneficially manipulating the wireless channel vectors of all users, so that one user's channel vector can be aligned with the other one's **[10].**

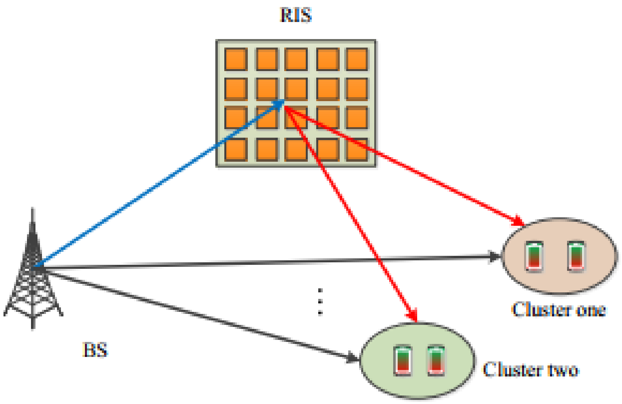

Figure 3.8.RIS-aided NOMA systems **[10].**

F. RIS-aided Multicast Networks

Multicast transmission based on content reuse has attracted wide research attention, since it is capable of mitigating the tele-traffic, hence it will play a pivotal role in future wireless networks. Some typical examples using multicast transmission include video conferencing, video gaming and TV broadcast. In multi-group multicast communications, identical content is shared within each group, and each group's data rate is limited by the user with the weakest channel gain. To deal with this issue, an RIS-aided multicast architecture was proposed as shown in Figure 3.9. By carefully tuning the RIS phase shifts, the channel conditions of the weakest link can be enhanced.

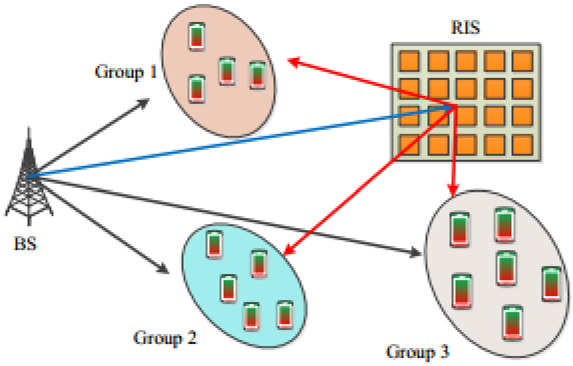

Figure 3.9.RIS-aided Multicast systems **[10].**

G. *RIS-aided Physical Layer Security (PLS) Networks*

Due to the broadcast nature of wireless transmission, wireless links are prone to security threats such as jamming attacks or secure information leakage. Recently, PLS techniques have received extensive research attention, since they can avoid complex key exchange protocols, and are suitable for latency sensitive applications. In order to maximize the rate of a secure communication link, both artificial noise and multiple antennas have been proposed. However, when both the legitimate users and eavesdroppers have correlated channels or when the eavesdroppers are closer to the BS than the legitimate users, the achievable secure rate remains limited. To tackle this issue, an RIS was deployed in a network operating in the presence of an eavesdropper as shown in Figure.3.10, for mitigating the information leakage to the eavesdroppers, while simultaneously increasing the received signal power at the legitimate users

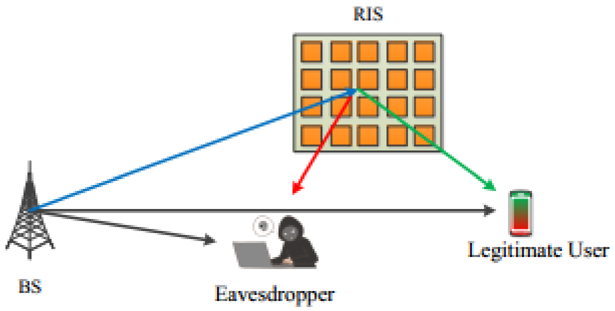

Figure 3.10.RIS-aided PLS systems **[10].**

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H. *RIS-aided Cognitive Radio (CR) Networks*

CRs are capable of enhancing the SE by allowing secondary users (SUs) to reuse the same spectrum with primary users (PUs) while controlling the interference inflicted by the SU transmitters (SU-TXs) on the PU receivers (PU-RXs). Standard approach is to use beam-forming for maximizing the sum-rate of the SUs, while ensuring that the interference power at the PU-RXs remains below the interference temperature (IT) limit. However, the beam-forming gain is limited, when the SU-TX to SU-RX link is weak, and the channel gain between the SU-TX and PU-RX is much higher. To handle this issue, a RIS can be deployed in the vicinity of the PU-

RXs, as shown in Figure 3.11. The RIS is used for mitigating the interference towards the PU-RXs, while improving the signal power at the SU-RXs.

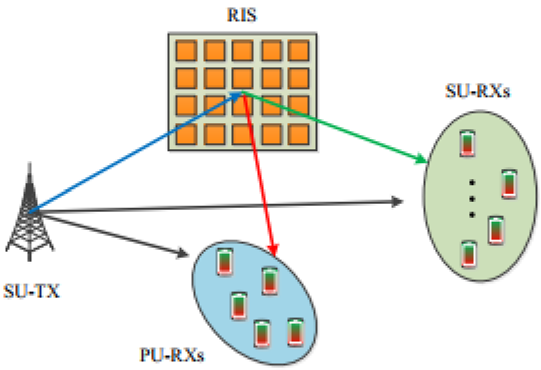

Figure 3.11.RIS-aided CR networks **[10].**

3.4 Principal RIS uses

RIS technology is a key enabler for wireless communications, essentially a reconfigurable meta-material made of scattering particles or meta-atoms. By controlling the phase-shift of each unit cell, RIS can control the behavior of the radio wave it impinges upon. This emerging transmission technology has four major uses in recent literature, including signal transmission and receiving, as illustrated in Figure 3.12 **[4].**

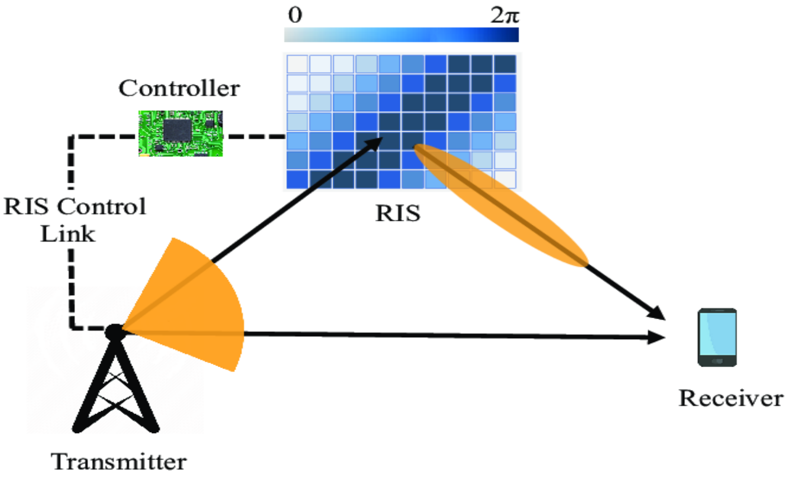

Figure 3.12. Schematic representation of reconfigurable intelligent surface aided communication **[8].**

3.4.1 Anomalous Reflection/Transmission

The RIS is a device that reflects or refracts radio waves in specific directions, despite not adhering to reflection and refraction laws. It operates independently of fading channels and receiver locations, but its limitations include not maximizing the signal-to-noise ratio (SNR) and not achieving system capacity.

3.4.2 Beam-forming/focusing

The RIS is a device that directs radio waves towards specific locations, maximizing signal-to-noise ratio (SNR) at the desired locations. However, its optimization relies on fading channels and receiver locations, and system capacity is often not achieved.

3.4.3 Joint Transmitter/RIS Encoding

The RIS optimizes system capacity by utilizing meta-atom status to modulate additional data. However, the transmitter and RIS need joint optimization, and setup depends on fading channels and receiver locations, making it a challenge to jointly optimize both components.

3.4.4 Single-RF Multi-Stream Transmitter Design

The operation involves a simple radio frequency (RF) feeder near a radio frequency (RIS) transmitter, which emits an un modulated carrier to reflect multiple data modulated signals. This approach is suitable for multi-stream transmitters using a limited number of RF chains. RIS is relatively inexpensive, energy-efficient, and easy to deploy, especially in buildings due to its 2D shape. Compared to phased arrays, multi-antenna transmitters, and relays, RISs require the largest number of scattering elements but require the least and least costly components. Additionally, RISs are nearly passive, requiring no signal processing capability, reducing the need for power amplifiers or energy-consuming components like RF chains in MIMO systems.

3.5 RIS challenges

Some of the main challenges that may face the potential gains of RIS in wireless communications applications **[2].**

3.5.1 Channel estimation

Channel estimation represents a fundamental bottleneck against achieving performance gains in RIS-aided wireless communications. The tuning process for the reflection coefficients of the unit cells in the RIS mainly relies on an accurate channel estimation process. In RIS applications, the channel estimation problem is quite different and far more complicated than that in traditional communications. Because in this scenario, two more channel estimates are needed which are the channel between the RIS and BS and the channel between the RIS and user, in addition to the direct channel between the BS and user. Moreover, the RIS doesn't include any powerful signal processing capability which increases the difficulty of the channel estimation process. The direct channel between the BS and user can be performed by setting the RIS into the absorption mode and then using the traditional channel estimation techniques. However, advanced and efficient techniques that maintain the power consumption and complexity of the RIS as low as possible are required to conduct the estimation process for the RIS/BS and RIS/user channels.

