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Intitulé

On the outage and ergodic performance of RIS-aided wireless systems

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Dedications

After an academic journey that carried with it fatigue and joy, here I am standing on the threshold of graduation. Thank Allah for the opportunity to begin and reach endings. I dedicate my success to the one whose name I carry with pride, to the one who supported me and inspired me to continue my path, and made adversity easier for me with her prayers, to the lamp that illuminated the path for me, my mother. Dear, to the one who strived all his life to be better than him, to the one who supported me without limits and gave me for nothing in return, my dear brother, Amine.

To my best and brightest days, to those who supported me, to those who showered me with love and appreciation, to those who were the shadow of my success, my brothers Siham, Amine, and Yaakoub, and my cousin, Donia Redaoui, who always encouraged me, to my friends from near and far.

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To my brother's wife, Awatif Maatougui, and my brother's fiancée, Romaissa Bouzrida

To my dear grandfather, may God enlighten his grave, Hajj Aissa Redaoui

To the people of Gaza and its valiant resistance that seeks freedom…. To the depleted people of Gaza.

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R.Maatougui

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List of abbreviations

0G	Zeroth Generation
1G	First Generation
2D	Two Dimensions
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
6G	sixth Generation
IRS	intelligent reflecting surfaces
MIMO	Multiple Input Multiple Output
GPS	global positioning system
(FDX)	A full-duplex system allows communication in both directions
p-2-p	point-to-point
ITU	International Telecommunication Union
Gbps	Gigabit Per Second
LTE	Long Term Evolution
WIFI	Wireless fidelity

Introduction

In our modern world, wireless communications have become an integral part of our daily lives, providing us with the means to communicate and transfer data in ways that were unimaginable in the past. Wireless systems are also witnessing continuous development, but the basic challenges that still prevail, which are represented by a large energy consumption of communications in addition to a wireless environment that we cannot predict in reality, and the inability to control the wireless environment has always been one of the biggest problems facing us. As technology develops, wireless networks have become more complex and efficient, prompting researchers to explore new ways to improve their performance. One such method is to use reconfigurable smart surfaces (RIS) to enhance the performance of wireless networks.

Reconfigurable smart surfaces (RIS) potentially address the unpredictability of this wireless environment.

The concept of wireless communications and its importance:

Communications is the process of exchanging information between two or more parties. In a wireless context, this process occurs without the need for physical connections, providing greater flexibility and mobility. By eliminating the need for cables, installation and maintenance costs are reduced, and mobile users are supported, leading to the proliferation of mobile devices and the Internet of Things.

The goal of this project is

Performance analysis of wireless networks supported by reconfigurable smart surfaces (RIS) by evaluating service outage probability and rest rate or studying the effect of using reconfigurable smart surfaces on the performance of wireless systems in terms of connection dropouts and ergonomic performance. This research provides a comprehensive analysis of how these surfaces improve the performance of wireless networks, paving the way for their wider use in 5G applications and beyond.

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 IRS-aided wireless network.

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

Chapter 1

Some basics of cellular networks

Cellular networks 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, cellular networks rapidly evolved into a complex system capable of efficiently delivering mobile communication services with comprehensive coverage. Cellular networks are widely used in everyday life, whether for voice calls, data transmission, or even wireless internet technologies. The success of these networks relies on several factors, including efficient use of wireless frequencies and providing adequate service coverage. This reflects the continuous advancement in this field and the increasing need to improve the performance and expand the coverage to meet the growing demands for wireless communications in this digital world.

1.1 A brief history of wireless communications

Wireless communication technology plays a crucial role in various aspects of our daily lives. It is an integral component of essential devices such as telephones, radios, the internet, and smartphones. All of these rely on some form of wireless technology for their functionality [1]. One of the earliest methods of wireless transmission can be traced back to ancient China, where smoke signals were employed as a means of communication. Guardians stationed along the great wall would ignite smoke signals to notify nearby towers of impending attacks. Smoke signals had the remarkable ability to be visible from a distance of approximately 300 miles, enabling towers to receive timely alerts [2]. In 1880, 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, the photo phone transmitted sound through light [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 wireless communication [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 transmission 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 as television, radio, internet, and navigation systems like the global positioning system (GPS). Other wireless technologies include WiFi, 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.

However, a notable drawback is the potential for interference between wireless connections, which can affect the quality and reliability of the transmission [1]. It is evident that our reliance on wireless transmission has become increasingly significant in today's technological advancement.

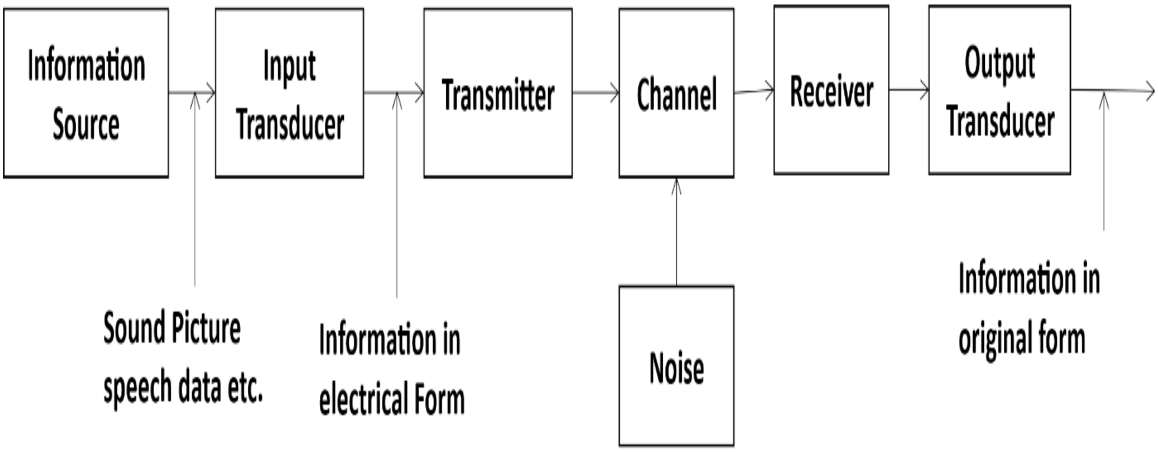


FIGURE 1.1 – A block diagram for a generic wireless communication system.

1.2 What exactly communication is and what’s the benefit to be wireless?

Communication is the fundamental process of exchanging information. It can be classified into two main categories: wired communication and wireless communication. Wired communication utilizes cables as the medium to transmit information from a source to a destination [1]. Wired Communication offers the potential to handle numerous tasks. 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 [3], [1]. So, in order to overcome the problems encountered by wired communication, wireless communication has been used.

The introduction of Wireless Communication has brought about increased mobility and global connectivity. This form of communication enables the transfer of information from a source to a destination without the need for any physical medium [2]. Wireless Communication 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, wireless communication incurs minimal loss to the communication infrastructure compared to wired Communication [3]. The figure below shows the block diagram of a wireless communication system. The initial component in the communication system is the source, which generates the message signal. This message signal can take the form of non-electric data, which is then converted into an electrical signal using a transducer. For instance, a microphone converts our voice into an electrical signal. The next component is the transmitter, responsible for various signal processing tasks such as restricting the range of audio frequencies, signal amplification, and modulation. The channel represents the medium through which the message travels from the transmitter to the receiver. However, unwanted signals, known as noise, can interfere with the desired signal during transmission. The receiver block is responsible for reproducing the message signal in its electrical form. Finally, the output transducer block serves as the last stage, converting the received electrical message signal back into its original form.

1.3 Some concepts of cellular networks?

Cellular networks are the foundation of mobile wireless communications, supporting users in locations not easily served by cable networks. They are the underlying technology for mobile phones, smartphones, tablets, wireless Internet, and applications.

1.4 Overview of cellular networks

1.4.1 Organization of cellular networks

The essence of a cellular network is the use of several transmitters of low power, of the order of 100 W or less, or even much less. Like the scope of such a transmitter is weak, an area can be divided into cells, each served by its own antenna. Each cell is assigned a band of frequencies and is served by a base station, consisting of a transmitter, a receiver and a control unit. Adjacent cells are assigned different frequencies to avoid interference or crosstalk. However, cells far enough apart from each other can use the same frequency band.

1.4.2 Propagation effects in mobile radio communications

Mobile radio communication introduces complexities not found in wired communication or in fixed wireless communication. Two areas General concerns are signal strength and propagation effects of the signal:

- Signal strength: the signal strength between the base station and the mobile unit must be strong enough to maintain the signal quality at the level of the receiver, but not to the point of creating too much interference in the same channel with the channels of another cell using the same frequency band. Several complicating factors exist. Human-made noise varies considerably, resulting in a variable noise level. For example, the sound of an automobile ignition in the frequency range cellular is more important in the city than in the suburbs. Others Signal sources vary from location to location. Signal intensity varies depending on the distance between the BS and a point inside its cell. Additionally, the signal intensity varies dynamically as the mobile unit moves due to concealment of obstacles and geography
- Fading: even if the signal strength is within an effective range, signal propagation effects may disrupt the signal and cause errors.

1.4.3 Power control in a cellular network

A number of design issues make it desirable to include dynamic power control capability in a cellular system:

- The power received must be sufficiently higher than the background noise to effective communication, which dictates the required transmitted power. As the mobile unit moves away from the transmitter, the received power decreases due to normal attenuation. Furthermore, the effects of reflection, diffraction and scattering can cause rapid changes in power levels received over small distances. Indeed, the level of power is the sum of signals coming from a number of paths different and the phases of these paths are random, adding up sometimes and sometimes evading. As the mobile unit becomes moves, the contributions along various paths change.

- At the same time, it is desirable to minimize the signal power transmitted by the mobile unit, to reduce co-channel interference (interference with channels on the same frequency in cells remote), alleviate health problems and save energy in the battery.
- In spread spectrum (SS) systems using an access multiple code division (code division multiple access (CDMA)), it is desirable to equalize the received power level at the BS of all mobile units when signals arrive. This is crucial for system performance because all users have the same attribution frequency.

1.4.4 The global cellular network

The cellular revolution is manifested in the growth of the mobile phone market alone. mobile telephony. In 1990, the number of users was around 11 million [6]. There are several reasons for the predominance of mobile devices. Electronics mobiles are practical; they move with people. Furthermore, by their nature, they are aware of location. Mobile cellular devices communicate with regional base stations located at locations fixed. In many geographic areas, mobile phones are the only economical way to provide telephone service to the population. Operators can erect base stations quickly and inexpensively cost compared to digging into the ground to lay cables in difficult terrain. Today, there is no single cellular network. The devices support supports multiple technologies and generally only works within the limits of the network of a single operator. To go beyond this model, researches are underway to define and implement standards. The dominant first-generation wireless network in North America was the Advanced Mobile Phone System (AMPS). The main wireless systems of second generation are the global mobile communications system (Global System for Mobile Communications (GSM)), the communications service Personal Communications Service (PCS) IS-136 and PCS IS-95. The PCS IS-136 standard uses time division multiple access (time division multiple access (TDMA)); GSM uses a combination of TDMA and frequency division multiple access (FDMA)) and IS-95 uses code division multiple access (code division multiple access (CDMA)). 2G systems mainly provide services voice, but also provide moderate speed data services. The two main third generation systems are CDMA2000 and Universal Mobile Telephone Service (UMTS). Both use CDMA and are intended to provide packet data services. CDMA2000 released 1xRTT (1 time radio transmission technology) then 1xEV-DO (1 time Evolution-Data Only) via version 0, revision A and revision B. Competing UMTS uses broadband CDMA. It is developed by the Third Generation Partnership Project (3GPP); its first version was labeled Release 99 in 1999, but the Subsequent releases were labeled Releases 4 and later. The move to the fourth generation mainly involved competition between IEEE 802.16 WiMAX and Long-Term Evolution (LTE). Both use a different approach from CDMA for high spectral efficiency in a channel wireless called orthogonal frequency division multiplexing (orthogonal frequency division multiplexing (OFDM)). 4G requirements arise from guidelines of the International Telecommunications Union (ITU), according to which 4G networks must provide all-IP services at peak data rates of up to approximately 100 Mbps for high mobility mobile access and up to approximately 1 Gbps for low mobility access. LTE, also developed by 3GPP, has become the predominant technology for 4G, and 3GPP Release 8 was its first release. Although LTE version 8 does not meet ITU requirements (even if marketers called it "4G LTE"), the latest version 10 achieved the objectives and is called LTE-Advanced [7].

1.5 5G radio access

Fifth generation (5G) mobile communication is expected to significantly expand the capabilities of mobile networks. New technologies and Features are being introduced for 5G systems in various areas: access wireless, transportation, cloud, applications and management systems [8]. These advances target traditional mobile broadband users as well as mobile broadband users emerging machine type, so that new superior services can be activated for consumers and industries in general, freeing the potential of the Internet of Things (IoT) and virtual and augmented. Reality. According to a recent survey carried out in 10 different industries [7], global revenues generated by 5G technologies will reach $1.3 trillion by 2026. It is estimated that by 2023 there will be around 3.5 billion IoT connections cellular [8]. The backbone of any mobile communications system is its access technology wireless, which connects devices to radio base stations. Like almost all companies and industries are eagerly awaiting the 5G revolution with its specific set of requirements, the design of 5G wireless access is a challenge. 5G wireless access technology expected to deliver extreme data rates, ubiquitous coverage, ultra-reliability, very low latency, high energy efficiency and a massive number of heterogeneous connections. Emerging human-centered applications include augmented reality, virtual reality and online games, which require extreme throughput and low latency. For machine type communication, there are two main segments: massive IoT and critical IoT. Massive IoT is characterized by a number high level of low-cost device connections, supporting small volumes of data per device with long battery life and coverage extended (e.g. for underground and remote areas). Applications relate to smart buildings, public services, transport logistics, agriculture and fleet management. Critical IoT is characterized by ultra-reliable and ultra-low latency connectivity, for example to support charges autonomous vehicles, smart grids, surgery robotics, road safety and industrial control.

1.6 Conclusion

wireless communications have evolved significantly since their inception in the late 19th century. Advancements in technology have led to the development of mobile phones, communication networks, and fifth-generation (5G) networks. The benefits of wireless communication include flexibility, mobility, and freedom from cables. Cellular networks play a crucial role in providing effective coverage through the use of base stations and a hierarchical structure. The propagation effects in mobile radio communications, power control, and the global cellular network have all contributed to the efficiency and effectiveness of wireless communication. With 5G radio access, users can expect high speeds, low latency, and high connection density, highlighting the continuous innovation and improvement in wireless communication technologies.

1.7 References

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

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

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

[4] Lakshmanan, Madan Kumar, and Homayoun Nikookar. "A review of wavelets for digital wireless communication." Wireless personal communications 37 (2006): 387-420.

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

[6] Collins II, Jeffrey, Suku Nair, and Krish Prabhu. "5G deployment considerations to enable consumer innovation." In 2021 IEEE International Conference on Consumer Electronics (ICCE), pp. 1-6. IEEE, 2021.

[7] Pätzold, Matthias. "Fifth-generation technology offers trillion-dollar business opportunities [mobile radio]." IEEE Vehicular Technology Magazine 12, no. 3 (2017): 4-11.

[8] Ericsson mobility report. https://www.ericsson.com/assets/local/mobilityreport/documents/2018/ericsson-mobility-report-june-2018.pdf , June 2018.

Chapter 2

Relay-aided cooperative communications

This chapter discusses communication systems utilizing relays, focusing on cooperative communications' foundations, application scenarios, advantages and disadvantages, and various relaying protocols.

Introduction

Relay-aided cooperative communications have emerged as a promising technique to improve the performance and reliability of wireless communication systems. Traditional point-to-point communication schemes face challenges such as fading channels, coverage limitations, and signal attenuation over long distances. In relay-aided systems, intermediate nodes, called relays, assist in transmitting signals from the source to the destination, effectively extending the communication range and enhancing reliability. Additionally, the network spectral efficiency offered by relay-assisted systems depends on the duplexing protocol used for transmission. If a protocol half duplex (HD) relay is used, transmitters and relays are not allowed to be transmitted simultaneously on the same physical resource. This problem can be solved using a full duplex (FD) relay protocol, but at the cost of: (i) the introduction of high loopback self-interference at the relay due to the simultaneous transmission and reception of signals; (ii) generate co-channel interference at the destination, because relays and transmitters transmit different information on the same physical resource; and (iii) increase the complexity of signal processing and power consumption Relays. The relays are therefore used adaptively, depending on channel and interference conditions, to improve the performance of the network [1].

2.1 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. 2.1. The source node S wishes transmit information to the destination node D and the relay node R assists Communication.

