COMPARATIVE ASSESSMENT OF RECONFIGURABLE INTELLIGENT SURFACES AND RELAYING TECHNIQUES WITH QAM IMPERFECTIONS

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I dedicate this dissertation to my cherished parents, whose enduring encouragement and wisdom have sparked my curiosity and shaped every part of my path.

ABSTRACT

The growing demand for reflecting and improving systems in electromagnetic wave communication, the ever-increasing demand for data traffic and the limitations of traditional cellular architectures are driving the need for innovative solutions in electromagnetic wave communication systems. Here's a breakdown of the key factors fueling the demand for reflecting and improving systems like relays and Reconfigurable Intelligent Surfaces (RIS). Conventional cellular architectures' constraints drive the imperative for innovative solutions within electromagnetic wave communication systems, notably reflecting and improving systems such as relays and RIS. Existing cellular networks struggle with capacity limitations, coverage gaps, and signal degradation, particularly evident in rural or geographically challenging areas and at higher frequencies like millimeter wave (mmWave). Relays serve as intermediary stations, amplifying and retransmitting weak signals to extend coverage and bolster signal strength in remote regions, while RIS, equipped with intelligent metamaterial panels, strategically manipulate signal reflection to enhance coverage, mitigate blockages, and create adaptable propagation paths. These advancements promise augmented network capacity, expanded coverage, and refined signal quality, catering to diverse applications including cellular expansion, indoor coverage enhancement, mmWave communication, and the facilitation of smart cities and IoT deployments. Overall, the demand for reflecting and improving systems like relays and RIS is driven by the need for higher capacity, wider coverage, and better signal quality in electromagnetic wave communication systems. These technologies offer promising solutions to address the challenges of existing cellular networks and pave the way for future advancements in wireless communication. This thesis investigates the potential of RIS

to improve Bit Error Rate (BER) performance in wireless communication systems. A comprehensive model is presented that explores various RIS configurations employing Equal Power Allocation (EPA). This model allows for the evaluation of how RIS design parameters impact system performance, paving the way for optimized network deployments across different frequency bands.

The core of the research focuses on analyzing the influence of two crucial RIS design aspects: surface element position and quantity. By systematically varying these parameters within the model, the study sheds light on how RIS configurations can be tailored to achieve superior BER performance. The research investigates a range of scenarios, including configurations with varying numbers of surface elements, from modest deployments to large-scale applications with 2048 elements for mmWave and 328 elements for Wi-Fi bandwidth. This comprehensive analysis provides valuable insights into the scaling behavior of RIS technology for different deployment scenarios and frequency bands.

Furthermore, the thesis conducts a rigorous comparative analysis between RIS-enhanced dual-hop transmission schemes and conventional relaying techniques, specifically Amplify and Forward (AF) and Decode and Forward (DF). This comparison allows for a clear evaluation of the relative merits of RIS technology. The findings convincingly demonstrate that RIS-assisted communication outperforms traditional relaying methods in terms of BER performance. This observation underscores the efficacy of RIS in facilitating non-line-of-sight (NLOS) communication systems.

In the last part of this dissertation, we consider comparing the performance of RIS and AF and DF relay systems in mitigating channel impairments in imperfect Quadrature Amplitude Modulation (QAM) coherent systems. Imperfect QAM systems are susceptible to various impairments that degrade signal quality and Bit Error Rate (BER) performance. These impairments include:

*Carrier Frequency Offset (CFO): Deviation of the receiver's carrier frequency from the transmitter's, causing constellation rotation.

*Timing Offset: Misalignment of symbol timing between transmitter and receiver, leading to inter-symbol interference (ISI).

*Phase Noise: Random phase fluctuations in the transmitted signal, resulting in distorted constellation points.

Traditional relaying techniques like AF and DF address signal weakness but can introduce additional noise and distortions. RIS technology, on the other hand, offers a promising alternative by intelligently reflecting signals. This approach can potentially mitigate channel impairments without introducing noise amplification. This thesis delves into a meticulous comparison of RIS and AF/DF relaying for mitigating the aforementioned impairments in QAM systems. The research employs a comprehensive model to analyze the impact of RIS configurations, including surface element positioning and quantity, on BER performance. Additionally, the study investigates the effectiveness of AF and DF relaying in various channel conditions with varying levels of impairments. By comparing the performance of these techniques, the thesis aims to identify the most suitable approach for different communication scenarios, considering factors such as network complexity, achievable capacity, and robustness to channel impairments. The findings of this research can provide valuable insights for optimizing wireless communication systems, particularly in scenarios where mitigating channel impairments is crucial for achieving reliable and high-performance data transmission.

ÖZETÇE

Elektromanyetik dalga iletişim sistemlerinde yansıtıcı ve iyileştirici sistemlere olan talep, veri trafiğinin sürekli artması ve geleneksel hücresel mimarilerin sınırlamaları nedeniyle artmaktadır. Geleneksel hücresel mimarilerin kısıtlamaları, elektromanyetik dalga iletişim sistemlerinde yenilikçi çözümler gerektirir; bu çözümler arasında röleler ve Yeniden Yapılandırılabilir Akıllı Yüzeyler (RIS) gibi yansıtıcı ve iyileştirici sistemler bulunmaktadır. Mevcut hücresel ağlar, kapasite sınırlamaları, kapsama boşlukları ve sinyal bozulmaları ile mücadele etmektedir; bu sorunlar özellikle kırsal veya coğrafi açıdan zorlu bölgelerde ve milimetre dalga (mmWave) gibi yüksek frekanslarda belirgindir.