3.5.2 RIS reconfiguration

In classical wireless communication, the reconfiguration of the transmitter and receiver given the wireless channel has been extensively studied. However, in RIS-aided wireless communication, the propagation environment itself becomes an optimization parameter and the RIS is typically composed of a massive number of elements. Therefore, there configuration of RIS in wireless applications becomes highly non-trivial. The RIS reconfiguration problem typically has multiple non-convex constraints which increase the complexity of the problem. In the literature, the RIS reconfiguration problems are usually solved by alternating optimization which may be computationally prohibitive. Therefore, light-weight algorithms for the RIS reconfiguration are needed that are capable of reconfiguring the propagation environment in real-time.

3.5.3 Network optimization

When the network contains multiple BSs and is assisted with many distributed RISs to serve a massive number of users, the real-time configuration of the entire network will be a challenging task. In this scenario, the network consists of multiple separated components so, to reach a global optimum over the whole network will require an enormous amount of control signals for the resource allocation, power allocation, users' scheduling and RISs configuration. Thus, It becomes crucial to develop new network optimization schemes that have reasonable computational overhead and energy consumption.

3.6 Passive and Active RISs

3.6.1 Passive RIS

The RISs widely studied in most existing works are passive RISs Specifically, as shown in Figure 3.13(a), a passive RIS comprises a large number of passive elements each being able to reflect the incident signal with a controllable phase shift. In general, each passive RIS element consists of a reflective patch terminated with an impedance-adjustable circuit for phase shifting. Thanks to the passive mode of operation without active radio-frequency (RF) components, a passive RIS element practically consumes zero direct-current power, and the introduced thermal noise is usually negligible. Thereby, the signal model of an N-element passive RIS widely used in the literature is given as follows **[9]:**

$$\boldsymbol{y} = \boldsymbol{\Theta}\boldsymbol{x}, \qquad \textbf{(1)}$$

where($\boldsymbol{x} \in \mathbb{C}^{\boldsymbol{N}}$)denotes the incident signal.

$\boldsymbol{\Theta}$=diag$\left(e^{j\theta_1}, \dots, e^{j\theta_N}\right)\mathbb{C}^{N\times N}$denotes the reflection coefficient matrix of the passive RIS with θ_n being the phase shift of the n-th passive element, and$y \in \mathbb{C}^N$denotes thesignal reflected by the RIS. Note that the impact of noise isneglected in (1). As a consequence, by properly adjusting $\boldsymbol{\Theta}$ to manipulate the *N* signals reflected by the *N* RIS elements to coherently add with the same phase at the receiver, a high array gain can be achieved. This is expected to significantly increase the receiver SNR which is one of the key reasons for why RISs have attracted so much research interest recently. Unfortunately, in practice, this expected high-capacity gain often cannot be realized, especially in communication scenarios where the direct link between the transmitter and the receiver is not weak. The reason for this negative result is the “multiplicative fading” effect introduced by passive RISs. Specifically, the equivalent path loss of the transmitter-RIS-receiver reflected link is the product (instead of the sum) of the path losses of the transmitter-RIS and RIS-receiver links, and therefore, it is thousands of times larger than that of the unobstructed direct link. Thereby, for an RIS to realize a noticeable capacity gain, thousands of RIS elements are required to compensate for this extremely large path loss **[9].**

3.6.2 Active RIS

To overcome the fundamental performance bottleneck caused by the “multiplicative fading” effect of RISs, we propose active RISs as a promising solution. As shown in Figure 3.13(b), similar to passive RISs, active RIS scan also reflect the incident signals with reconfigurable phase shifts. Different from passive RISs that just reflect the incident signals without amplification, active RISs can further amplify the reflected signals. To achieve this goal, the key component of an active RIS element is the additionally integrated active reflection-type amplifier, which can be realized by different existing active components, such current-inverting converters, asymmetric current mirrors, or some integrated circuits with reflection-type amplifiers supported by a power supply, the reflected and amplified signal of an *N*-element active RIS can be modeled as follows:

$$\boldsymbol{y} = \boldsymbol{\Psi x} + \boldsymbol{\Psi v} + \boldsymbol{n_s}, \tag{2}$$

where $\boldsymbol{\Psi} := \mathbf{diag}\left(\mathbf{p_1 e^{-j\theta_1}}, \dots, \mathbf{p_N e^{-j\theta_N}}\right) \in \mathbb{C}^{\boldsymbol{N\times N}}$ denotes the reflection coefficient matrix of the active RIS, where in $p_n \in \mathbb{R}_+$denotes the amplification factor of the *n*-th active element and $p_n$can be larger than one thanks to the integratedreflection-type amplifier. Due to the use of active components, active RISs consume additional power for amplifying thereflected signals, and the thermal noise introduced by activeRIS elements cannot be neglected as is done for passive RISs. Particularly, as shown in (2), the noise introduced at active RISs can be classified into dynamic noise $\boldsymbol{\Psi v}$ and static noise $\boldsymbol{n_s}$, where $\boldsymbol{\Psi v}$ is the noise introduced and amplified by thereflection-type amplifier and $\boldsymbol{n_s}$ is generated by the patch and the phase-shift circuit. More specifically, $\mathbf{v}$ is related to the input noise and the inherent device noise of the active RIS elements, while the static noise $\boldsymbol{n_s}$ is unrelated to $\boldsymbol{\Psi}$ and isusually negligible compared to the dynamic noise $\boldsymbol{\Psi v}$ **[9].**

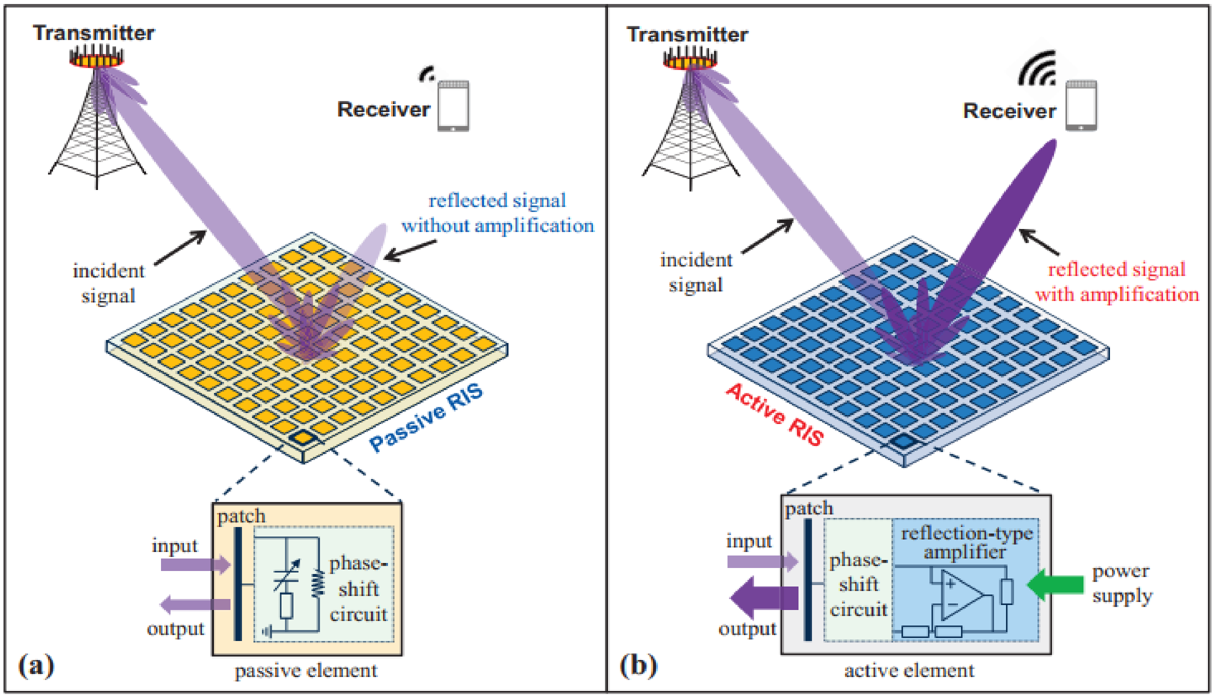

Figure 3.13. An illustration of the hardware architectures of (a) a passive RIS and (b) an active RIS **[9].**

3.7 Key applications of RIS

Reconfigurable Intelligent Surfaces (RIS) technology significantly boosts wireless performance in both indoor and outdoor settings. This is thanks to its **low material cost**, **minimal power usage**, and **easy deployment** on diverse surfaces like indoor walls, aerial platforms, roadside billboards, highway poles, vehicle windows, and even pedestrian clothing. Furthermore, it's **environmentally friendly** and **integrates seamlessly** into existing wireless systems, making it valuable for a wide array of applications.