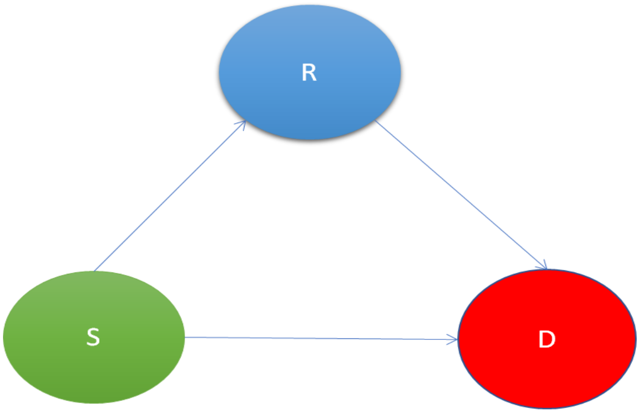
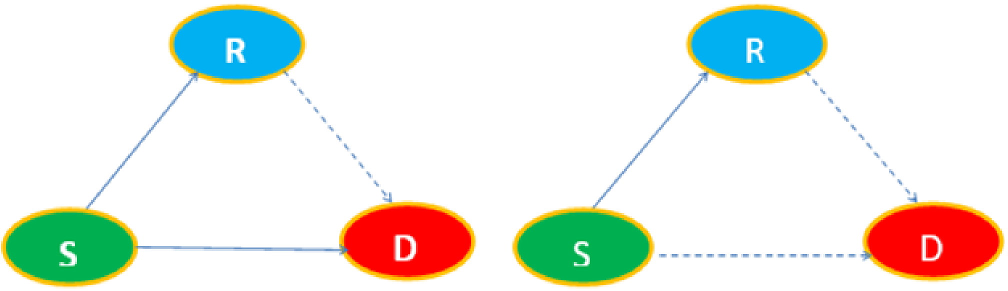
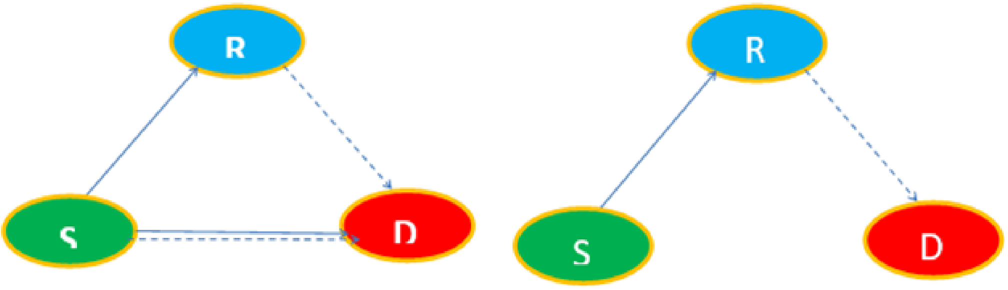


FIGURE 2.1– Relay-assisted communication scheme [15].

In general, communication between devices can be full duplex or half-duplex. In full duplex communication, a node can receive and transmit data at the same time or in the same band; In half-duplex communication, a node cannot transmit and receive in same time or in the same band. [2].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 (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 Fig. 2.2 where the lines 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:



(a) Protocol I. (b) Protocol II.



(c) Protocol III. (d) Protocol IV.

FIGURE 2.2 – Semi-duplex relay protocols in a three-node scenario [2].

- ✓ 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 Fig. 2.2(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 Fig. 2.2(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 Fig. 2.2(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 Fig. 2.2(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 [3]. 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 maximizes 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 Fig. 2.3, can be summarized as follows:

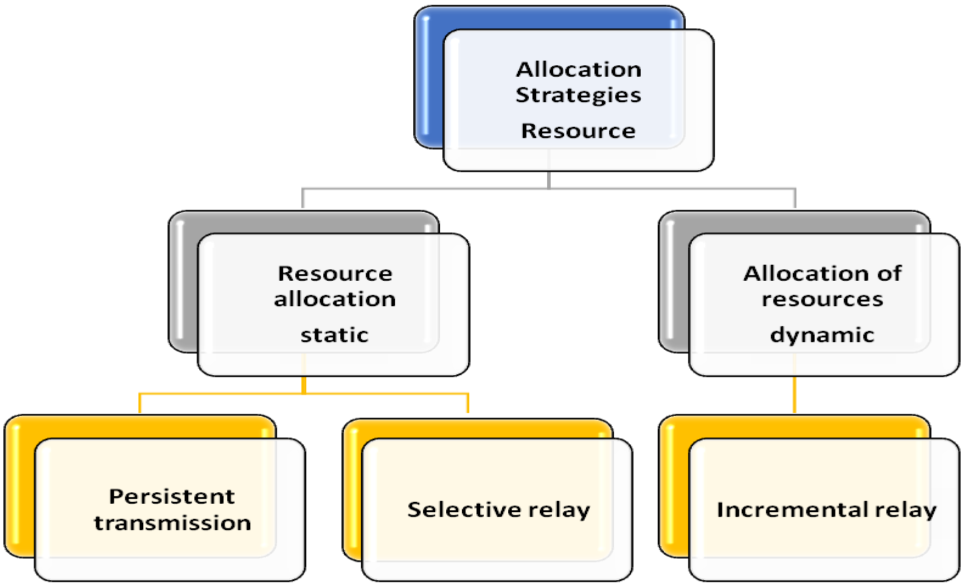


FIGURE 2.3 – Resource allocation strategies in assisted communication by relay [15].

- **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 [2].

TABLE 2.1 – Relay level retransmission schemes for different protocols

Allocation relay static resources	Half-duplex relay protocols			
	Protocol I	Protocol II	Protocol III	Protocol IV
Persistent transmission	✓	✓	✓	✓
Selective relay	✓	✓	✓	×
Incremental relay	✓	×	✓	×

- **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 is received by mistake. The different retransmission schemes at the relay level for the protocols available half duplex (HD) are shown in Table 2.1.

2.2 Some application scenarios

Cooperative communications play a vital role in many scenarios of application and overcome problems related to communication by direct connection [4]. Cooperation between nodes is beneficial in several practical applications, ranging from cellular networks to networks of wireless sensors, as shown in Figs. 2.4-2.9. Indeed, the use of relay can provide a solution to network problems that are caused by limited resource usage in terms of bandwidth and power [15]**.**

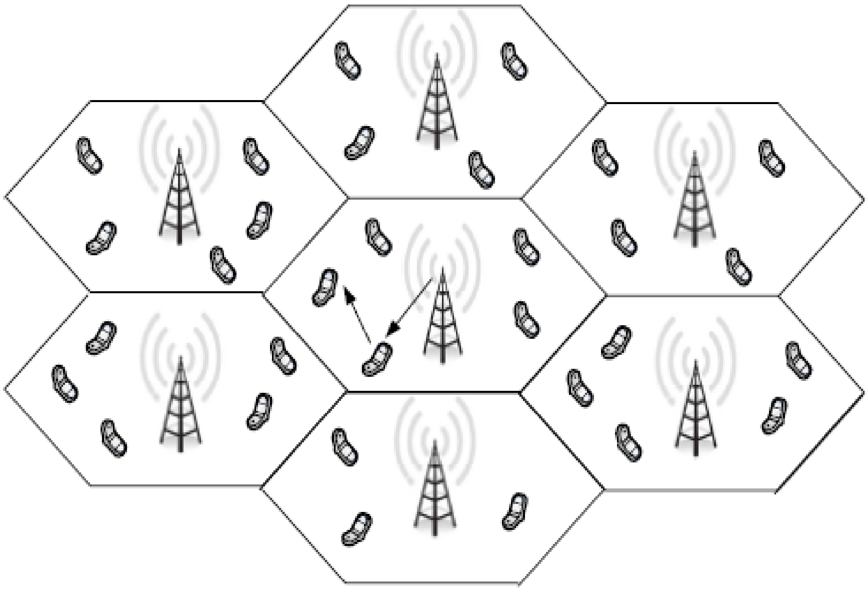


FIGURE 2.4 – Cellular scenario: the relay improves user performance in terms of capacity, coverage or interference [15].

2.2.1 Cellular networks

Cellular networks are a typical scenario, which are limited in resources per cell. By increasing the number of users per cell, resources are unable to satisfy user demand; by Consequently, the cellular capacity offered becomes insufficient and the power limit transmitted is reflected on the coverage. In addition, inter- and intracellular are detrimental performance factors. The problems capacity, coverage and interference can be reduced using communications assisted by relays, where cooperative transmission helps the connection directly to ensure better performance. Figure 2.4 shows an example of cooperative cellular networks, where coverage of the network is improved, particularly at the periphery of the cell. Indeed, in this part of the cell, the signal received from the base station is characterized by a low SNR [5]. By using relay-assisted communication, the area of total coverage of the cell increases thanks to the strong signal that the mobile station receives from the relay station. In addition, improving signal quality for the user located at the periphery of the cell leads to a reduction in resources required from the base station.

2.2.2 Wireless local networks (WLANs)

Wireless Local Area Networks (WLANs) take support network communication over short 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. Figure 2.4 shows an example of WLAN with home WLAN access points and users located on the street and in the house. In particular, the home access point can communicate with a user on the street using of another user who provides communication assisted by relay [15].

2.2.3 Vehicle-to-vehicle (V2V) communications

However, vehicle-to-vehicle (V2V) communication systems are a type of networks where vehicles communicate with each other them to exchange information, as shown in Fig. 2.6. In a scenario urban and suburban, this type of cooperative communication can bring very significant advantages for reducing traffic, security and parking problems. Data from vehicles and infrastructures and their interactions improve mobility management and influence both the economic and social development of the country. This cooperative approach offers high bond stability and can be more effective in avoiding accidents and traffic jams [15].

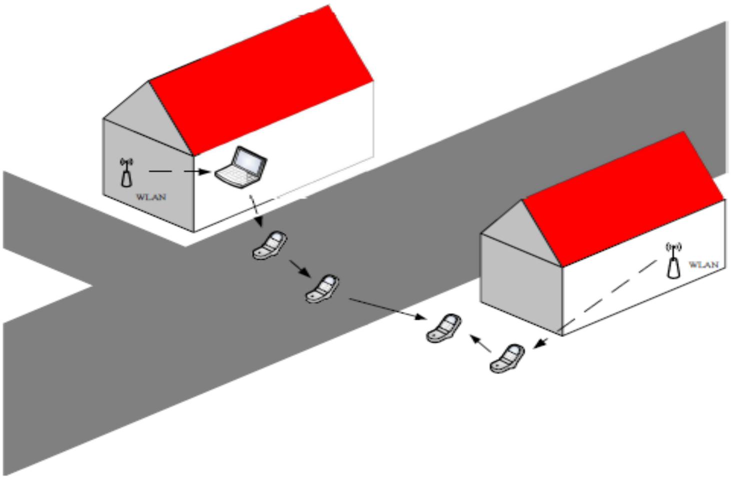


FIGURE 2.5 – A WLAN station installed inside a house provides access to users on the street via relays [15].

2.2.4 Wireless sensor networks (WSN)

Wireless sensor networks (WSN) must be properly designed to maximize the lifespan of the network, ensuring efficient communications between sensor nodes. In fact, the main problem of these networks is the limited battery power of the sensor nodes. Also in this scenario, relay-assisted communications are beneficial to maintain network integrity, avoiding performance degradation. Figure 2.7 shows an example of a cooperative WSN, where nodes sensors are limited in coverage [15]**.**

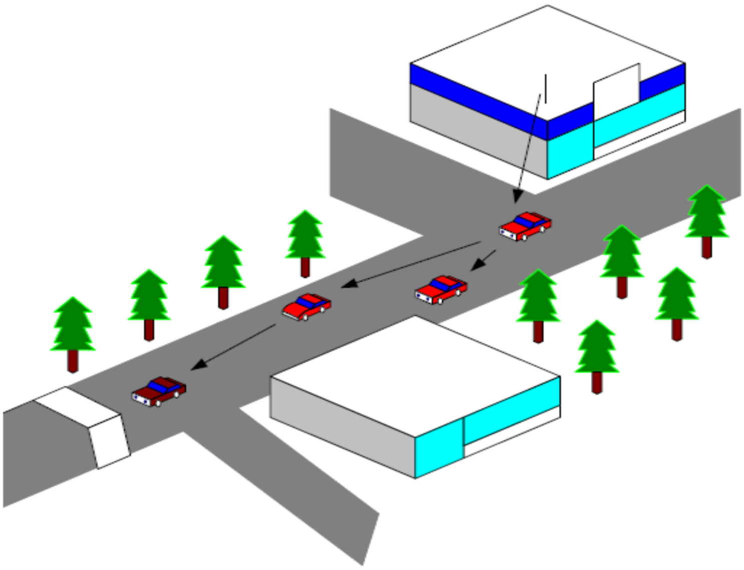


FIGURE 2.6 – Distributed V2V communication scenario, where vehicles cooperate to reduce communication delays [15].

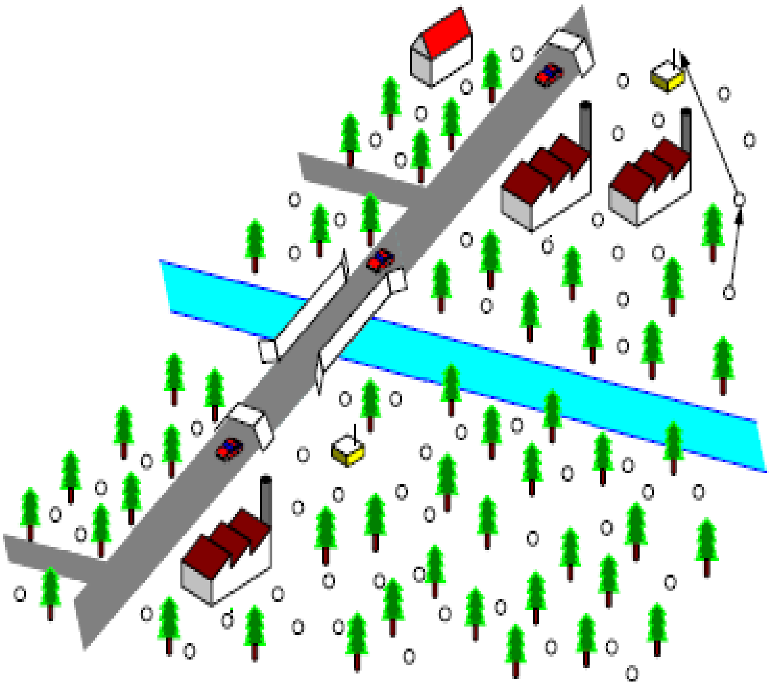


FIGURE 2.7 – WSN scenario, where sensors cooperate to obtain a better coverage

[15].

2.2.5 Network location

Many applications require knowledge of the node position to know where data is collected to perform data analysis or to determine the actions to be taken. Traditional methods node location includes attaching a GPS receiver (Global Positioning System (GPS)) in each node or manual configuration of the position of each node. By increasing the scale of networks, these methods become unfeasible due to their high cost and inconvenience. THE localization algorithms use special nodes, called anchor nodes, who know their positions to facilitate the determination of positions other nodes (called common nodes). An emerging paradigm is cooperative localization, in which nodes help each other to determine their locations. Cooperative localization has attracted keen interest from robotics, optimization and wireless communications communities wire [6], [7], [8], [10]. Figures. 2.8 and 2.9 show a simple example to compare localization conventional and cooperative. A non-cooperative device can recover information from a single base station. This information could be used to determine an area where the mobile may be located. That means that, taking into account the power of the signal received. We assume that the mobile found in a certain area defined by a certain level, as shown Fig. 2.8. In cellular networks, a typical structure environment is the tri-sector, also known as the trefoil, which is made up of three sectors, each served by a separate antenna. Each sector has a pursuit direction distinct from 120 compared to adjacent sectors. He is therefore possible to define a more precise location area. In a scenario cooperative, two cell phones can send their information in using short-range communication technology. By exploiting the information received, the location area is now given by the intersection zones individualized by each information exchanged by cooperating, as the shows Fig. 2.9.

In general, cooperative localization can significantly increase localization performance in terms of accuracy and coverage [15].

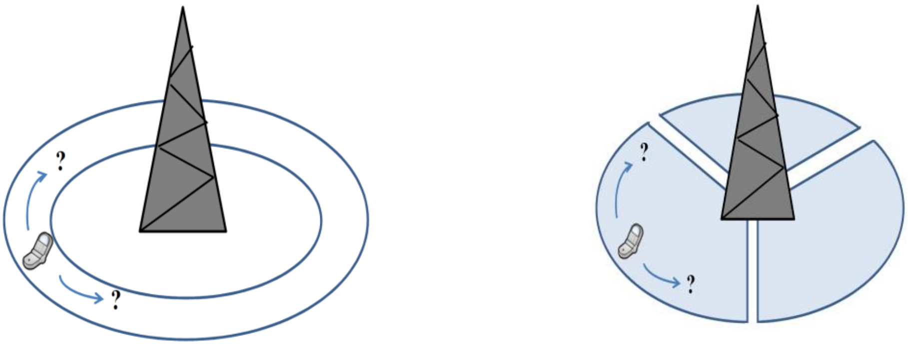


FIGURE 2.8 – An area where it is more likely to find a mobile device if the cooperation is not used [15].

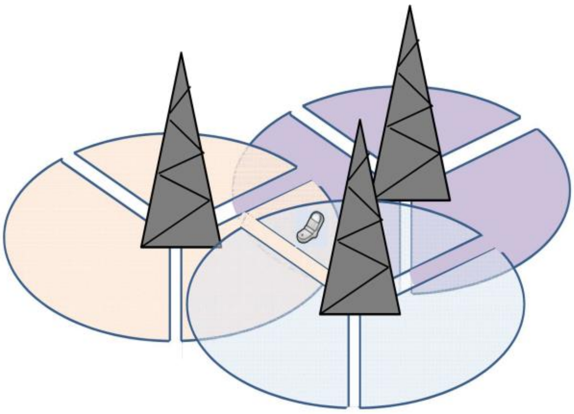


FIGURE 2.9 – An area where it is more likely to find the mobile device if the cooperation is used [15].