Röleler, sinyalleri güçlendirip yeniden ileterek kapsama alanını genişletir ve sinyal gücünü artırır. Bu arada, RIS'ler, akıllı metamaterial panellerle donatılmış olup, sinyal yansımasını stratejik olarak manipüle ederek kapsama alanını genişletir, engelleri azaltır ve uyarlanabilir yayılım yolları oluşturur. Bu gelişmeler, ağ kapasitesinin artırılmasını, kapsama alanının genişletilmesini ve sinyal kalitesinin iyileştirilmesini vaat eder. Bu teknoloji, hücresel genişleme, iç mekan kapsama alanının iyileştirilmesi, mmWave iletişimi ve akıllı şehirler ile Nesnelerin İnterneti (IoT) dağıtımları dahil olmak üzere çeşitli uygulamalara hitap eder. Genel olarak, elektromanyetik dalga iletişim sistemlerinde yansıtıcı ve iyileştirici sistemlere olan talep, daha yüksek kapasite, daha geniş kapsama alanı ve daha iyi sinyal kalitesi ihtiyacından kaynaklanmaktadır. Bu teknolojiler, mevcut hücresel ağların zorluklarını çözmek için umut verici çözümler sunar ve kablosuz iletişimde gelecekteki ilerlemelerin yolunu açar.

Bu tez, RIS'lerin kablosuz iletişim sistemlerinde Bit Hata Oranı (BER) performansını iyileştirme potansiyelini araştırmaktadır. Eşit Güç Dağılımı (EPA) kullanan

çeşitli RIS yapılandırmalarını inceleyen kapsamlı bir model sunulmaktadır. Bu model, RIS tasarım parametrelerinin sistem performansını nasıl etkilediğini değerlendirerek farklı frekans bantlarında optimize edilmiş ağ dağıtımları için bir yol açar.

Araştırmanın merkezinde, iki kritik RIS tasarım unsurunun etkisini analiz etmek yer alır: yüzey elemanı konumu ve miktarı. Bu parametreleri model içinde sistematik olarak değiştirerek, RIS yapılandırmalarının üstün BER performansına ulaşmak için nasıl özelleştirilebileceğini gösterir. Araştırma, farklı sayıda yüzey elemanı içeren yapılandırmaları, mütevazı dağıtımlardan milimetre dalga (mmWave) için 2048 eleman ve Wi-Fi bant genişliği için 328 eleman içeren büyük ölçekli uygulamalara kadar çeşitli senaryoları incelemektedir. Bu kapsamlı analiz, RIS teknolojisinin farklı dağıtım senaryoları ve frekans bantları için ölçeklenme davranışı hakkında değerli içgörüler sağlar.Ayrıca, tez, RIS destekli çift atlama iletim şemaları ile geleneksel röle tekniklerini, özellikle Güçlendir ve Gönder (AF) ve Çözümle ve Gönder (DF) tekniklerini karşılaştıran titiz bir karşılaştırmalı analiz yapar.

Bu karşılaştırma, RIS teknolojisinin nispi avantajlarını net bir şekilde analiz olanağı tanır. Bulgular, RIS destekli iletişimin BER performansı açısından geleneksel röle yöntemlerini geride bıraktığını açıkça göstermektedir.

Tezin son bölümünde, RIS ve AF ile DF röle sistemlerinin kusurlu Dörtlü Genlik Modülasyonu (QAM) uyumlu sistemlerde kanal bozulmalarını hafifletmedeki performanslarını karşılaştırmayı ele alıyoruz. Kusurlu QAM sistemleri, sinyal kalitesini ve Bit Hata Oranı (BER) performansını düşüren çeşitli bozulmalara karşı hassastır. Bu bozulmalar arasında:

*Taşıyıcı Frekans Ofseti (CFO): Alıcının taşıyıcı frekansının vericiden sapması, konstelasyonun dönmesine neden olur.

*Zamanlama Ofseti: Verici ile alıcı arasındaki sembol zamanlamasının uyumsuzluğu, semboller arası girişime (ISI) yol açar.

*Faz Gürültüsü: İletilen sinyalde rastgele faz dalgalanmaları, konstelasyon noktalarının bozulmasına neden olur.

Geleneksel röle teknikleri gibi AF ve DF, sinyal zayıflığını giderir, ancak ek gürültü ve bozulmalar getirebilir. Diğer yandan, RIS teknolojisi, sinyalleri akıllıca yansıtarak kanal bozulmalarını hafifletmek için umut verici bir alternatif sunar. Bu yaklaşım, gürültü amplifikasyonu getirmeden kanal bozulmalarını potansiyel olarak hafifletebilir. Bu tez, QAM sistemlerindeki yukarıda belirtilen bozulmaları hafifletmek için RIS ve AF/DF röle tekniklerinin titiz bir karşılaştırmasını yapar. Araştırma, RIS yapılandırmalarının, yüzey elemanlarının konumlandırılması ve miktarı dahil, BER performansı üzerindeki etkisini analiz eden kapsamlı bir model kullanır. Ayrıca, çeşitli kanal koşullarında ve farklı bozulma seviyeleriyle AF ve DF röle tekniklerinin etkinliğini inceler. Bu tekniklerin performansını karşılaştırarak, ağ karmaşıklığı, elde edilebilir kapasite ve kanal bozulmalarına karşı dayanıklılık gibi faktörleri dikkate alarak, farklı iletişim senaryoları için en uygun yaklaşımı belirlemeyi amaçlar.

Araştırmanın bulguları, özellikle güvenilir ve yüksek performanslı veri iletimi için kanal bozulmalarının hafifletilmesinin kritik olduğu senaryolarda, kablosuz iletişim sistemlerini optimize etmek için değerli içgörüler sağlayabilir.