3.7.1 The relationship between the outside environment and smart cities

The RIS can be installed on the buildings in order to enhance the coverage, increase the spectral efficiency, and reduce the exposure to the EM radiation in outdoor environments as shown in Figure 3.14, since the deployment of RISs may reduce the amount of network infrastructure needed **[11].**

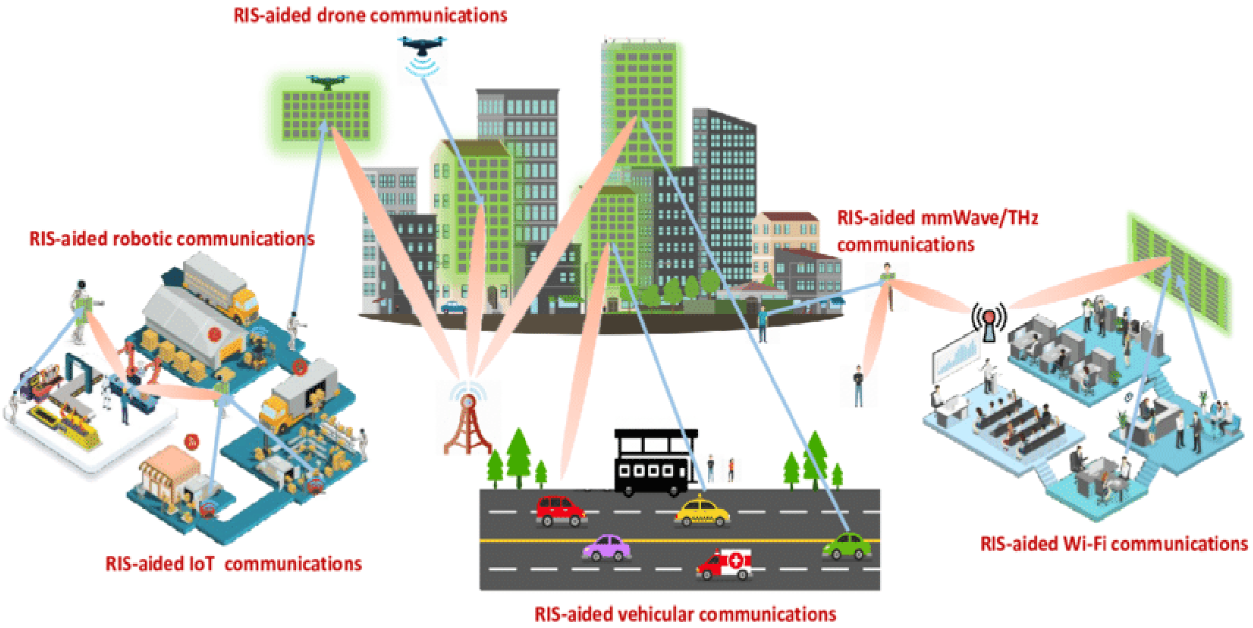

Figure 3.14. RIS-aided wireless network applications in multi-user communication systems **[13].**

3.7.2 Smart Buildings

In buildings, large windows can be made of special glasses that can selectively enable indoor to-outdoor and outdoor-to-indoor connectivity as shown in Figure 3.15**[11].**

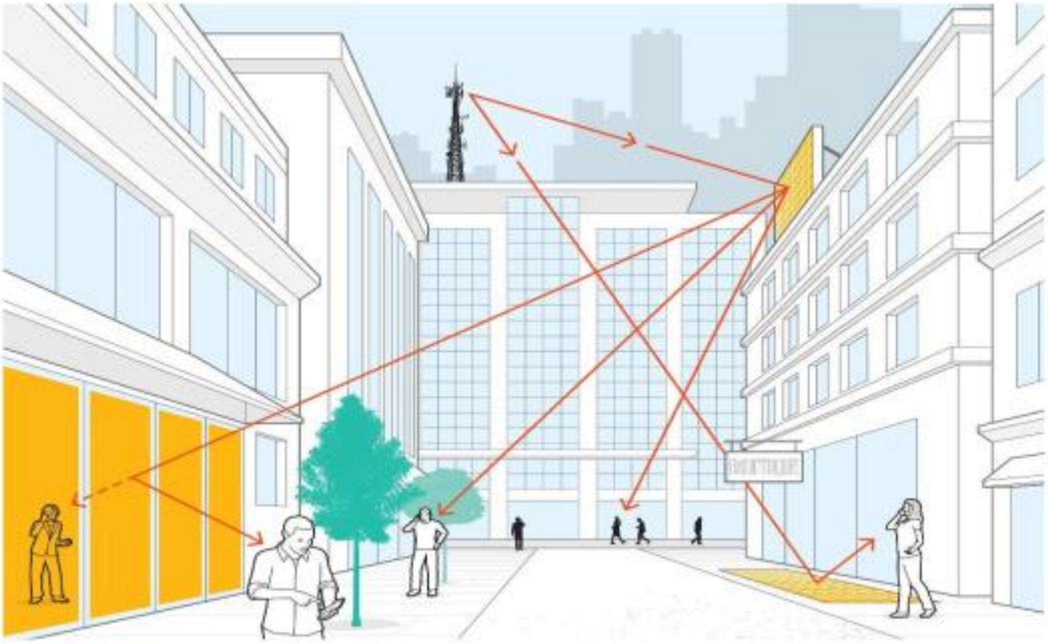

Figure 3.15 RIS applications in an outdoor setting **[11].**

3.7.3 Smart Vehicles

RISs can be installed on trains, airplanes, and cars to enhance vehicle-to-vehicle and vehicle-to-infrastructure communications. Cars can have their glasses and roof coated with RISs for moving nearly passive relays, in Figure 3.16. For example, Trains can have their interior coated with RISs for better signal coverage and reduced passenger exposure to electromagnetic fields. Airplanes can have overhead bins coated with RISs for high-speed internet and reduced EM field exposure.

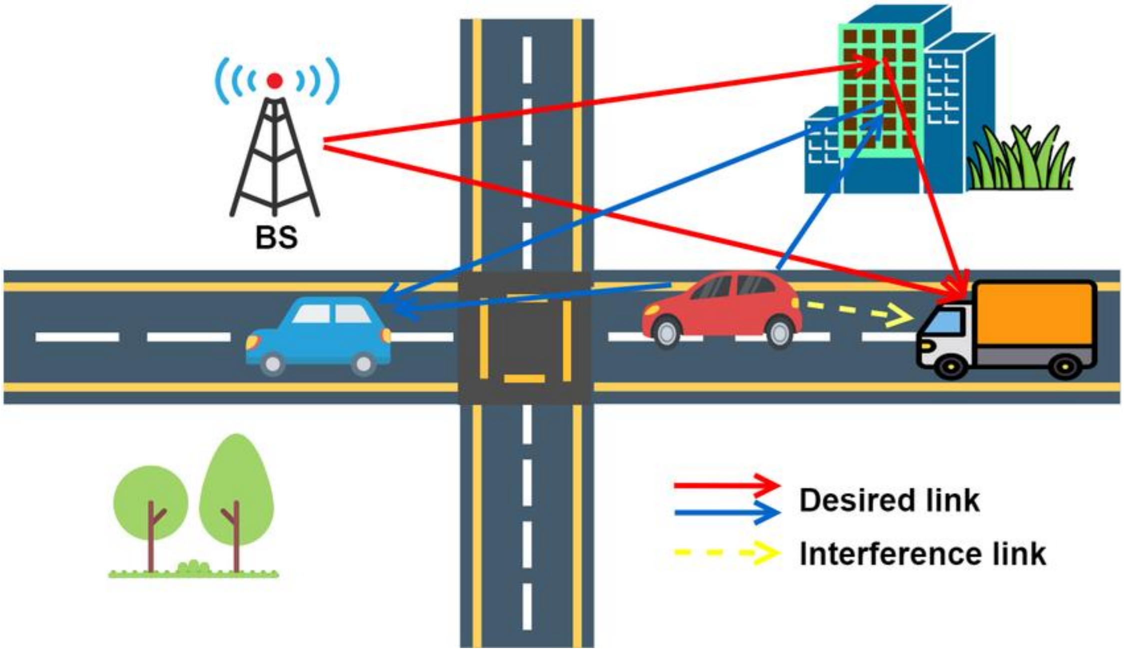

Figure 3.16. RIS-assisted vehicular communication system **[11].**

3.7.4 Smart Homes

The RIS can be installed on house walls to enhance device connectivity, and smart glasses can also be installed to improve local connectivity.

