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L'ENSEIGNEMENT SUPERIEUR ET DE LA RECHERCHE SCIENTIFIQUE
UNIVERSITE MOHAMED BOUDIAF - M'SILA**

**FACULTE DE TECHNOLOGIE
DEPARTEMENT D'ELECTRONIQUE**



**DOMAINE : SCIENCE ET TECHNOLOGIE
FILIERE: ELECTRONIQUE
OPTION : INGENIERIE DES
TELECOMMUNICATIONS (ITLC)**

**Mémoire présenté pour l'obtention
Du diplôme de Master**

Par:

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Intitulé

**Performance Analysis of IRS-enhanced AF Cooperative
relaying**

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Année universitaire : 2025 / 2026

Dedications

To those who plant the hope in my heart, I thank God for His blessings and guidance throughout my honorable academic journey. It was during this time that I suffered an eye injury, but thankfully, I was able to continue my studies with strength and determination. This is thanks to my mother and father, whose influence and support throughout my studies were invaluable. They stood by me and encouraged me. I also extend my greetings to my siblings Abdelmalek, Zakaria, Hadjar, and Noussaiba, each by name. I love you all. I especially remember my grandparents, both maternal and paternal, may God protect and preserve them, each by name and position. To the soul of my uncle, Mihoubi Azzedine, I wish you could have been with me during my university studies, but Allah's will prevailed. May God have mercy on you and grant you Paradise. To my teacher, *Professor* **BENMAHMOUD Slimane**, thank you for your support and guidance.

Acknowledgement

First and foremost, I would like to express my sincere gratitude to Allah for granting me the strength, patience, and guidance to complete this work. I would like to extend my deepest appreciation to my supervisor ***Prof. BENMAHMOUD Slimane*** for his valuable guidance, continuous support, and constructive advice throughout this thesis. His encouragement and expertise greatly contributed to the completion of this research. I would also like to thank the members of the jury for accepting to evaluate this work and for their time and valuable remarks. Special thanks go to all the teachers and staff of the department for the knowledge and support they provided during my academic journey. Finally, I would like to express my heartfelt gratitude to my family and friends for their unconditional support, motivation, and encouragement throughout my studies.

Thank you all.

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List of abbreviations

- (IRS)** Intelligent Reconfigurable Surfaces.
- (IoT)** Internet of Things.
- (NTT)** Nippon Telephone and Telegraph.
- (ETSI)** European Telecommunications Standards Institute.
- (URLLC)** ultra-reliable and low-latency communication.
- (CNs)** Cellular networks.
- (MAC)** multiple access channel.
- (WCs)** wireless communications.
- (RF)** Radio frequency.
- (LoS)** line-of-sight.
- (FM)** frequency modulation.
- (AM)** amplitude modulation.
- (GPS)** global positioning system.
- (GSM)** Global System for Mobile communications.
- (UHF)** ultrahigh frequency.
- (VHF)** very high frequency.
- (QoS)** quality-of-service.
- (HD)** half-duplex.
- (FD)** full duplex.
- (WLANs)** Wireless local networks
- (FDMA)** Frequency division multiple-access
- (MIMO)** Multiple Input Multiple Output
- (EM)** electromagnetic
- (5G)** Fifth Generation
- (6G)** sixth Generation.

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 (IRS) to enhance the performance of wireless networks. Reconfigurable smart surfaces (IRS) 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

The goal of this work

The goal of this research work is to investigate and evaluate the performance of intelligent reflecting surface (IRS)-assisted amplify-and-forward (AF) relay networks, focusing on key metrics such as signal-to-noise ratio outage probability and ergodic capacity.

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 study the performance of the IRS-aided relaying cooperative network and we present our simulation results.

Chapter 1: An overview of cellular networks

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

1.1 Introduction

Cellular networks are considered one of the most important innovations in modern communication systems. They have completely changed the way people communicate and stay connected over long distances. At the beginning, the main goal of cellular networks was simply to provide wireless signal coverage in different areas. However, over time, they developed into advanced and complex systems capable of delivering reliable mobile communication services with wide coverage.

Today, cellular networks are an essential part of our daily lives. We use them for voice calls, sending messages, data transmission, and accessing the internet through mobile devices. The effectiveness of these networks depends on several key factors, such as the efficient use of radio frequencies and the ability to provide strong and continuous coverage. The continuous development of cellular networks reflects the rapid technological progress in this field. It also shows the increasing need to enhance network performance and expand coverage in order to satisfy the growing demand for wireless communication in our modern digital world.

1.2 A brief history of wireless communications

Wireless technology has a long history, and it began around the time that James C. Maxwell theoretically predicted and then proved the existence of electromagnetic waves in the 1860s, and when Heinrich R. Hertz experimentally confirmed the actual existence of the electromagnetic wave in 1888 [1].

In 1895, Guglielmo Marconi succeeded in receiving Morse code on a radio wave transmitted by a spark-gap transmitter with a receiver 2.4 km away. This experiment demonstrated the basic

concept and framework of wireless communication today. In wireless communication, the transmitter sends target information by superimposing it on a carrier wave, and the receiver obtains the information by extracting the superimposed information from the carrier wave. After that, research into wireless communication was advanced mainly for military use, and various wireless technologies were developed and improved. Wireless communication was also expanded on a commercial basis in the area of broadcasting, one of the significant applications of wireless communication. Radio broadcasts started in the first half of the 20th century and TV broadcasts started in the second half. Since the late 1980s, wireless communication has been widely used in mobile phones and other mobile terminals by individuals as these technologies, principally in semiconductor and software, have rapidly developed in line with the spread of the new infrastructure of the Internet. These are also even changing models of business and social life [1].

Wireless communication technologies are being developed and spreading in various fields of industry. In particular, the research and development of wireless sensor network technology and its applications are in rapid progress.

New systems are being developed, which integrate general purpose sensor nodes and devices, and can operate for several years with batteries while autonomously configuring their own networks. Meanwhile, wireless digital technologies have advanced, and their practical use for resolving security issues such as radio interception or interference, which are problems with conventional analog wireless systems, have significantly progressed, on the basis of development of these platforms, the applications of wireless communication technologies are spreading to various fields, including disaster prevention, disaster response, crime prevention, security checks, environmental protection, health and welfare, transport and logistics, and monitoring and control of buildings and facilities [1].

Yokogawa has developed field wireless devices and systems for various sites in industries, and they are currently used in many plants. Their effectiveness in many actual applications is proven—such advantages as no need of wiring, and the potential for mounting sensors on mobile or rotating bodies, something physically impossible with traditional wired systems [1].

1.3 A General Overview of Cellular network systems

The vision of wireless communications supporting information exchange between people or devices is the communications frontier of the next few decades, and much of it already [2].

1.3.1 The evolution of first-generation analog networks

The 1970s saw a revived interest in cellular communications. In scientific research, these years saw the formulation of models for path loss, Doppler spectra, fading statistics, and other quantities that determine performance type of analog telephone systems. A highlight of that work was Jakes' book *Microwave Mobile Radio* that summed up the state of the art in this area. The 1960s and 1970s also saw a lot of basic research that was originally intended for landline communications, but later also proved to be instrumental for wireless communications. For example, the basics of adaptive equalizers, as well as multicarrier communications, were developed during that time. For the practical use of wireless telephony, the progress in device miniaturization made the vision of "portable" devices more realistic. Companies like Motorola and AT&T vied for leadership in this area and made vital contributions. Nippon Telephone and Telegraph (NTT) established a commercial cell phone system in Tokyo in 1979. However, it was a Swedish company that built up the first system with large coverage and automated switching: up to that point, Ericsson AB had been mostly known for telephone switches while radio communication was of limited interest to them. However, it was just that expertise in switching technology and the (for that time, daring) decision to use digital switching technology that allowed them to combine different cells in a large area into a single network, and establish the Nordic Mobile Telephone (NMT) system. Note that while the switching technology was digital, the radio transmission technology was still analog, and the systems became therefore known as analog systems. Subsequently, other countries developed their own analog phone standards. The system in the U.S.A., e.g., was called Advanced Mobile Phone System (AMPS). An investigation of NMT also established an interesting method for estimating market size: business consultants equated the possible number of mobile phone users with the number of Mercedes 600 (the top-of-the-line luxury car at that time) in Sweden. Obviously, mobile telephony could never become a mass market, could it? Similar thoughts must have occurred to the management of the inventor of cellular telephony, AT&T. Upon advice from a consulting company, they decided that mobile telephony could never attract a significant number

of participants and stopped business activities in cellular communications. The analog systems paved the way for the wireless revolution. During the 1980s, they grew at a frenetic pace and reached market penetrations of up to 10% in Europe, though their impact was somewhat less in the U.S.A. In the beginning of the 1980s, the phones were "portable," but definitely not handheld. In most languages, they were just called "car-phones," because the battery and transmitter were stored in the trunk of the car and were too heavy to be carried around. But at the end of the 1980s, handheld phones with good speech quality and quite acceptable battery lifetime abounded. The quality had become so good that in some markets digital phones had difficulty establishing themselves - there just did not seem to be a need for further improvements [2].

1.3.2 Advancements in the second-generation digital systems

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

1.3.3 The evolution of mobile telephony

The evolutions of mobile telephony are extremely popular and lucrative worldwide: these are the systems that ignited the wireless revolution. Cellular systems provide two-way voice and data communication with regional, national, or international coverage. Cellular systems were initially designed for mobile terminals inside vehicles with antennas mounted on the vehicle roof. Today these systems have evolved to support lightweight handheld mobile terminals operating inside and outside buildings at both pedestrian and vehicle speeds [7].

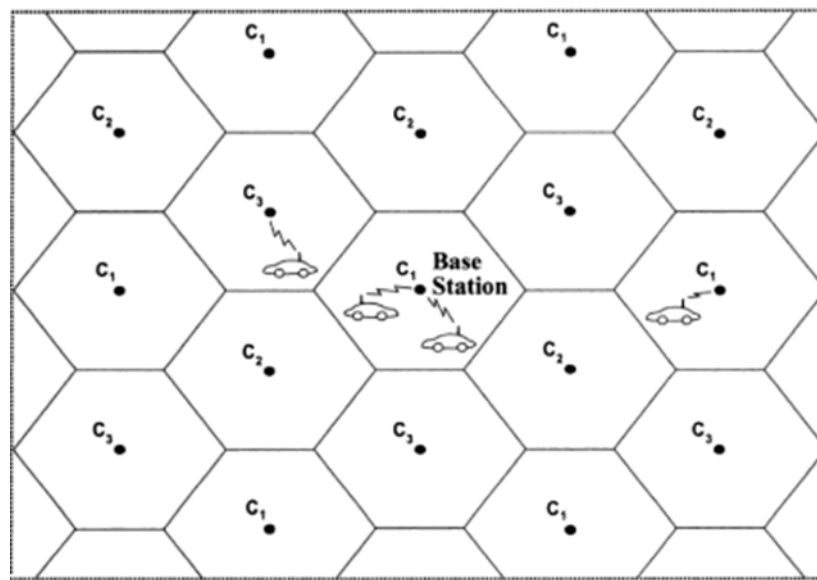


Figure 1.1. A cellular network [7].

The basic premise behind cellular system design is frequency reuse, which exploits the fact that signal power falls off with distance to reuse the same frequency spectrum at spatially separated locations. Specifically, the coverage area of a cellular system is divided into non overlapping cells, where some set of channels is assigned to each cell. This same channel set is used in another cell some distance away, as shown in **Fig 1.1**, where C_i denotes the channel set used in a particular cell. Operation within a cell is controlled by a centralized base station, as described in more detail below. The interference caused by users in different cells operating on the same channel set is called inter cell interference. The spatial separation of cells that reuse the same channel set, the reuse distance, should be as small as possible so that frequencies are reused as often as possible, thereby maximizing spectral efficiency. However, as the reuse distance decreases, inter cell

interference increases owing to the smaller propagation distance between interfering cells. Since inter cell interference must remain below a given threshold for acceptable system performance, reuse distance cannot be reduced below some minimum value. In practice it is quite difficult to determine this minimum value, since both the transmitting and interfering signals experience random power variations due to the characteristics of wireless signal propagation. In order to determine the best reuse distance and base station placement, an accurate characterization of signal propagation within the cells is needed [7].

1.4 Strategic Developments and Future Outlook of Wireless Networks

The growth of mobile subscribers may lead to the explosively increasing mobile data traffic. The latest data from [3] indicates that the global mobile broadband subscriptions have reached the 5.1 billion figures in 2018 and it is predicted to grow to 5.7 billion by 2023. Furthermore, the number of connected devices may surpass the global population in the future due to the growth of machine-to-machine (M2M) communications and Internet of Things (IoT) applications, which further contributes to global mobile traffic growth. In addition, the demand for rich multimedia content has increased drastically in recent years and hence inevitably contributes to further increase in mobile traffic.

As highlighted by a study in [4], mobile video content contributed more than half of the global data traffic since 2012 and it is expected to reach 78% of global traffic by 2021, prompting the need for thousand-fold increase in capacity and wireless resources in order to accommodate the mobile traffic demand. Innovative solutions, including massive MIMO, network densification and advanced multiple access schemes, are crucial to address the challenges of the ever-increasing capacity requirement [5].

There are high expectations for the fifth generation (5G) technology to effectively support advanced and crucial applications, which have been broadly categorized by the International Telecommunication Union (ITU) into three main groups: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low-latency communication (URLLC). To meet the demands of these use cases, the ITU has outlined specific performance targets. These targets encompass peak rates of 20 Gbps for downlink and 10 Gbps for

uplink, a user experience data rate of 100 Mbps, latency below 1ms, mobility support up to 500 km/h, and connectivity density reaching 1 million devices per square kilometer, as detailed in [6].

1.5 Antennas technologies and propagation characteristics

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

1.5.1 Antenna parameters

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

- *Frequency range*: The frequency range is the range of frequencies over which an antenna is designed to operate. Antennas Activate Windows as ultrahigh frequency (UHF), very high frequency (VHF), or GHz, depending on the application.
- *Gain*: Gain is a measure of the ability of an antenna to direct and concentrate energy in a specific direction. It is usually measured in decibels (dB) and is relative to an isotropic radiator (an ideal antenna that radiates energy uniformly in all directions).
- *Directivity*: Directivity is a measure of the ability of an antenna to concentrate energy in a particular direction. It is the ratio of the maximum radiation intensity in a specific direction to the average radiation intensity over all directions.
- *Radiation pattern*: The radiation pattern is a graphical representation of the directionality of an antenna's radiation. It shows the distribution of energy in space around the antenna.
- *Polarization*: Polarization is the orientation of the electric field of the electromagnetic wave with respect to the antenna. It can be either linear or circular, and different types of antennas are designed to work with different polarizations.

- *Impedance*: Impedance is the measure of opposition to the flow of an alternating current in an electrical circuit. The impedance of an antenna must match the impedance of the transmission line to ensure maximum power transfer and efficient operation.
- *Bandwidth*: Bandwidth is the range of frequencies over which an antenna can operate without significant loss of performance. The broader the bandwidth, the better the antenna is at receiving and transmitting.

Gain and directivity are the two main characteristics that characterize antennas. The directionality of a beam of radiation describes how strongly it is focused in one direction. Therefore, directional antennas have smaller radiation patterns than omnidirectional ones while omnidirectional antennas are rather uniformly focused in all three dimensions. **Fig 1.3** shows the directional antenna patterns with specific antenna gains. This is typically achieved by mixing several different types of radiating pieces. The gain of an antenna is a common metric listed in technical documents, and it is used to rate the amount of power emitted by the antenna. For the IoT to operate in the unlicensed industrial, scientific, and medical (ISM) bands, the equivalent (or effective) isotropic radiated power (EIRP) must be less than or equal to that of a licensed digital transmitter, reducing the potential for interference in the increasingly crowded radio spectrum. To achieve the same signal intensity as the antenna under test (AUT) in the direction of its strongest beam, the ideal isotropic antenna would have to emit a total power equal to the EIRP. This metric gives a more complete picture of the transceiver module because it considers not only gain but also transmitter output power and antenna feed loss [8].