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CHAPTER I

INTRODUCTION

1.1 Motivation

The advent of reconfigurable intelligent surfaces (RIS) has introduced a transformative approach to wireless communications by enabling the manipulation of the propagation environment to achieve desired performance outcomes. Traditional wireless communication systems are often constrained by the fixed nature of the physical environment, leading to suboptimal signal transmission and reception. RIS technology addresses these limitations by using reconfigurable passive elements that can dynamically adjust their electromagnetic responses. This ability to control the propagation environment opens up new possibilities for enhancing signal quality, coverage, and overall system capacity. Moreover, as wireless communication systems evolve towards 5G and beyond, there is an increasing demand for innovative solutions to meet the stringent requirements of high data rates, low latency, and reliable connectivity. RIS technology, with its potential to improve signal propagation and reduce interference, stands out as a promising candidate to meet these demands. Additionally, the comparative analysis of RIS [1, 2] with traditional relay-assisted transmission techniques, such as amplify-and-forward (AF) [3, 4] and decode-and-forward (DF) relays [5, 6, 7], further underscores the importance of understanding and optimizing these technologies to enhance overall system performance. The emergence of the Internet of Things (IoT), smart cities, and autonomous systems has also intensified the need for robust and flexible communication infrastructures. RIS technology, by offering a means to reconfigure the propagation environment dynamically, can play a crucial role in supporting these advanced applications. For instance, in IoT networks, where devices are often deployed in challenging environments with varying propagation conditions, RIS can ensure consistent connectivity and performance. Furthermore, RIS [8, 9, 10] technology presents significant energy efficiency advantages. Unlike traditional active components, RIS are passive devices that do not require continuous power for signal processing, making them highly energy-efficient. This characteristic is particularly valuable in scenarios where power resources are limited, such as in remote sensing applications or in the deployment of sustainable communication networks. Another critical aspect of the motivation for RIS technology is its potential to reduce the cost and complexity of network deployments. Traditional methods of improving network performance, such as deploying additional base stations or relays, often involve substantial financial investments and logistical challenges. In contrast, RIS can be easily integrated into existing infrastructure, providing a cost-effective solution for enhancing network performance without extensive modifications [11, 12, 13]. In summary, the motivation for exploring RIS technology stems from its potential to address the evolving demands of modern wireless communication systems, including higher data rates, lower latency, improved coverage, energy efficiency, and cost-effectiveness. By enabling dynamic control over the propagation environment, RIS offer a promising solution to the limitations of traditional communication methods and pave the way for the next generation of wireless technologies.

1.2 Overview of RF Applications

Radio Frequency (RF) applications encompass a wide range of technologies and use cases in wireless communications. Each application faces unique challenges related to signal propagation, interference management, and coverage optimization. Understanding these applications provides context for the role that RIS technology can play in enhancing RF communication systems [14].

1.2.1 Cellular Networks

Cellular networks are the backbone of modern communication, providing voice, data, and multimedia services to billions of users worldwide. The evolution from 4G to 5G has introduced new challenges, including the need for higher data rates, increased capacity, and ultra-reliable low-latency communication (URLLC).[15, 16] Traditional methods to meet these demands include the deployment of more base stations, advanced MIMO (Multiple-Input Multiple-Output) techniques, and beamforming. However, these solutions often come with increased complexity and cost. RIS technology offers a novel approach to enhancing cellular networks by dynamically adjusting the propagation environment to improve signal strength and coverage. For instance, in urban areas with high building densities, RIS can mitigate signal blockages and enhance coverage in shadowed regions. By reflecting and refracting signals optimally, RIS can create virtual line-of-sight paths, thereby improving overall network performance without the need for additional infrastructure. Wireless Local Area Networks (WLANs) WLANs, commonly known as Wi-Fi, are essential for providing wireless connectivity in homes, offices, and public spaces. The main challenges in WLANs include ensuring reliable indoor coverage, high data rates, and minimizing interference from neighbouring networks. Traditional solutions involve deploying multiple access points and using advanced modulation schemes to maximize throughput [17, 18, 19]. RIS technology can significantly enhance WLAN performance by optimizing signal propagation within indoor environments. By strategically placing RIS elements [20, 21], it is possible to direct signals towards areas with poor coverage, enhance signal strength, and reduce interference. This can lead to more stable and higher-speed connections, improving the user experience in densely populated areas such as offices and public venues.

1.2.2 Satellite Communications

Satellite communications play a critical role in providing connectivity to remote and underserved regions, supporting broadcasting services, and enabling global navigation systems. The primary challenges [22] in satellite communications include long-distance signal transmission, atmospheric attenuation, and maintaining reliable links under varying conditions. RIS technology can enhance satellite communication systems by improving signal propagation through the atmosphere and mitigating the effects of attenuation [23]. By using RIS elements on satellite surfaces or ground stations, it is possible to optimize the signal paths and enhance link reliability. This can lead to improved performance in satellite-based services such as internet connectivity, broadcasting, and global positioning systems (GPS).

1.2.3 IoT Networks

The proliferation of IoT devices has led to the creation of complex networks with diverse communication requirements. IoT applications range from smart homes and industrial automation to healthcare and environmental monitoring. The main challenges in IoT networks include ensuring low-power operation, reliable connectivity, and efficient spectrum utilization.[11, 12, 13] RIS technology can address these challenges by dynamically optimizing the propagation environment to ensure consistent connectivity for IoT devices. In scenarios where devices are deployed in challenging environments with varying propagation conditions, RIS can enhance signal strength and reduce interference. This can lead to more reliable and efficient IoT networks [20], supporting a wide range of applications with varying communication needs.

1.3 RIS Overview

RIS represent a significant advancement in the field of wireless communications. An RIS is composed of a large number of small, passive, and reconfigurable elements that can reflect, refract, or modulate incoming electromagnetic waves [11, 12, 13]. These elements can be individually controlled to alter the phase, amplitude, and polarization of the reflected signals, thereby shaping the propagation environment to achieve specific communication objectives.