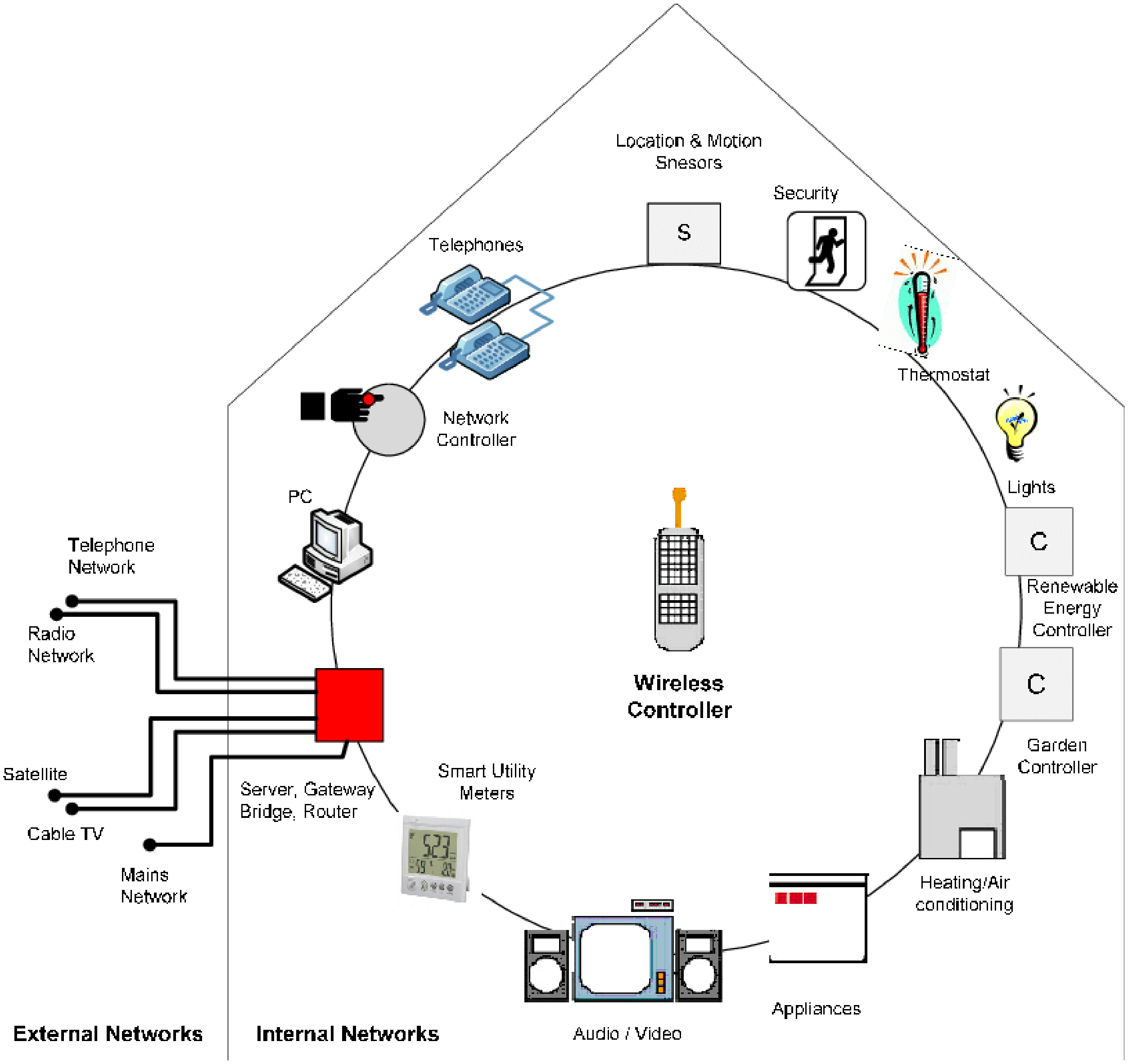

Figure 3.17. RIS-Smart home topology diagram **[12].**

3.8 Reflection Principle

In electromagnetic wave theory (EM), reflection occurs when a radio wave reaches the interface between two different media, causing some part to return to the origin medium. In RIS-aided systems, reflection occurs when the transmitter's signal encounters reflection elements at the RIS. To accurately characterize the reflected signal, Maxwell's equations are solved by applying boundary conditions and considering the permittivity and permeability of the reflecting elements. However, the calculation of these equations is complex and requires simplifications. In wireless engineering, transmission line theory is used as an adequate simplification of Maxwell' equations with effective parameters

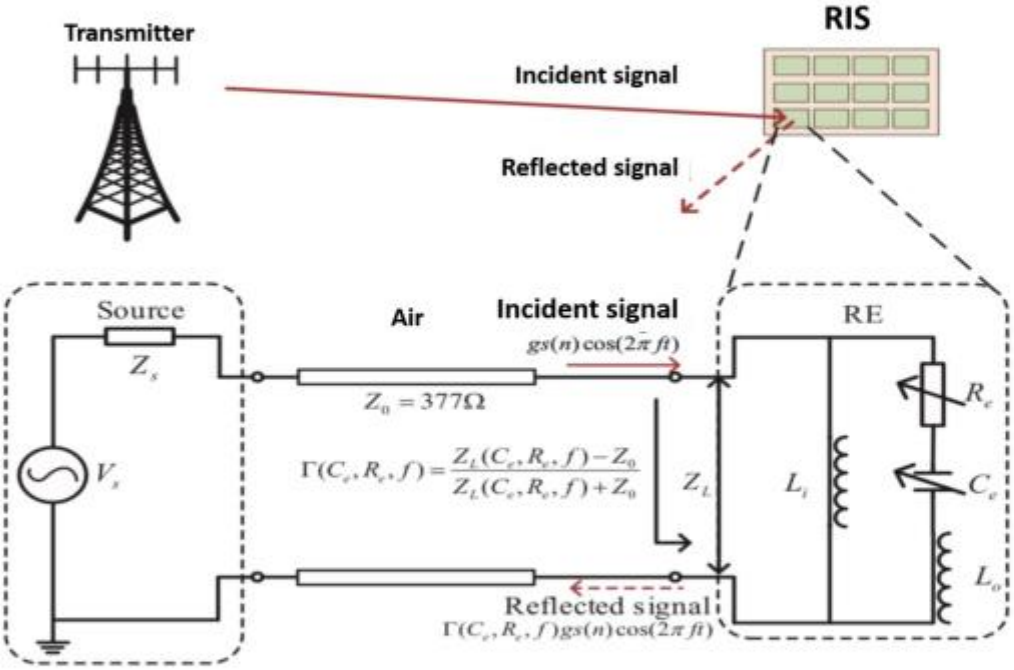

Figure 3.18: The equivalent circuit for the RIS reflecting element based on transmission line theory **[11]**.

The reflection coefficient is a complex number used to illustrate the ratio between input and output electric fields. It is characterized by the characteristic impedance Z0and the load impedance ZL. The characteristic impedance is fixed and determined by the geometry and materials of the transmission line, while the load impedance is reconfigurable. This allows for a tunable reflection coefficient by varying the load impedance. The simplest way to change reflection coefficients is to deploy a switch on preset load impedances, but continuous phase shifts of reflecting elements are desirable. In a printed circuit board (PCB)-based RIS, a semi-conductor diode, typically a positive-intrinsic-negative (PIN) diode, is embedded into the metal element in the outer layer to tune the reflection coefficients. The PIN diode can be replaced with the equivalent circuit model, where Ce and Re are the effective capacitance and resistance **[14]**.

3.9 Conclusion

As stated at the outset, the field of high-data-rate, spectrally efficient and reliable wireless communication, is currently receiving much attention. Intelligent Reflecting Surfaces (RIS) are a groundbreaking technology designed to significantly improve wireless communication by precisely manipulating electromagnetic signals. Key applications of RIS involve anomalous reflection/transmission, efficient beam-forming/focusing, coordinated joint transmitter/RIS encoding, and enabling single-RF multi-stream transmission. By offering benefits like improved spectral efficiency**,** reduced interference**,** an enhanced signal quality, RIS has the potential to transform communication networks and boost overall performance.

3.10 References

[1] Xu, Jindan, Wei Xu, and Chau Yuen. "On Performance of Distributed RIS-aided Communication in Random Networks." IEEE Transactions on Wireless Communications (2024).

[2] Emad Ibrahim, "Selected Topics on Reconfigurable Intelligent Surfaces" Dept. of Computer Science and Electrical Engineering Lulea University of Technology Lulea, Sweden.

[3] T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, and Q. Cheng, \Coding metamaterials, digital metamaterials and programmable metamaterials," Light: Science & Applications, vol. 3, no. 10, pp. e218{e218, 2014.

[4] M. Di Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. De Rosny, andS. Tretyakov, \Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," IEEE Journal on Selected Areas in Communications, vol. 38, no. 11, pp. 2450{2525, 2020.

[5] B. O. Zhu, J. Zhao, and Y. Feng, Active impedance metasurface with full 360 reflection phase tuning," Scientific reports, vol. 3, no. 1, pp. 1{6, 2013.

[6] H. Yang, X. Chen, F. Yang, S. Xu, X. Cao, M. Li, and J. Gao. Design of resistor loaded reflect-array elements for both amplitude and phase control," IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 1159{1162, 2016.

[7] M. E. Bialkowski, A. W. Robinson, and H. J. Song, \Design, development, and testing of x-band amplifying reflectarrays," IEEE Transactions on Antennas and Propagation, vol. 50, no. 8, pp. 1065{1076, 2002}.

[8] Shamasundar, Bharath &Daryanavardan, Negar &Nosratinia, Aria. (2023). Channel Training & Estimation for Reconfigurable Intelligent Surfaces: Exposition of Principles, Approaches, and Open Problems. IEEE Access. PP. 1-1. 10.1109/ACCESS.2023.3236909.

[9] Zhang, Z., Dai, L., Chen, X., Liu, C., Yang, F., Schober, R., & Poor, H. V. (2022). Active RIS vs. passive RIS: Which will prevail in 6G?. IEEE Transactions on Communications, 71(3), 1707-1725.

[10] Pan C, Ren H, Wang K, Kolb JF, Elkashlan M, Chen M, Di Renzo M, Hao Y, Wang J, Swindlehurst AL, You X. Reconfigurable intelligent surfaces for 6G systems: Principles, applications, and research directions. IEEE Communications Magazine. 2021 Jun;59(6):14-20.

[11] Fadel, Ahmed Ben, Taissir Elganimi, Khaled Rabie, Galym zhan Nauryzbayev,and Xingwang Li. "Irregular STAR-RIS-Aided Wireless Systems with a Limited Number of Passive Elements." Authorea Preprints (2023)

[12] Al-Qutayri, Mahmoud &Jeedella, Jeedella. (2010). Integrated Wireless Technologies for Smart Homes Applications. 10.5772/8412.

[13] Cao, Xuelin& Yang, Bo &Chongwen, Huang & Yuen, Chau & Di Renzo, Marco & Han, Zhu &Niyato, Dusit & Poor, H. Vincent & Hanzo, L.. (2021). AI-Assisted MAC for Reconfigurable Intelligent-

Surface-Aided Wireless Networks: Challenges and Opportunities. IEEE Communications Magazine. 59. 10.1109/MCOM.001.2001146.