1.5.2 Antennas for Internet of things

Internet everywhere and Internet of things (IoT) everywhere! This time frame and future ones are all about connecting with everyone via whatever method. Communication is always at the tip of a digital noodle. The technology is being developed at an exponential rate right now, much faster than humanity as a whole ever dreamed of. The connectivity option, IoT, contains several heterogeneous end systems, such as smart homes, the industrial IoT, smart agriculture, and smart cities. And the smart grid can connect to them all. Developing a wireless product involves more unknowns than market fit and return on investment. Some unknowns are more physics-based, but

still affects the economics of a product. Range is one such unknown. But what is range? Let's try to answer this question in the simplest way possible. How far apart do we need two devices to have working communication between them? Why does range matter? Because if we go over the wireless range, network quality will start to suffer. We don't want to lose data. We don't want to deliver some data later, we don't want to reduce the number of devices we can support, and maybe even lose control of our devices because they are out of range. If we know what range to expect, we should be able to answer questions like: how far apart can you place devices? How many devices can you have in a network? How much data can you send in the network? What will the installation procedures be? These questions really matter from the business vantage point. How important? In one instance, there was a \$430 million lawsuit against wireless range, simply because it didn't cover as much distance as people wanted. Theoretical predictions: What are they? Let's first look at what the theory tells us. In the real world, the antennas are notoriously fixed in their designs, and so there are only a few things that you have to consider during the design and production process. The difficult balance between physical size, performance, and cost that antenna designers often face is heavily influenced by a bunch of factors and IoT specifics [8].

1.5.4 Applications and frequencies

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

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

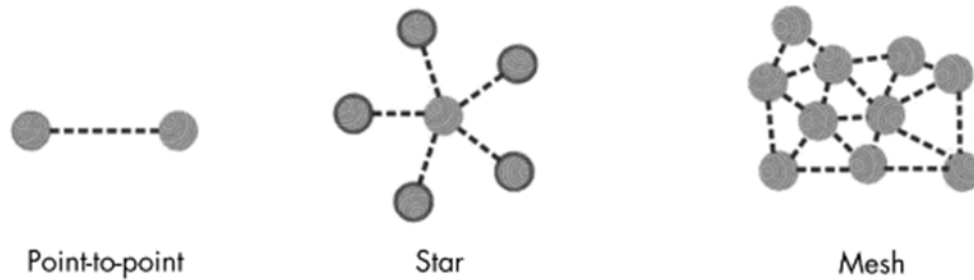


Figure 1.2 IoT network communication topologies [8].

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

Overall, the frequency that an IoT device chooses, will depend on the requirements of the specific application (e. g. range, data rate and power consumption). Over time as IoT technology continues to develop it is likely that new frequencies and wireless protocols will be developed to support the new IoT applications [8].

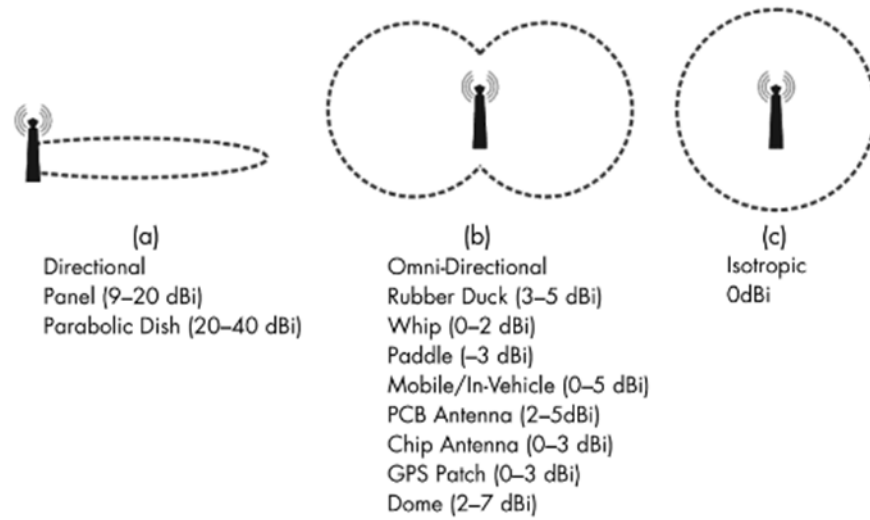


Figure 1.3 Patterns of radiating antenna depending on the type of gain [8].

1.6 5G Technologies and Drivers

The basic elements of 5G include the following:

- *Access and Mobility Management (AMF)*: Provides encryption and integrity protection, mobility management, authentication and authorization, etc.
- *Session Management (SMF)*: Performs UE IP address allocation and management, UPF selection and control, roaming, etc.
- *Unified Data Management (UDM)*: Performs subscription management, user data management, registration management, mobility management, etc.
- *Policy Control Function (PCF)*: Executes policy rules for CP functions, etc.
- *User Plan Function (UPF)*: Performs external interconnection point to the data network, UP quality of service management, etc.
- *Application Function (AF)*: Interacts with the policy framework for policy control, etc.

1.6.1 5G Technologies

Expected to be commercially available around 2021, 5G mobile networks are the subject of intense planning and development activities. Compared to current 4G mobile networks, 5G networks are expected to support enormous system capacity, significantly lower latency, and approximately 1,000 times more devices per square kilometer, among other requirements. To meet these requirements, several new technologies have been proposed and are under development for 5G networks. These technologies include, but are not limited to: massive MIMO, software-defined networking, mm-Wave, cloud radio access network (cloud-RAN), non-orthogonal multiple access, M2M communications, mobile edge computing, wireless caching, ultra-dense networks, and full-duplex communication. We briefly describe some of these technologies below.

1.6.2 Driving Factors

5G cellular systems must represent a significant leap in features and performance compared to LTE, as incremental improvements are undesirable and do not justify the substantial capital investments required by operators to deploy 5G services. It is important to note that we have maintained a single global cellular standard. The driving factors for 5G are [9]:

- Increased user data throughput
- Increased system capacity
- Massive number of connections
- Reduced end-to-end latency
- Heterogeneous mix of services
- Flexible bandwidth deployments
- Network flexibility
- Transition to more energy-efficient communications.
- The ITU has published a diagram to identify 5G services. The three significant use cases (corners of the triangle) are intended to encapsulate the expected future uses of 5G:
 - Enhanced Mobile Broadband (eMBB)
 - Massive Machine-to-Machine Communication (mMTC)
 - Ultra-Reliable Low-Latency Communications (URLLC).

These 5G use cases range from smart homes, connected drones, e-health, connected energy, autonomous vehicles, real-time virtual reality/augmented reality gaming, and more, in preparation for a wide variety of 5G services [9].

The 5G cellular system is expected to support these use cases by using the following technologies:

- *Flexible spectrum deployments*: licensed, unlicensed, and shared spectrum, higher and contiguous bandwidth, multi-RAT, etc.
- *Enhanced network architecture*: support for the ICT industry's cloud trend, SDN/NFV, network slicing, multi-access edge computing, lower latency, etc.
- *Flexible numerology*: supports a wide variety of use cases and spectral deployments (below and above 6 GHz bands), flexible time slots and transmission bandwidths, etc.
- *Modulation and coding*: QAM modulation continues to provide a reasonable compromise between spectrum and energy efficiency, polar error correction codes and others.

1.7 Conclusion

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

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Chapter 2: Relay-aided cooperative communication

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

2.1 Introduction

Cooperative communication and networking represent a new paradigm that leverages transmission and distributed processing to significantly increase the capacity of wireless communication networks. Current wireless networks face the challenge of meeting the ever-growing expectations and demands of users. This is primarily due to the scarcity of available radio frequency spectrum, the unreliability of wireless links, and the limited battery capacity of wireless devices. The emerging paradigm of cooperative wireless networks can address these challenges. The basic idea of cooperative wireless networks is that wireless devices work collaboratively through a sharing strategy to achieve their individual or common goals. During cooperation, wireless devices share resources (e.g., wireless links, antennas, etc.) through short-range communication. The advantages of cooperation are as follows:

- First, cooperation can improve the communication capabilities, reliability, transmission distance, and quality of service (QoS) of wireless devices.
- Second, cooperation can reduce information exchange costs (e.g., transmission power, transmission time, spectrum, etc.).

Collaborative communication and networking will be key components of next-generation wireless networks [1]. Furthermore, the spectral efficiency of relay-based systems depends on the duplex protocol used. When using a half-duplex (HD) relay protocol, the transmitter and the relay cannot occupy the same physical resources simultaneously. This problem can be solved by using a full-duplex (FD) relay protocol [2].

2.2 Fundamentals of cooperative wireless communications

This type of communication differs from point-to-point 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.

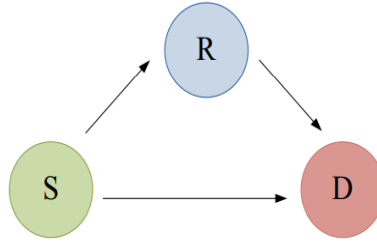


Figure 2.1 Relay-assisted communication scheme [3].

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. [3]. 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:

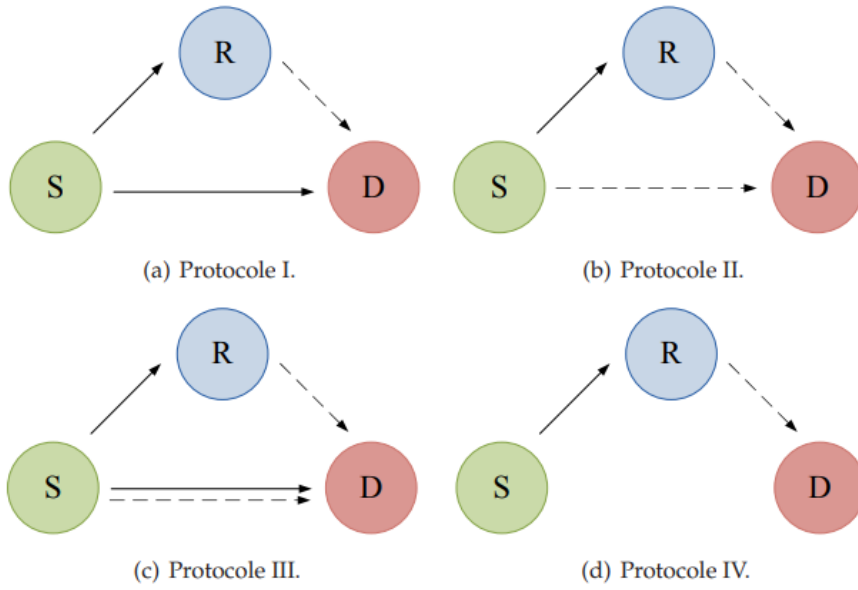


Figure 2.2. Semi-duplex relay protocols in three-node scenarios [3].

2.2.1 Relaying protocols

Protocol I. In the receiver relay phase, the source broadcasts the information towards the destination and the relay; in the transmitter relay phase, the relay communicates with the destination, as shown in **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 [4].

2.2.2 Resource allocation

The Static resource allocation relay is assumed when transmission is carried out in two time slots with a fixed duration. Possible examples applications are a centralized cellular scenario based on TDMA or a system where the channel model is characterized by statistical information. On the contrary, the dynamic resource allocation relay requires that the source knows all the qualities of the links. With this knowledge, the allocation adaptive resources on each phase maximize spectral efficiency relay-assisted communication. The static resource allocation relay can evaluate knowledge about the successful transmission to the destination or relay and involves multiple schemes retransmission at the relay level to increase spectral efficiency. The different types of static resource allocation strategies, illustrated on **Fig2.3**, can be summarized as follows [3].

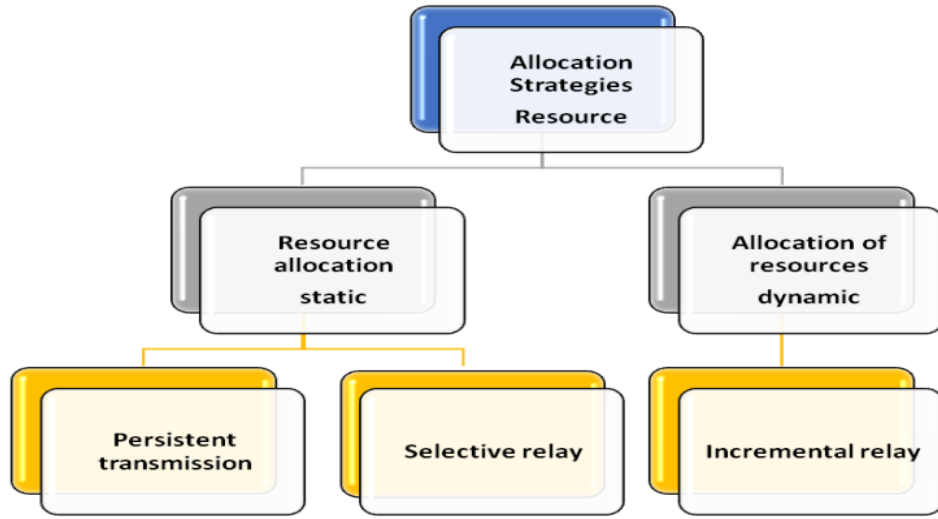


Figure 2.3. Resource allocation strategies in assisted communication by relay [3].

Persistent transmission: In this retransmission scheme, the relay terminal can still transmit.

Selective relay: This retransmission scheme is applied to the retransmission strategy decoding and transfer (DF), because it considers the success or failure of the source-relay connection. If the relay is not receiving the signal correctly or if the state of the channel of the source-relay link is less than a threshold, the source retransmits the message while the relay remains silent. Otherwise, if the relay correctly receives the signal from the source, the relay retransmits the message to the destination.

Incremental relay: This retransmission scheme considers success or the failure of the source-destination link during the receiver relay phase. The relay transmits the information when the message to the destination received by mistake. [3].

2.3 Cooperative relay networks

Wireless networks can be classified into two major categories: traditional infrastructure networks and multi-hop networks. In traditional networks, the communication is performed directly between the BS and the MS and vice versa, so, there is only one hop. Though obstacles may degrade the

line-of-sight (LoS) S-D link quality in this scheme, the source makes no use of the cooperation potential of other terminals in the network to compensate for the impairments [1]

2.3.1 Strategies of relay-assisted transmission

The traditional S-D communication mode has been transformed into the S-R-D mode, and the role of the relay can be selected from a variety of working modes, which will affect the maximum achievable data rate of the system. For half-duplex relay, the resources allocated to each stage of the relay-based transmission will also significantly affect the achievable data rate. Therefore, the relay-based transmission strategy must take into account the decoding mode and resource allocation of the relay. The three decoding modes analyzed in the literature are: amplify forwarding (AF), decode forwarding (DF) and compress forwarding (CF) [1].

A) Amplify-and-forward (AF)

This is the simplest strategy that a relay node can use. The relay node amplifies the signal received from the source node and forwards it to the destination node without decoding. Therefore, it is also called non-regenerative relay. The main drawback of this strategy is that the relay node amplifies the received noise at the same time. Applying this strategy to cooperative communication can achieve a lower bit error rate (BER) than direct transmission. The failure probability of cooperative communication has been derived, and it shows that second-order diversity can be achieved for two cooperative users. If the relay node is equipped with multiple antennas and the channel state information of the S-R/R-D link is available, the AF strategy can achieve a significant advantage over direct transmission by performing optimal linear filtering on the forwarded data [1].

B) Decode-and-forward (DF)

Compared to the AF strategy, this strategy increases the complexity of the receiver. The relay must now estimate the message received from the sender; therefore, the overall performance depends on the success rate of message decoding. Depending on the type of retransmitted symbol, the relay uses either repetition coding (RC) or unrestricted coding (UC). With RC, the relay retransmits the same previously estimated symbol; while with UC, the transmitted symbol does not match the received symbol, but contains the same information sent by the sender (the sender and relay use different codebooks). Therefore, this protocol is also called regeneration retransmission [1].

C) Compress-and-forward (CF)

In this strategy, the relay node does not decode the data, but instead performs lossy Wyner-Ziv source coding on the estimated symbols of the received signal. Then, the compressed signal is sent from the relay node to the destination node. This strategy has been proposed. Depending on the channel gain of each link, the CF strategy may be superior to the DF strategy. However, it increases the complexity of the system [1].