1.3.1 Key Features and Benefits of RIS Technology

1. Dynamic Control RIS can dynamically adjust their electromagnetic properties in real-time, allowing for adaptive optimization of the communication environment. This dynamic control enables the system to respond to changing propagation conditions and user requirements,[24] providing a flexible and efficient solution for improving wireless performance.

2. Improved Signal Propagation By manipulating the path of electromagnetic waves, RIS can enhance signal strength and coverage, especially in challenging environments such as urban areas with high building density. This capability is precious for overcoming obstacles and ensuring reliable connectivity in shadowed regions.

3. Interference Mitigation RIS can be used to reduce interference by directing signals away from interfering sources and towards intended [25] receivers. This selective control of signal paths can lead to significant improvements in signal-to-noise ratio (SNR) and overall system capacity.

4. Energy Efficiency As passive devices, RIS consume significantly less power compared to active elements like traditional relays [25] and base stations. This energy efficiency makes RIS an attractive solution for sustainable network deployments and applications where power resources are limited.

5. Cost-Effectiveness The deployment of RIS can be more cost-effective than installing additional active infrastructure, making it an attractive solution for

improving network performance without extensive modifications [26, 27]. This cost-effectiveness is particularly beneficial in scenarios where budget constraints or logistical challenges limit the deployment of traditional infrastructure.

1.3.2 Operational Principles of RIS Technology

RIS technology operates by leveraging the properties of metamaterials, which are engineered materials with unique electromagnetic characteristics. These metamaterials are designed to have specific responses to [28, 29] electromagnetic waves, allowing for precise control over how the waves are reflected, refracted, or absorbed. The individual elements of an RIS can be electronically reconfigured to alter their electromagnetic response [15, 16, 30], enabling dynamic control over the propagation environment.

1. Phase Control: By adjusting the phase of the reflected signals, RIS can create constructive or destructive interference patterns, enhancing signal strength in desired directions and reducing interference in others. This phase control is achieved through the use of tunable components such as varactors or micro-electromechanical systems (MEMS).

2. Amplitude Control: RIS elements can also modulate the amplitude of the reflected signals, allowing for further optimization of signal [28, 29] propagation. This amplitude control can be used to balance signal strength across different paths and ensure consistent coverage.

3. Polarization Control: In some applications, RIS can adjust the polarization of the reflected signals to match the requirements of the communication system. This polarization control can enhance signal quality and reduce the effects of polarization mismatch.

In summary, RIS technology represents a significant advancement in the field of wireless communications, offering dynamic control over the propagation environment and

[31, 32] enabling a wide range of applications. By leveraging the unique properties of metamaterials, RIS can enhance signal strength, reduce interference, improve coverage, and contribute to the development of energy and cost-effective communication networks.

1.4 Dissertation Outline

The dissertation has five main parts that can be outlined as follows

1. In the first part of this thesis, we explore the theoretical foundations and system models of AF [33, 34, 35] and DF [5, 6, 7] relay systems. This includes a detailed analysis of their operational principles, advantages, and limitations. We present mathematical models for AF [3, 4, 36] and DF relaying schemes and investigate their performance in enhancing wireless communication by extending coverage, improving signal strength, and mitigating propagation issues.

2. In the second part of this thesis, we delve into the concept of RIS. We provide an overview of RIS technology, detailing its key features and benefits, such as dynamic control over the electromagnetic environment, improved signal propagation, interference mitigation, energy efficiency, and cost-effectiveness. We present system models for RIS and compare their performance with traditional relay systems [37].

3. In the third part of this thesis, we address the impact of Quadrature Amplitude Modulation (QAM) coherent imperfections on the performance of RIS, AF, and DF [6, 26, 38] relay systems. Specifically, we examine the effects of frequency offset, phase offset, and symbol timing offset. We discuss the challenges these imperfections pose and present various compensation techniques to mitigate their adverse effects on system performance.

4. In the fourth part of this thesis, we conduct a comprehensive simulation study

to compare the performance of RIS, AF, and DF relay systems under various conditions. We analyze performance metrics such as SNR, bit error rate (BER), and overall system capacity. The simulations consider the presence of QAM coherent imperfections and the effectiveness of compensation techniques in improving system performance.

5. In the fifth part of this thesis, we provide detailed path loss calculations for RIS-aided systems [25, 28, 39], considering both near-field and far-field scenarios. We discuss the methodologies used for path loss calculation and the impact of various parameters on system performance. Guidelines for optimizing RIS deployment to achieve desired performance outcomes are also provided.

By following this structured approach, the thesis aims to provide a thorough exploration of RIS technology, its comparative performance with relay-assisted transmission techniques, and the impact of QAM coherent imperfections on system performance. This comprehensive analysis offers valuable insights into the potential of RIS to enhance future wireless communication systems.

1.5 Organization

The rest of this thesis is organized as follows

1. Section II Transmission Models for AF, DF Relaying, and RIS In this section, we present the theoretical foundations of AF, DF [40] relaying, and RIS technologies. Detailed mathematical models are provided for each technique, along with explanations of their operational principles. This section also addresses the impact of QAM coherent system performance and discusses various compensation techniques.

2. Section II Transmission Models for RIS [41, 42] In this section, we present the theoretical foundations of RIS technologies. Detailed mathematical models

are provided for each technique, along with explanations of their operational principles. This section also addresses the impact of QAM coherent system performance and discusses various compensation techniques.

3. Section III Path Loss Calculations for RIS-Aided Systems In this section, we provide detailed information about the methodologies used for path loss calculation in RIS-aided systems. Both near-field and far-field scenarios are considered, and the impact of various parameters on path loss is discussed. Guidelines for optimizing RIS deployment to achieve desired performance outcomes are also provided.