[14] Abrardo, Andrea, Davide Dardari, Marco Di Renzo, and Xuewen Qian. "MIMO interference channels assisted by reconfigurable intelligent surfaces: Mutual coupling aware sum-rate optimization based on a mutual impedance channel model." IEEE Wireless Communications Letters 10, no. 12 (2021): 2624-2628.

Chapter 4: Simulations and results

In this chapter, we provide the simulation results for the performance evaluation of an IRS-aided wireless network. We first discuss the system's model. Then we go through an analytical performance analysis. Finally, we analyze using Monte Carlo simulations, the performance of the network under consideration in terms of two metrics such namely the outage probability and the ergodic rate. These simulations are conducted considering Rayleigh and Nakagami fading channels.

4.1 System Model and analytical performance analysis

4.1.1 System Model

This work investigates signal transmission from a single-antenna source (S) to a user (U) through an N-element Intelligent Reflecting Surface (IRS) as shown in figure 4.1. We assume the absence of a direct line-of sight link between S and U due to a dense urban setting. Furthermore, the IRS is presumed to have perfect phase control to ensure constructive signal interference at U. The channel link g_n follows a nakagami-m fading model while the link h_n is using a Rayleigh fading model. With the channel envelopes assumed to be independently, but not necessarily identically, distributed (i.n.i.d.) **[1].**

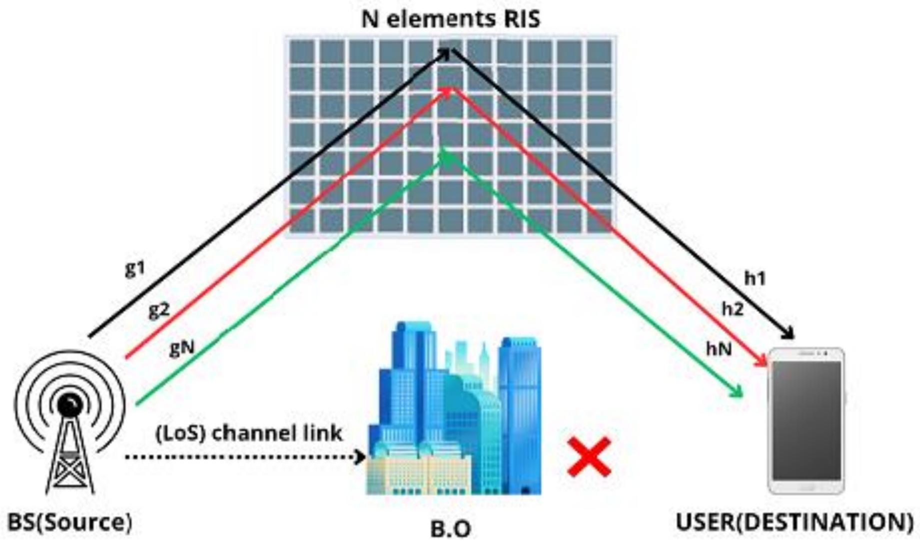

Figure 4.1. RIS-aided wireless network

The signal received at U can be written as **[1]**

$$y = \sqrt{Ps}\left(\sum_{n=1}^{N} g_n\, h_n d_{sr}^{\frac{-\tau}{2}} d_{ru}^{\frac{-\tau}{2}} \alpha_n e^{j\theta_n}\right) x + n, \tag{1}$$

where$\mathrm{P_S}$, x and n are the transmit power, message of S and additive white Gaussian noise (AWGN) at a receiver node, with varianceN_0, respectively. $d_{sr}$and $d_{ru}$are the distances related to the *S*-LIS and LIS-*U* links; τ stands for the path-loss exponent. $\theta_n$and $\alpha_n$are the adjustable phase shift and reflection coefficient of the *n*th LIS element. Thus, the corresponding SNR at *U* can be expressed as **[1]:**

$$\gamma = Ps\frac{\left|\sum_{n=1}^{N} g_n h_n d_{br}^{\frac{-\tau}{2}} d_{ru}^{\frac{-\tau}{2}} \alpha_n e^{j\theta_n}\right|^2}{N_0} \tag{2}$$

Recalling the perfect phase adjustment, in order to maximize the received SNR, the phase shifts can be optimized as **[1]:**

$$\left(\theta_1^{opt}, \dots, \theta_N^{opt}\right) = \left(-\left(\arg[g_1] + \arg[h_1]\right), \dots, -(\arg[g_N] + \arg[h_N])\right), \tag{3}$$

So that eventually each term in the summation is co-phased. Consequently, the optimal received SNR can be expressed as **[1]:**

$$\gamma = \frac{Ps}{N_0}\left(\sum_{n=1}^{N} |g_n||h_n|\bar{\gamma}_n\right)^2, \tag{4}$$

where$\bar{\gamma}_n = \alpha_n d_{br}^{\frac{-\tau}{2}} d_{ru}^{\frac{-\tau}{2}}$.

4.1.2 Analytical performance analysis

In this section, we study the OP, for the considered RIS-assisted wireless system.

a) Outage Probability

Mainly, the OP is defined as the probability that the achievable received SNR at the destination node falls below the predefined SNR-associated rate threshold γ_{th}.The reliability of the communication link is usually assessed by using the OP **[2]**, which is defined as:

$$\begin{aligned} P_{out}\left(\gamma_{th}\right) &= Pr\left\{\gamma \leq \gamma_{th}\right\} \\ &= Pr\left\{X \leq \sqrt{\frac{\gamma_{th}}{\bar{\gamma}}}\right\} \end{aligned} \tag{5}$$

where $X = \sum_{n=1}^{N}\left|g_n\right|\left|h_n\right|\bar{\gamma}_n, with\, \bar{\gamma} = \frac{Ps}{N_0}$.

b) Ergodic capacity

EC can be defined as **[3]:**

$$C = \mathbb{E}[log_2(1+\gamma)] = \frac{1}{ln(2)}\int_0^\infty ln\,(1+x^2\bar{\gamma})f_X(x)dx, \tag{6}$$

where $f_X(x)$is the probability density function (PDF) of $X = \sum_{n=1}^{N}|g_n||h_n|\bar{\gamma}_n$.

4.2 The different approximations

4.2.1 CLT approximation (Gaussian)

The CLT states that with a given sufficiently large number of passive LIS elements, the probability density function (PDF) and cumulative density function (CDF) of the sum of *N (*i.n.i.d) **[1].** The product of a Nakagami-*m* and a Rayleigh RV can be approximated by a Gaussian distribution as:

$$f_X^{CLT}(x) = \frac{\emptyset_X}{\sqrt{2\pi\sigma_X^2}} exp\left(\frac{(x-\mu_X)^2}{2\sigma_X^2}\right) \tag{7}$$

$$F_X^{CLT}(x) = 1 - \emptyset_X Q\left(\frac{x-\mu X}{\sigma_X}\right) \tag{8}$$

where $\emptyset_X = 1/Q\left(-\frac{\mu_X}{\sigma_X}\right)$is the normalization coefficient, and $Q(\cdot)$ is the Gaussian *Q* function.

4.2.2 Gamma approximation

Another approach is to apply the Gamma approximation **[1]**, whose PDF and CDF are given by

$$f_X^{\Gamma}(x) = \frac{1}{\Gamma(l)\theta^l}x^{l-1}\exp\left(-\frac{x}{\theta}\right), \tag{9}$$

$$F_X^{\Gamma}(x) = \frac{1}{\Gamma(l)}\gamma\left(l,\frac{x}{\theta}\right), \tag{10}$$

where $\gamma(s,x) = \int_0^x t^{s-1}\,exp(-t)dt$is the lower incomplete Gamma function,*l*and θ are the shape and scale parameters calculated after equating the mean and variance of the Gamma distribution ($l\theta$ *and* $l\theta^2$) to $\mu_X$and σ_X^2.

4.3 Numerical Results and Discussion

This section presents and discusses the Monte Carlo simulation results for the outage probability (OP) and ergodic capacity (EC) of the considered IRS-assisted wireless network. These simulations investigate the impact of various key system parameters on performance. Unless a parameter is explicitly varied in a specific plot, the following default parameters are utilized for the simulations: number of reflecting elements $N = 32$, Nakagami-m shape parameter $m = 1$ for the Source-RIS (S-RIS) link, Nakagami-m spread parameter $\Omega = 0.5$ for the S-RIS link, Rayleigh scale parameter $\sigma = 0.8$ for the RIS-User link, combined path loss coefficient $\alpha = 1$, and distances $d_{SR} = d_{RU} = 10$ units.

4.3.1 Outage Probability (OP)

This subsection analyzes the outage probability. Across all figures related to the OP, the y-axis represents the outage probability on a logarithmic scale from 10^{-5} to 10^{0}, and the x-axis represents the Transmit SNR in dB, typically ranging from 0 to 30-40 dB.

- ✓ ***Impact of the Number of IRS Elements (N)***

The effect of varying the number of IRS reflecting elements (N) on the OP is illustrated in Figure 4.2. The plot showcases OP curves for $N = 16{,}24{,}32,$ and 64. For all values of N, the OP consistently decreases as the transmit SNR increases. Most notably, for a given transmit SNR, increasing N leads to a substantial reduction in OP, highlighted by an arrow indicating this trend. For instance, at a transmit SNR of 20 dB, the OP diminishes by approximately two orders of magnitude when N is increased from 16 to 64. This significant performance enhancement is attributed to the increased passive beamforming gain from a larger IRS. A higher N allows for a more effectively focused signal reflection towards the user, thereby increasing the received signal power and reducing the outage probability.