2.3.2 Relaying techniques

A) Half Duplex Relaying

High-definition relay is a two-way signal transmission process, but it can only transmit in one direction at a time. Walkie-talkies are an example. Although both the sender and receiver can send signals, they must take turns. During data exchange, the two walkie-talkies must be used alternately. One person must press a button to speak and transmit their voice to the other person. Only after releasing the button can the other person receive the other's transmission [5].

B) Full Duplex Relaying

Full-frequency relay is a technology that allows simultaneous transmission and reception. In recent years, full-frequency relay technology has been widely used in 5G networks. Advances in antenna technology and signal processing technology have made full-frequency relay more flexible. However, it is susceptible to self-interference in residual loops. Full-frequency relay can be divided into two main categories: full-frequency self-relay (FDAF) and full-frequency distributed relay (FDDF). With full-frequency relay, users can transmit and receive data simultaneously. This makes it crucial for improving spectrum efficiency and reducing the probability of failure [5].

2.4 Relay Transmission Topologies

Serial relay transmission: used for long-distance communication and range extension within shielded areas. It provides power amplification. In this topology, signals propagate from one relay to the next, and the channels of adjacent relays are orthogonal to avoid interference.

Fig2.4 shows a serial relay transmission topology [6].



Figure 2.4. Serial relay transmission topology [6].

Parallel relay transmission: The serial relay transmission suffers from multi-path fading. For outdoors and non-line of sight communication, signal wavelength may be large and installation of multiple antennas is not possible. To increase the robustness against multipath fading, parallel relay transmission can be used. In this topology, signal propagates through multiple relay paths in same hop and destination combines the signals received with the help of various combining schemes. It provides power gain and diversity gain simultaneously. **Fig 2.5** shows the parallel relay transmission topology [6].

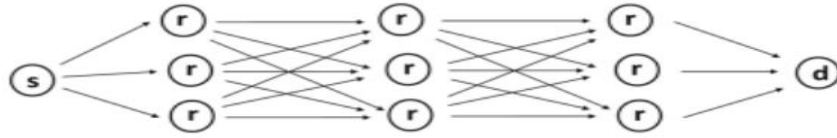


Figure 2.5. Parallel relay transmission topology [6].

2.5 Some application scenarios

Cooperative communications play a vital role in many scenarios of application and overcome problems related to communication by direct connection [7]. Cooperation between nodes is beneficial in several practical applications, ranging from cellular networks to networks of wireless sensors, as shown in **Fig. 2.6**.

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 [8].

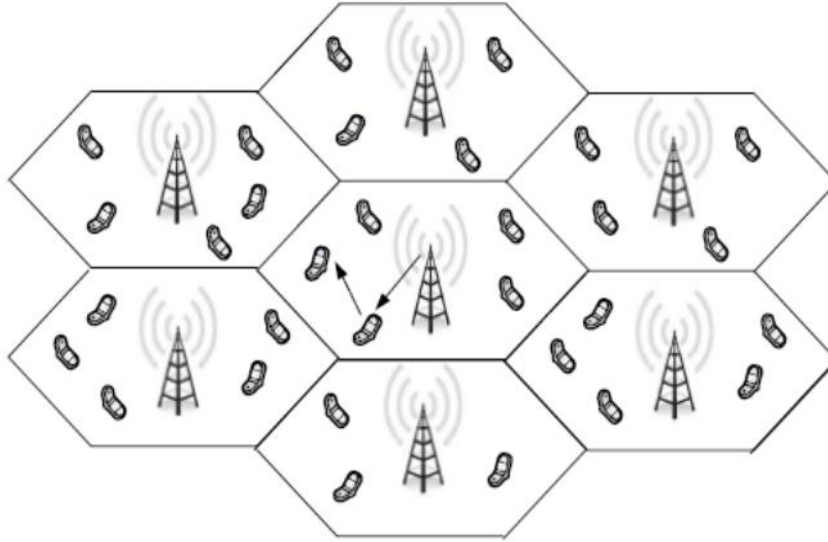


Figure 2.6 Cellular scenario: the relay improves user performance in terms of capacity, coverage or interference [8].

2.5.1 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. **Fig 2.6** 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 [9].

2.5.2 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. **Fig 2.7** 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 [8].

2.5.3 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 2.8**. 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 [8].

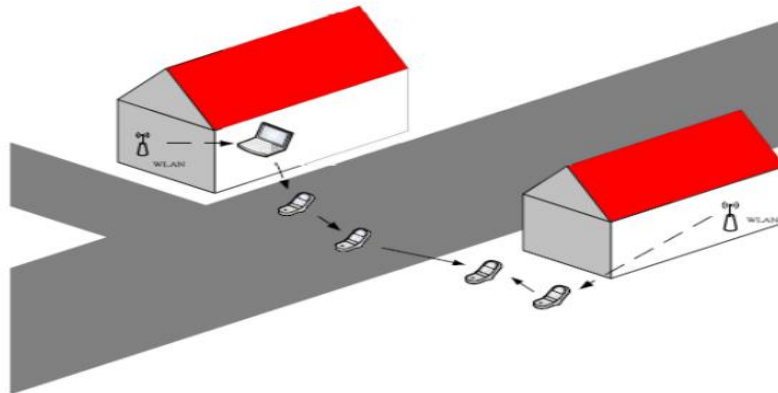


Figure 2.7 A WLAN station installed inside a house provides access to users on the street via relays [8].

2.5.4 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. **Fig 2.9** shows an example of a cooperative WSN, where nodes sensors are limited in coverage [8].

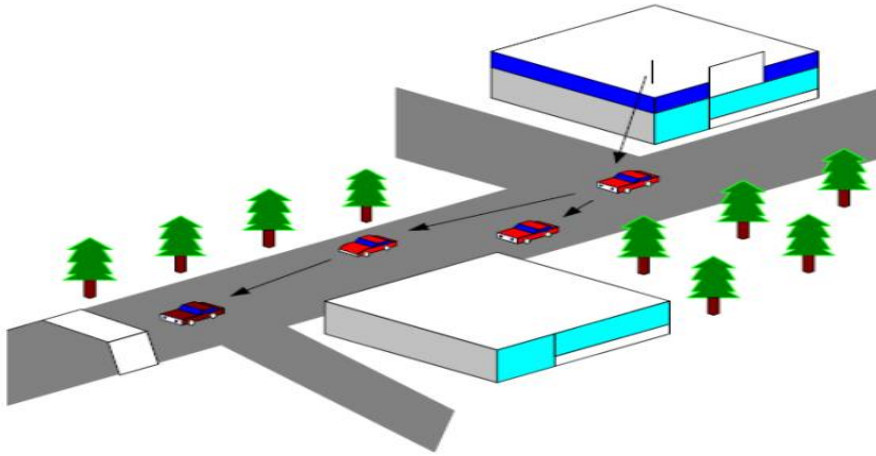


Figure 2.8 Distributed V2V communication scenario, where vehicles cooperate to reduce communication delays [8].

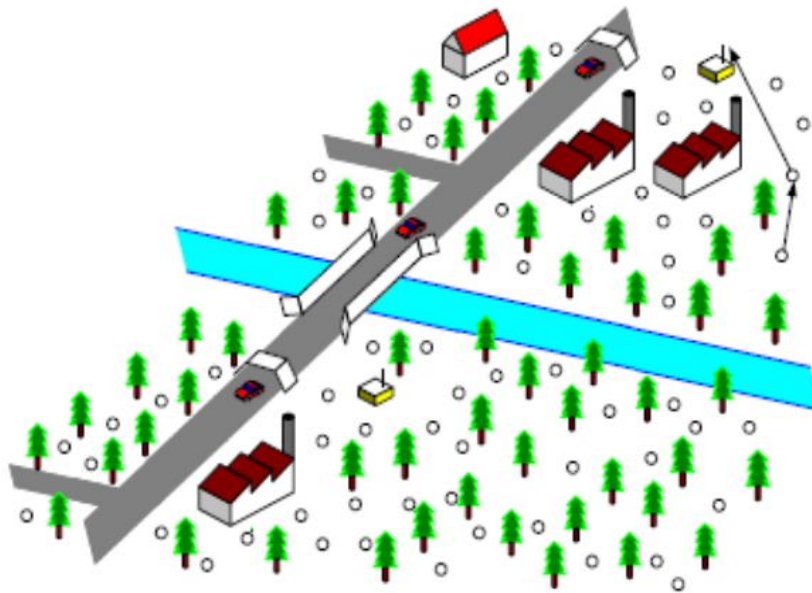


Figure 2.9 WSN scenario, where sensors cooperate to obtain a better coverage [8].

2.6. The advantages and disadvantages of 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 number 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 [11].

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. **Fig 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:

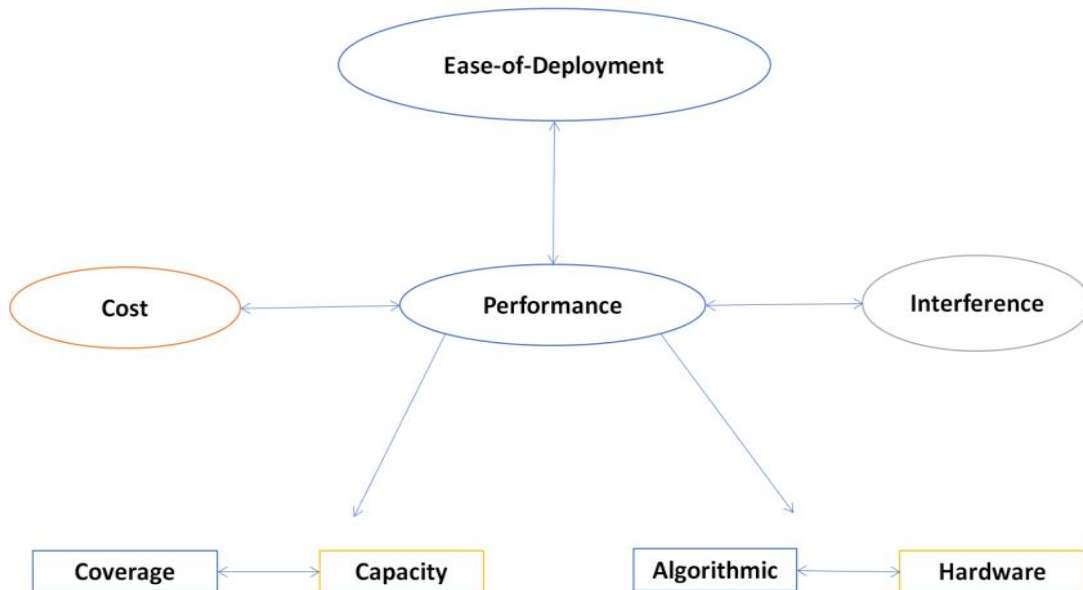


Figure 2.10 Trade-offs in system performance: Coverage, capacity, algorithmic design, and hardware complexity [11].

- ✓ *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 [11].

2.7. Cooperative communication's 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 [11].

2.8 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. Although actual implementation requires meticulous attention to synchronization, resource management, and protocol development, the benefits of exploiting spatial diversity with cooperative tactics are enough to make this technology especially useful for the growing needs of the next generation of wireless systems and an array of new emerging technologies, thus providing advanced wireless networks that are more powerful and efficient.

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Chapter 3: RIS-assisted communication networks

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

3.1 Introduction

In this digital age, the concept of connectivity plays a crucial role in bridging urban and rural areas in terms of access to telecommunications technology. With the rapid development of communication technologies, a significant portion of the population in rural areas still does not have access to a reliable radio network, resulting in what are commonly called “white zones”.

This lack of coverage is often attributed to the reluctance of mobile network operators to invest in areas with limited profitability. In response to this challenge, our work explores innovative solutions to deploy cost-effective communication networks that can adapt to the environmental conditions of rural areas.

One such solution would be to design and implement Smart Reflective Surfaces as relays for base stations in rural areas. This approach involves planning for network densification, optimizing the performance of smart radio environments, and cost-effective site deployment. The ultimate goal is to improve radio signal coverage, reduce infrastructure costs, provide flexibility and scalability, and minimize interference in rural communication networks [1].

3.2 Fundamentals of IRS

3.2.1 The Structure of an IRS element

An IRS can consist of a relatively straightforward 2D configuration, composed of conductive patches, diodes, and conductive power/signal lines.

This structure includes a positive-intrinsic-negative (PIN) diode, and the associated biasing circuitry is depicted in **Fig. 3.1**.

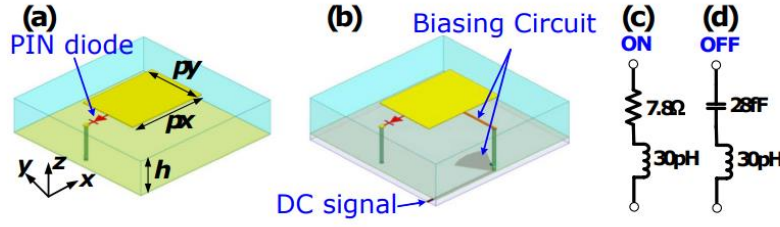


Figure 3.1. The structure of an IRS unit (As proposed in [2]). (a) Schematic of the element, with specific dimensions. (b) The biasing architecture. (c,d) The equivalent circuits of the PIN diode at ON and OFF states, respectively.

A diagram illustrating the structure of an IRS element is shown in **Fig. 3.1(a)**. This unit features a sandwich-like configuration, comprising a basic rectangular patch and a metal ground plane, with a substrate positioned between them that possesses specific dielectric constant and loss tangent values [3]. A PIN diode is utilized to establish a connection between one edge of the patch and the ground using a metal via. This configuration results in an anisotropic element that exhibits binary-coded reflective characteristics along the x direction. To simplify the biasing process in real-world applications, a direct current (DC) circuit is incorporated into the element's design, as depicted in **Fig. 3.1(b)**. The deliberately designed bias circuit includes the quarter-wavelength microstrip line, the open-ended radial stub and DC signal line. The quarter-wavelength microstrip line and the open-ended radial stub are employed to choke the RF signal and ensure a good isolation between the DC and RF performance. The PIN diode is modeled as an equivalent circuit shown in **Fig. 3.1(c,d)** when biasing circuit is switched ON or OFF, respectively. Furthermore, it is noticeable that numerous elements are compactly arranged within a structure to compose a surface. Through the integration of multiple elements in this array like metamaterial surface, the intelligent reflecting surface (IRS) can achieve a diverse range of manipulative functions on the incident electromagnetic (EM) wave [2]. Particularly, the EM wave that is reflected can be skillfully controlled in terms of its polarization state, power distribution, and concentration towards any chosen direction. In order to achieve such specific functions, precise manipulation of the excitation and phase of individual electronic elements is necessary, which is accomplished through processors utilizing a predetermined control strategy, such as employing a field programmable gate array (FPGA) [4], [5].

This approach enables the manipulation of the phase and amplitude of the incoming EM wave on the surface, allowing for controlled reflection in desired directions. This forms the basis for creating a programmable wireless channel.

3.2.2 Architecture

The architecture of a IRS is as shown in **Fig 3.2**, where a thin planar surface of multiple unit cells is connected to a smart controller [6].

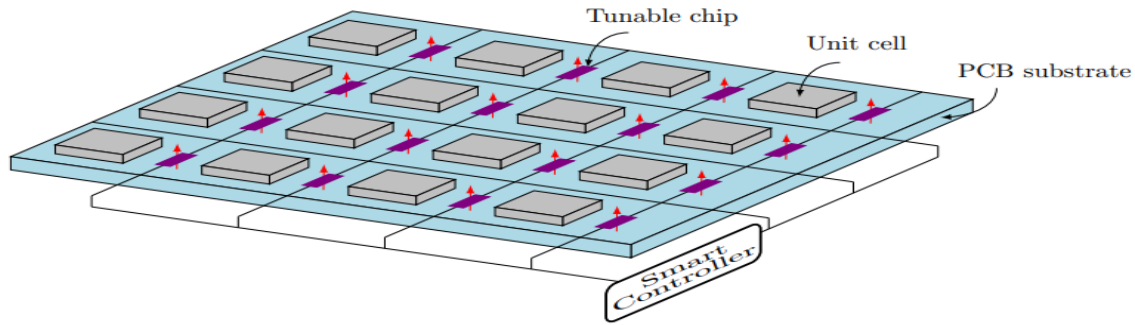


Figure 3.2. The architecture of IRS [6].