2.3 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 [10]. 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:

- 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.

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 [16].

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 2.10 shows these trade-offs and provides at-a-glance system design parameters to optimize. In particular, a good choice takes into account the following aspects:

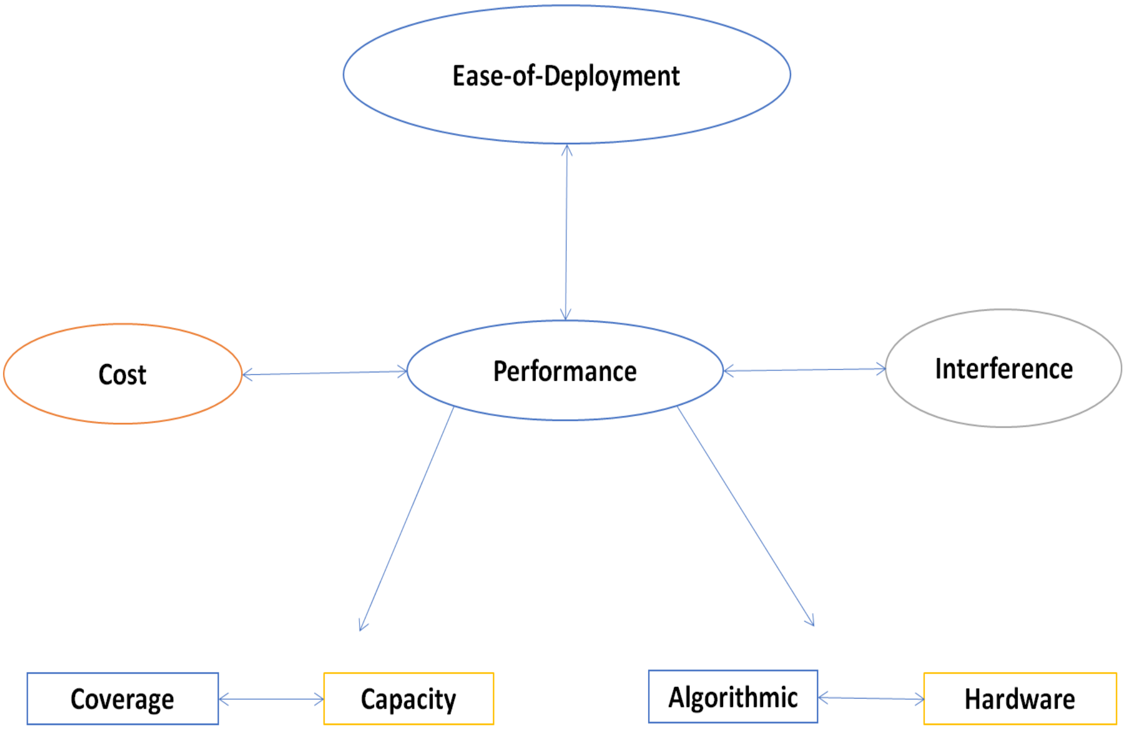


FIGURE 2.10 – At a given performance level, coverage can be traded capacity and algorithmic with hardware complexity. Performance can also be traded against amount of interference, ease-of-deployment and cost [16].

- 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 a 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 [16].

2.4 Cooperative Performance Bounds

This section discusses the potential of cooperative relaying systems, focusing on achievable performance bounds. Capacity bounds indicate a scheme's performance, impacting hardware and OSI stack protocol design. The book also discusses achievable rate gains, outage probability gains, and DMT in cooperative systems, without going into great mathematical detail [16].

2.4.1 Capacity Gains

Shannon's theory demonstrates that codes with a communication rate of R bits/symbol can be designed with arbitrarily small error, even for infinite duration codes. The maximum data rate for reliable communication is called the channel's capacity, which is determined by signal and noise power.

$$\mathrm{C} = \log 2\left(1 + \frac{\mathrm{S}}{\mathrm{N}}\right) \tag{2.1}$$

which has been normalized by the bandwidth W; the units are hence [C] = bits/s/Hz. Signals, however, typically traverse a wireless channel that impacts the received signal power S and hence the capacity offered by such a channel. Whilst the deterministic effect of pathloss only scales the useful signal power. In Equation (2.1), the randomness introduced by the wireless channel changes the capacity since the useful signal power effectively varies over the duration of the transmitted codeword. Depending on the type of channel variations, one typically distinguishes ergodic and nonergodic fading channels [16].

2.4.1.1 Ergodic Channel

A channel characteristic typically assumed in the context of Shannon capacity is that of an ergodic channel. Rigorously speaking, a process is ergodic if the time averages may be used to replace ensemble averages. In more practical terms, this means that the channel varies sufficiently rapidly over the duration of the transmission and hence traverses all fading states.

Ergodicity allows one to apply the concept of averages since the channel's average mutual information over all (infinitely long codewords) is the same. This means that an ergodic channel can support the following maximum error-free transmission rate with 100% reliability

$$\mathrm{C} = \mathrm{Eg}\left\{\mathrm{log2}(1 + \mathrm{g}\frac{\mathrm{S}}{\mathrm{N}})\right\} \tag{2.2}$$

where g is the instantaneous channel gain/power and $\mathrm{Eg}\cdot$ denotes the expectation operator. The random channel fluctuation g may comprise the effects of fading and shadowing but typically only includes fading due to shadowing as being a fairly slowly varying effect. The notion of an ergodic channel $\mathrm{w.r.t.}$ two transmitted codewords of infinite duration is illustrated in Figure 2.11.

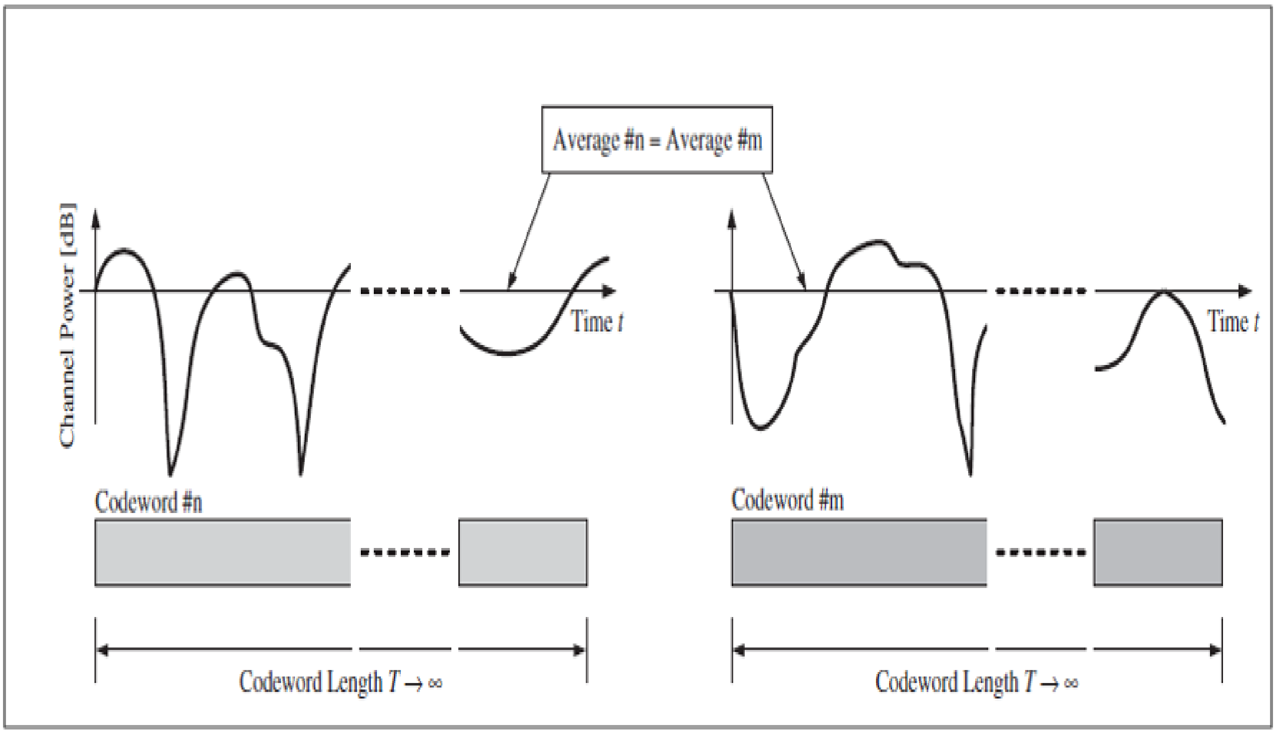


Figure 2.11 shows that in an ergodic channel, all fading states are traversed over a Shannon codeword duration, thereby ensuring an average channel capacity [16].

2.4.1.2 Capacity Gains

The analysis in illustrates the capacity gains of simple cooperative relaying schemes assuming Rayleigh fading channels, as shown in Figures 2.12 and 2.13, with symmetric communication scenarios and significantly better average fading power between nodes. [15]**.**

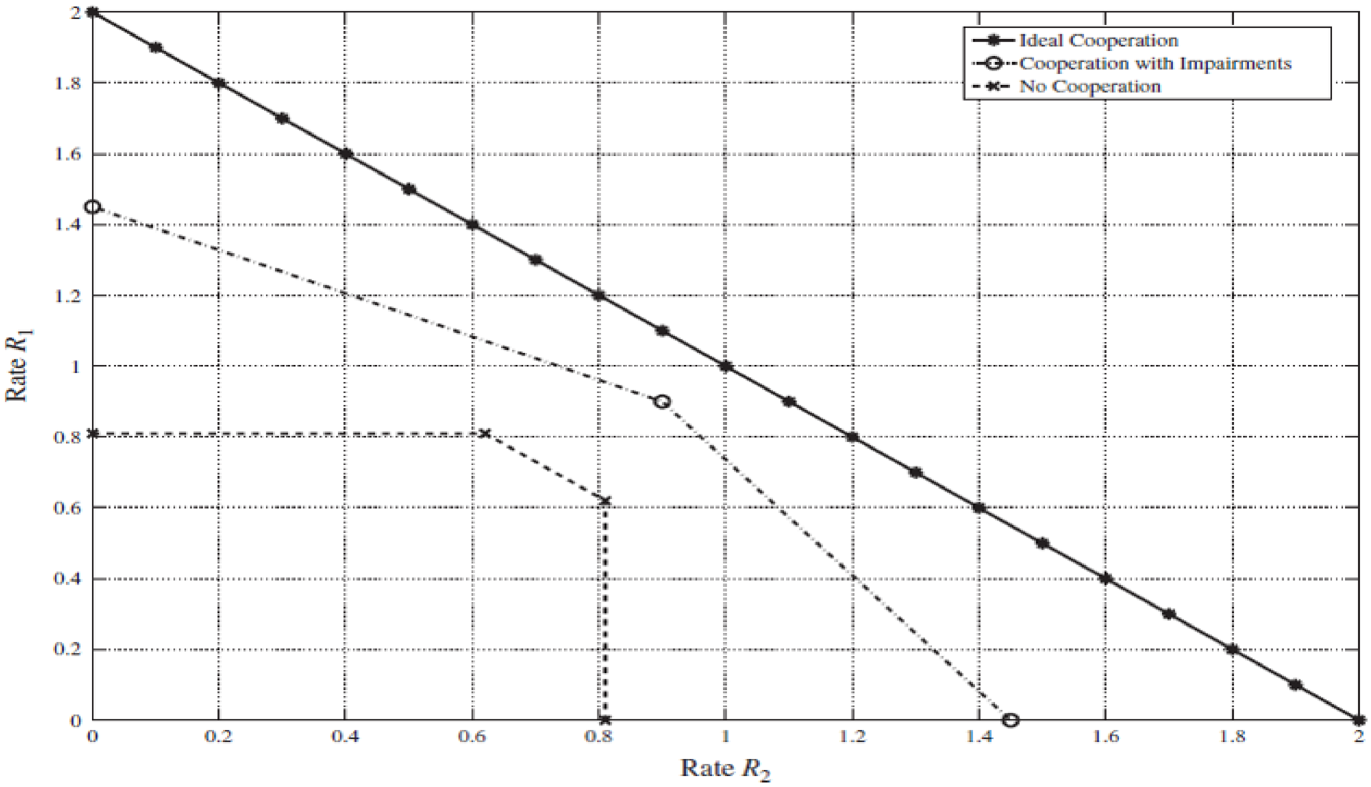


Figure 2.12 illustrates a symmetric rate region where both users have equal channel conditions to the destination, assuming no cooperation, ideal cooperation with error-free inter-user channels, and cooperation with good inter-user channels [14].

The ideal cooperation scenario involves a noiseless inter-user channel, with no cooperation resulting in multiple access channels. As the inter-user channel degrades, performance approaches no cooperation. Key points of interest include Equal Rate Point $(R1 = R2)$, which indicates equal priority for both users, and Maximum Rate Sum Point $(\max(R1 + R2))$, which indicates the total system capacity's importance, yielding a maximum rate sum gain of 20% and 10%, respectively [16].

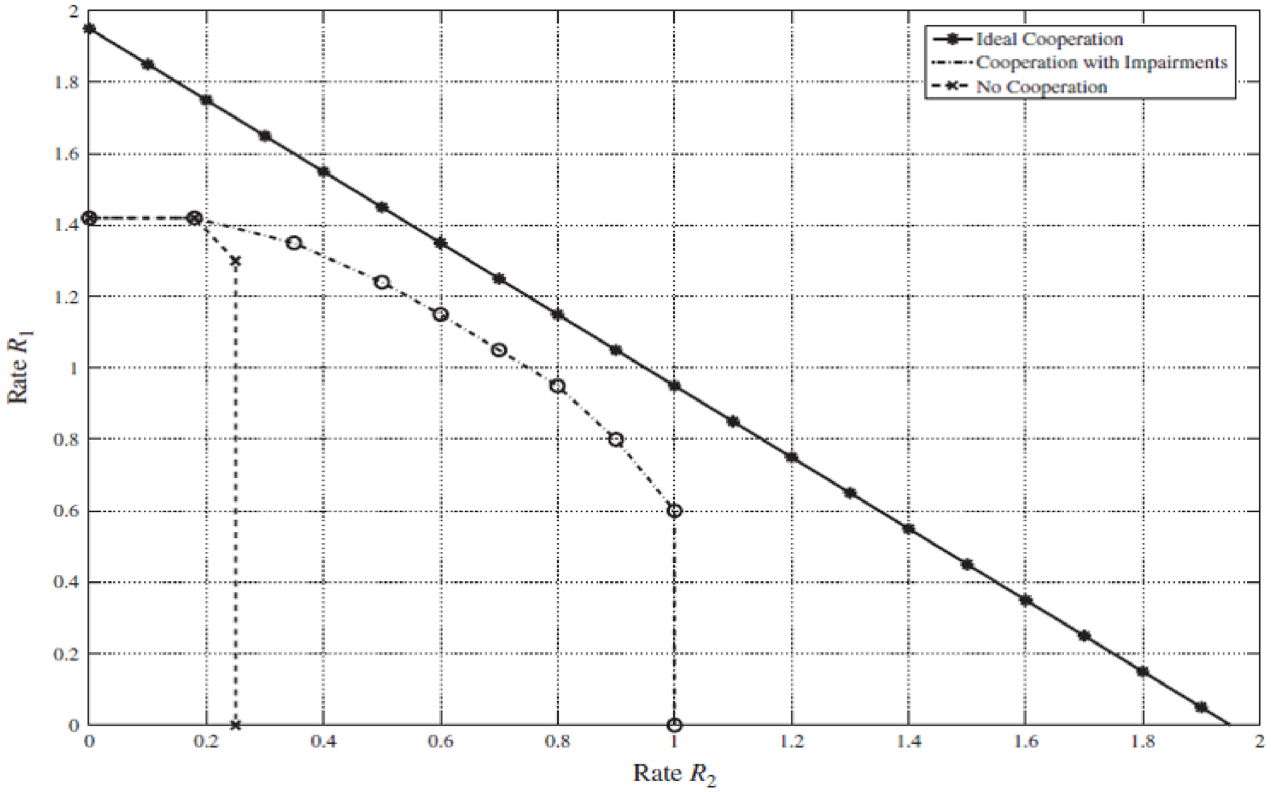


Figure 2.13 illustrates an asymmetric rate region where the first user has better channel conditions to the destination than the second user, assuming no cooperation [12].

The study reveals that cooperative relaying significantly improves the capacity of each user and the network, especially in the asymmetric case where one user suffers from bad channel conditions. The results have inspired research into practical communication schemes capable of achieving promised rate gains. It has been shown that an increase in sum capacity equals the increase in coverage area, and a simple repetition-based coding scheme using CDMA spreading sequences performs well within the rate regions.

2.4.2 Rate Outage Gains

Shannon's information theory doesn't address communication scenarios with changing average channel conditions. The concept of rate outage probability has been introduced for cooperative relaying systems.