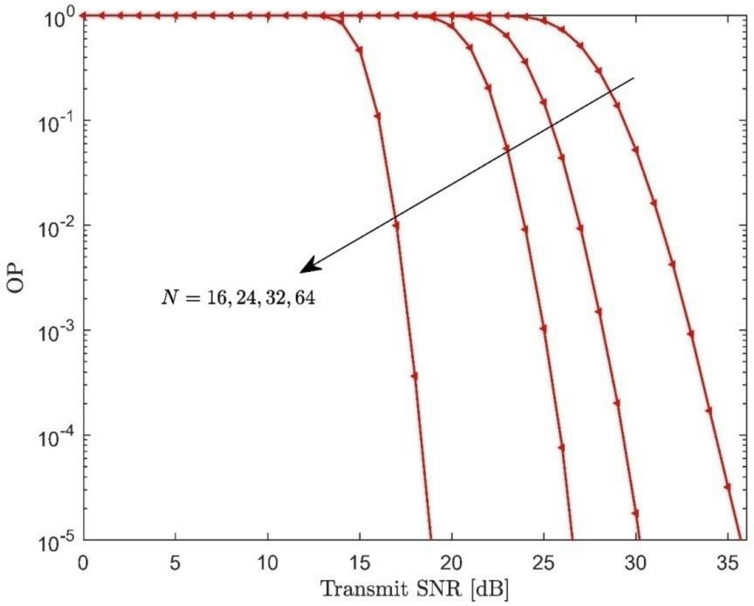

Figure 4.2. *The OP vs. the SNR for different values of* N.

- ✓ ***Impact of S-RIS Channel Spread Parameter (Ω)***

Figure 4.3 demonstrates the influence of the S-RIS channel's Nakagami-m spread parameter, Ω, on the OP, with values $\Omega = 0.1,0.5,1,$ and 1.5 being considered. The simulations maintain other parameters, such as $N = 32$ and $m = 1$, at their default values. The results clearly indicate that for any given transmit SNR, the OP decreases as Ω increases. The parameter Ω is directly related to the average power of the S-RIS channel; with $m = 1$ (indicative of Rayleigh fading conditions for the channel envelope), a larger Ω signifies a stronger average channel between the source and the IRS. This improved S-RIS link quality enhances the overall end-to-end channel, consequently leading to a lower outage probability.

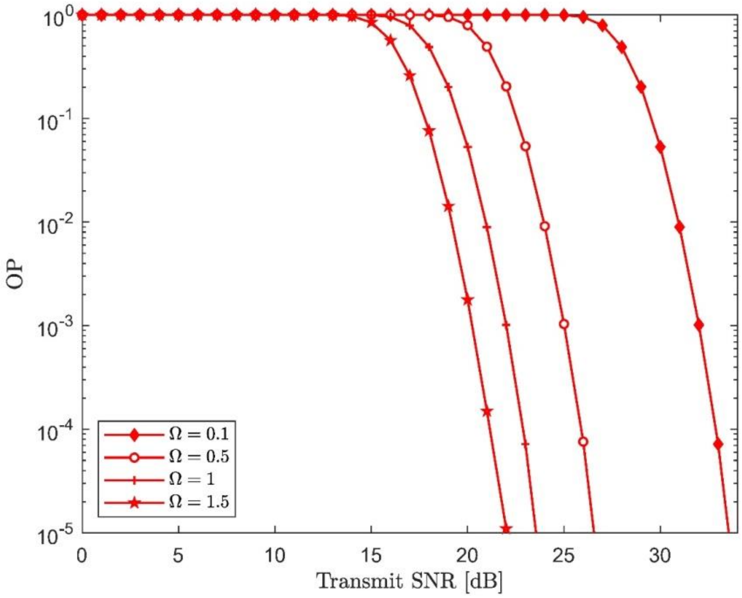

Figure 4.3. *The OP vs. the SNR for different values of Ω.*

- ✓ ***Impact of RIS-User Channel Scale Parameter (σ)***

The impact of the RIS-User channel quality, represented by the Rayleigh scale parameter σ, is presented in Figure 4.4. This plot shows OP curves for $\sigma = 0.1,0.5,1,$ and 1.5, with the default σ being 0.8. As observed, for a constant transmit SNR, the OP decreases as σ increases. The average power of the Rayleigh-fading RIS-User channel is proportional to σ^2. Thus, a larger σ value implies a stronger average channel between the IRS and the user. This enhancement in the RIS-User link translates to improved system performance and a reduced likelihood of outage.

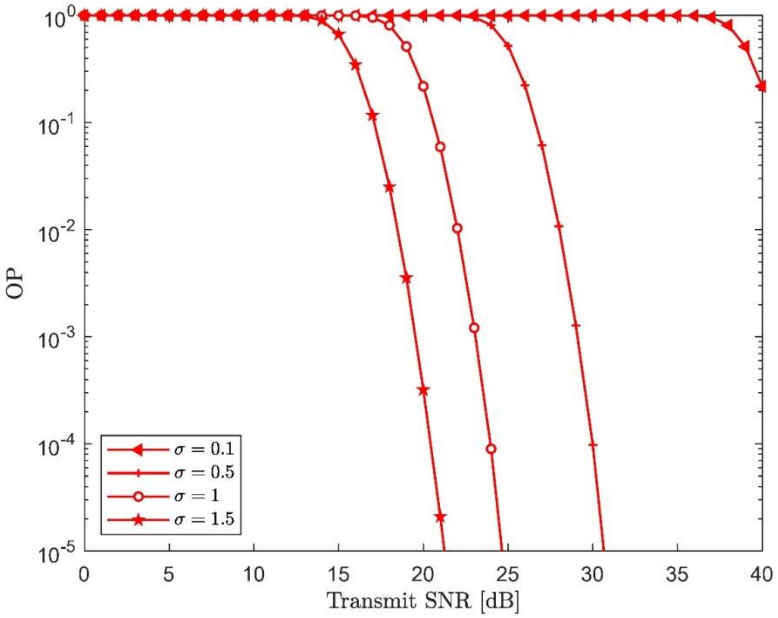

Figure 4.4. *The OP vs. the SNR for different values of* σ.

✓ ***Impact of IRS-User Distance ($\mathbf{d_{RU}}$)***

Figure 4.5 examines the effect of the distance between the IRS and the user (d_{RU}) on the OP. The plot compares three scenarios: ($d_{SR} = 10, d_{RU} = 10$), ($d_{SR} = 10, d_{RU} = 30$), and ($d_{SR} = 10, d_{RU} = 60$). It is evident that as d_{RU} increases from 10 to 60 units (while d_{SR} is fixed at 10 units), the OP increases for any given transmit SNR. The configuration with $d_{RU} = 10$ units shows the lowest OP, while $d_{RU} = 60$ units results in the highest OP among the evaluated distances. This trend is a direct consequence of path loss; greater distances lead to increased signal attenuation. As d_{RU} increases, the signal propagating from the IRS to the user weakens more significantly, thus increasing the outage probability.

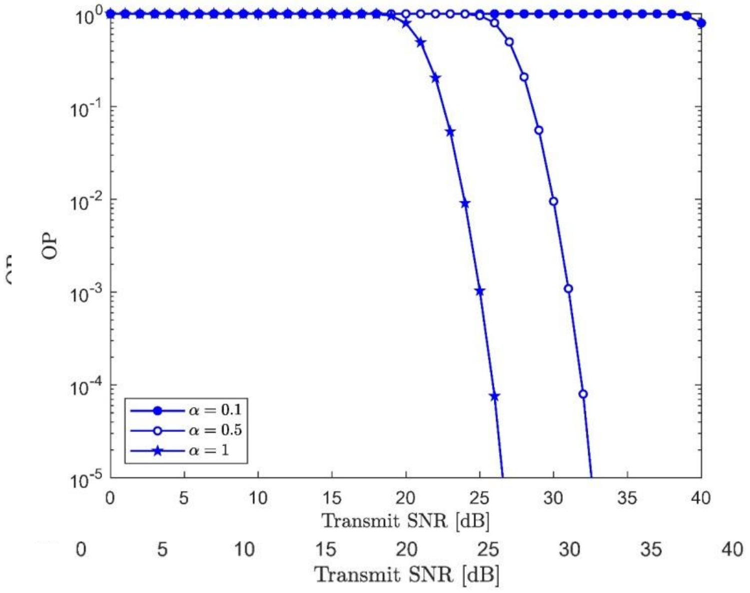

Figure 4.5. *The OP vs. the SNR for different values of* d_{sr}*and* d_{ru}.

✓ *Impact of Combined Path Loss Coefficient (α)*

The influence of the combined path loss coefficient, α, on OP is depicted in Figure 4.6. This figure presents OP curves for $\alpha = 0.1, 0.5,$ and 1, where $\alpha = 1$ is the default value. The simulation results show that for a fixed transmit SNR, the OP decreases as the value of α increases. Specifically, $\alpha = 1$ yields the best performance (lowest OP), while $\alpha = 0.1$ results in the poorest performance (highest OP). The coefficient αgenerally models the overall large-scale fading effects or calibration of path loss. A larger α suggests more favorable channel conditions or a lower effective path loss, leading to stronger received signal strength and, consequently, a reduced outage probability.