The unit cells are the main constructing component of the IRS, whereas the role of the smart controller is to adapt the interaction of the unit cells to the impinging waves. In general, the concept of meta-material is the key enabler for building the IRS. The research field of meta-material is interested in building materials of reconfigurable EM properties that don't exist in natural materials [7]. That is why the IRS is widely known as a meta-surface, in addition to other names such as intelligent reflecting surface, large intelligent surface, digitally controllable scatterers, and software controllable surface. On the other hand, the unit-cell is known as a meta-atom, reflecting element, and scattering element. The unit cell can be conceptually realized as a sub-wavelength metallic or dielectric scattering particle such as a small antenna that is connected to tunable electronics circuits as positive intrinsic negative (PIN) diodes, varactors, or micro electromechanical system (MEMS) switches [8]. The tunable electronic circuits are responsible for the configuration of the unit cell's response towards the incident EM waves. The EM wave manipulation capability of the IRS resides mainly in controlling the reflection coefficient of each unit cell to the impinging waves. The reflection coefficient of the unit cell is commonly alternated by controlling the load impedance connected to the reflecting element [9]. For instance, in the case

of having a PIN diode as a tunable chip for each element. Then the PIN diode can be switched between on and off states by controlling its bias voltage which will vary the load impedance connected to the element between short-circuit and open-circuit. Thus, generating a π phase shift difference for the reflection coefficient between the on and off. Furthermore, for the sake of full phase shift control, multiple PIN diodes or varactors can be connected to each unit cell which will allow multiple choices or continuous configuration for the connected load impedance. Moreover, the amplitude of the reflection coefficient can be configured by attaching a variable resistor load to each unit cell which will control the energy dissipated portion of the incident wave in the unit cell [10]. Moreover, a major advantage of the IRS is that it is a highly energy-efficient unit as it doesn't have any power amplifier, radio frequency (RF) chain, or complex signal processing capabilities. That is why the IRS is widely known for nearly-passive IRS as it doesn't consume any power for transmission and the main energy is used in the control process of the tunable circuits to alternate the impinging wave. However, active IRS which can additionally amplify the impinging radio waves are possible by integrating amplifiers to the unit cells which may be practically costly and energy inefficient [11].

3.2.3 Electromagnetic functions

The IRS can be configured to support multiple functions for the incident EM waves. In **Fig 3.3**, we discuss some of the possible functions of the IRS [6]:

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

- ✓ *Splitting*: The IRS creates multiple reflected and refracted waves for a single impinging wave. This function can be satisfied by dividing the IRS into several sub-surfaces and configuring them independently to split the incident wave.
- ✓ *Absorption*: The IRS ensures minimum reflection and refraction power of the impinging waves which may be possible by controlling the amplitude reflection coefficients of the unit cells.
- ✓ *Polarization*: The IRS is utilized to change the polarization state between the incident and reflected/refracted waves. This function usually relies on dual polarized unit cells which could excite two orthogonal polarization states and induce independent phase shifts per each polarization state whenever a wave is incident on them.

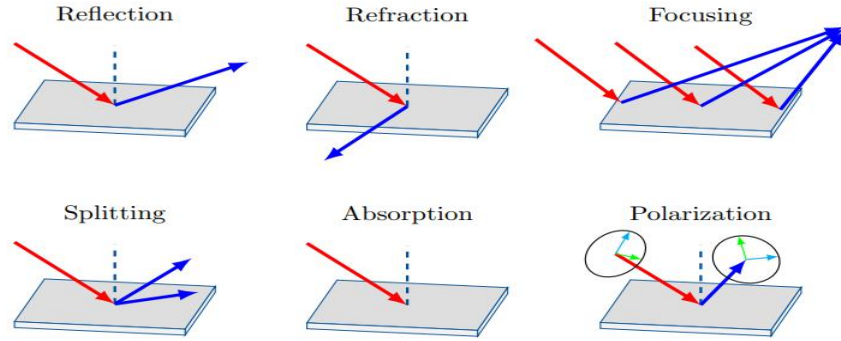


Figure 3.3. Electromagnetic functions of IRS [6].

3.2.4 Typical features of IRS

By judiciously tuning the phase shifts of the reflecting elements of the IRS, the reflected signals can be constructively superimposed with those from the direct paths for enhancing the desired signal power, or destructively combined for mitigating deleterious effects of multiuser interference. Hence, IRSs provide additional degrees of freedom to further improve the system performance. In the following, we list some typical IRS applications in various emerging systems [12].

A. IRS-aided mm-Wave Systems

Mm-Wave techniques have the potential of supporting high data rates given their high bandwidth. However, communication at Mm-Wave frequency also has some drawbacks, such as its severe

path loss. Fortunately, this can be mitigated by its huge array gain provided by a large antenna array within a compact space, given its short wavelength. Another impediment is that it is vulnerable to blockages by cars, pedestrians, and trees. The readily penetration loss is also high, which cannot be readily addressed by using a large antenna array. Instead, IRSs can be deployed to construct an auxiliary transmission link even when the direct link is blocked.

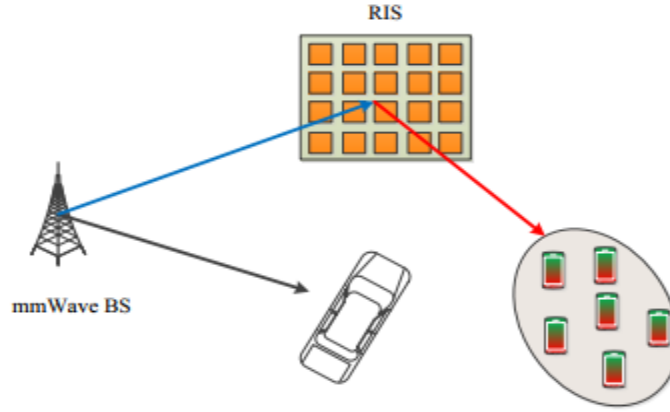


Figure 3.4.IRS-aided mm-Wave systems [12].

B. *IRS-aided Multi-cell Networks*

To maximize spectrum efficiency (SE), multiple BSs in different cells reuse the same scarce frequency resources, which leads to inter-cell interference, especially for the cell-edge users. Specifically, the desired signal power received by the cell-edge user from its serving BS is comparable to the interference received from its neighboring cells. Hence, the cell-edge users suffer from a low signal-to-interference-plus-noise ratio (SINR). To address this issue, it is proposed to deploy an IRS at the cell boundary as shown in **Fig. 3.5**. In such a setting, the IRS is able to simultaneously enhance the signal gleaned from the serving BS, and mitigate the interference from the other.

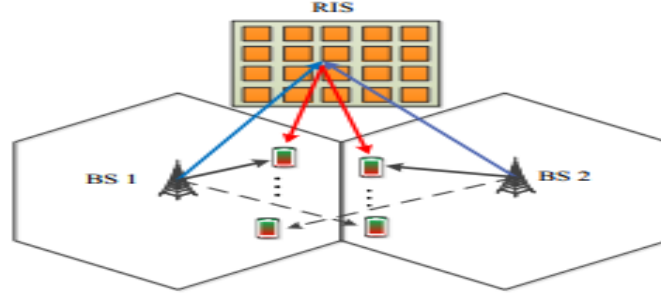


Figure 3.5.IRS-aided multi-cell networks [12].

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

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

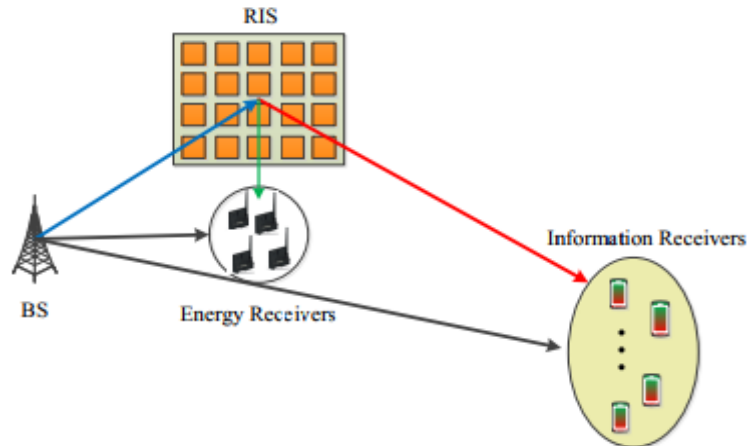


Figure 3.6.IRS-aided SWIPT systems [12].

D. IRS-aided Mobile Edge Computing (MEC) Networks

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

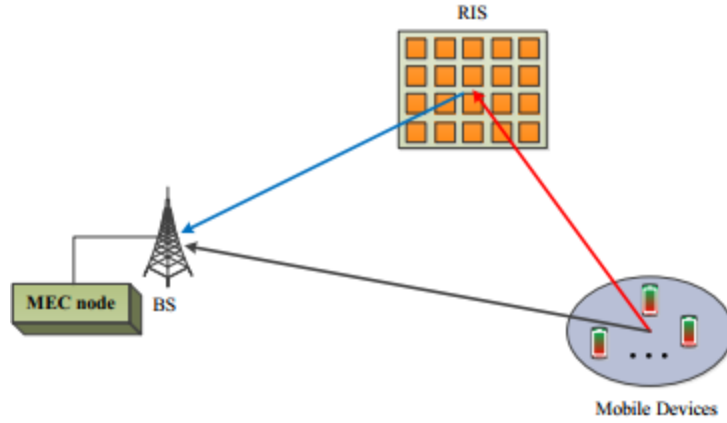


Figure 3.7.IRS-aided (MEC) Networks [12]

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

NOMA constitutes a promising future multiple access technique in future wireless networks, in which each orthogonal resource block is shared by multiple simultaneous users. This significantly enhances the spectral efficiency of conventional orthogonal multiple access (OMA). However, in some special cases when the users' channel vectors are orthogonal to each other, NOMA may not be a good option. The ideal implementation scenario for NOMA is when all the users' channel vectors represent the same angular direction. To broaden the application of NOMA, IRS can be introduced into the system or beneficially manipulating the wireless channel vectors of all users, so that one user's channel vector can be aligned with the other ones [12].

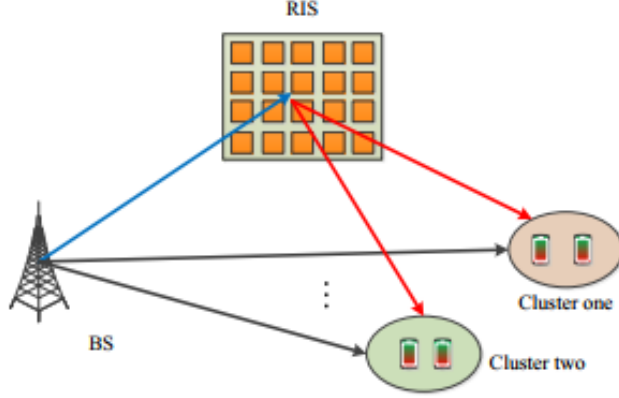


Figure 3.8.IRS-aided NOMA systems [12].

F. IRS-aided Multicast Networks

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

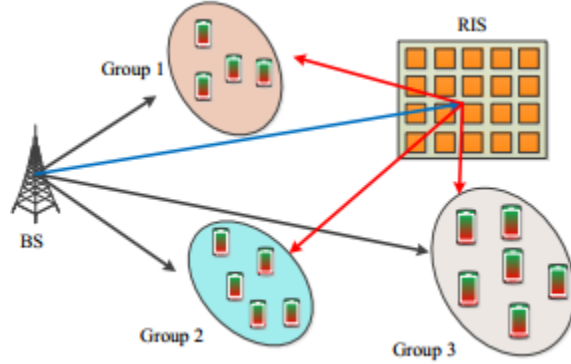


Figure 3.9. IRS-aided Multicast systems [12].

G. IRS-aided Physical Layer Security (PLS) Networks

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

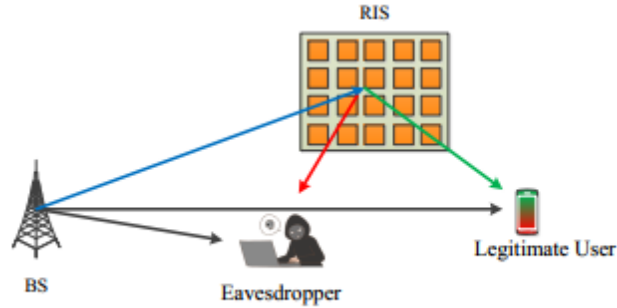


Figure 3.10.IRS-aided PLS systems [12].

H. IRS-aided Cognitive Radio (CR) Networks

CRs are capable of enhancing the SE by allowing secondary users (SUs) to reuse the same spectrum with primary users (PUs) while controlling the interference inflicted by the SU transmitters (SU-TXs) on the PU receivers (PU-RXs). Standard approach is to use beam-forming for maximizing the sum-rate of the SUs, while ensuring that the interference power at the PU-RXs remains below the interference temperature (IT) limit. However, the beam-forming gain is limited, when the SU-TX to SU-RX link is weak, and the channel gain between the SU-TX and PU-RX is much higher. To handle this issue, a IRS can be deployed in the vicinity of the PU-RXs, as shown in **Fig 3.11**. The IRS is used for mitigating the interference towards the PU-RXs, while improving the signal power at the SU-RXs.

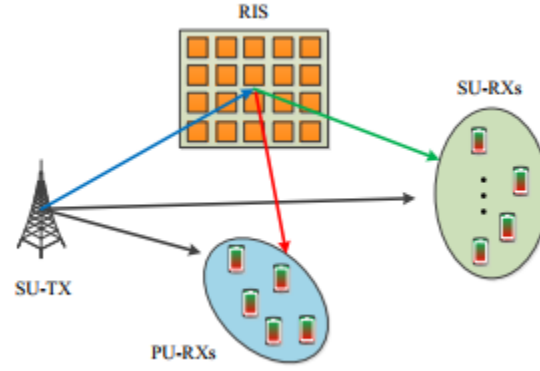


Figure 3.11.IRS-aided CR networks [12].

3.3 Major uses of IRS

IRS technology is a key enabler for wireless communications, essentially a reconfigurable meta-material made of scattering particles or meta-atoms. By controlling the phase-shift of each unit cell, IRS 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 **Fig 3.12** [8].

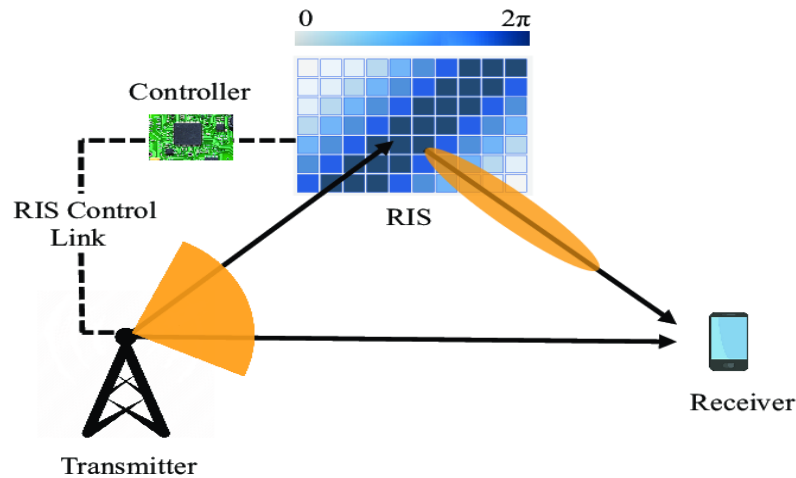


Figure 3.12. Schematic representation of reconfigurable intelligent surface aided communication [13].