4. Section IV Simulation Results This section provides a comprehensive analysis of the simulation results for the three systems (RIS, AF, and DF relays) under the same settings. Performance metrics such as SNR, BER, and overall system capacity are analyzed. The results are presented in graphical form to highlight the advantages and limitations of each technique under various conditions, including the presence of coherent imperfections and their compensation.

5. Section V Concluding Remarks Here, we summarize the key findings of our study and their implications for future wireless communication systems. We discuss the potential areas for further research and development, emphasizing the importance of continued exploration and optimization of RIS technology.

By following this structured approach, the thesis aims to provide a thorough exploration of RIS technology, its comparative performance with relay-assisted transmission techniques, and the impact of QAM coherent imperfections on system performance. This comprehensive analysis offers valuable insights into the potential of RIS to enhance future wireless communication systems.

CHAPTER II

RELAY TRANSMISSION

In this chapter, some of the concepts that will be used throughout the work will be introduced, along with the objective of this work.

2.1 Introduction

RIS have recently emerged as a revolutionary technology poised to transform the landscape of wireless communications. RIS consist of numerous passive elements, often referred to as metasurfaces, which can be dynamically configured to manipulate electromagnetic waves. This ability to control wave propagation offers the potential to enhance signal strength, improve coverage, and reduce interference in wireless networks. The growing interest in RIS is driven by their capacity to address some of the critical challenges faced by conventional wireless communication systems, including path loss, fading, and interference. Traditional relay-assisted transmission methods, such as AF [43] and DF [5, 6, 7] relays, have been extensively employed to enhance wireless communication by relaying signals between the transmitter and receiver. In AF relaying, the relay node amplifies the received signal before retransmitting it, while in DF relaying, the relay node decodes the received signal, processes it, and then retransmits it. These techniques exploit the broadcast nature of wireless signals and create a virtual antenna array through cooperating nodes, thereby improving coverage and reliability. However, these methods also introduce additional complexity and potential delays due to the active signal processing involved. In contrast, RIS [3, 4] offer a more elegant and potentially more efficient solution by passively reflecting and refracting signals towards the receiver without the need for complex signal processing. By adjusting the phase shifts of the elements on the surface, RIS can steer the reflected signals to desired directions, thereby enhancing the overall transmission performance. This passive nature not only simplifies the design and implementation of RIS but also reduces energy consumption, making them a promising candidate for future energy-efficient wireless communication systems. The performance comparison between RIS and traditional relay-assisted systems is a subject of significant interest in the research community. While both approaches aim to enhance wireless communication by improving signal quality and coverage, the underlying mechanisms and their impact on system performance are fundamentally different. RIS manipulate the propagation environment to optimize signal paths, whereas relay systems actively process and forward the signals. This thesis aims to provide a comprehensive comparative analysis of these two approaches, focusing on key performance metrics such as BER[33, 34, 35] and path loss. This study diverges from previous research by presenting a special transmission scenario that systematically compares RIS with dual-hop AF and DF relay systems under various conditions, including Non-Line-of-Sight (NLOS) [43] environments. By employing detailed simulations, this research evaluates the impact of different system configurations and positions on the performance of RIS and relay-assisted systems. The findings of this thesis are expected to offer valuable insights into the relative advantages and limitations of these approaches, thereby guiding the design and implementation of next-generation wireless communication systems.

2.1.1 AF Relaying Transmission

AF [3] relaying is a fundamental technique in wireless communication systems designed to extend coverage and improve the reliability of signal transmission. The basic principle of AF relaying is to use an intermediate relay node that amplifies the received signal and then forwards it to the destination.

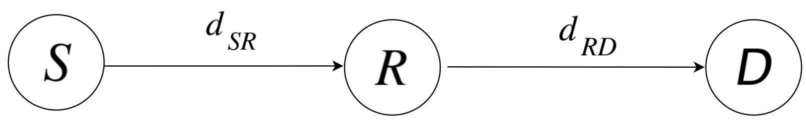

Figure 1: AF relaying transmission model.

This method is particularly beneficial in scenarios where direct communication between the source and the destination is impaired by obstacles, long distances, or other factors that cause significant path loss and signal fading. The deployment of relay nodes in wireless communication systems can greatly enhance the quality and robustness of the communication link. By introducing a relay node between the source and the destination, the communication link is effectively divided into two shorter hops. Each hop experiences less path loss and signal degradation compared to a single long-distance transmission. This not only improves the signal quality at the destination but also increases the overall system capacity and coverage area. [44, 45, 46] In an AF relaying system, the relay operates in a half-duplex mode, meaning it cannot transmit and receive signals simultaneously. This operational mode is chosen to avoid self-interference, which can degrade the performance of the relay. The half-duplex mode ensures that the relay first receives the signal from the source, amplifies it, and then forwards it to the destination in a subsequent time slot. Consider a communication system comprising three nodes the source (S), the relay (R), and the destination (D). These nodes are strategically placed in a two-dimensional plane to optimize the communication process. The distances between the nodes are crucial parameters that influence the system's performance. The distance between the source and the relay is denoted as d_{SR}, and the distance between the relay and the destination is denoted as d_{RD}. The signal transmission process in an AF relaying system can be divided into two main phases. In the first phase, the source transmits the signal to the relay. The received signal at the relay includes the desired signal component and noise. In the second phase, the relay amplifies the received signal and forwards it to the destination. This amplified signal again comprises the desired signal component and noise, which is further propagated to the destination. The effectiveness of AF relaying is influenced by several factors, including the quality of the channel between the nodes, the noise levels, and the amplification factor at the relay. The relay's amplification factor is carefully chosen to balance the trade-off between amplifying the desired signal and minimizing the amplification of noise. A higher amplification factor can enhance the signal strength but also increase the noise power, which can degrade the overall system performance.