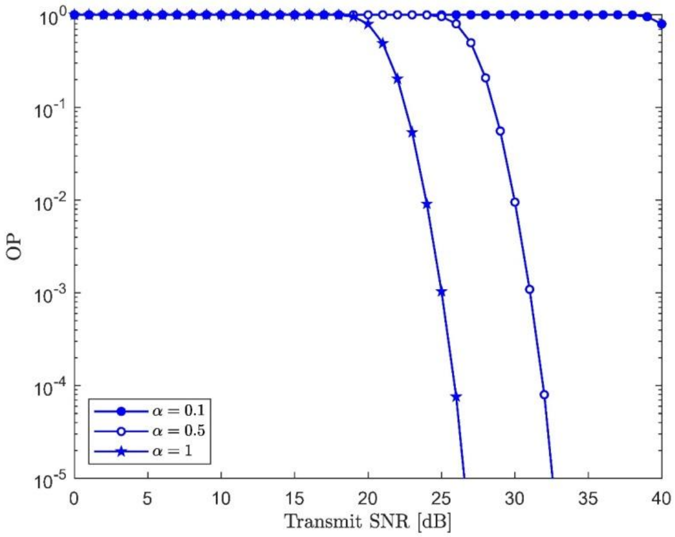

Figure 4.6. The OP vs. the SNR for different values of $\boldsymbol{\alpha}$

In all presented scenarios for OP, it is consistently observed that the outage probability decreases with an increase in the transmit SNR. This underscores the fundamental principle that higher signal power relative to noise and interference leads to improved communication reliability.

4.3.2 Ergodic Capacity (EC)

This subsection discusses the Monte Carlo simulation results for the ergodic capacity (EC) of the IRS-assisted wireless network in consideration. The x-axis in all EC plots represents the Transmit SNR [dB] from 0 to 40 dB.

- ✓ ***Impact of the Number of IRS Elements (N)***

Figure 4.7 shows the EC versus transmit SNR for different numbers of IRS elements: $N = 16,24,32,$ and 64 . The y-axis for EC in this plot is linear. A clear trend is that EC increases with the transmit SNR for all values of N. Furthermore, at any given transmit SNR, increasing N results in a higher EC. The arrow in the plot indicates this positive correlation. For example, at an SNR of 20 dB, the EC increases from approximately 3 bits/s/Hz to over 5 bits/s/Hz as N goes from 16 to 64. This improvement is due to the enhanced array gain from more elements, leading to a stronger effective channel and thus higher achievable data rates.

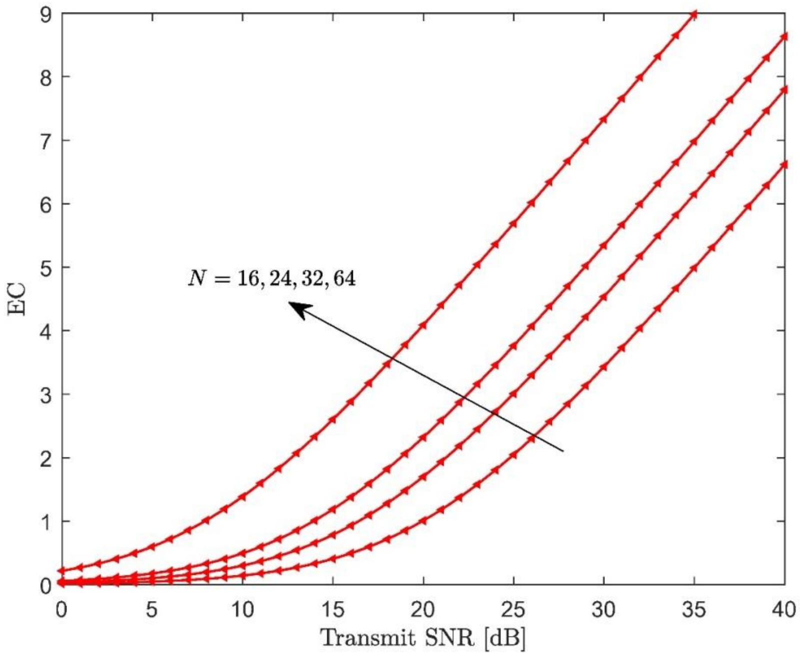

Figure 4.7. *The EC vs. the SNR for different values of N.*

- ✓ ***Impact of S-RIS Channel Spread Parameter (Ω)***

The effect of the S-RIS channel's Nakagami-m spread parameter Ω on EC is presented in Figure 4.8 The EC is plotted against transmit SNR for Ω values of $0.1, 0.5, 1,$ and 1.5. The y-axis for this plot is on a logarithmic scale, ranging from 10^{-2} to 10^{1}. As Ω increases, the EC also increases for any given transmit SNR. A larger Ω corresponds to a stronger average S-RIS channel, which improves the overall link quality and supports higher data rates. The improvement is more pronounced at lower to mid SNRs.

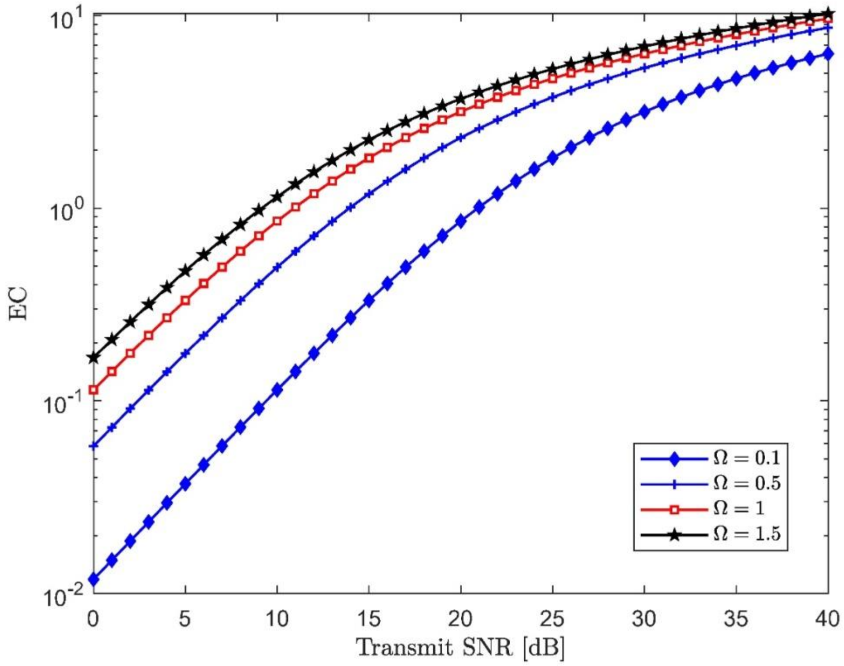

Figure 4.8. *The EC vs. the SNR for different values of Ω.*

- ✓ ***Impact of RIS-User Channel Scale Parameter (σ)***

Figure 4.9. illustrates how the EC changes with the RIS-User channel's Rayleigh scale parameter σ, for $\sigma = 0.1, 0.5, 1$, and 1.5. The y-axis is logarithmic, spanning from 10^{-4} to 10^{2}. Similar to the previous parameters, increasing σ leads to a higher EC at any fixed transmit SNR. A larger σ indicates a stronger average RIS-User channel, which contributes to better overall channel conditions and thus higher ergodic capacity. The impact of σ is significant across the entire SNR range.

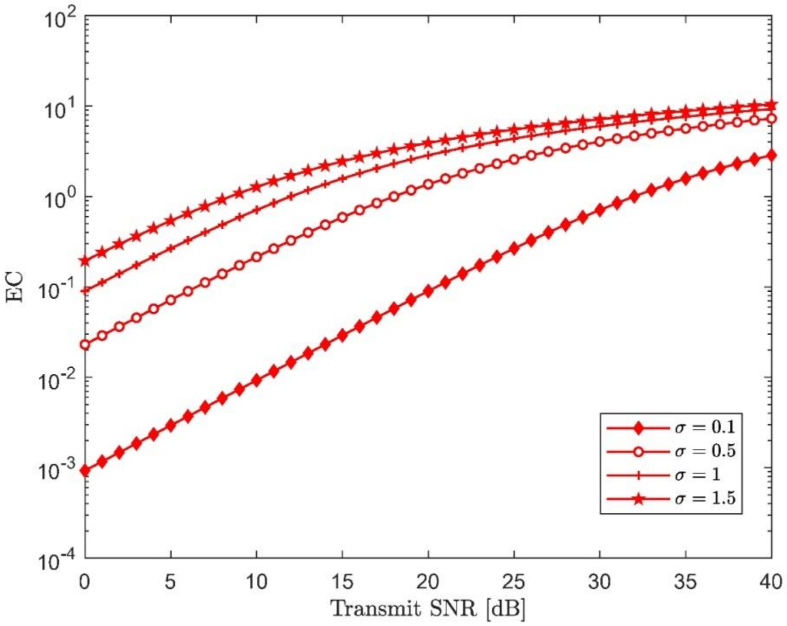

Figure 4.9. *The EC vs. the SNR for different values of* σ.

✓ *Impact of IRS-User Distance ($\mathbf{d}_{RU}$)*

The influence of the IRS-User distance d_{RU} on EC is shown in Figure 4.10. The plot compares scenarios with ($d_{SR} = 10, d_{RU} = 10$), ($d_{SR} = 10, d_{RU} = 30$), and ($d_{SR} = 10, d_{RU} = 60$). The y-axis is logarithmic, from 10^{-3} to 10^{1}. As d_{RU} increases, the EC decreases for any given transmit SNR. The best performance (highest EC) is achieved with the shortest d_{RU} (10 units), while the longest d_{RU}(60 units) results in the lowest EC. This is expected, as increased distance leads to higher path loss, a weaker received signal, and consequently, a lower achievable capacity.