3.3.1 Anomalous Reflection/Transmission

The IRS 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 Beam-forming/focusing

The IRS 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/IRS Encoding

The IRS optimizes system capacity by utilizing meta-atom status to modulate additional data. However, the transmitter and IRS 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 (IRS) 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. IRS 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, IRSs require the largest number of scattering elements but require the least and least costly components. Additionally, IRSs 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 IRS challenges

Some of the main challenges that may face the potential gains of IRS in wireless communications applications [6].

3.4.1 Channel estimation

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

3.4.2 IRS reconfiguration

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

3.4.3 Network optimization

When the network contains multiple BSs and is assisted with many distributed IRSs to serve a massive number of users, the real-time configuration of the entire network will be a challenging task. In this scenario, the network consists of multiple separated components so, to reach a global optimum over the whole network will require an enormous amount of control signals for the resource allocation, power allocation, users' scheduling and IRSs configuration. Thus, it becomes

crucial to develop new network optimization schemes that have reasonable computational overhead and energy consumption.

3.5 Passive and Active IRSs

3.5.1 Passive IRS

The IRSs widely studied in most existing works are passive IRSs. Specifically, as shown in **Fig 3.13(a)**, a passive IRS comprises a large number of passive elements each being able to reflect the incident signal with a controllable phase shift. In general, each passive IRS element consists of a reflective patch terminated with an impedance-adjustable circuit for phase shifting. Thanks to the passive mode of operation without active radio-frequency (RF) components, a passive IRS element practically consumes zero direct-current power, and the introduced thermal noise is usually negligible. Thereby, the signal model of an L -element passive IRS widely used in the literature is given as follows [14]:

$$\mathbf{y} = \mathbf{\Theta}\mathbf{x}, \quad (1)$$

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

$\mathbf{\Theta} = \text{diag}(e^{j\theta_1}, \dots, e^{j\theta_N}) \in \mathbb{C}^{N \times N}$ denotes the reflection coefficient matrix of the passive IRS with θ_n being the phase shift of the n -th passive element, and $\mathbf{y} \in \mathbb{C}^N$ denotes the signal reflected by the IRS. Note that the impact of noise is neglected in (1). As a consequence, by properly adjusting $\mathbf{\Theta}$ to manipulate the N signals reflected by the N IRS elements to coherently add with the same phase at the receiver, a high array gain can be achieved. This is expected to significantly increase the receiver SNR which is one of the key reasons for why IRSs have attracted so much research interest recently. Unfortunately, in practice, this expected high-capacity gain often cannot be realized, especially in communication scenarios where the direct link between the transmitter and the receiver is not weak. The reason for this negative result is the “multiplicative fading” effect introduced by passive IRSs. Specifically, the equivalent path loss of the transmitter-IRS-receiver reflected link is the product (instead of the sum) of the path losses of the transmitter-IRS and IRS-receiver links, and therefore, it is thousands of times larger than that of the unobstructed direct link. Thereby, for an IRS to realize a noticeable capacity gain, thousands of IRS elements are required to compensate for this extremely large path loss [14].

3.5.2 Active IRS

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

$$\mathbf{y} = \mathbf{\Psi}\mathbf{x} + \mathbf{\Psi}\mathbf{v} + \mathbf{n}_s, \quad (2)$$

where $\mathbf{\Psi} = \text{diag}(\mathbf{p}_1\mathbf{e}^{-j\theta_1}, \dots, \mathbf{p}_N\mathbf{e}^{-j\theta_N}) \in \mathbb{C}^{N \times N}$ denotes the reflection coefficient matrix of the active IRS, where in $p_n \in \mathbb{R}_+$ denotes the amplification factor of the n -th active element and p_n can be larger than one thanks to the integrated reflection-type amplifier. Due to the use of active components, active IRSs consume additional power for amplifying the reflected signals, and the thermal noise introduced by active IRS elements cannot be neglected as is done for passive IRSs. Particularly, as shown in (2), the noise introduced at active IRSs can be classified into dynamic noise $\mathbf{\Psi}\mathbf{v}$ and static noise $\mathbf{n}_s$, where $\mathbf{\Psi}\mathbf{v}$ is the noise introduced and amplified by the reflection-type amplifier and $\mathbf{n}_s$ is generated by the patch and the phase-shift circuit. More specifically, $\mathbf{v}$ is related to the input noise and the inherent device noise of the active IRS elements, while the static noise $\mathbf{n}_s$ is unrelated to $\mathbf{\Psi}$ and is usually negligible compared to the dynamic noise $\mathbf{\Psi}\mathbf{v}$ [14].

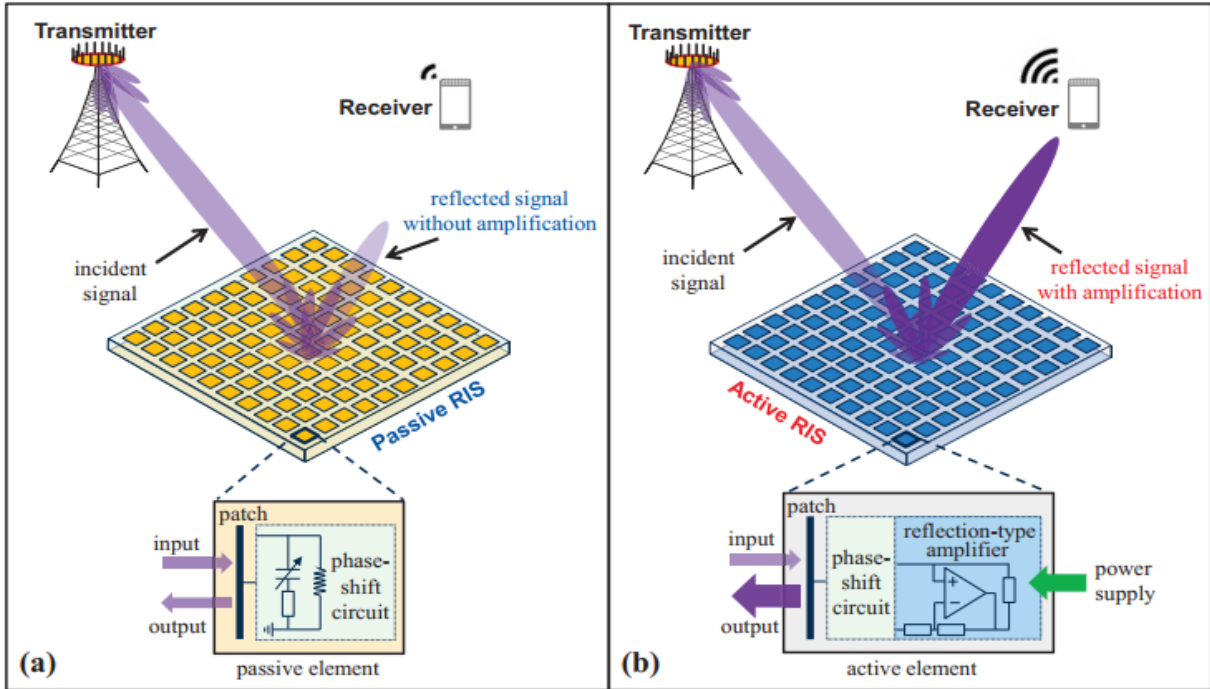


Figure 3.13. An illustration of the hardware architectures of (a) a passive IRS and (b) an active IRS [14].

3.6 Key applications of IRS

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

3.6.1 The relationship between the outside environment and smart cities

The IRS 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 **Fig 3.14**, since the deployment of IRSs may reduce the amount of network infrastructure needed [15].

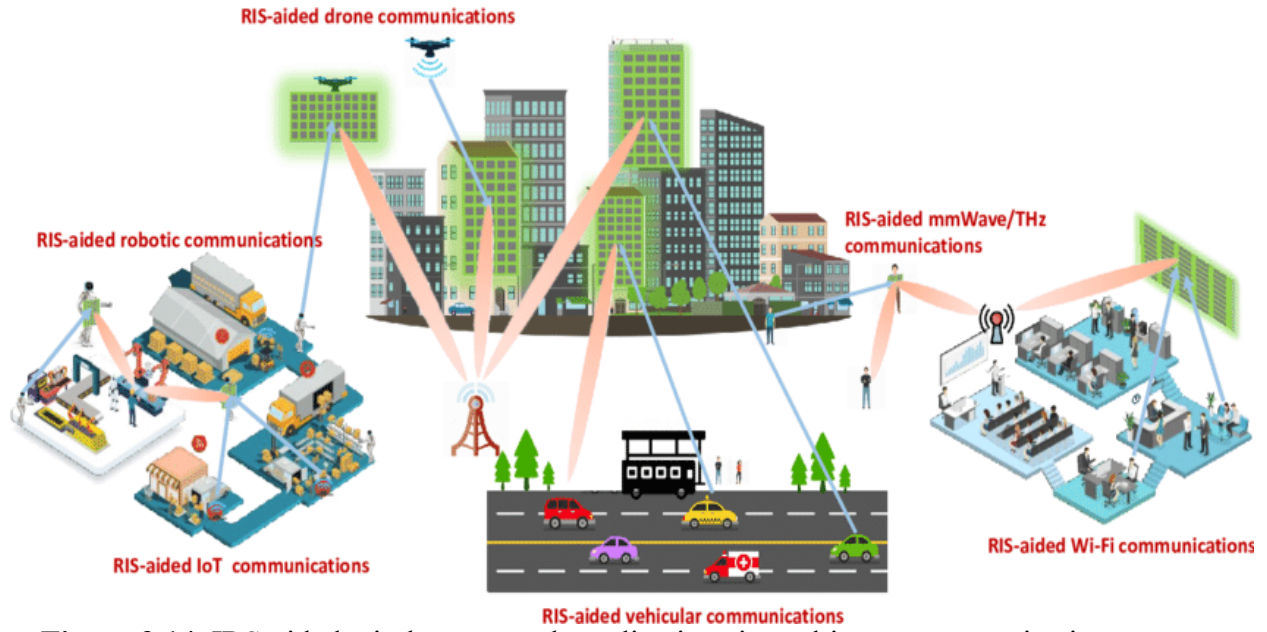


Figure 3.14. IRS-aided wireless network applications in multi-user communication systems [16].

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 **Fig 3.15** [15].

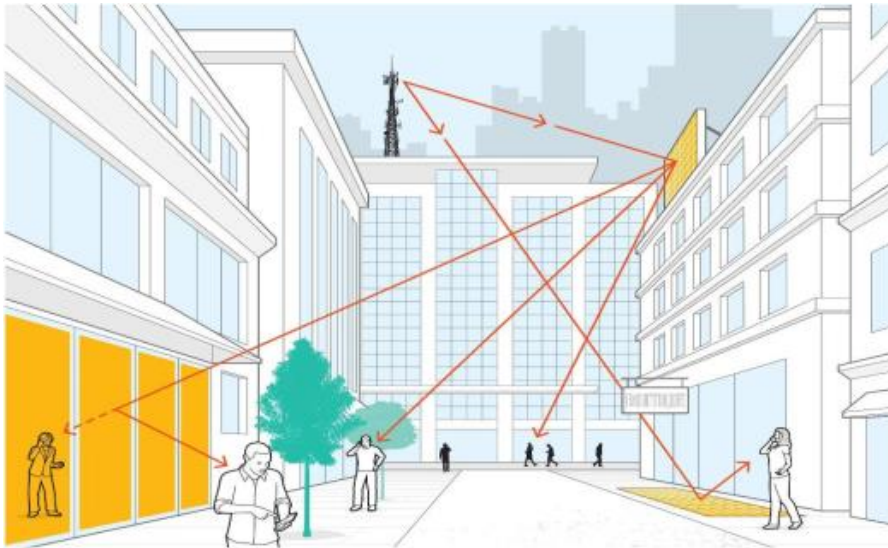


Figure 3.15 IRS applications in an outdoor setting [15].

3.6.3 Smart Vehicles

IRSs 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 IRSs for moving nearly passive relays, in Fig 3.16. For example, Trains can have their interior coated with IRSs for better signal coverage and reduced passenger exposure to electromagnetic fields. Airplanes can have overhead bins coated with IRSs for high-speed internet and reduced EM field exposure.

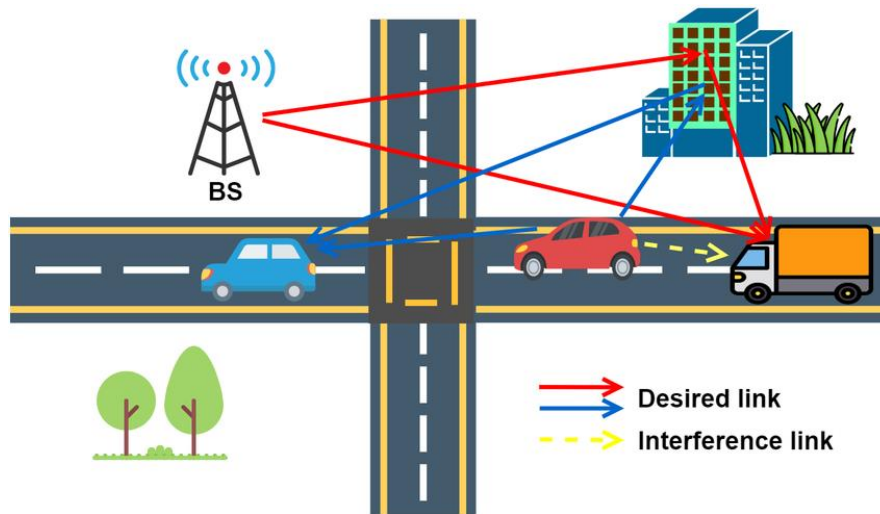


Figure 3.16. IRS-assisted vehicular communication system [15].

3.6.4 Smart Homes

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

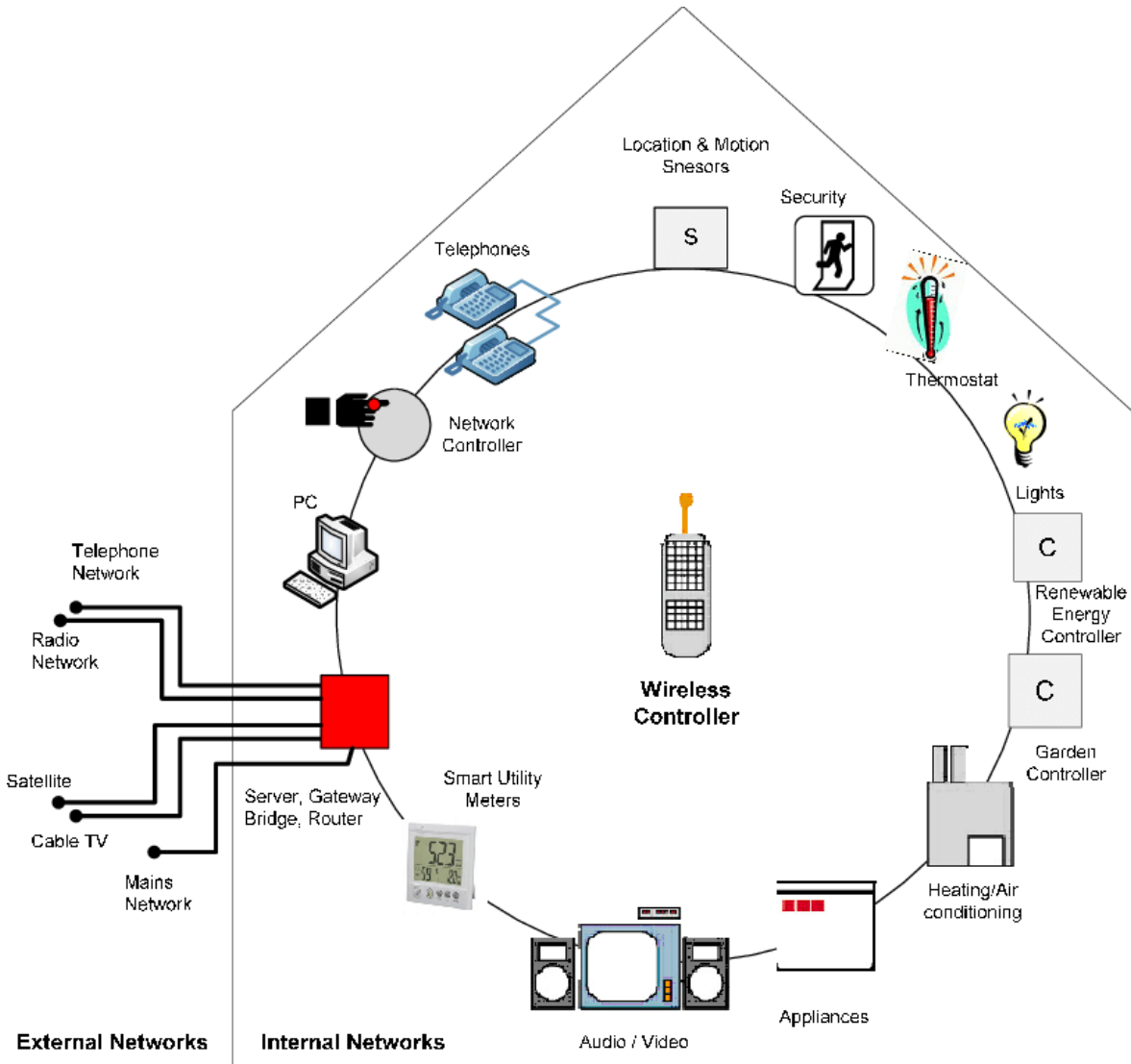


Figure 3.17. IRS-Smart home topology diagram [17].