2.4.2.1 Nonergodic Channel

A nonergodic channel is a type of communication channel where the channel does not vary fast enough to traverse all fading states over the communication duration. This occurs when the channel is slow fading or experiences severe shadowing. Averages are not meaningful in nonergodic channels, as they differ for each transmitted codeword. However, they can support any rate with a certain rate outage probability.

Nonergodic channels cannot support a maximum error-free transmission rate with 100% reliability, but can support any given rate with a certain probability, known as the rate outage probability, illustrated in Figure 2.14 [16].

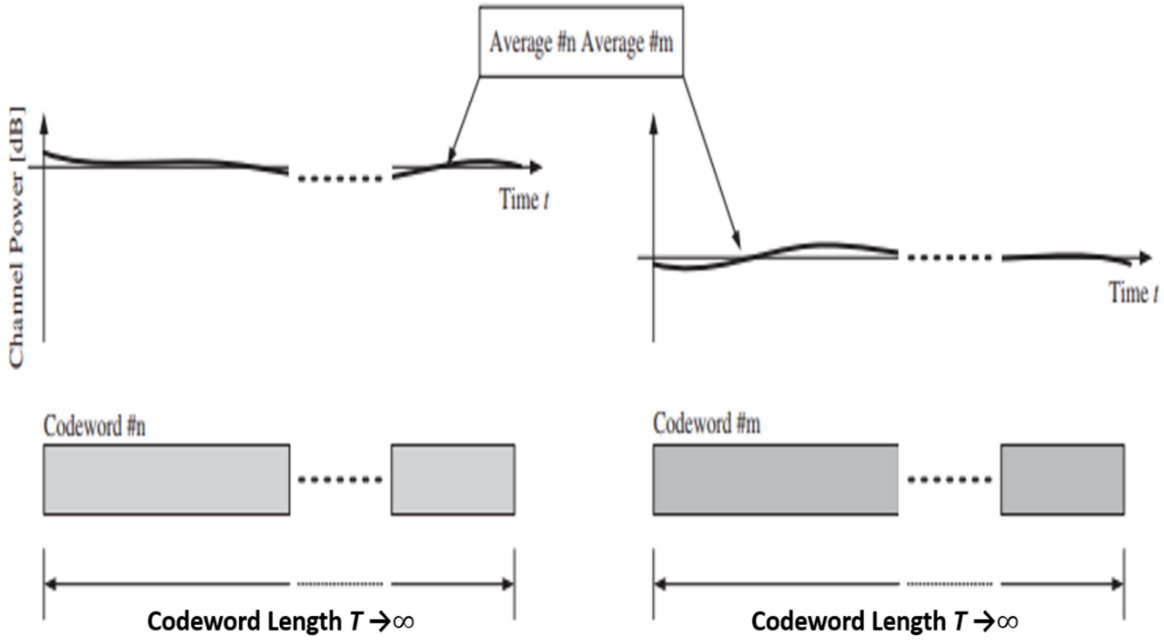


Figure 2.14 In the case of a nonergodic channel not all fading states are traversed over the duration of a Shannon codeword, thereby preventing the provision of an average channel capacity and hence requiring the concept of outage to be invoked

To quantify the outage probability, we assume an instantaneous power $\gamma = gS/N$ at the decoder input due to which an information rate of $C(\gamma) = \log2(1 + \gamma)$bits/s/Hz z can be supported. The channel is in outage if this rate falls below a threshold information rate R; the corresponding outage event is $C(\gamma) < Ror\gamma < 2R - 1$. The outage probability is hence

$$P_{out} = Pr\big(\gamma < (2^R - 1)\big) \int_0^{2^R - 1} p_\gamma(\gamma) d\gamma \ , \qquad 2.3$$

Where $Pr(\cdot)$ denotes the probability and $p_\gamma(\gamma)$ the PDF of the SNR. For instance, for a Rayleigh fading process with mean power $\overline{\gamma}$ and PDF given in the previous section, the outage probability is

$$P_{out} = 1 - \exp\left(-\frac{2^R - 1}{\bar{\gamma}}\right). \qquad 2.4$$

From Equation (2.4) it is clear that the outage probability decreases quickly with increasing SNR; since the system designer is interested in low outage probabilities, it is therefore customary to plot the outage or its compliment in logarithmic scale.

2.4.2.2 Rate Outage Gains

The communication model depicted in Figure 2.15 will be used to illustrate rate outage probability gains. The protocol involves both users sending data to the destination and each other. If a user correctly decodes the other's information, it relays it to the destination, while if not, it continues sending its own information.

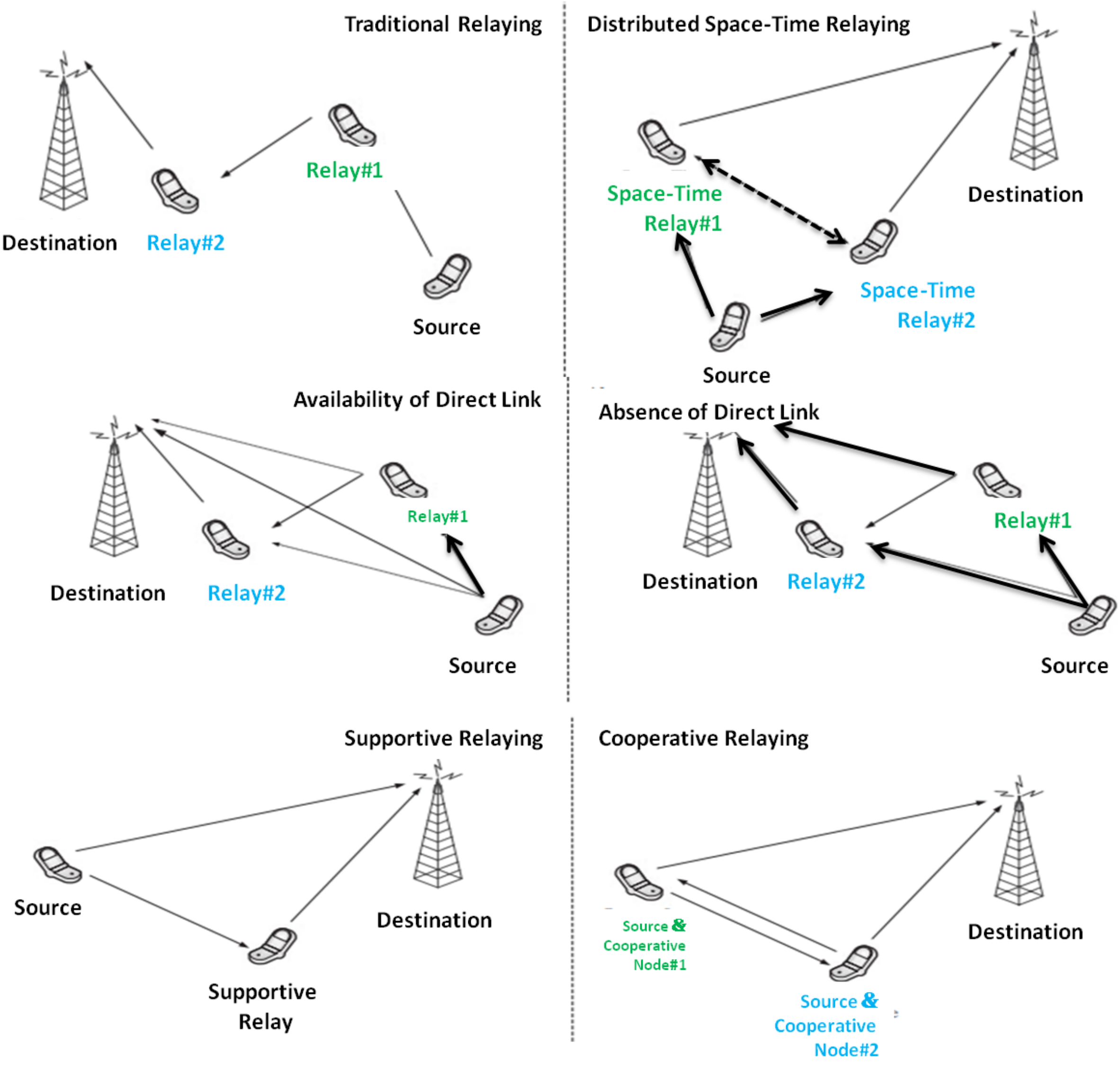


Figure 2.15 The compares traditional relay architectures, including space-time processing relaying, direct link availability, and cooperative relaying, highlighting the potential for transparent or regenerative relaying [16].

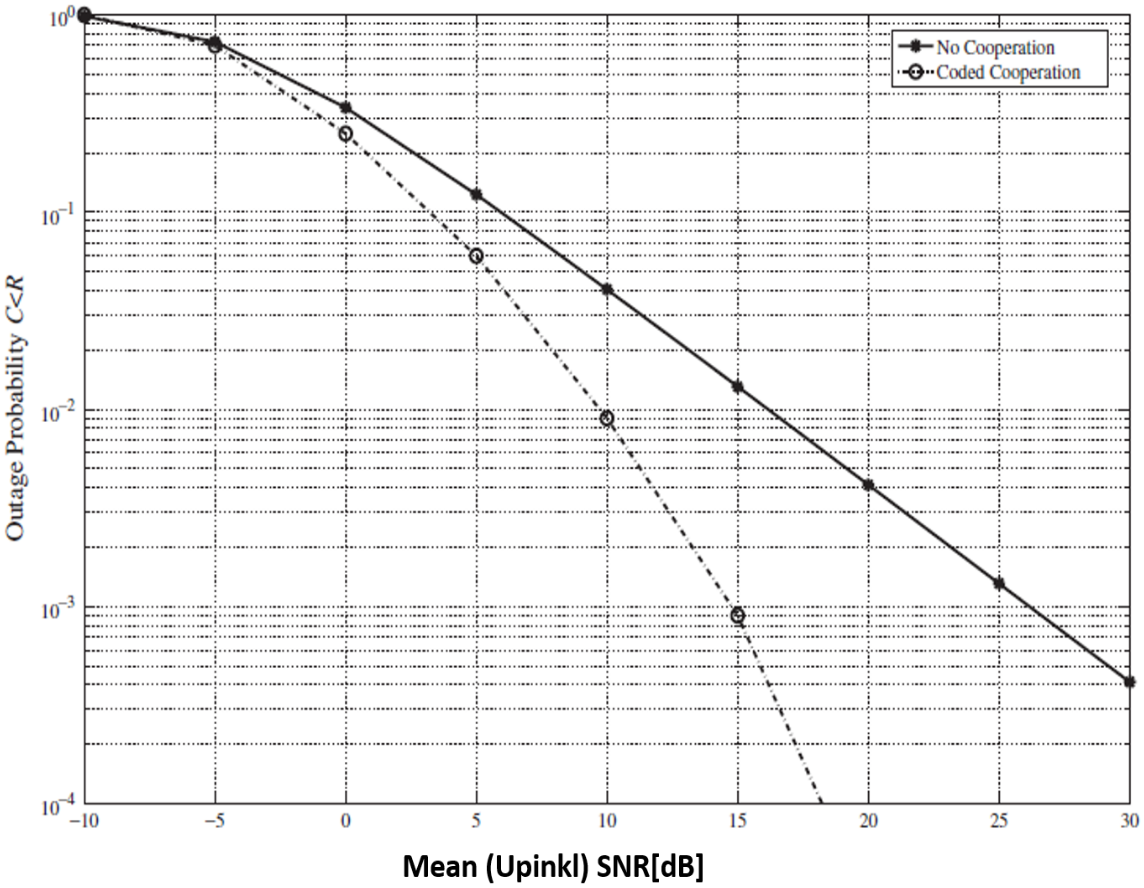


Figure 2.16 Outage versus average uplink SNR, where inter-user channel is significantly weaker; R = 0.5 bits/s/Hz [13].

As per Figure 2.16, the outage gains due to cooperation are significant. In the region of interest, that is typically between 1 and 10% outage probability, up to 6 dB transmission power can be saved on average. These gains are attributed to the fact that the probability of both direct and cooperative relaying link being in outage is much lower than just the direct link being in outage. More complex topologies and protocols follow the same trend and cooperation is generally able to provide significant outage gains, whether the random channel fluctuations be due to fading or shadowing.

2.4.3 Diversity-Multiplexing Tradeoff

The diversity-multiplexing trade-off (DMT) is a concept used by system designers to determine the trade-off between reliability and rate in real-world systems. It describes how the probability of outage decreases and the communication rate increases with an increase in SNR. Although the concept is only applicable to nonergodic channels, it can be applied to any system operating over slow or fast-fading channels.

The Shannon sense outage probability (Pout (R, SNR)) and diversity gain (d) are used to calculate the multiplexing gain relationship. At high SNR, the gradient of outage curves is equivalent, and $\mathrm{d} = 0$ means no decrease in outage is achieved. A steeper gradient yields increasing gains with increasing SNR. The multiplexing gain relationship can be reformulated as

$$\mathrm{r} = \lim_{\mathrm{SNR}\to\infty} (\mathrm{R(SNR)} / (\log 2\ \mathrm{SNR})) \tag{2.5}$$

The rate or multiplexing gain, denoted by r, is equivalent to the gradient of capacity curves at high SNR. If $\mathrm{r} = 0$, no rate increase is achieved, indicating potential gains are used elsewhere. The general DMT expression is

$$\mathrm{d} = -\lim_{\mathrm{SNR}\to\infty} \left(\frac{\log\mathrm{Pout(r \log 2\ SNR)}}{\log \mathrm{SNR}}\right). \tag{2.6}$$

The DMT for the real-world communication scheme using QAM can be calculated by integrating Equation (2.6) into Equation (2.5).

$$\mathrm{d} = 1 - \mathrm{r} \tag{2.7}$$

The text explains that with increasing SNR, reliability can exhibit a maximum gradient of one, doubling the reliability in log scale. For the degraded point at $\mathrm{d_{max}} = 1$ and $\mathrm{r_{min}} = 0$, the data multiplexing capability can also exhibit a maximum gradient of one. For other points, simple time multiplexing can be achieved. For example, to achieve a diversity gain of d = 0.5 and a multiplexing gain of r = 0.5, communication should be half-time using a constant modulation for reliability benefits and half-time using an adaptive modulation for rate benefits [16].

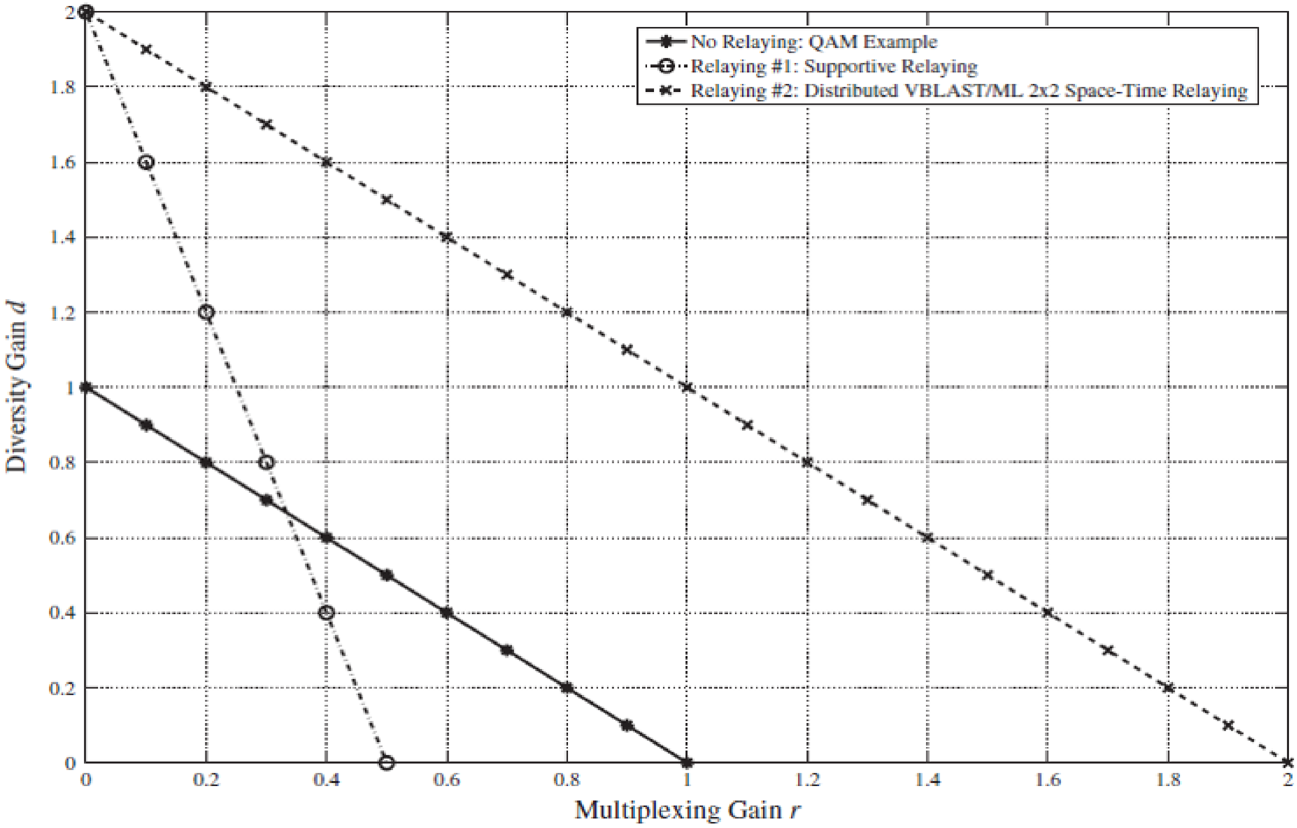


Figure 2.17 demonstrates that SNR decreases outage or error probability, while multiplexing gain increases rate. Simple repetition-based relaying increases diversity order but not multiplexing gain [16].