In summary, AF relaying plays a critical role in modern wireless communication systems by enhancing coverage and reliability through the use of relay nodes. By breaking the communication link into shorter hops and amplifying the received signals, AF relaying helps mitigate the effects of path loss and signal fading, ensuring robust and efficient communication in various scenarios. The next sections will delve deeper into the technical details of the AF transmission model, including the path loss and channel model, signal transmission, and the derivation of key performance metrics such as the SNR and BER. These analyses provide valuable insights into the operation and performance of AF relaying systems, paving the way for their optimization and deployment in future wireless networks [26, 27].

2.2 Path Loss and Channel Model

In wireless communication systems, the path loss and channel model are critical components that determine the performance and reliability of signal transmission. The path loss represents the reduction in signal strength as it propagates through the medium, while the channel model characterizes the effects of the propagation environment on the signal.

2.2.1 Path Loss

Path loss is a fundamental factor in the design and analysis of wireless communication systems. It quantifies the attenuation that a signal experiences as it travels from the transmitter to the receiver. The path loss depends on various factors, including the distance between the transmitter and receiver, the frequency of the transmitted signal, and the characteristics of the propagation environment. In free space, the path loss can be modelled by using the Friis [5] transmission equation as

$$P_L\left(d\right) = \left(\frac{4\pi d}{\lambda}\right)^2, \tag{1}$$

where $P_L\left(d\right)$ is the path loss at distance d, λ is the wavelength of the transmitted signal. This model assumes a line-of-sight (LOS) path between the transmitter and receiver, which is often referred to as the free space path loss (FSPL). For practical scenarios where the signal propagates through a complex environment with obstacles and reflections, the path loss exponent α is introduced to account for the additional attenuation. The generalized path loss model is given by

$$P_L\left(d\right) = \left(\frac{4\pi d}{\lambda}\right)^\alpha. \tag{2}$$

In this model, α is the path loss exponent, which typically ranges from 2 (free space) to 4 (urban environments) or even higher, depending on the density and nature of obstacles in the propagation path. In an AF relaying system, the path losses between the source and relay (d_{SR}) and between the relay and destination (d_{RD}) are described by [36]

$$P_L^{SR} = \frac{\lambda^2 G_t}{\left(4\pi\right)^2 d_{SR}^\alpha}, P_L^{RD} = \frac{\lambda^2 G_r}{\left(4\pi\right)^2 d_{RD}^\alpha}, \tag{3}$$

where G_t and G_r are the antenna gains at the transmitter and receiver, respectively. These equations provide a basis for calculating the path losses in the first and second hops of the AF relaying process.

2.2.2 Channel Model

The channel model characterizes the effects of the propagation environment on the transmitted signal. In wireless communication, the channel can introduce various impairments, including path loss, shadowing, and multipath fading. Multipath fading occurs when the transmitted signal reflects off multiple surfaces before reaching the receiver, causing constructive and destructive interference. In the context of AF relaying, the channel gains between the nodes are essential for determining the system's performance. The channel gain G_{SR} between the source and relay, and G_{RD} between the relay and destination, are given by [36]

$$G_{SR} = \frac{P_t}{P_L^{SR}}, G_{RD} = \frac{P_t}{P_L^{RD}}, \tag{4}$$

where P_t is the transmit power. These channel gains incorporate the effects of path loss and are crucial for analyzing the received signal strength at the relay and destination.

The received signal at the relay can be expressed as

$$r_R = \sqrt{G_{SR}} h_{SR} x + n_R, \tag{5}$$

where

- h_{SR} and h_{RD} are channel coefficients between the source to relay and the relay to destination, modelled as a zero-mean complex Gaussian random variable with a variance of 0.5 per dimension (Rayleigh fading).
- x is the transmitted signal with unit energy.
- n_R, n_D are the noises at the relay and destination, modelled as a zero-mean complex Gaussian random variable with variance $N_0/2$ per dimension.

Rayleigh fading is a common model used to describe the statistical variation of the signal amplitude due to multipath propagation. In environments without a dominant line-of-sight path, the signal experiences rapid fluctuations, which can be modelled as Rayleigh distributed. The channel coefficient h_{SR} captures this behaviour and significantly influences the received signal quality. In the second phase of the AF relaying process, the relay amplifies the received signal and forwards it to the destination. The amplified signal transmitted by the relay is

$$r_R = \sqrt{G_{SR}} h_{SR} x + n_R. \tag{6}$$

The received signal at the destination, incorporating the effects of the relay's amplification and the second hop's channel characteristics as

$$r_D = \sqrt{\frac{G_{SR} G_{RD}}{G_{SR} + N_0}} h_{RD} h_{SR} x + n_D. \tag{7}$$

This detailed model of the received signal at the destination provides a comprehensive understanding of the factors influencing the performance of AF relaying systems. By incorporating path loss and channel characteristics, it is possible to analyze and optimize the relay's operation to achieve reliable and efficient wireless communication.

2.2.3 DF Relaying

In a single-input single-output (SISO) scenario featuring DF relay nodes, the source, relay, and destination nodes operate in a half-duplex mode, each equipped with a single transmit and receive antenna. Situated in a two-dimensional plane, the positions of the nodes are defined by distances where d_{SR}, and d_{RD} denote corresponding to the source-to-relay (S→R), and relay-to-destination (R→D) links, respectively. Taking into account the impact of path loss, the signals received in the initial time slot at the relay nodes are expressed as

$$r_R = \sqrt{G_{SR} P} h_{SR} x + n_R, \tag{8}$$

where P signifies the overall transmit power jointly utilized by the source and relay nodes. For the system, half of the power is considered at the source and half of the power is considered at the relay [11]. Within equations (5) and (6), the terms n_R and n_D represent the additive noise variables, assumed to follow a complex Gaussian distribution with a mean of zero and a variance denoted by N_0. When granted permission to collaborate, the relay node undertakes demodulation and subsequently transmits the re-encoded symbol $\hat{x}$ during the second time slot. As a result, the signal received at the destination node is expressed as

$$r_D = \sqrt{G_{RD} P} h_{RD} \hat{x} + n_D. \tag{9}$$

Following this, the destination node proceeds to decode the symbol transmitted by the source. The channel gain ratio between the source to the relay G_{SR} and the relay to the destination G_{RD} according to d_{SR} and d_{RD}.