3.7 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 IRS-aided systems, reflection occurs when the transmitter's signal encounters reflection elements at the IRS. To accurately characterize the reflected signal, Maxwell's equations are solved by applying boundary conditions and considering the permittivity and permeability of the reflecting elements. However, the calculation of these equations is complex and requires simplifications. In wireless

engineering, transmission line theory is used as an adequate simplification of Maxwell' equations with effective parameters.

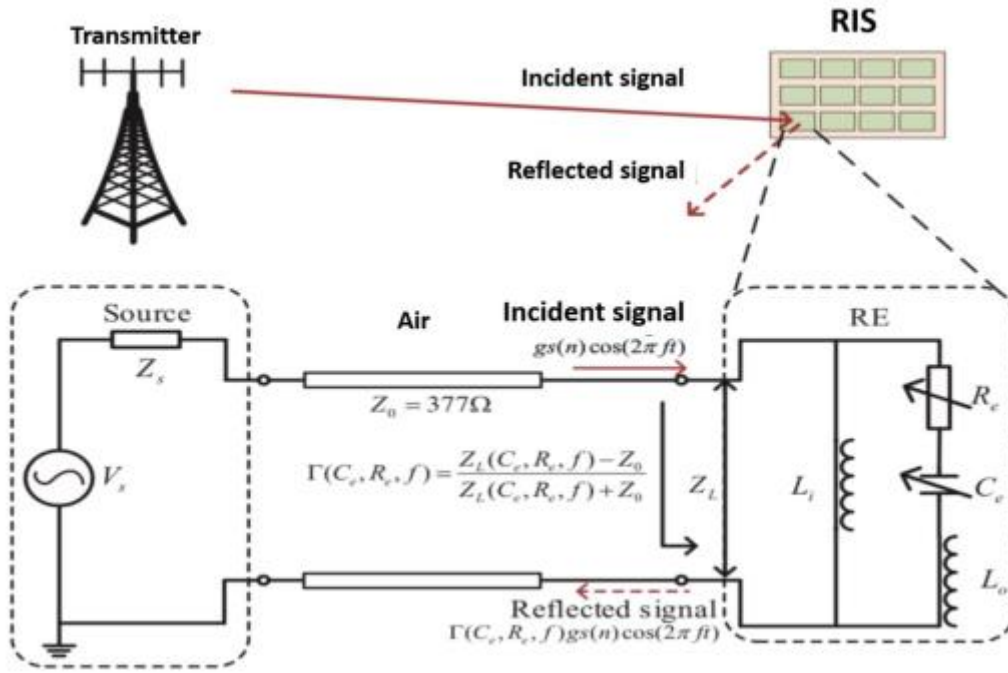


Figure 3.18: The equivalent circuit for the IRS reflecting element based on transmission line theory [15].

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 Z_0 and the load impedance Z_L . The characteristic impedance is fixed and determined by the geometry and materials of the transmission line, while the load impedance is reconfigurable. This allows for a tunable reflection coefficient by varying the load impedance. The simplest way to change reflection coefficients is to deploy a switch on preset load impedances, but continuous phase shifts of reflecting elements are desirable. In a printed circuit board (PCB)-based RIS, a semi-conductor diode, typically a positive-intrinsic-negative (PIN) diode, is embedded into the metal element in the outer layer to tune the reflection coefficients. The PIN diode can be replaced with the equivalent circuit model, where C_e and R_e are the effective capacitance and resistance [18].

3.8. The difference between IRS and relay

Since both IRSs and current relays can serve as aids to improve wireless communications between the transmitter and the receiver, they are also seen to be comparable. But there are a number of significant distinctions [19].

- *IRS vs. AF Relay*: An IRS eliminates the need for transmit power consumption by reflecting incident signals as a passive array without a transmitter, whereas AF relays aid in source-destination transmission by regenerating and boosting the signals. An IRS is designed to function in full duplex mode, which makes it more spectrum efficient, whereas AF operates in half duplex mode due to heavy interference in full duplex mode, which requires effective interference cancellation techniques [20].
- *IRS vs. DF Relay*: DF relays work similarly to AF relays in that they decode and retransmit the signal from the source to the destination. They are substantially more complicated and require a lot of signal processing power because of the decoding process. IRS systems, on the other hand, just engage in passive reflection and do not decode, as was previously mentioned. As a result, they are less costly and use less electricity [20].

3.9 Conclusion

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

3.10 References

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Chapter 4: IRS-aided Relaying cooperative networks

This chapter investigates the performance of Reconfigurable Intelligent Surfaces (IRS)-assisted relay systems based on existing works. The optimal SNR is considered as presented in the literature. An approximate CDF is used to characterize its behavior, and known approximations are employed to analyze the achievable rate, outage probability.

4.1 Introduction

By providing distinct delays to the reflected electromagnetic (EM) waves, an IRS with a large number of tiny passive reflectors can provide a controllable wireless propagation environment [1, 2, 3, 4]. These delays result in configurable phase shifts, which may be used to vary the propagation characteristics of EM waves across the wireless medium intelligently. By employing the feature of constructive additions of EM waves at a designated destination, this IRS can improve the signal-to-noise ratio (SNR) of an end-to-end connection between a transmitter, and a receiver [5]. The IRS's passive beamforming nature allows for energy-efficient communication without the need for active radio-frequency chains/amplifiers to generate extra EM signals [1]. As a result, IRSs have been identified as a crucial contributor to the next-generation wireless physical layer [1, 2].

4.2 Relay Networks

A relay is any intermediary terminal that acts as a repeater between the transmitter and receiver. Despite the fact that this procedure consumes time, bandwidth, and power while communicating, the coverage, spectral/energy efficiency, and communication reliability of the system can be improved by a relay-aided communication system [6–7]. As a result, in massive MIMO installations, the relay may be employed to increase reliability in the link and extend the coverage while also increasing possible user rates by mitigating high path-loss and shadowing effects. Furthermore, an intermediate relay minimizes transmission distances, which reduces the system's energy usage. Based on their functioning, the relays can be classified into amplify-and-forward (AF) relays and decode-and-forward (DF) relays [8, 9].

4.3 Intelligent Reconfigurable Surface (IRS)

An IRS is made out of tiny reflecting elements, whose phase-shifts can be intelligently controlled. Each of these reflecting elements consists of a meta-surface, and hence, it can induce a phase-shift for the incident EM signals [10]. The invent of IRSs paved the way to smartly control the propagation environment, and this feature can be exploited to design wireless systems intended for next-generation wireless standards. Thus, IRSs constitute a novel physical-layer technology. The current state-of-the-art wireless standard is fifth-generation (5G), and it does not consider IRSs. It has emerged as a novel concept for the sixth-generation (6G) and beyond to meet the rising communication demands for higher data rates, improved network coverage, increased reliability, and energy/spectral efficiency. The primary benefit of the IRSs technology is that it recycles existing electromagnetic (EM) waves emitted by a transmitter. More specifically, IRSs can be deployed to constructively combine the signals transmitted by a source node at a desired destination. Moreover, the phase-shifts at IRSs can be controlled mitigate the interference. To this end, IRSs can be embedded within the propagation environment on walls, buildings, and passage ways [1, 2, 3, 4]. Thus, is can be deployed to assist the end-to-end communications in various settings, and thereby, the corresponding performance metrics can be considerably improved [11, 12]. To this end, IRSs have a great potential in fulfilling the demands for next-generation wireless standards, including smarter, greener, more sustainable, and cost-effective wireless connections [13, 11].

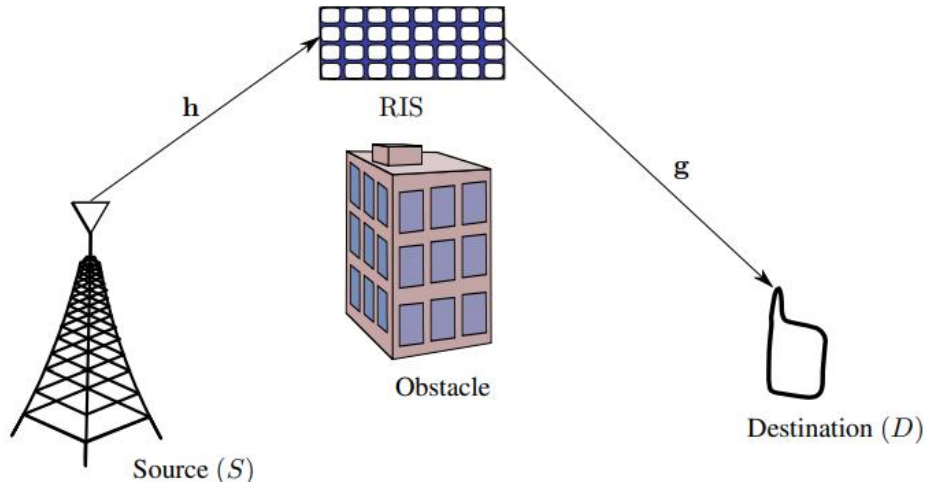


Figure 4.1. System and channel models for an RIS-aided Communication system.

Consider an IRSs assisted single-hop communication scenario modeled with a single-antenna source (S), an IRSs consisting of M reflective elements, and a destination-antenna (D) as shown in **Fig 4.1**. Our assumption is that there is no direct channel from the source to the destination. This is possible when there is severe shadowing/path-loss between the source to the destination. The channel between the source and the m^{th} IRSs elements is denoted by h_m . The channel between the m^{th} IRSs element and the destination is denoted by g_m . We model h_m and g_m according to Rayleigh distribution. These channels can be written in a unified manner as

$$u = \rho_u e^{j\theta_u} \quad (1.1)$$

where $u \in \{h_m, g_m\}$ is the channel coefficient. Moreover, ρ_{h_m} and ρ_{g_m} denotes the envelope of u , and θ_u denotes the phase of u . We consider ρ_{h_m} and ρ_{g_m} to follow complex Gaussian distribution with mean equal to zero and variance equal to unit:

$\rho_{h_m} \sim \text{CN}(0, 1)$, $\rho_{g_m} \sim \text{CN}(0, 1)$. Thus, we can model h_m and g_m as follows:

$$h_m = \sqrt{\zeta_{h_m}} \tilde{h}_m \quad \text{and} \quad g_m = \sqrt{\zeta_{g_m}} \tilde{g}_m \quad (1.2)$$

where ζ_{h_m} and ζ_{g_m} capture the large-scale fading/path-losses of the corresponding channels.

If x is the signal transmitted by S , then the baseband signal received at D can be expressed as:

$$y_D = \sqrt{p_t} \sum_{m=1}^M g_m \eta_m e^{j\theta_m} h_m x + n_D, \quad (1.3)$$

where n_D is the additive white Gaussian noise (AWGN) at the destination such that $n_D \sim \text{CN}(0, \sigma_D^2)$. Moreover, P_t is the transmit power at S .

In (1.3), the parameters η_m and θ_m are the reflection coefficient and phase-shifts introduced by the m^{th} reflecting element of IRS, respectively. Alternatively, (1.3) can be expressed as [14]

$$y_D = \sqrt{p_t} \mathbf{g}^T \mathbf{\Theta} \mathbf{h} + n_D, \quad (1.4)$$

where $\mathbf{h} = [h_1, \dots, h_M]^T$ is the channel vector between S and IRS, and

$\mathbf{g} = [g_1, \dots, g_M]^T$ is the channel vector between IRS and D .

$\Theta = \text{diag} (\eta_1 e^{j\theta_{\eta_1}} \dots, \eta_m e^{j\theta_{\eta_m}}, \dots, \eta_M e^{j\theta_{\eta_M}})$ is a diagonal matrix that captures the reflection properties of M reflecting elements of IRS.

The signal-to-noise ratio (SNR) at the destination can be written as:

$$\gamma = \frac{p_t |\sum_{m=1}^M h_m \eta_m e^{j\theta_{\eta_m}} h_m|^2}{\sigma^2_D} \quad (1.5)$$

Since the IRS provides an adjustable phase shift, we can co-phase the signals reflected by IRS setting $\theta_{\eta_m} = \theta_{h_m} + \theta_{h_m}$ to maximize the SNR. Upon optimizing the phase-shift matrix at the IRS, the optimal SNR is given by:

$$\gamma = \bar{\gamma} (\sum_{m=1}^M \rho_{h_m} \eta_{h_m} \rho_{g_m})^2 \quad (1.6)$$

where $\bar{\gamma} p_t / \sigma^2_D$ is the average transmit SNR

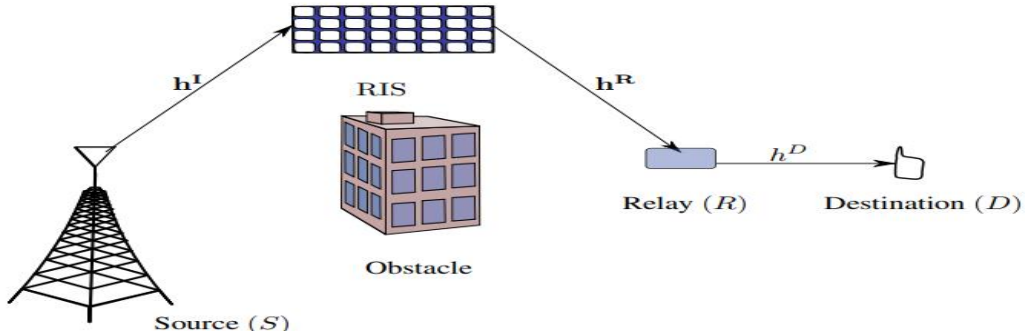


Figure 4.2. System model-IRS-assisted relay network.

4.4 System, channel and signal models

4.4.1 System and channel model

Fig 4.2 depicts an IRS-assisted relay system in which a source (S) serves a destination (D) through a cascaded IRS-relay channel. The relay (R) has a single antenna and operates in the

half-duplex AF mode. Due to strong blocking effects, the direct channels S - R and S - D are assumed to be unavailable. The IRS is made up of N passive reflectors, and the phase-shifts of EM waves impinging on them may be intelligently controlled to guarantee that the received signal at D is combined constructively. For simplicity, we'll refer to the IRS's passive reflectors as $N \in \{1, \dots, N\}$. Here, h_n^I represents the channel coefficient between S and the IRS's n th reflector, where as h_n^R represents the channel between the n th reflector and R . Furthermore, h^D denotes the channel between R and D . All of these channels may be represented in polar form as:

$$u = \beta_u e^{j\theta_u} \quad (2.1)$$

where $u \in \{h_n^I, h_n^R, h^D\}$ and $n \in N$. β_u is the envelop of u , and θ_u is the phase of u in (2.1). Here, β_u is assumed to be independent Rayleigh distributed as [15]

$$f_{\beta_u}(x) = (x/\xi_u) e^{-x^2/(2\xi_u)} \quad (2.2)$$

where $\xi_u = \xi_u/2$ is the Rayleigh parameter, and ξ_u accounts for the large-scale fading/path-loss of the channel u . Because the RIS reflectors are co-located, we assume that the large-scale fading parameters for the S -IRS and IRS- R channels are the same.