Figure 2.17 illustrates the impact of two cooperative relaying protocols. The first is a repetition-based protocol that yields double diversity gain but half multiplexing gain. The second protocol aims to increase multiplexing capabilities through relaying, such as distributed 2 × 2 space-time relaying. If the channel between source and transmit relay and destination and receive relay is ideal, a V-BLAST scheme with maximum likelihood (ML) receiver achieves the DMT. The ability to trade reliability against rate is beneficial for system designers. For example, wideband channels offer more diversity, which can be improved by a relaying system at the expense of rate improvement. This has motivated research into practical cooperative relaying protocols [16].

2.5 Conclusion

relay-aided cooperative communications offer numerous benefits in various application scenarios such as cellular networks, WLANs, V2V communications, WSN, and network location. While cooperation can lead to improved capacity, coverage, and reduced interference, it also comes with challenges such as implementation complexity and coordination requirements. Understanding cooperative performance bonds such as capacity gains, rate outage gains, and the diversity-multiplexing tradeoff is essential for optimizing network performance in relay-aided cooperative communications.

2.6 References

[1] 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.

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

[3] 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.

[4] Dardari, Davide, Andrea Conti, Jaime Lien, and Moe Z. Win. "The effect of cooperation on UWB-based positioning systems using experimental data." EURASIP Journal on Advances in Signal Processing 2008 (2008): 1-11.

[5] Wymeersch, Henk, Ulric Ferner, and Moe Z. Win. "Cooperative Bayesian self-tracking for wireless networks." IEEE communications letters 12, no. 7 (2008): 505-507.

[6] Patwari, Neal, Joshua N. Ash, Spyros Kyperountas, Alfred O. Hero, Randolph L. Moses, and Neiyer S. Correal. "Locating the nodes: cooperative localization in wireless sensor networks." IEEE Signal processing magazine 22, no. 4 (2005): 54-69.

[7] Zhao, Jian. Analysis and design of communication techniques in spectrally efficient wireless relaying systems. Vol. 12. Logos Verlag Berlin GmbH, 2010.

[8] Subrt, Ludek, and Pavel Pechac. "Controlling propagation environments using intelligent walls." In 2012 6th European Conference on Antennas and Propagation (EUCAP), pp. 1-5. IEEE, 2012.

[9] Subrt, Ludek, and Pavel Pechac. "Intelligent walls as autonomous parts of smart indoor environments." IET communications 6, no. 8 (2012): 1004-1010.

[10] Zimmermann, Ernesto, Patrick Herhold, and Gerhard Fettweis. "On the performance of cooperative diversity protocols in practical wireless systems." In 2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No. 03CH37484), vol. 4, pp. 2212-2216. IEEE, 2003.

[11] Kaina, Nadège, Matthieu Dupré, Geoffroy Lerosey, and Mathias Fink. "Shaping complex microwave fields in reverberating media with binary tunable metasurfaces." Scientific reports 4, no. 1 (2014): 6693.

[12] Vannithamby, Rath, and Shilpa Talwar, eds. Towards 5G: Applications, requirements and candidate technologies. John Wiley & Sons, 2017.

[13] Cui, Tie Jun, Mei Qing Qi, Xiang Wan, Jie Zhao, and Qiang Cheng. "Coding metamaterials, digital metamaterials and programmable metamaterials." Light: science & applications 3, no. 10 (2014): e218-e218.

[14] Sendonaris, Andrew, Elza Erkip, and Behnaam Aazhang. "User cooperation diversity. Part I. System description." IEEE transactions on communications 51, no. 11 (2003): 1927-1938.

[15] AICHAOUI Redha and BOUCHERIT Moussa (2022) Analyse de la performance d’un système de transmission SISO assisté par des surfaces intelligentes 5G [Master's thesis]. Link

[16] Dohler, Mischa, and Yonghui Li. *Cooperative communications: hardware, channel and PHY*. John Wiley & Sons, 2010.

Chapter 3

IRS-assisted communication networks

This chapter deals with reconfigurable intelligent surfaces (RISs), a promising emerging technology for wireless communication networks due to their ease of development, low cost, and increased spectral and power efficiencies. It also discusses its features and applications.

3.1 Overview

Over the past four decades, mobile communication networks have evolved through five generations, with a new generation emerging every ten years. Each generation offers upgraded technologies and capabilities to enhance work and lifestyle. The pre-cell phone era began with the zeroth generation (0G), which provided basic radio communication. The first generation (1G) introduced voice communication using analogue technology in the 1980s. The second generation (2G) transitioned from analogue to digital, supporting data services like SMS. The third generation (3G) introduced mobile broadband services, enabling new applications like multimedia message services, mobile television, and video calls [6].

The fourth generation (4G), also known as long-term evolution (LTE), introduced enhanced mobile broadband services, specifically voice over IP (VoIP) [6].

5G mobile communication networks are being deployed globally, with network softwarization being a key technology enabling programmability and dynamicity. These networks have applications in mixed reality, IoT, autonomous vehicles, and industry. Research is ongoing on future 6G wireless systems, offering seamless access and enhanced mobile broadband with higher data rates. This advancement is paving the way for innovative applications in the future [6].

The evolution of 5G has gained traction, but its revolutionary view, running entirely at millimeter wave frequencies and enabling diverse IoT services, remains elusive. Despite the 5G wireless network being deployed globally, academia and industry are excited about B5G, which aims to satisfy more demanding requirements such as ultra-high data rates, energy efficiency, global coverage, spectral efficiency, and high reliability for 5G and 6G systems. 6G aims to deliver a higher data rate than 5G, with a peak data rate of 1000 Gbps and a user experience data rate of 1 Gbps. To deliver advanced multimedia services, the network performance must be enhanced, aiming for spectral efficiency twice as high as 5G. Therefore, developing sustainably new and inventive technologies is crucial to enable future wireless network capacity increase at a moderate budget, complexities, and power consumption, while addressing the widespread adoption of user devices in the future of IoT.

Time-varying wireless channels pose a significant challenge in establishing ultra-reliable wireless communications due to user mobility. Traditional solutions include modulation, coding, and diversity plans to compensate for channel fading, but these methods require additional costs and have limited influence over the random nature of wireless channels. Signal transmission is also subject to reflection, diffraction, and scattering, resulting in arbitrarily degraded and deferred source waves due to the unpredictable radio environment [6].

Modern physical layer solutions are insufficient and progress is modest, requiring new solutions. New communication patterns exploit propagation environment randomness to achieve simplicity and QoS. Academic researchers have added RIS technology to wireless communications, making the wireless environment configurable and adjustable, facilitating the concept of service requirements [6].

3.2 What is RIS?

RIS is a versatile, inexpensive surface that can modulate wireless signals using external inputs. It is a meta-surface, a two-dimensional electromagnetic material composed of multiple passive scattering units. Each unit can be modified by software to alter the EM characteristics of the incident signal's reflection on the scattering units. By placing RISs in wireless networks and organizing their reflections intelligently, propagating signals can be freely reconfigured to obtain targeted realizations and distributions. This flexibility makes RISs an essential component in wireless communication systems.

Conventional wireless communication systems use transmitters to send information to receivers through uncontrollable propagation environments. Real-time reconfigurable propagation environments (RIS) are becoming increasingly important for B5G technologies and future wireless communication systems. RIS can increase the number of users served and improve communication rates. 6G mobile technology is popular due to its high transmission rate, reliability, and capacity. IoT integration is a popular research area, integrating various emerging technologies.

However, future wireless networks face challenges such as large-scale access, high energy consumption, and high hardware costs. To meet users' high QoS and data rate requirements, solutions with low power consumption and high economic benefits are needed. Ambient back scatter and RIS, passive devices, have been introduced into wireless communication research.

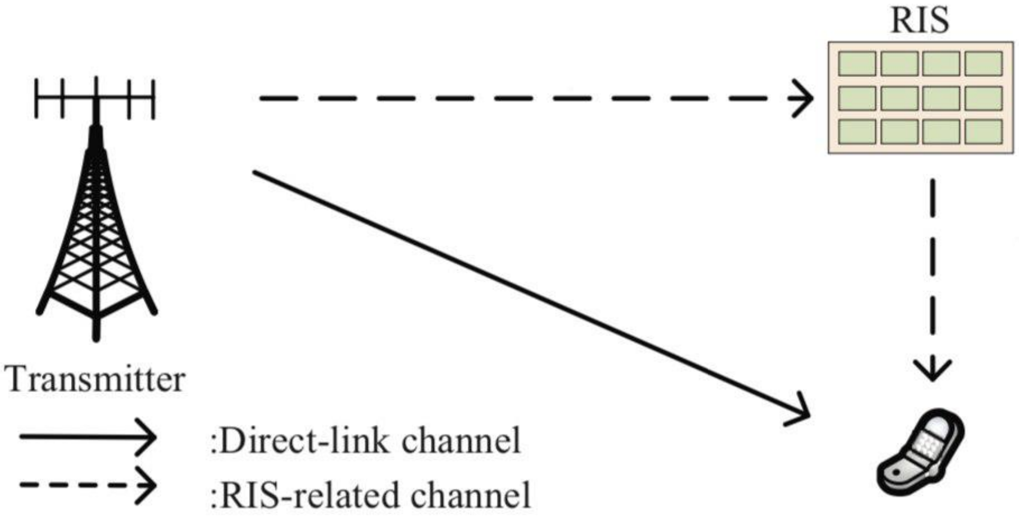


Figure 3.1: Reconfigurable intelligent surface-aided system [6].

Hypersurface tiles can be used to re-engineer waves, including total absorption and polarization manipulation. They are used to cover indoor and outdoor items, such as building facades. An external software service determines the ideal interaction types per tile. Wireless networks aided by RIS are expected to change existing optimization patterns by incorporating the smart wireless environment and taking a proactive role in future wireless networks [1].

3.3 Major Uses of RISs

RIS technology is a key enabler for wireless communications, essentially a reconfigurable metamaterial 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 3.2 [2].

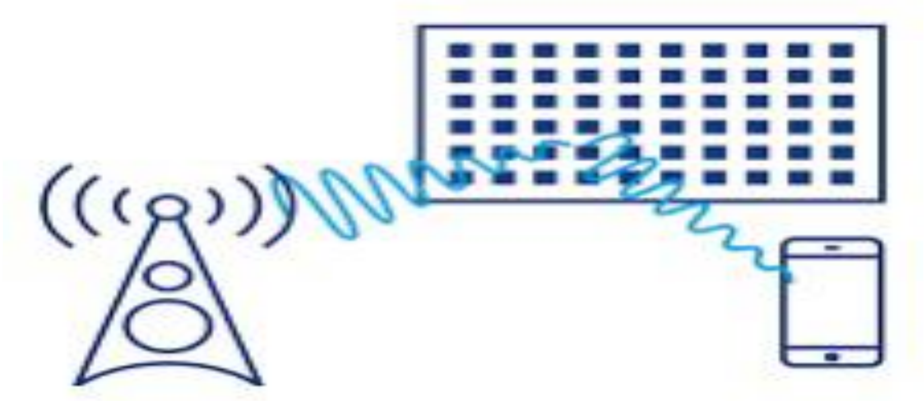


Figure 3.2: Wave Reflected in the Surface [6].

3.3.1 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.

3.3.2 Beamforming/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.

3.3.3 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.

3.3.4 Single-RF Multi-Stream Transmitter Design

The operation involves a simple radio frequency (RF) feeder near a radio frequency (RIS) transmitter, which emits an unmodulated 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.

3.4 Overview of the features of RIS

Intelligent Reflecting Surfaces (RISs), also known as intelligent meta-surfaces and passive holographic MIMO surfaces, are envisioned as the key enabler of Super Reflective Engineering (SRE). These thin sheets, made of nearly passive and inexpensive meta-materials, can introduce independent reconfigurations on incident EM waves and adapt their responses in real-time. They are made nearly passive using low-cost electronics without RF chains and can be easily placed on ordinary objects like walls, ceilings, or facades of buildings [3].

RIS (Reflecting Antenna) can be integrated into wireless networks to improve communications at a low cost. It acts like a large reflecting antenna array, causing controllable phase shifts on incident signals. By optimizing these phase shifts, RIS can combat unfavorable wireless channel conditions and achieve desired channel responses at receivers. However, new challenges in physical layer design, such as channel estimation, passive beamforming design, and resource allocation, need to be addressed. The knowledge of channel state information (CSI) is crucial for efficient CSI acquisition algorithms for RIS system design. RIS can provide additional channel diversity via RIS-related links, enabling active transmission even if the direct link is blocked. Properly designing the reflection coefficient matrix can enhance signal transmission through phase alignment of the reflected signal [6].

3.5 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's equations with effective parameters.

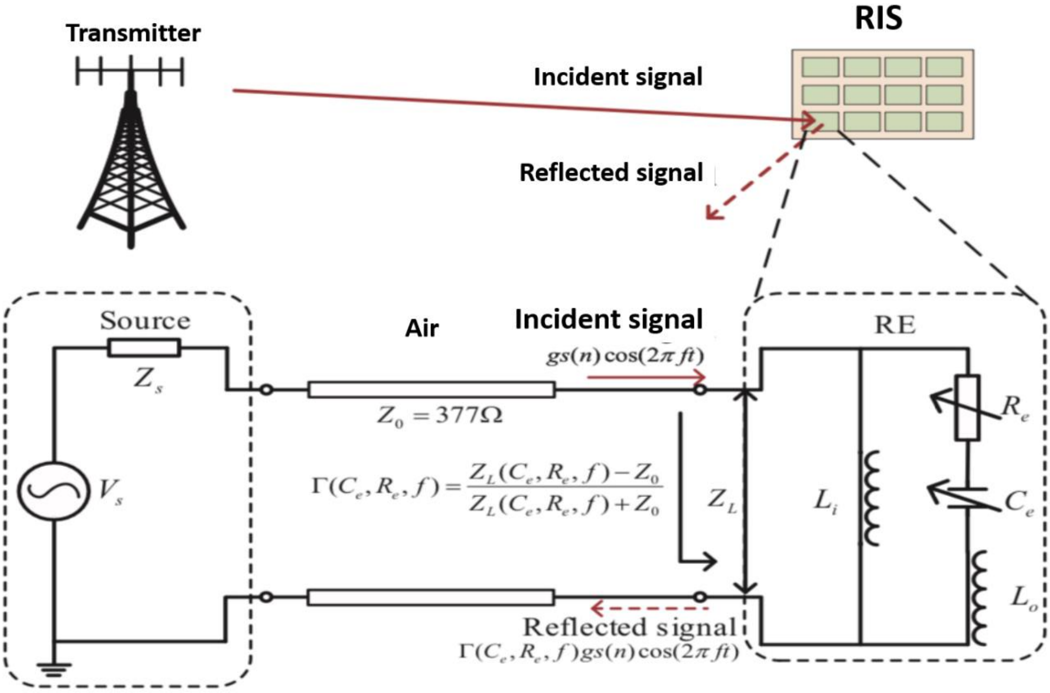


Figure 3.3: The equivalent circuit for the RIS reflecting element based on transmission line theory [6].

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 Z0 and 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 semiconductor 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 [4].

3.6 RIS Applications

RIS technology offers significant performance improvements in both indoor and outdoor wireless environments due to its low material cost, low power usage, and easy deployment on various structures like indoor walls, aerial platforms, roadside billboards, highway polls, vehicle windows, and pedestrian clothes. It is environmentally friendly and can be easily integrated into the current wireless environment, making it beneficial in a wide range of applications.

3.6.1 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 3.4, since the deployment of RISs may reduce the amount of network infrastructure needed [6].