2.2.4 SNR

The SNR at the destination is a key performance metric that determines the quality of the received signal. The SNR can be derived as follows. The power of the desired signal component at the destination as

$$\text{Signal Power} = \left| \sqrt{\frac{G_{SR} G_{RD} P_t}{P_{SR}^L + N_0}} h_{RD} h_{SR} \right|^2. \tag{10}$$

The power of the noise components at the destination is

$$\text{Noise Power} = \left| \sqrt{\frac{G_{RD}}{P_{SR}^L + N_0}} h_{RD} n_R \right|^2 + |n_D|^2. \tag{11}$$

Thus, the SNR at the destination is

$$\text{SNR} = \frac{\frac{G_{SR} G_{RD} P_t |h_{RD}|^2 |h_{SR}|^2}{P_{SR}^L + N_0}}{\frac{G_{RD} N_0}{P_{SR}^L + N_0} + N_0}. \tag{12}$$

Simplifying further, we obtain

$$\text{SNR} = \frac{G_{SR} G_{RD} P_t |h_{RD}|^2 |h_{SR}|^2}{G_{RD} N_0 + (P_{SR}^L + N_0) N_0}. \tag{13}$$

2.3 Conclusion

AF relaying is a fundamental technique in wireless communication systems that provides significant improvements in coverage and reliability by utilizing intermediate relay nodes. The basic principle involves the relay node receiving the signal from the source, amplifying it, and then forwarding it to the destination. This method effectively mitigates the adverse effects of path loss and signal fading, ensuring robust communication even in challenging environments. The detailed analysis and numerical results presented in this section highlight the key aspects and performance metrics of AF relaying. By examining the path loss and channel model, we gain insights into how the signal attenuates over distance and how various environmental factors affect signal propagation. The channel model, which may include the effects of multipath fading and shadowing in more realistic scenarios, is crucial for understanding the real-world performance of AF relaying systems. The SNR at the destination is a critical metric for evaluating the performance of AF relaying. The derived expressions for SNR and the corresponding BER provide a quantitative measure of the system's effectiveness. These metrics demonstrate how AF relaying improves signal quality by enhancing the received signal strength at the destination, despite the amplification of noise [44, 45, 46]. Several enhancements can further improve the efficiency and effectiveness of AF relaying systems. Optimal power allocation between the source and relay is one such enhancement. By intelligently distributing the available transmit power, the system can maximize the SNR at the destination, thereby improving the BER performance. This optimization involves solving a power allocation problem that considers the path loss, channel conditions, and noise levels. Adaptive relaying is another powerful enhancement. By dynamically switching between AF and DF modes based on the received signal quality, adaptive relaying ensures that the most appropriate relaying method is used under varying conditions. This adaptability enhances the system's robustness and efficiency, providing error correction capabilities when the signal quality is high and maintaining connectivity even when the signal quality is poor. Cooperative diversity, where multiple relay nodes work together to relay the signal, is another technique that can significantly enhance system performance. By combining the signals from multiple relays using techniques such as maximum ratio combining (MRC) or selection combining (SC), the system can achieve higher SNR and improved BER performance. Cooperative diversity leverages the spatial diversity of the relays to combat multipath fading and shadowing, providing more reliable communication. In summary, AF relaying is a robust and versatile technique that enhances wireless communication systems by extending coverage and improving reliability. Through the amplification and forwarding of signals, AF relaying helps mitigate the effects of path loss and fading, ensuring robust communication in various scenarios. By exploring and implementing enhancements such as optimal power allocation, adaptive relaying, and cooperative diversity, we can further improve the efficiency and effectiveness of AF relaying systems. These advancements pave the way for more reliable and high-performance wireless networks, capable of meeting the growing demands of modern communication applications [3].

CHAPTER III

RIS TRANSMISSION

3.1 Introduction

RIS represent a paradigm shift in wireless communication, poised to revolutionize the way signals propagate and interact with the environment. As the demand for higher data rates, improved connectivity, and reliable wireless communication grows, traditional methods face challenges in addressing issues such as path loss, interference, and signal blockage. RIS emerges as a transformative technology designed to enhance wireless transmission by dynamically manipulating electromagnetic waves to optimize communication channels [28, 29]. The concept of RIS involves the use of surfaces embedded with numerous small, controllable elements, often referred to as meta-atoms or meta-elements. These elements can reflect incoming signals with adjustable phase shifts, effectively steering the signals towards desired directions or destinations. This ability to control the reflection of signals enables RIS to overcome obstacles and mitigate interference, thereby enhancing the overall performance of wireless communication systems [31, 32]. One of the primary distinctions between RIS and traditional relay systems, such as AF and DF relays, lies in their operational mechanisms. Traditional relay systems actively retransmit signals, which introduces additional complexity, latency, and power consumption. In contrast, RIS operates passively, reflecting signals without the need for active processing. This passive nature of RIS results in lower power consumption and reduced system complexity, making it a more efficient and cost-effective solution. The importance of the transmission part in RIS systems cannot be overstated. The transmission mechanism involves the precise configuration of the phase shifts of individual RIS elements to ensure that the reflected signals combine constructively at the receiver. This constructive interference enhances signal strength and quality, leading to improved SNR, BER, and overall throughput. The ability to fine-tune the phase shifts of RIS elements is a key factor in optimizing the performance of RIS-assisted communication systems. In this paper, we will delve into the transmission mechanisms of RIS, providing a comprehensive analysis of the underlying principles, mathematical models, and performance metrics. We will begin with an overview of RIS technology and its distinguishing features compared to traditional relay systems. Subsequently, we will explore the transmission model for RIS, detailing the interaction between incident signals and RIS elements, and the resulting impact on path loss and signal reflection [11, 13]. The significance of the transmission part in RIS systems extends beyond theoretical models. Practical implementation and numerical analysis play crucial roles in validating the effectiveness of RIS. We will present simulation results and performance comparisons between RIS-assisted systems and traditional relay systems under various scenarios. These comparisons will highlight the advantages of RIS in terms of efficiency, signal quality, and overall system performance. In conclusion, the transmission part of RIS systems is pivotal to realizing the full potential of this innovative technology. By leveraging advanced control of signal reflection and phase shifts, RIS can significantly enhance wireless communication, addressing the growing demand for reliable and high-performance connectivity. This paper aims to provide a thorough understanding of RIS transmission mechanisms, supported by mathematical models and empirical analysis, to underscore the transformative impact of RIS on wireless communication [24].