4.4.2 Signal Model

The signal sent by S is received by D through the IRS- R cascaded channel. To this end, the signal received at R during the first time-slot may be expressed as:

$$y_R = \sqrt{P_t} (h^R)^T \Theta h^I x + w_R, \quad (2.3)$$

where P represents the transmit signal power R at S , x is the signal meant for D satisfying $\mathbb{E}[|x|^2] = 1$, and $w_R \sim \mathcal{CN}(0, \sigma^2 w_R)$ is an additive white Gaussian noise (AWGN) with a mean of zero and a variance of $\sigma^2 w_R$. Furthermore, the channel vector between S and IRS is given by $h^I = [h_1^I, \dots, h_n^I, \dots, h_N^I]^T \in \mathbb{C}^{N \times 1}$, and the channel vector between the IRS and R is represented by $(h^R)^T = [h_1^R, \dots, h_n^R, \dots, h_N^R] \in \mathbb{C}^{1 \times N}$ represents the channel vector between the IRS and R . In 2.3, the diagonal matrix

$\Theta = \text{diag}(\eta_1 e^{j\theta_1}, \dots, \eta_n e^{j\theta_n}, \dots, \eta_N e^{j\theta_N}) \in \mathbb{C}^{N \times N}$ is used to capture the IRS' reflective properties. Here, the n th diagonal element, $\eta_n e^{j\theta_n}$, represents the complex-valued

reflection coefficient of the n th reflector of the IRS, where η_n is its magnitude and θ_n is the phase-shift. By exploiting the properties of θ , we can write the signal received at R as:

$$y_R = \sqrt{P} \sum_{n \in \mathcal{N}} h_n^R \eta_n e^{j\theta_n} h_n^I x + w_R. \quad (2.4)$$

During the second time slot, R amplifies the received signal before forwarding it to D [16, 17]. As a result, the signal received at D can be represented as:

$$\begin{aligned} y_D &= Gh^D y_R + w_D \\ &= \sqrt{P} Gh^D \sum_{n \in \mathcal{N}} h_n^R \eta_n e^{j\theta_n} h_n^I x + Gh^D w_R + w_D, \end{aligned} \quad (2.5)$$

where $w_D \sim \text{CN}(0, \sigma_{w_D}^2)$ is an AWGN at D , and G specifies the relay amplification factor, which is meant to constrain the instantaneous transmit power (P_R) at R as:

$$G = \sqrt{P_R / (P |\sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I} e^{j\phi_n}|^2 + \sigma_{w_R}^2)}, \quad (2.6)$$

where $\phi_n = \theta_n + \theta_{h_n^R} + \theta_{h_n^I}$. Using (2.5), we compute the received SNR at D as:

$$\gamma = \frac{P |Gh^D \sum_{n \in \mathcal{N}} h_n^R \eta_n e^{j\theta_n} h_n^I|^2}{|Gh^D|^2 \sigma_{w_R}^2 + \sigma_{w_D}^2}. \quad (2.7)$$

Then, we rewrite this SNR in terms of the channel phases by substituting (2.1) into (2.7) a

$$\gamma = \frac{P |G \beta_{h^D} e^{j\theta_{h^D}} \sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I} e^{j\phi_n} h_n^I|^2}{|G \beta_{h^D} e^{j\theta_{h^D}}|^2 \sigma_{w_R}^2 + \sigma_{w_D}^2}. \quad (2.8)$$

We maximize the received SNR at D in (2.8) by smartly adjusting the phase-shifts (θ_n) at each reflector to allow constructive addition of the signal terms inside the summation of the numerator of (2.8). The optimal choice of θ_n to maximize the received SNR at D is given by

$$\theta_n^* = \arg\max_{-\pi \leq \theta_n \leq \pi} \gamma = -(\theta_{h_n^R} + \theta_{h_n^I}), \text{ for } n \in \mathcal{N} \quad (2.9)$$

By substituting θ_n^* into (2.8), the optimal SNR at D can be derived as:

$$\gamma^* = \frac{P(G^*)\beta^2_{h^D}(\sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I})^2}{P(G^*)\beta^2_{h^D} \sigma^2_{w_R} + \sigma^2_{w_D}} \quad (2.10a)$$

$$= \frac{\bar{\gamma}_R \bar{\gamma}_D \beta^2_{h^D} (\sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I})^2}{\bar{\gamma}_R (\sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I})^2 + \bar{\gamma}_D \beta^2_{h^D} + 1}, \quad (2.10b)$$

where $\bar{\gamma}_R = P_R / \sigma^2_{w_R}$ and $\bar{\gamma}_D = P / \sigma^2_{w_D}$. Furthermore, G^* is the optimal relay gain in (2.10a),

which can be found by replacing θ_n^* into (2.6).

4.5 Preliminary Analysis

In this section, the optimal received SNR (2.10b) is probabilistically characterized by obtaining a close approximation to its CDF. To begin, we define $Z = (\sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I})$. Then, by invoking the CLT [15] and using the fact that the envelopes $\beta_{h_n^R}$ and $\beta_{h_n^I}$ are independent Rayleigh distributed random variables, Z is closely approximated by a one-sided Gaussian distributed random variable ($\tilde{Z}$) as [20]

$$f_Z(y) \approx f_{\tilde{Z}}(y) = \frac{\psi}{\sqrt{2\pi\sigma^2_Z}} \exp\left(-\frac{(y-u_Z)^2}{2\sigma^2_Z}\right), \text{ for } y \geq 0. \quad (2.11)$$

Here, we use $\psi \triangleq 1/Q(-u_Z/\sigma_Z)$ to normalize the PDF of Z such that $\int_{-\infty}^{\infty} f_{\tilde{Z}}(x) dx = 1$, and $Q(\cdot)$ represents the Gaussian- Q function [15]. Moreover, u_Z and σ^2_Z are given by [20]:

$$u_Z = \left(\sum_{n \in \mathcal{N}} \pi \eta_n \xi_{h_n^R} \xi_{h_n^I} \right)^{1/2} \quad (2.12a)$$

$$\sigma^2_Z = \sum_{n \in \mathcal{N}} \eta_n^2 \xi_{h_n^R} \xi_{h_n^I} (16 - \pi^2) / 4 \quad (2.12b)$$

Next, we define γ_R to be [20]:

$$\gamma_R = \bar{\gamma}_R Z^2 = \bar{\gamma}_R (\sum_{n \in \mathcal{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I})^2 \quad (2.13)$$

The PDF transformation technique can be used with (2.11) to evaluate a tight approximation for the PDF of γ_R [20]:

$$f_{\gamma_R}(y) \approx \frac{\psi}{2\sqrt{\pi\sigma_R^2 x}} \exp\left(\frac{-(\sqrt{x}-u_R)^2}{2\sigma_R^2}\right), \text{ for } x \geq 0, \quad (2.14)$$

where $u_R = \sqrt{\bar{\gamma}_R} u_Z$ and $\sigma_R^2 = \bar{\gamma}_R \sigma_Z^2$ by using g (2.14), we derive an approximated CDF for γ_R as [20]:

$$F_{\gamma_R}(x) \approx 1 - \psi \varrho((\sqrt{x}-u_R)/\sigma_R), \text{ for } x \geq 0. \quad (2.15)$$

Then, we define γ_D to be $\gamma_D = \bar{\gamma}_D \beta_{h^D}^2$. The CDF of γ_D can be derived from the PDF of β_{h^D} in (2.2) as [20]:

$$F_{\gamma_D}(x) = 1 - e^{-x/\sigma_D^2}, \text{ for } x \geq 0, \quad (2.16)$$

where $\sigma_D^2 = \bar{\gamma}_D \zeta_{h^D}$. Then, since the exact derivation of the CDF of γ^* (2.10b) appears to be mathematically involved, we resort to an asymptotically exact upper bound as [18]

$$\gamma^* = \tilde{\gamma}^* = \min(\bar{\gamma}_R (\sum_{n \in \mathbb{N}} \eta_n \beta_{h_n^R} \beta_{h_n^I})^2, \bar{\gamma}_D \beta_{h^D}^2).$$

By noticing that $\tilde{\gamma}^* = \min(\gamma_R, \gamma_D)$ we derive the approximated CDF of γ^* (or the exact CDF of $\tilde{\gamma}^*$) as [15]

$$\begin{aligned} F_{\tilde{\gamma}^*}(y) &= 1 - (1 - F_{\gamma_R}(y))(1 - F_{\gamma_D}(y)) \\ &= 1 - \psi \varrho((\sqrt{y}-u_R)/\sigma_R) e^{-y/\sigma_D^2}. \end{aligned} \quad (2.18)$$

4.6 Performance Analysis

4.6.1 Average achievable rate

First, the average achievable rate may be defined as follows:

$$\mathcal{R} = \mathbb{E} \left[\frac{1}{2} \log_2(1 + \gamma^*) \right], \quad (2.19)$$

where the pre-log factor of 1/2 is owing to the fact that half-duplex relay mode necessitates two time-slots for end-to-end data transmission for the proposed system model. The exact derivation of $\mathcal{R}$ in (2.19) appears mathematically intractable, therefore, we again resort to a tight upper

bound by using the Jensen's inequality as [19]

$$\mathcal{R} \leq \mathcal{R}_{ub} = \frac{1}{2} \log_2(1 + \mathbb{E}[\gamma^*]) \approx \frac{1}{2} \log_2(1 + \mathbb{E}[\tilde{\gamma}^*]). \quad (2.20)$$

Then, by evaluating the expectation term in (2.20), an achievable rate upper bound is computed as [20]

$$\mathcal{R}_{ub} = \frac{1}{2} \log_2(1 + 2\psi\sigma_D^2 \varrho(-u_R/\sigma_R)). \quad (2.21)$$

4.6.2 The SNR/rate outage probability

For the proposed system, SNR outage probability is the probability that the instantaneous SNR (γ) falls below a threshold SNR (γ_{th}). Thus, we obtain an approximation to this SNR outage probability from (2.18) as

$$P_{out} = P_r(\gamma^* \leq \gamma_{th} \approx F_{\gamma^*}(\gamma_{th})). \quad (2.22)$$

The rate outage probability can also be readily obtained as

$$\begin{aligned} P_{out} &= P_r(\mathcal{R} \leq \mathcal{R}_{th}) = P_r(\gamma^* \leq 2^{2\mathcal{R}_{th}} - 1) \\ &\approx F_{\gamma^*}(2^{2\mathcal{R}_{th}} - 1), \end{aligned} \quad (2.23)$$

where $\mathcal{R} = \frac{1}{2} \log_2(1 + \gamma^*)$ is the achievable rate, and $\mathcal{R}_{th}$ denotes a threshold rate.

4.7 Numerical Analysis

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

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

4.7.1 Outage Probability (OP)

This subsection analyzes the outage probability. Across all figures related to the OP, the y-axis represents the outage probability on a logarithmic scale from 10^{-2} to 10^0 , and the x-axis represents the Transmit SNR in dB, typically ranging from -10 to 40 db.

❖ Impact of the Number of IRS Elements (L)

The effect of varying the number of IRS reflecting elements (L) on the OP is illustrated in **Fig 4.3**. The plot showcases OP curves for $L = 4, 8, 16, 32$. For all values of L , the OP consistently decreases as the transmit SNR increases. Most notably, for a given transmit SNR, increasing L leads to a substantial reduction in OP, highlighted by an arrow indicating this trend. For, the OP diminishes by approximately two orders of magnitude when L is increased from 8 to 32. This significant performance enhancement is attributed to the increased passive beamforming gain from a larger IRS. A higher L allows for a more effectively focused signal reflection towards the user, thereby increasing the received signal power and reducing the outage probability.

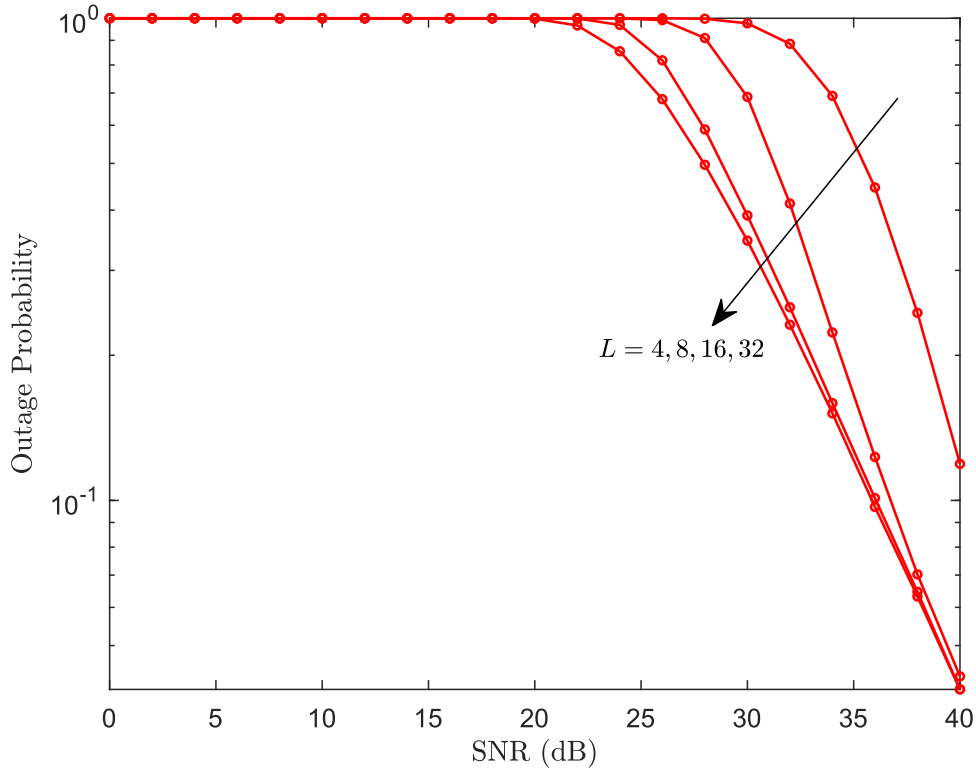


Figure 4.3. The OP vs. the SNR for different values of L .

❖ Impact of Gamma Threshold (γ_{th})

The effect of varying the number gamma threshold (γ_{th}) on the OP is illustrated in **Fig 4.4**. The plot showcases OP curves for $\gamma_{th} = 0.1, 1, 2, 5$. For all values of γ_{th} , the OP consistently decreases as the transmit SNR increases. Most notably, for a given transmit SNR, increasing γ_{th} the OP consistently decreases as the transmit SNR increases, which is consistent. The results demonstrate that the system performance is highly sensitive to the required threshold; specifically, for a fixed transmit SNR, increasing the γ_{th} leads to a higher OP. This behavior occurs because a higher threshold imposes a more stringent condition for successful decoding, making the system more susceptible to outages. The arrow in the figure highlights the performance improvement as the threshold value becomes less restrictive.