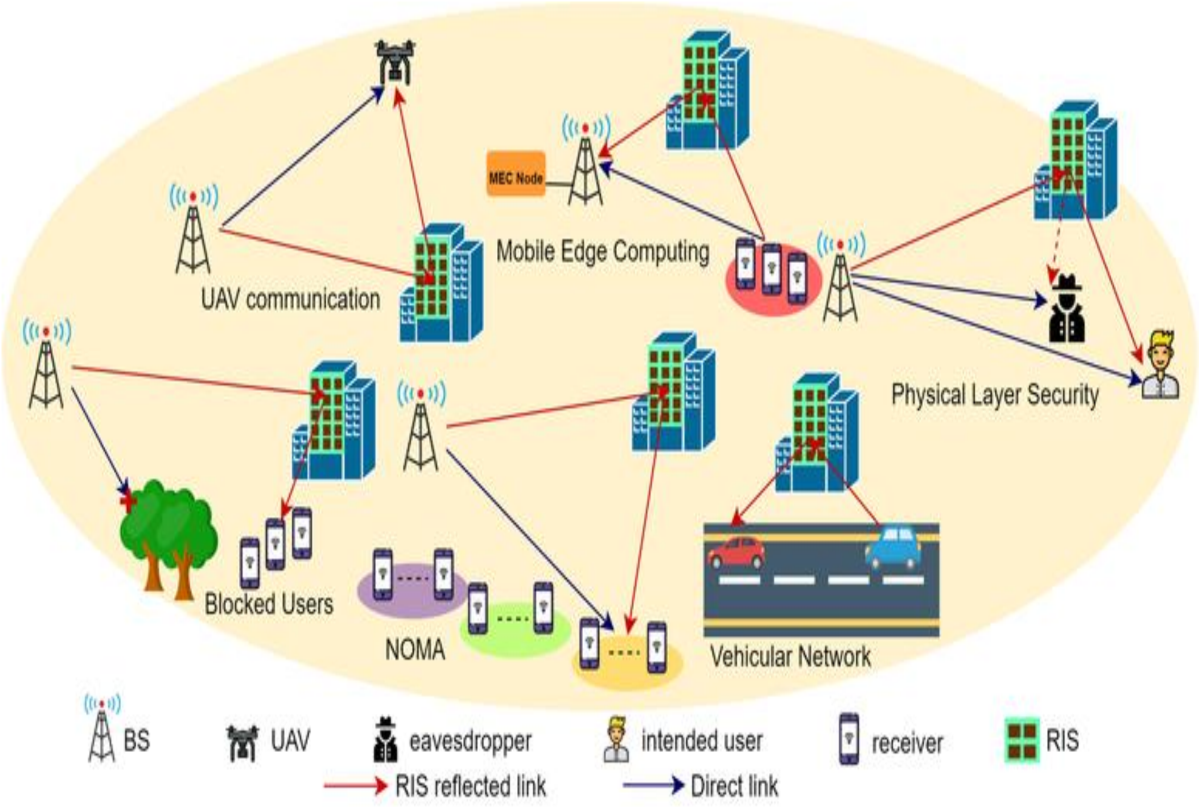


Figure 3.4 The application of RIS in a city environment [6].

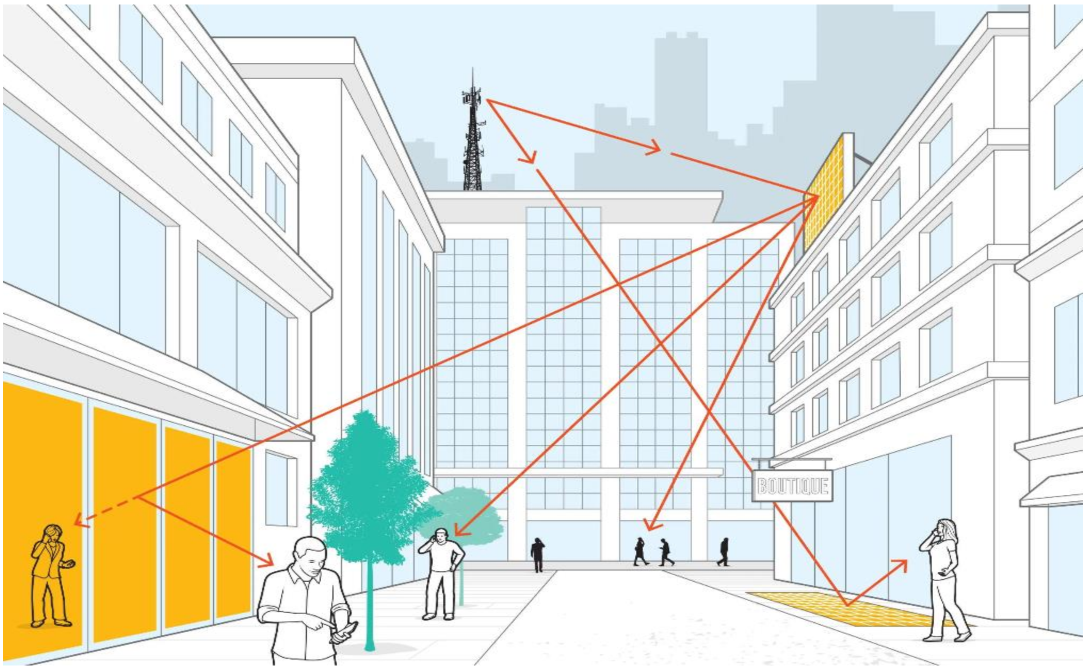


Figure 3.5 depicts the representation of RIS applications in an outdoor setting [6].

3.6.2 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 3.5.

3.6.3 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 3.6. 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 [6].

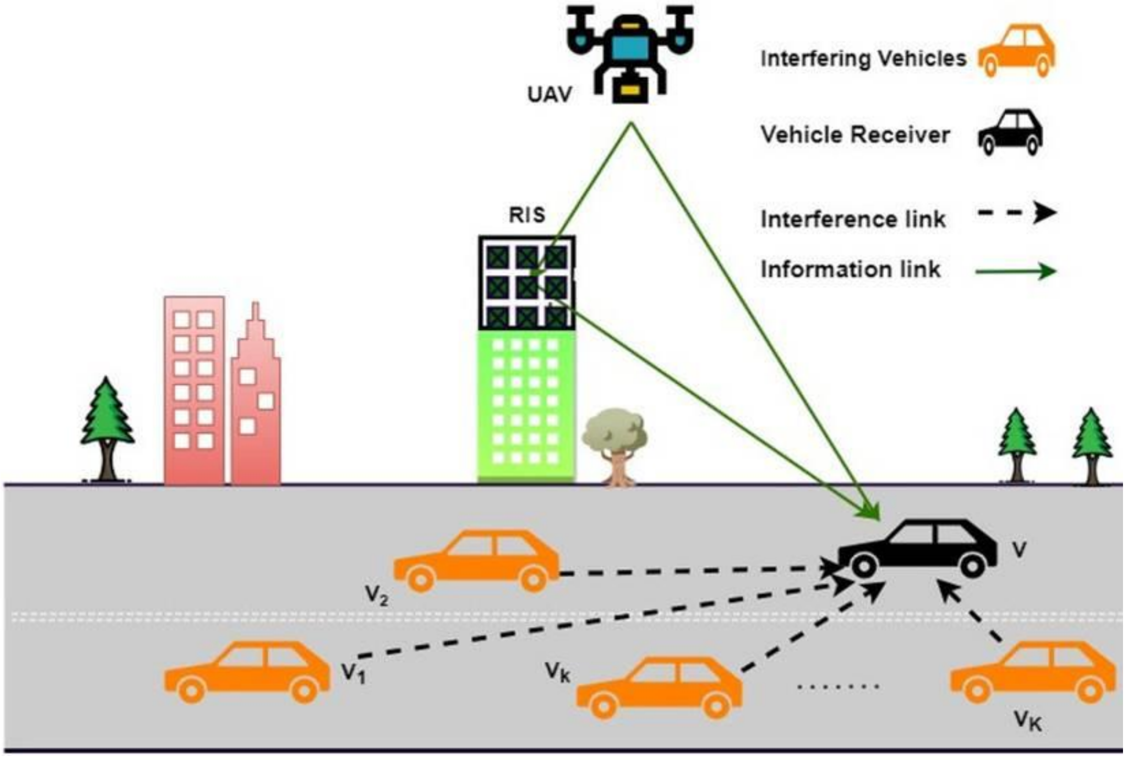


Figure 3.6: RIS-assisted vehicular communication system[6].

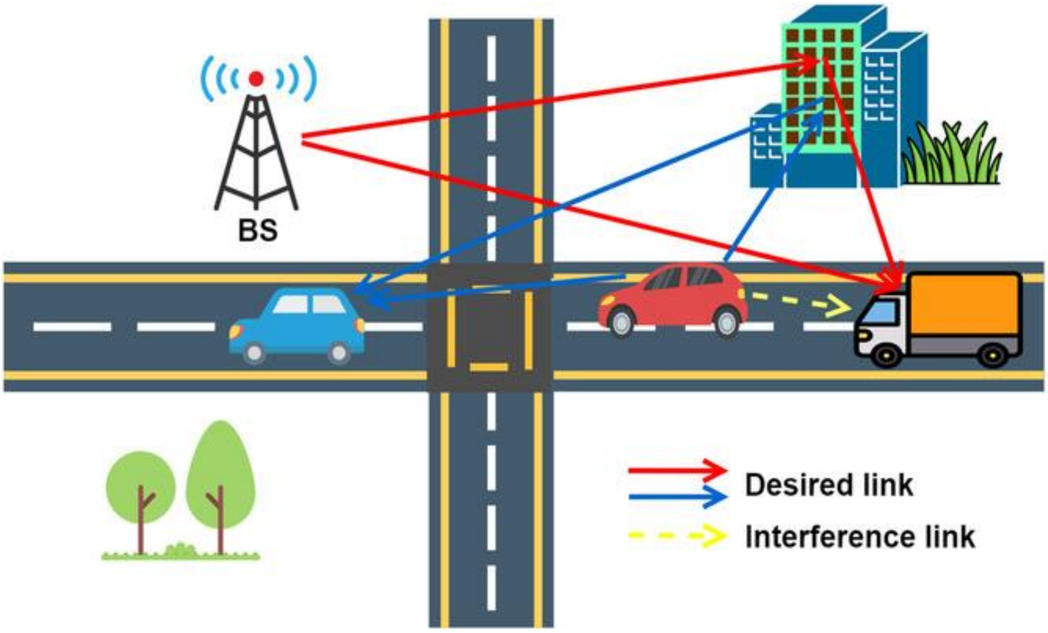


Figure 3.7: Representation of RIS application in smart vehicles [6].

3.6.4 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.

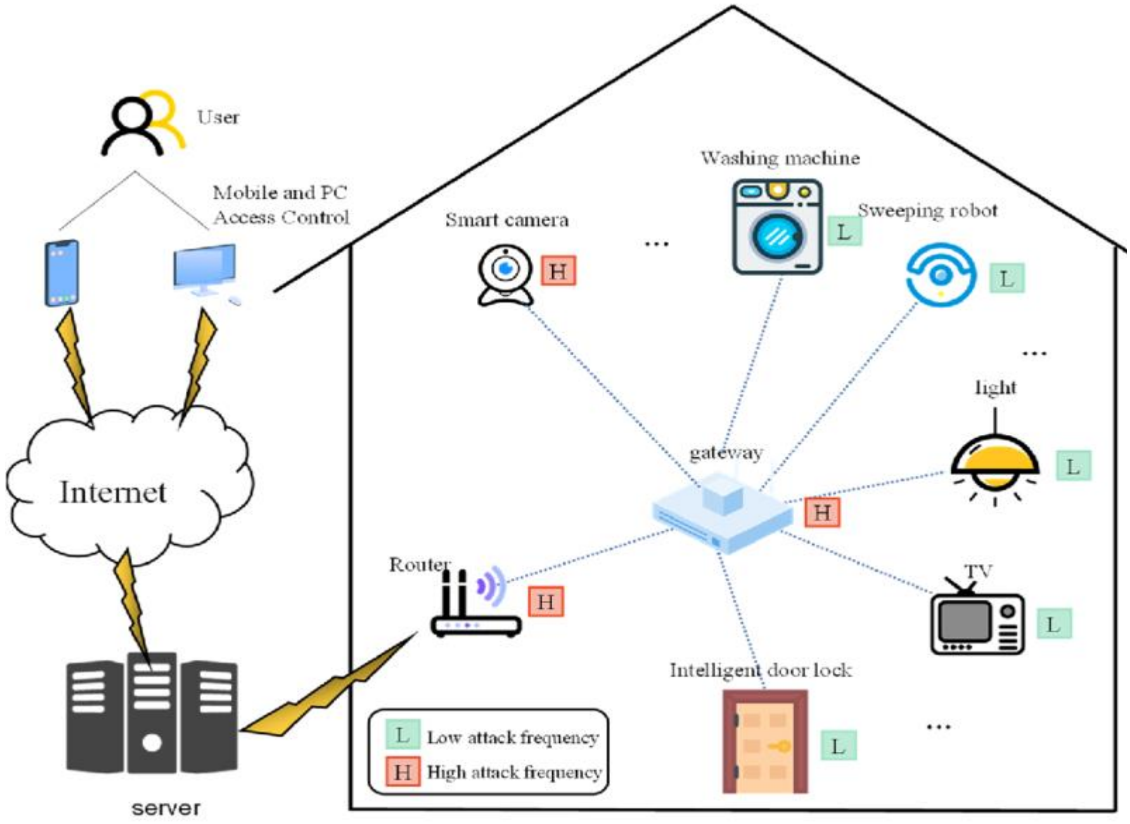


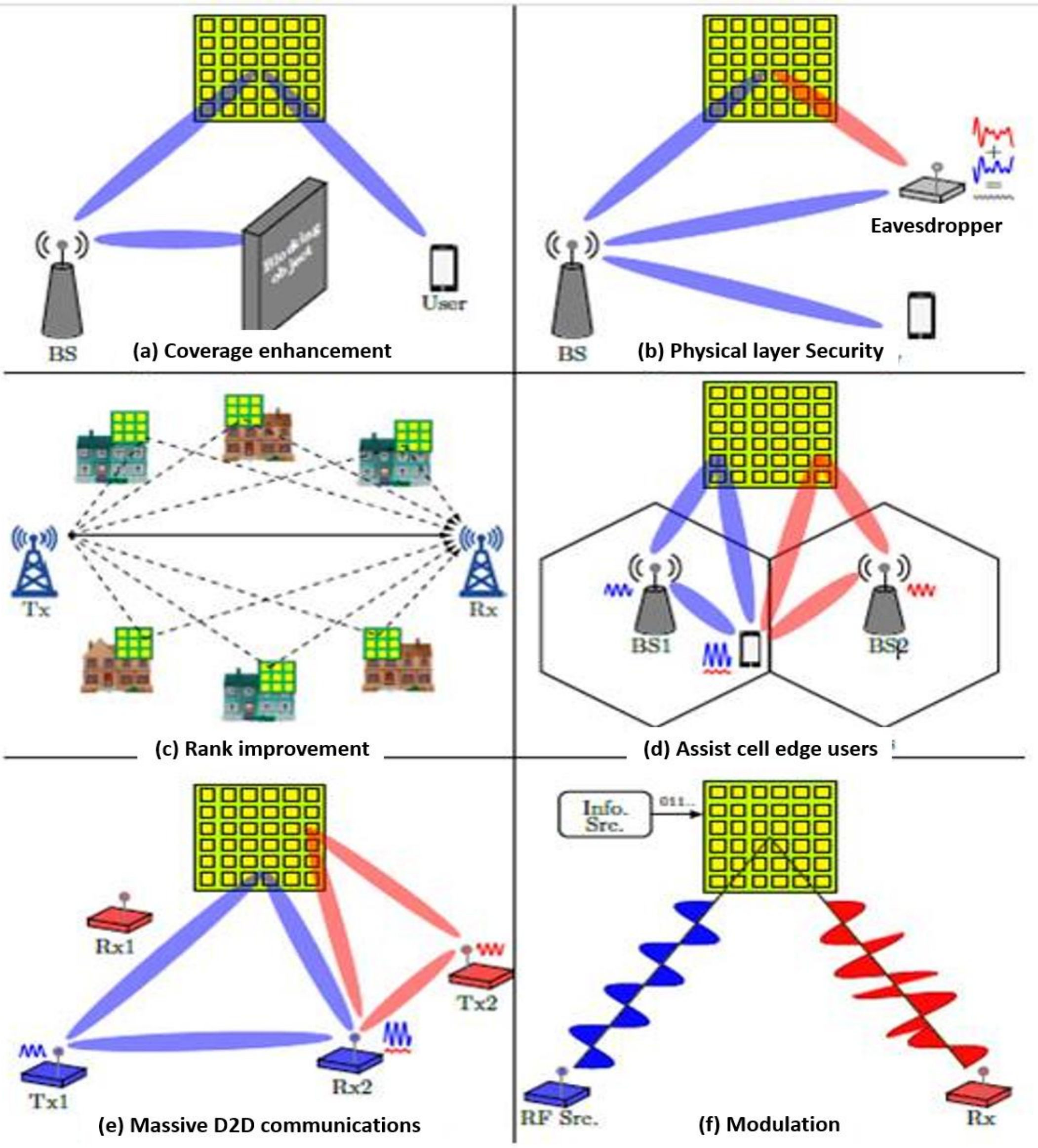
Figure 3.8-Smart home topology diagram

3.7 RIS Implementation

The use of RIS in propagation environments can be utilized to solve fundamental limitations in classical wireless communications and create new technologies by shaping the radio environment. Typically, the RIS is tuned to solve an optimization problem based on the performance metric of interest in each use case [5].

- **Coverage enhancement:** RIS can be configured to improve the connections in low coverage areas, where communication is not expected or is not sufficient. It is also possible to support tracking, location and mapping applications for mobile devices, the base station (BS) and users who suffer from low received signal strength or blockage. This application could offer a promising solution for coverage extension especially for mmWave and terahertz communications which are vulnerable to blockages by obstacles[6].