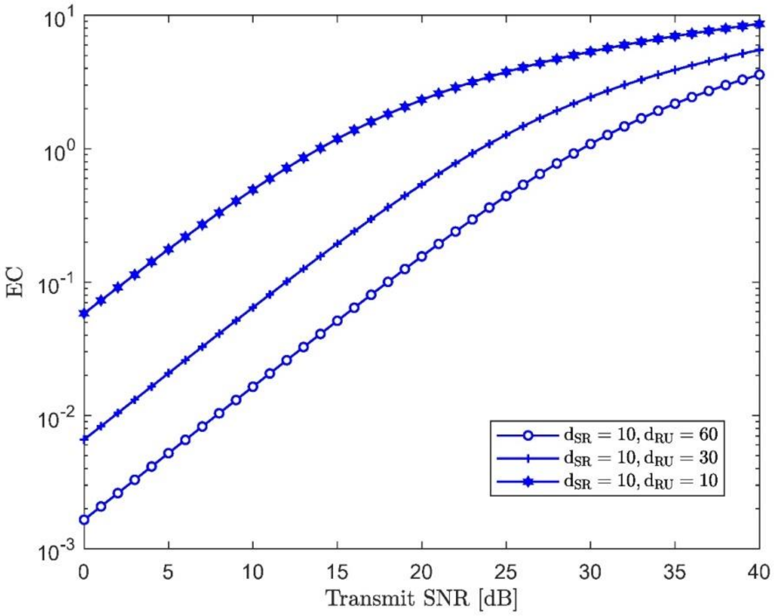

Figure 4.10. *The EC vs. the SNR for different values of* d_{sr}*and* d_{ru}.

✓ ***Impact of Combined Path Loss Coefficient (α)***

Figure 4.11 displays the EC for different values of the combined path loss coefficient $\alpha = 0.1, 0.5$, and 1. The y-axis is logarithmic, from 10^{-4} to 10^{1}. The EC increases as α increases for a fixed transmit SNR. A larger α implies better overall channel conditions (lower effective path loss), resulting in a stronger received signal and supporting higher ergodic capacity. The highest EC is observed for $\alpha = 1$.

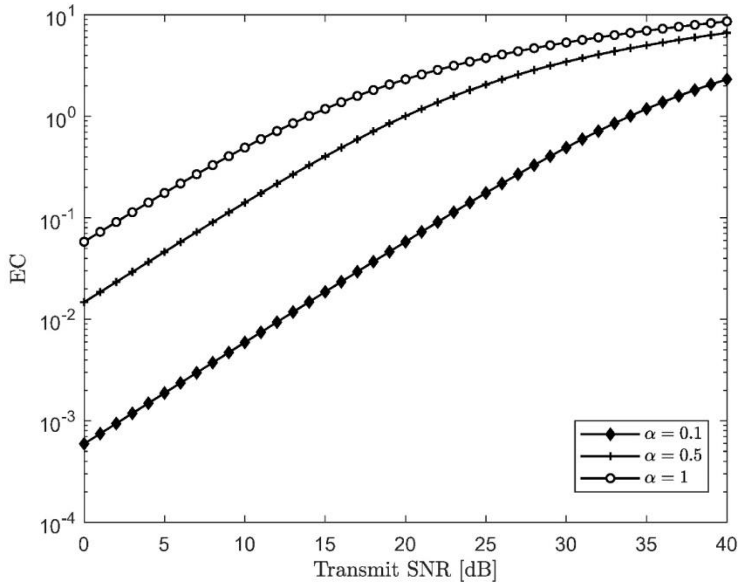

Figure 4.11. *The EC vs. the SNR for different values of* α.

For all investigated parameters concerning EC, the ergodic capacity consistently increases with the transmit SNR. This is because a higher SNR provides a greater potential for reliable high-rate data transmission. Factors that improve the effective channel strength, such as a larger N, stronger channel parameters (Ω, σ, α), or shorter distances, all contribute to an increased ergodic capacity.

4.4 Conclusion

This chapter analyzes the performance of the IRS-enabled network in terms of the OP, and the EC metrics considering the influence of various system parameters. The results show a strong dependence on these parameters, particularly the number of IRS elements.

4.5 References

[1] Makin, Madi, GalymzhanNauryzbayev, SultangaliArzykulov, and Mohammad S.Hashmi. "Performance of large intelligent surface-enabled cooperative networksover Nakagami-m channels." In 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), pp. 1-6. IEEE, 2021.

[2] Yang, Liang, et al. "Accurate closed-form approximations to channel distributions of RIS-aided wireless systems." IEEE Wireless Communications Letters 9.11 (2020): 1985-1989.

[3] Goldsmith, Andrea J., and Pravin P. Varaiya. "Capacity of fading channels with channel side information." IEEE transactions on information theory 43, no. 6 (1997): 1986-1992.

Conclusion

In conclusion, this thesis has presented a comprehensive analysis of the outage and ergodic performance of RIS-aided wireless networks. By dynamically adjusting the phase and amplitude of incident signals, the unique capabilities of reconfigurable intelligent surfaces (RISs) can be effectively utilized to enhance the overall transmission process.

This investigation demonstrates that reconfigurable intelligent surfaces (RISs) offer a promising approach to enhancing signal quality and reliability across diverse propagation environments. The findings reveal that incorporating RISs can significantly mitigate the adverse effects of fading, resulting in a notable reduction in outage probability. Moreover, the ergodic capacity analysis confirms that RIS-assisted networks can achieve higher data rates by effectively optimizing the wireless channel conditions.

The theoretical models and simulation results presented in this work underscore the potential of RIS technology in next-generation wireless networks. However, practical implementation challenges such as real-time configuration, hardware limitations, and system scalability need to be addressed in future research. Overall, the insights gained from this thesis contribute to the understanding and development of RIS-aided wireless systems, paving the way for more resilient and efficient communication networks.

Abstract

The increasing demand for high data rates, high-speed communication services and high coverage in the future wireless networks will bring challenges to wireless systems' design. One of the promising techniques to fulfill the requirements of future wireless networks is reconfigurable intelligent surface (RIS). This thesis investigates the outage and ergodic performance of RIS-enabled wireless communication systems. By examining the outage probability (OP) and ergodic capacity (EC) metrics, we evaluate the impact of various system parameters on network performance. Our study reveals that incorporating RIS significantly improves both metrics, which demonstrates its potential in improving the wireless communication process. Through extensive simulations, we show that the performance of the system is highly dependent on specific parameters, in particular the number of RIS elements. The results underscore the critical role of RIS configuration in achieving superior signal quality and network reliability, paving the way for advances in next-generation wireless communications networks.

خلاصة

يشكّل الطلب المتزايد على معدلات نقل البيانات العالية، وخدمات الاتصالات فائقة السرعة، والتغطية الواسعة تحديًا كبيرًا في تصميم الشبكات اللاسلكية المستقبلية. وتُعد تقنية السطح الذكي القابل لإعادة التشكيل (RIS) من أبرز الحلول الواعدة لتلبية هذه المتطلبات. تتناول هذه الأطروحة دراسة أداء أنظمة الاتصالات اللاسلكية المدعومة بتقنية RIS ، من خلال تحليل مقاييس احتمالية الانقطاع (OP) والسعة المريحة(EC) ، بهدف تقييم تأثير المعلمات المختلفة للنظام على كفاءة الشبكة. وقد أظهرت نتائج الدراسة أن دمج تقنية RIS يساهم بشكل ملحوظ في تحسين كلا المقياسين، مما يؤكد فعاليتها في تعزيز جودة الاتصال اللاسلكي. كما توضح عمليات المحاكاة الموسعة أن أداء النظام يتأثر بدرجة كبيرة ببعض المعلمات، وعلى وجه الخصوص بعدد عناصرRIS .وتؤكد النتائج على الأهمية البالغة لتكوين RIS الأمثل في تحقيق جودة إشارة عالية وموثوقية أكبر للشبكة، مما يمهّد الطريق نحو تطوير شبكات الاتصالات اللاسلكية للجيل القادم.

Résumé

La demande croissante en débits de données élevés, en services de communication à très haut débit et en couverture étendue représente un défi majeur pour la conception des futurs systèmes sans fil. Parmi les solutions prometteuses pour répondre à ces exigences, les surfaces intelligentes reconfigurables (Reconfigurable Intelligent Surfaces, RIS) se démarquent par leur potentiel. Ce mémoire examine les performances en termes de probabilité de panne (outage) et de capacité ergodique des systèmes de communication sans fil assistés par des RIS. À travers l'analyse des indicateurs OP (Outage Probability) et EC (Ergodic Capacity), nous évaluons l'impact de différents paramètres système sur les performances globales du réseau. Les résultats obtenus montrent que l'intégration des RIS permet une amélioration significative de ces deux indicateurs, mettant ainsi en évidence leur efficacité dans l'optimisation des communications sans fil. Des simulations approfondies démontrent également que les performances du système sont fortement influencées par certains paramètres, en particulier le nombre d'éléments constituant la surface RIS. Ces observations soulignent l'importance cruciale d'un bon paramétrage des RIS pour garantir une qualité de signal optimale et une fiabilité accrue du réseau, ouvrant ainsi la voie au développement des réseaux de communication sans fil de nouvelle génération.