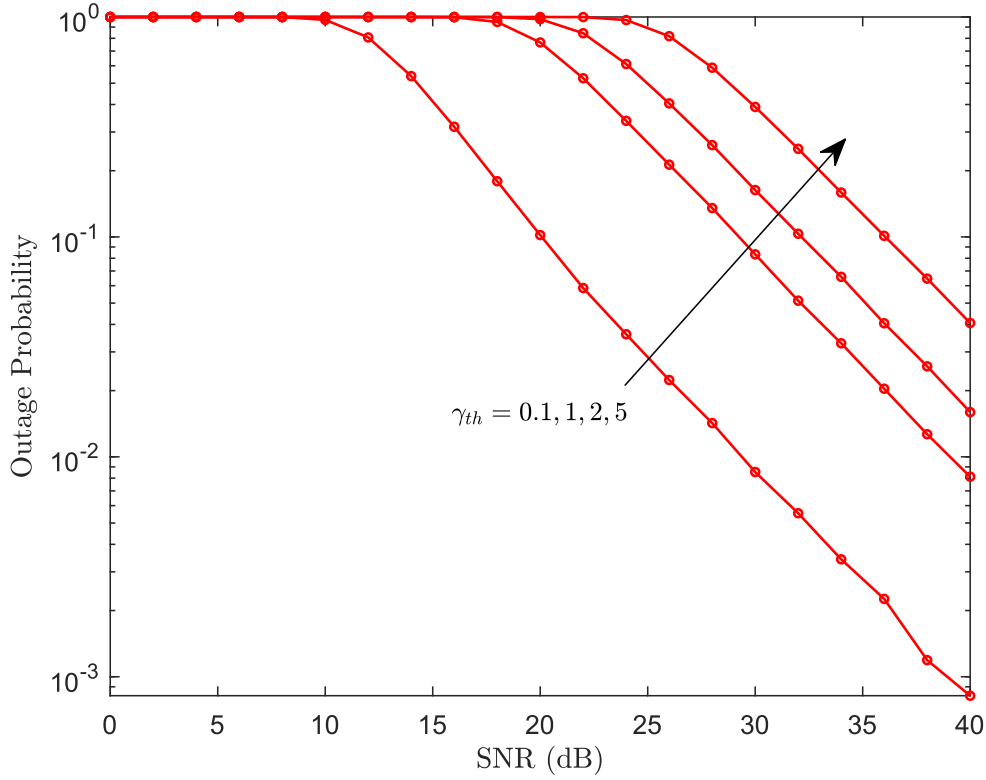


Figure 4.4. The OP vs. the SNR for different values of γ_{th} .

❖ Impact of reflection coefficient (η)

The influence of the efficiency coefficient η on the Outage Probability (OP) is depicted in **Fig4.5** for various values ranging for $\eta = 0.1, 0.2, 0.5, 0.8, 1$. As observed in the previous scenarios, the OP follows a declining trend as the transmit SNR increases across all values of η . The numerical results indicate that the system performance improves significantly as η increases. Specifically, higher values of η shift the OP curves toward the lower SNR region, suggesting that the system can maintain a reliable connection with less power when the hardware or energy efficiency is high. This behavior highlights that maximizing the efficiency of the reflecting elements or the amplification factor is crucial for minimizing outages. The arrow confirms this trend, showing that as $\eta \rightarrow 1$, the outage performance reaches its optimum level.

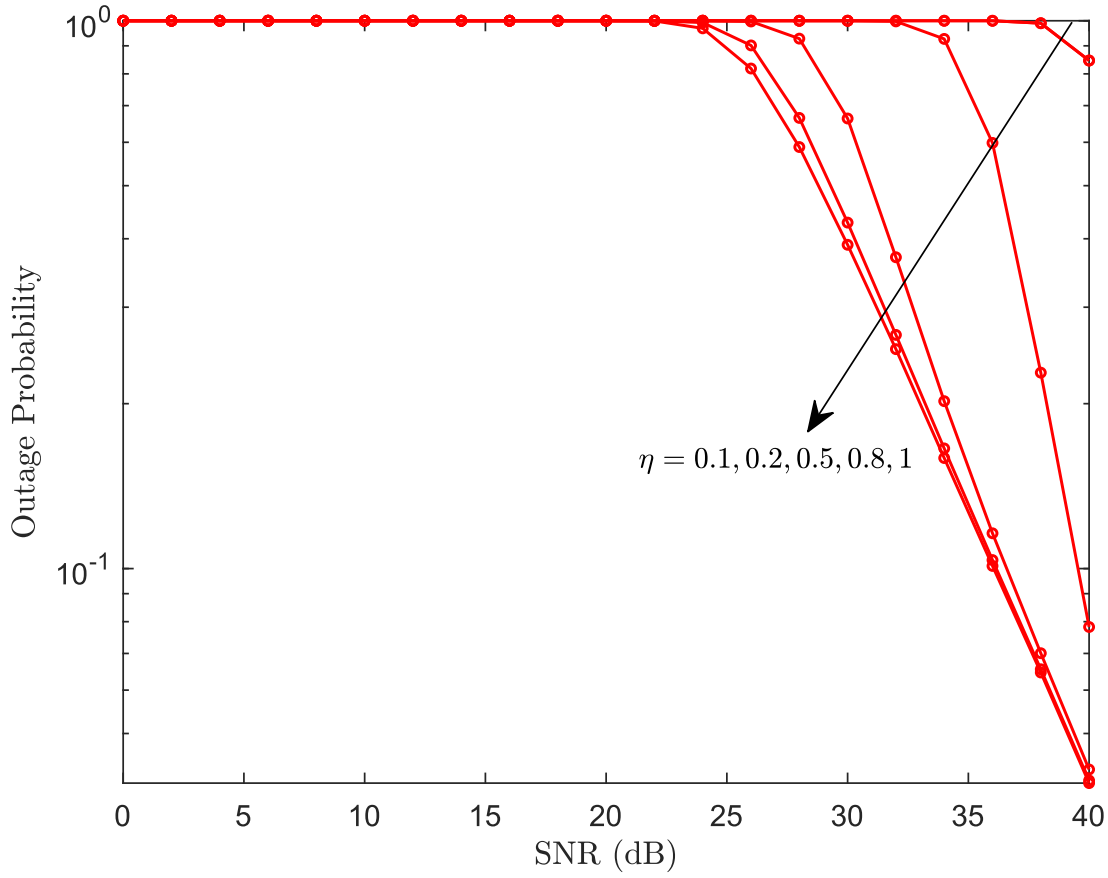


Figure 4.5. The OP vs. the SNR for different values of η

4.7.2 Ergodic Capacity (EC)

This subsection discusses the Monte Carlo simulation results for the ergodic capacity (EC) of the IRS-assisted wireless network in consideration. The x-axis in all EC plots represents the Transmit SNR [dB] from -10 to 40 dB.

❖ Impact of the Number of IRS Elements (L)

Fig 4.6 shows the EC versus transmit SNR for different numbers of IRS elements: $L = 4, 8, 16, 32$. The y-axis for EC in this plot is linear. A clear trend is that EC increases with the transmit SNR for all values of L . Furthermore, at any given transmit SNR, increasing L results in a higher EC. The arrow in the plot indicates this positive correlation. For example, at an SNR of 20 dB, the EC increases from approximately 3 bits/s/Hz to over 5 bits/s/Hz as L goes from 8 to 32. This

improvement is due to the enhanced array gain from more elements, leading to a stronger effective channel and thus higher achievable data rates.

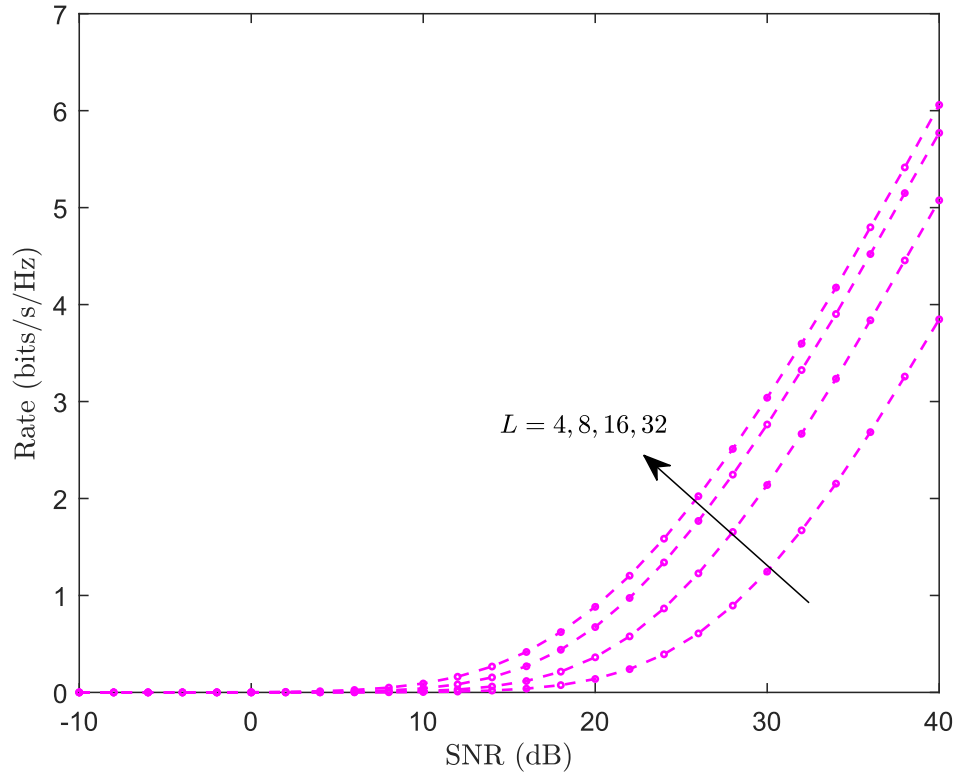


Figure 4.6. The Rate vs. the SNR for different values of L

❖ Impact of reflection coefficient (η)

Impact of reflection coefficient η on ergodic capacity **Fig4.7.** presents the ergodic capacity (Rate) as a function of the transmit SNR for varying values of the reflection coefficient, $\eta = 0.1, 0.2, 0.5, 0.8, 1$. The results indicate that the achievable data rate is positively correlated with both the SNR and the reflection coefficient. A significant increase in the rate is observed as η improves. When the system operates at a high efficiency ($\eta = 1$), it captures and utilizes the reflected/relayed energy more effectively, leading to a steeper rise in the capacity curves. In contrast, at low efficiency levels ($\eta = 0.1$), the system suffers from substantial power loss, resulting in a much flatter curve even at high SNR values, similar to the trend observed in the outage analysis.

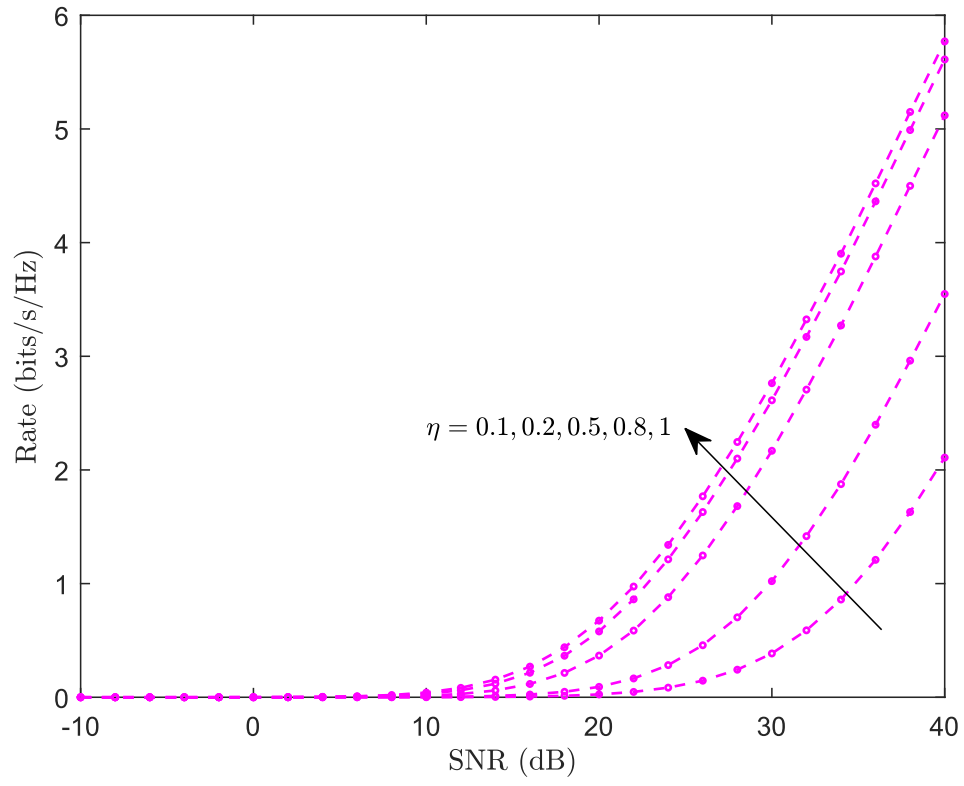


Figure 4.7. The Rate vs. the SNR for different values of η

4.8 Conclusion

The performance of an IRS-assisted relay system has been investigated. The optimal SNR that is attained through intelligent phase-shift controlling of the IRS elements has been probabilistically characterized by deriving a tight CDF approximation. Thereby, tight approximations/bounds for the fundamental performance metrics, including the average achievable rate, SNR/rate outage probability. The impact of Number of IRS Elements (L) and reflection coefficient (η) and Gamma Threshold (γ_{th}). The accuracy of our analysis has been validated through the Monte-Carlo simulation. A rigorous set of numerical results has been presented to investigate the performance of the proposed IRS-assisted relay system. From our numerical results, we reveal that the IRS-assisted relay systems can enhance the end-to-end wireless communication performance.

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Conclusion

Our conclusion, this thesis has provided a comprehensive analysis of the outage and ergodic performance of IRS-enhanced AF Cooperative relaying-aided wireless networks. The unique properties of IRSs can be leveraged by dynamically adjust the phase and amplitude of incident signals to improve the whole transmission process.

Our investigation highlights that IRSs offer a promising solution for enhancing signal quality and reliability in various propagation environments. Specifically, the results indicate that the integration of IRSs can effectively mitigate the detrimental effects of fading, leading to a substantial reduction in outage probability. Furthermore, the ergodic capacity analysis confirms that IRS-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 IRS 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 IRS-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 intelligent reconfigurable surface (IRS). This thesis investigates the outage and ergodic performance of IRS enhanced AF Cooperative relaying communication systems. By examining the outage probability (OP) and ergodic capacity (EC) metrics, we evaluate the impact of various system parameters on network performance of IRS enhanced AF. Our study reveals that incorporating IRS enhanced AF 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 IRS elements. The results underscore the critical role of IRS configuration in achieving superior signal quality and network reliability, paving the way for advances in next-generation wireless communications networks.

Keywords: Intelligent Reconfigurable Surface (IRS); Amplify-and-Forward (AF) Relaying; Cooperative Communications; Outage Probability; Ergodic Capacity; Wireless Network Performance; Next-Generation Wireless Networks.

الخلاصة

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

الكلمات المفتاحية: السطح الذكي القابل لإعادة التشكيل (IRS)؛ الترحيل بالتضخيم وإعادة الإرسال (AF)؛ الاتصالات التعاونية؛ احتمال الانقطاع؛ السعة الإرجودية؛ أداء الشبكات اللاسلكية؛ شبكات الاتصالات اللاسلكية من الجيل القادم.

Résumé

La demande croissante de débits de données élevés, de services de communication à haut débit et d'une couverture étendue pour les futurs réseaux sans fil posera des défis à la conception des systèmes sans fil. L'une des techniques prometteuses pour répondre à ces exigences est la surface reconfigurable intelligente (IRS). Cette thèse étudie les performances en termes de taux de panne et d'ergodique des systèmes de communication à relais coopératif AF améliorés par IRS. En examinant la probabilité de panne (OP) et la capacité ergodique (EC), nous évaluons l'impact de divers paramètres système sur les performances du réseau AF amélioré par IRS. Notre étude révèle que l'intégration d'une surface AF améliorée par IRS améliore significativement ces deux indicateurs, ce qui démontre son potentiel pour l'amélioration des communications sans fil. Grâce à des simulations approfondies, nous montrons que les performances du système dépendent fortement de paramètres spécifiques, notamment du nombre d'éléments IRS. Les résultats soulignent le rôle crucial de la configuration IRS pour obtenir une qualité de signal et une fiabilité réseau supérieures, ouvrant la voie aux progrès des réseaux de communication sans fil de nouvelle génération.

Mots-clés : Surface Reconfigurable Intelligente (IRS) ; Relais Amplifier-et-Transmettre (AF) ; Communications Coopératives ; Probabilité de Panne ; Capacité Ergodique ; Performance des Réseaux Sans Fil ; Réseaux Sans Fil de Nouvelle Génération.