- **Engineering interference**: RIS can be configured to route signals to specific destinations both to improve the quality of the signal but above all to suppress all those unwanted additional contributions that may interfere with other wireless communication systems.
- **Physical layer security:** RIS can be configured to create destructive interference for all signal interceptors, altering the reflection for unauthorized users to receive the signal.



(a) Coverage enhancement

(b) Physical layer Security

(c) Rank improvement

(d) Assist cell edge users

(e) Massive D2D communications

(f) Modulation

Figure 3.9: Applications of RIS [7].

This can be achieved by tuning the RIS such as the reflected links through it are added destructively to the signal of the legitimate user at the eavesdropper’s receiver which may decrease the information leakage.

- **Rank improvement:** In line-of-sight (LoS) environments, the MIMO channel matrix turns out to be rank deficient such that spatial multiplexing becomes unattainable. Thus, the deployment of distributed RISs to act as artificial scatterers and synthesize a sort of multipath propagation such that additional degrees of freedom are created.

- **Assist cell edge users:** An RIS can be deployed on the cell edges to serve users who conventionally suffer from both high signal attenuation from their serving BS and high interference from the neighbor BSs. In this scenario, the reflected signal from the RIS is added constructively at the intended users, to create a signal hotspot, and destructively at the unintended users to form an interference free region [6], [7].

3.8 Conclusion

Intelligent Reflecting Surfaces (RIS) are a cutting-edge technology that can significantly enhance wireless communication networks by controlling electromagnetic signals. The major uses of RIS include anomalous reflection/transmission, beamforming/focusing, joint transmitter/RIS encoding, and single-RF multi-stream transmitter. With features such as improved spectral efficiency, reduced interference, and enhanced signal quality, RIS have the potential to revolutionize communication networks and improve overall performance.

3.9 References

[1] Björnson, Emil, Henk Wymeersch, Bho Matthiesen, Petar Popovski, Luca Sanguinetti, and Elisabeth De Carvalho. "Reconfigurable intelligent surfaces: A signal processing perspective with wireless applications." IEEE Signal Processing Magazine 39, no. 2 (2022): 135-158.

[2] Di Renzo, M., M. Debbah, D. T. Phan-Huy, A. Zappone, M. S. Alouini, C. Yuen, V. Sciancalepore, G. C. Alexandropoulos, J. Hoydis, and H. Gacanin. "Smart radio environments empowered by AI reconfigurable meta-surfaces: An idea whose time has come., 2019, 2019." DOI: https://doi. org/10.1186/s13638-019-1438-9: 129.

[3] Liu, Yuanwei, Xiao Liu, Xidong Mu, Tianwei Hou, Jiaqi Xu, Marco Di Renzo, and Naofal Al-Dhahir. "Reconfigurable intelligent surfaces: Principles and opportunities." IEEE communications surveys & tutorials 23, no. 3 (2021): 1546-1577.

[4] 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.

[5] Huang, Chongwen, Alessio Zappone, George C. Alexandropoulos, Mérouane Debbah, and Chau Yuen. "Reconfigurable intelligent surfaces for energy efficiency in wireless communication." IEEE transactions on wireless communications 18, no. 8 (2019): 4157-4170.

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

[7] A. Redha and B. Moussa (2022) Analyse de la performance d'un système de transmission SISO assisté par des surfaces intelligentes 5G [Master's thesis]. Link

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 a Rayleigh fading channel.

4.1 System Model and analytical performance analysis

4.1.1 System Model

In this work, we examine signal transmission from a single-antenna source (S) to a user (U) via an IRS equipped with N passive elements (See to Fig. 4.1). Given the dense urban environment, it is assumed that S and U lack a direct line-of-sight (LoS) channel link. Additionally, the incident signal phases are assumed to be perfectly controlled for constructive signal accumulation at U, as described in [1]. All channel links g_n and h_n follow a Rayleigh fading model, with the channel envelopes assumed to be independently, but not necessarily identically, distributed (i.n.i.d.).

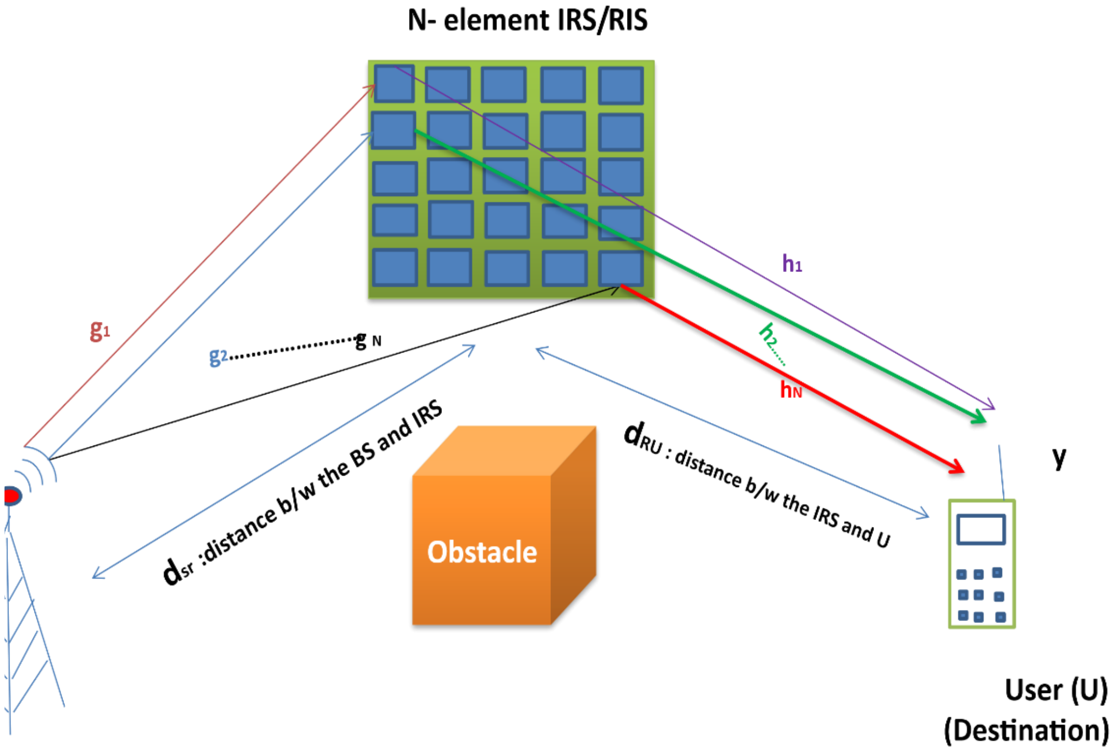


FIGURE 4.1 – An IRS-aided wireless network.

The signal received at U can be written as [2]

$$y = \sqrt{P_S \left(\sum_{n=1}^{N} g_n h_n d_{sr}^{-\frac{\tau}{2}} d_{ru}^{-\frac{\tau}{2}} \alpha_n e^{j\theta_n} \right)} x + n, \tag{4.1}$$

where P_S, x, and n represent the transmit power, the message from S, and the additive white Gaussian noise (AWGN) at the receiver node with variance N_0, respectively. The distances d_{sr} and d_{ru} correspond to the S-IRS and IRS-U links, respectively, and τ denotes the path-loss exponent. The adjustable phase shift and reflection coefficient of the nth IRS element are represented by θ_n and α_n, respectively. Consequently, the corresponding signal-to-noise ratio (SNR) at U can be expressed as [2]

$$\gamma = \frac{P_S \left| \sum_{n=1}^{N} g_n h_n d_{sr}^{-\frac{\tau}{2}} d_{ru}^{\frac{\tau}{2}} \alpha_n e^{j\theta_n} \right|^2}{N_0}. \tag{4.2}$$

Considering the perfect phase adjustment, the phase shifts can be optimized to maximize the received SNR, as demonstrated in [3]

$$\left(\theta_1^{\mathrm{opt}}, \dots, \theta_N^{\mathrm{opt}}\right) = \left(-(\arg[g_1] + \arg[h_1]), \dots, -(\arg[g_N] + \arg[h_N])\right), \tag{4.3}$$

so that eventually each term in the summation is co-phased. Consequently, the optimal received SNR can be expressed as [2]

$$\gamma = \frac{P_S}{N_0}\left(\sum_{n=1}^{N} |g_n||h_n|\tilde{\gamma}_n\right)^2, \tag{4.4}$$

where $\tilde{\gamma}_n = \alpha_n d_{sr}^{-\beta} d_{ru}^{-\beta}$.

4.1.2 Analytical performance analysis

In this section, we study the outage probability (OP) and the ergodic rate (EC) of the IRS-assisted wireless network under consideration.

a) Outage Probability

Generally, the OP is defined as the probability that the received SNR at the destination falls below a predefined SNR-associated rate threshold

In general, the outage probability (OP) is defined as the likelihood that the received SNR at the destination is less than or equal to a specified threshold corresponding to the desired rate γ_{th}. So

$$\begin{aligned} P_{out}(\gamma_{th}) &= \Pr\{\gamma \le \gamma_{th}\} \\ &= \Pr\{X \le \sqrt{\tfrac{\gamma_{th}}{\bar{\gamma}}}\}, \end{aligned} \tag{4.5}$$

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

b) Ergodic capacity

The EC is defined as [4]

$$C_{Erg} = \mathbf{E}[log_2(1+\gamma)] = \frac{1}{\ln(2)}\int_0^{\infty} \ln(1 + x^2\bar{\gamma})\, f_X(x)\mathrm{d}x \tag{4.6}$$

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

4.2 The Outage Probability

In this section we present the Monte Carlo simulation results for the OP and the EC of the IRS-assisted wireless network under consideration. We will see the impact of different parameters on these two performance's metrics. Unless otherwise specified, for the simulation purposes, the following parameters are considered: $N = 16$, $\sigma = 0.8$, $\alpha = 1$, $d_{sr} = d_{ru} = 10$.

Figures 4.2-4.5 illustrates the network's OP for different values of $\mathrm{N}, \sigma, d_{sr}$& d_{ru}, and α.

In Figures 4.2, 4.3 and 4.5, we can clearly see an increase in the concerned parameter will results in a decrease in the OP so an enhancement in the network's performance. In Fig 2.4, it is observed that the larger the d_{ru} distance (when the d_{sr} is fixed at a given value) is the poorer the outage performance is.

4.2.1 The effect of *N*

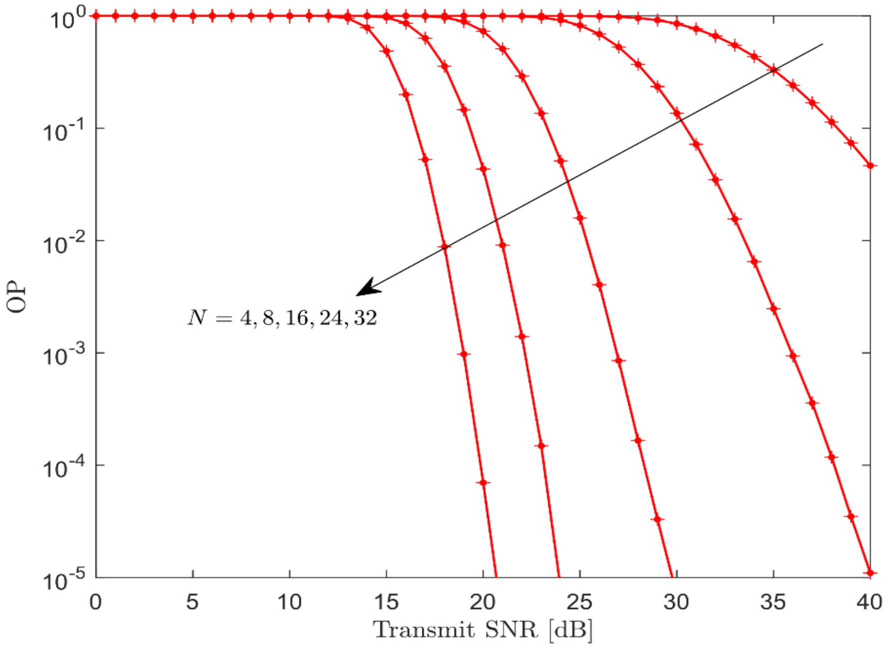


FIGURE 4.2 – The OP vs. the SNR for different values of N.

4.2.2 The effect of $\boldsymbol{\sigma}$

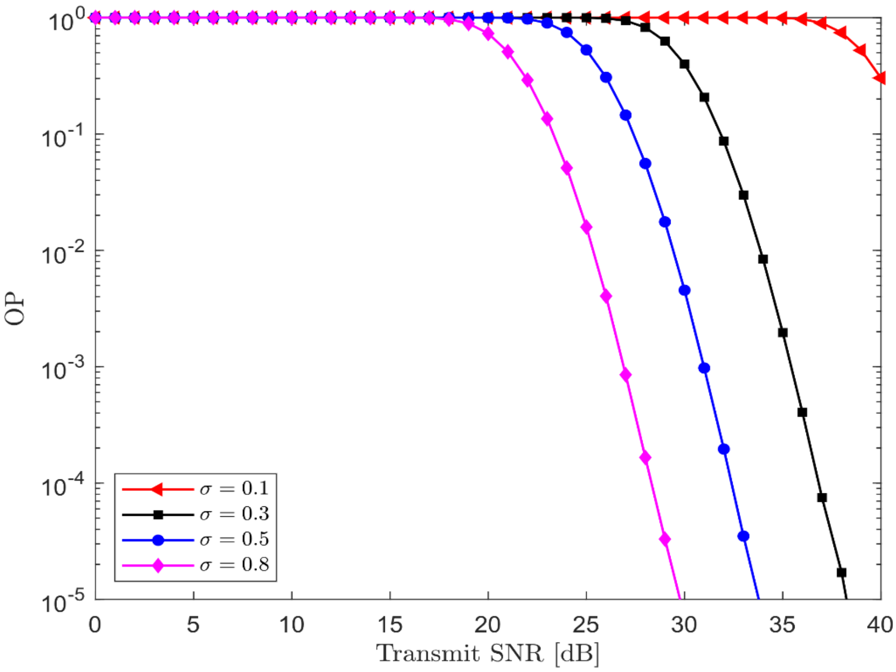


FIGURE 4.3 – The OP vs. the SNR for different values of $\boldsymbol{\sigma}$.

4.2.3 The effect of the distances ($\boldsymbol{d_{SR}}$ and $\boldsymbol{d_{RU}}$)

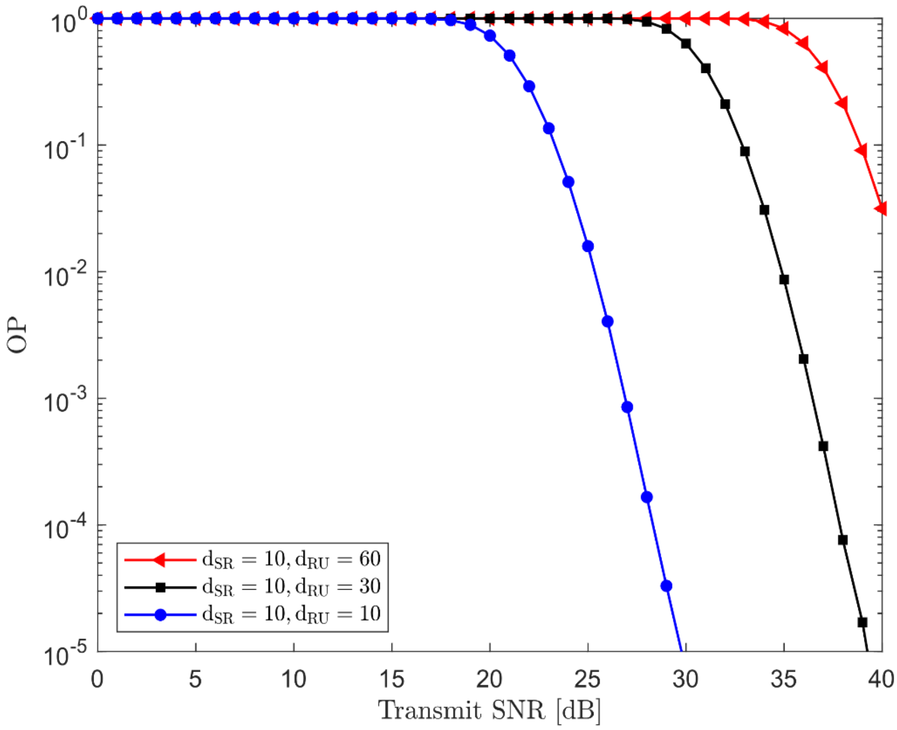


FIGURE 4.4 – The OP vs. the SNR for different values of $\boldsymbol{d_{SR}}$ and $\boldsymbol{d_{RU}}$.

4.2.4 The effect of α

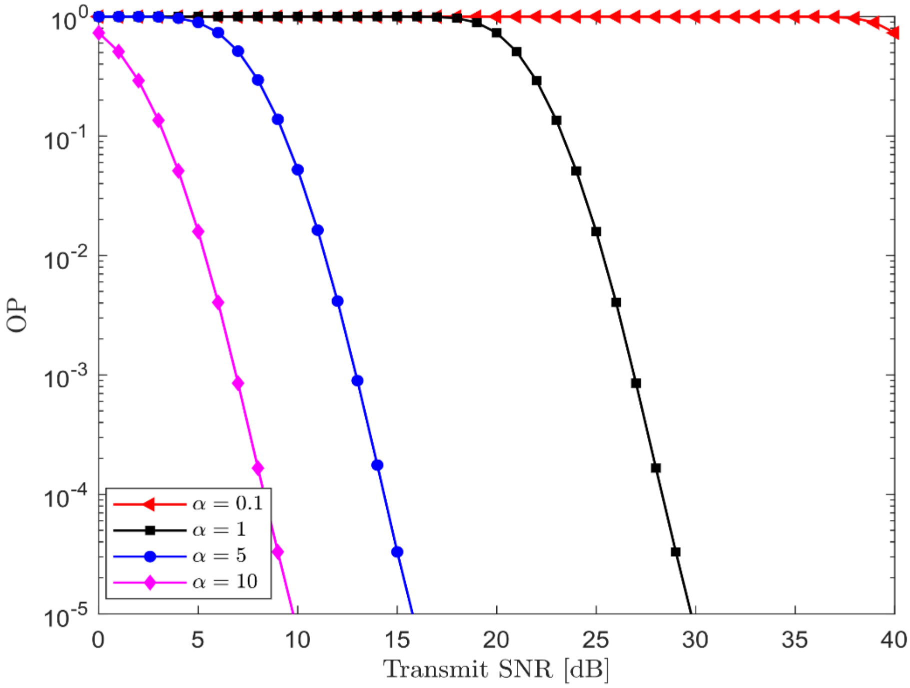


FIGURE 4.5 – The OP vs. the SNR for different values of α.

4.3 The Ergodic Capacity

The EC of the network under study for different values of N, σ, d_{sr}& d_{ru}, and α is given in figures 4.6-4.9.

We can clearly see, in Figures 4.6, 4.7 and 4.9, that an increase in the concerned parameter will results in an increase in the EC so an enhancement in the network's performance. In Fig 2.8, it is observed that the larger the d_{ru} distance (when the d_{sr} is fixed at a given value) is the poorer the outage performance is.

4.3.1 The effect of N

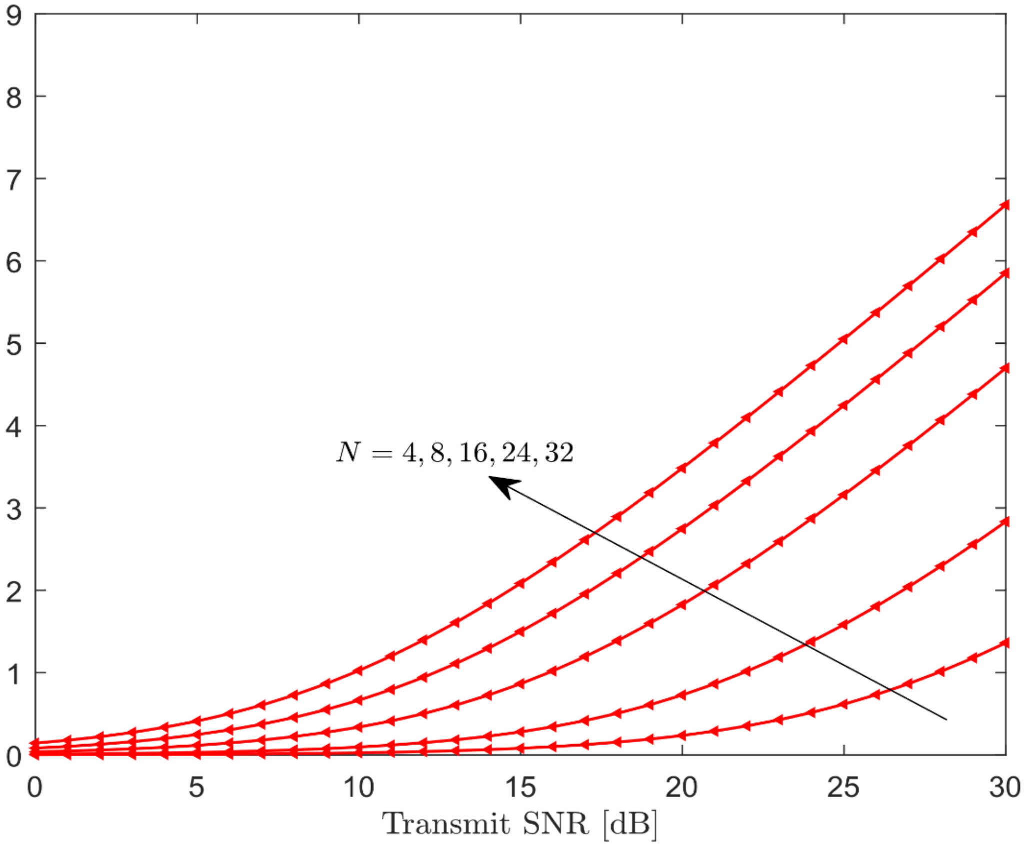


FIGURE 4.6 – The EC vs. the SNR for different values of N.

4.3.2 The effect of σ

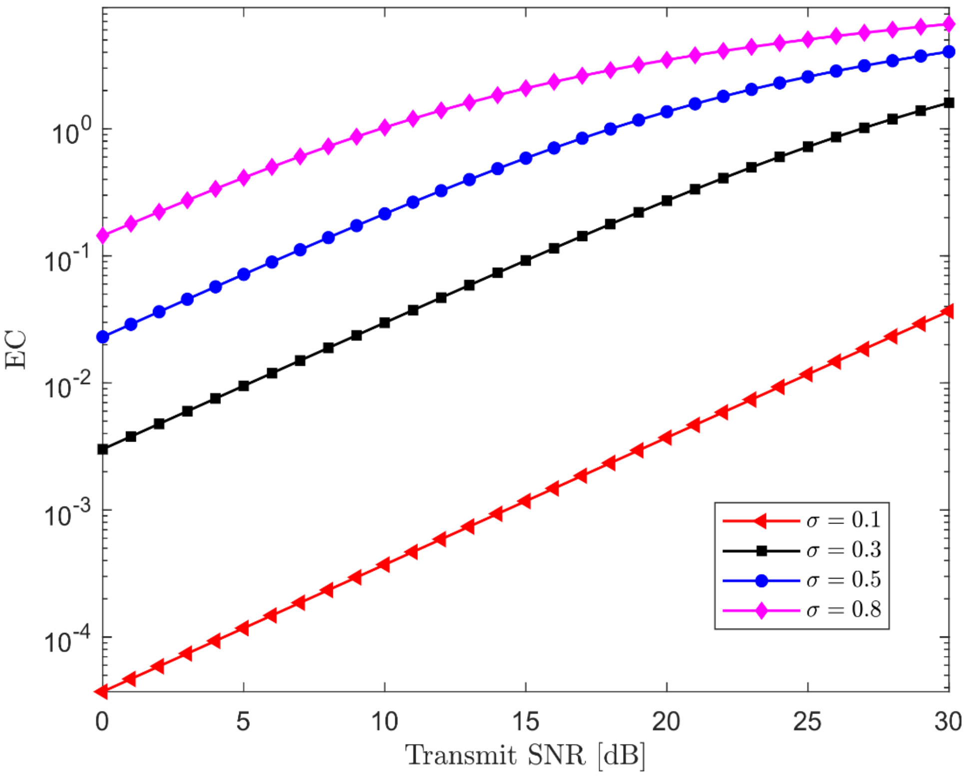


FIGURE 4.7 – The EC vs. the SNR for different values of **σ**.

4.3.3 The effect of the distances (d_{SR} and d_{RU})

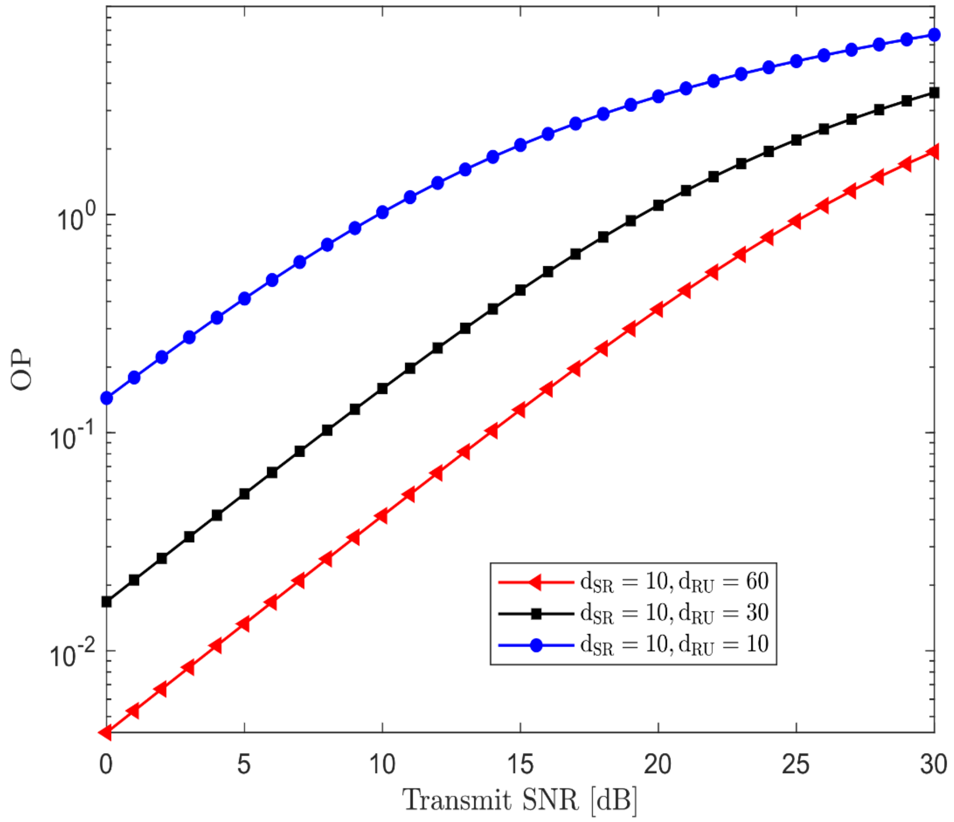


FIGURE 4.8 – The EC vs. the SNR for different values of d_{SR} and d_{RU} .

4.3.4 The effect of α

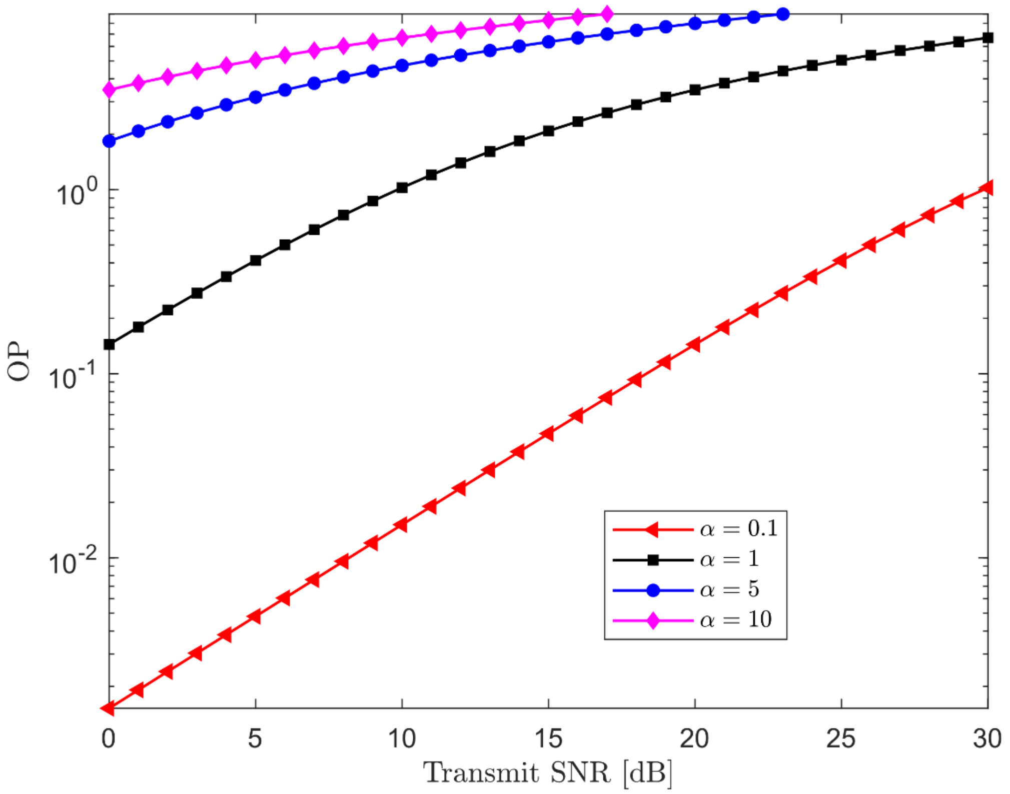


FIGURE 4.9 – The EC vs. the SNR for different values of α.

4.4 Conclusion

In this chapter, we have investigated the performance of the considered IRS-enabled network in terms of the OP, and the EC metrics considering the impact of various system's parameters. The results revealed that the system's performance is dependent on these parameters especially the number of the IRS elements.

4.5 References

[1] Basar, Ertugrul, Marco Di Renzo, Julien De Rosny, Merouane Debbah, Mohamed-Slim Alouini, and Rui Zhang. "Wireless communications through reconfigurable intelligent surfaces." IEEE access 7 (2019): 116753-116773.

[2] Makin, Madi, Galymzhan Nauryzbayev, Sultangali Arzykulov, and Mohammad S. Hashmi. "Performance of large intelligent surface-enabled cooperative networks over Nakagami-m channels." In 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), pp. 1-6. IEEE, 2021.

[3] Kudathanthirige, Dhanushka, Dulaj Gunasinghe, and Gayan Amarasuriya. "Performance analysis of intelligent reflective surfaces for wireless communication." In ICC 2020-2020 IEEE International Conference on Communications (ICC), pp. 1-6. IEEE, 2020.

[4] 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 provided a comprehensive analysis of the outage and ergodic performance of RIS-aided wireless networks. The unique properties of RISs can be leveraged - by dynamically adjust the phase and amplitude of incident signals- to improve the whole transmission process.

Our investigation highlights that RISs offer a promising solution for enhancing signal quality and reliability in various propagation environments. Specifically, the results indicate that the integration of RISs can effectively mitigate the detrimental effects of fading, leading to a substantial reduction in outage probability. Furthermore, the ergodic capacity analysis confirms that RIS-aided networks can achieve higher data rates by 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

إن الطلب المتزايد على معدلات البيانات المرتفعة وخدمات الاتصالات عالية السرعة والتغطية العالية في الشبكات اللاسلكية المستقبلية سيجلب تحديات لتصميم الأنظمة اللاسلكية. إحدى التقنيات الواعدة لتلبية متطلبات الشبكات اللاسلكية المستقبلية هي السطح الذكي القابل لإعادة التشكيل (RIS). تبحث هذه الأطروحة في انقطاع الخدمة والأداء المريح لأنظمة الاتصالات اللاسلكية التي تدعم RIS. من خلال فحص مقاييس احتمالية الانقطاع (OP) والسعة المريحة (EC)، نقوم بتقييم تأثير معلمات النظام المختلفة على أداء الشبكة. تكشف دراستنا أن دمج RIS يحسن بشكل كبير كلا المقياسين، مما يوضح إمكاناته في تحسين عملية الاتصال اللاسلكي. من خلال عمليات المحاكاة واسعة النطاق، نظهر أن أداء النظام يعتمد بشكل كبير على معلمات محددة، ولا سيما عدد عناصر RIS. تؤكد النتائج على الدور الحاسم لتكوين RIS في تحقيق جودة إشارة فائقة وموثوقية الشبكة، مما يمهد الطريق للتقدم في شبكات الاتصالات اللاسلكية من الجيل التالي.

Résumé

La demande croissante de débits de données élevés, de services de communication à haut débit et d'une couverture élevée dans les futurs réseaux sans fil posera des défis à la conception des systèmes sans fil. L'une des techniques prometteuses pour répondre aux exigences des futurs réseaux sans fil est les surfaces intelligentes reconfigurables (reconfigurable intelligent surface (RIS).). Ce mémoire étudie les performances ergodiques et de pannes des systèmes de communication sans fil aidés par des RIS. En examinant les mesures de probabilité d'outage (OP) et de capacité ergodique (EC), nous évaluons l'impact de divers paramètres du système sur les performances du réseau. Notre étude révèle que l'intégration de RIS améliore considérablement les deux mesures, ce qui démontre son potentiel dans l'amélioration du processus de communication sans fil. Grâce à des simulations approfondies, nous montrons que les performances du système dépendent fortement de paramètres spécifiques, notamment du nombre d'éléments dans la RIS. Les résultats soulignent le rôle essentiel de la configuration RIS dans l'obtention d'une qualité de signal et d'une fiabilité de réseau supérieures, ouvrant ainsi la voie aux progrès des réseaux de communications sans fil de nouvelle génération.