3.2 Transmission Mechanisms in RIS

RIS have emerged as a groundbreaking technology poised to revolutionize wireless communication. By leveraging the ability to dynamically manipulate electromagnetic waves, RIS can significantly enhance signal propagation, reduce interference, and improve overall communication performance. This section delves into the transmission mechanisms of RIS, presenting a comprehensive analysis of the underlying principles, mathematical models, and performance metrics.

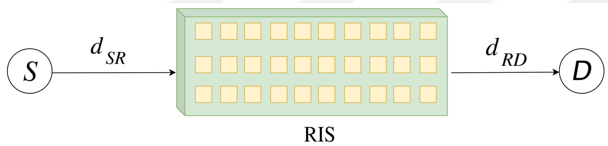

Figure 2: RIS transmission model.

3.2.1 RIS Concept and Operation

RIS are engineered surfaces composed of a large array of passive, low-cost, and programmable reflecting elements, also known as meta-atoms or meta-elements. Each element can independently adjust the phase and/or amplitude of the incident electromagnetic waves. By collectively tuning these elements, RIS can shape the reflected wavefronts to achieve desired communication objectives, such as enhancing signal strength at the receiver, mitigating interference, or redirecting signals to avoid obstacles. The fundamental principle of RIS operation is based on the law of reflection, modified by the phase shifts applied by each RIS element. The phase shift introduced by the i_{th} element can be represented as ϕ_i. By carefully designing the phase shifts across the entire RIS, it is possible to control the direction and shape of the reflected signals [47]. The operation of RIS can be explained through the concept of beamforming, where the reflected signals from all the elements are combined constructively at the receiver to enhance the signal strength. This is achieved by adjusting the phase shifts such that the path difference between the signals from different elements results in constructive interference. The phase shift ϕ_i for each element is determined based on the geometry of the system, including the positions of the transmitter, RIS, and receiver [1, 2].

Mathematically, the reflection coefficient of each RIS element can be expressed as

$$\Gamma_i = \alpha_i \mathrm{e}^{j\phi_i}, \tag{14}$$

where α_i is the amplitude reflection coefficient and ϕ_i is the phase shift. For ideal RIS elements, $\alpha_i = 1$, meaning no loss in signal strength upon reflection. The overall reflected signal at the receiver is a coherent sum of the contributions from all the RIS elements, given by

$$\sum_{i=1}^{N} \Gamma_i h_i x, \tag{15}$$

where h_i represents the channel coefficient between the i_{th} RIS element and the receiver, and x is the transmitted signal. By optimizing ϕ_i for all elements, the RIS can focus the reflected signal towards the receiver, maximizing the received power. The effectiveness of RIS depends on the precise control of phase shifts and accurate channel state information (CSI). Accurate CSI allows the optimization algorithm to determine the optimal phase shifts for the RIS elements, ensuring maximum constructive interference at the receiver.

3.2.2 Transmission Model for RIS

The transmission model for RIS involves the interaction between the incident signal, the RIS elements, and the reflected signal directed towards the receiver. Consider a communication system where a transmitter Tx sends a signal to a receiver Rx via an RIS. The RIS is placed such that it can effectively reflect the signal from the Tx towards the Rx. The received signal at the Rx can be expressed as

$$\sqrt{P_t}\left(\sum_{i=1}^{N} h_i \mathrm{e}^{j\phi_i}\right) + n_D, \tag{16}$$

where

1. P_t is the transmit power.

2. h_i is the channel coefficient between the i_{th} RIS element and the receiver.

3. ϕ_i is the channel coefficient between the i_{th} RIS element and the receiver.

4. N is the number of RIS elements.

5. n_D is the noise at the receiver.

The phase shifts ϕ_i are chosen to maximize the constructive interference at the receiver, thereby enhancing the received signal power. To develop a deeper understanding, let's consider the overall channel gain from the transmitter to the receiver via the RIS. The combined channel gain can be expressed as

$$H_{eff} = \sum_{i=1}^{N} g_i h_i \mathrm{e}^{j\phi_i}, \tag{17}$$

where g_i is the channel gain from the transmitter to the i_h RIS element. The received signal power at the receiver is then

$$P_r = P_t \left| \sum_{i=1}^{N} g_i h_i \mathrm{e}^{j\phi_i} \right|^2. \tag{18}$$

For effective signal reflection and maximization of the received power, the phase shifts ϕ_i need to be optimized. Ideally, each phase shift is set to align the phases of the reflected signals constructively. This optimal phase shift ϕ_i^{opt} can be derived as

$$\phi_i^{opt} = -arg\left(g_i h_i\right), \tag{19}$$

where $arg\,(g_i h_i)$ represents the phase of the product of channel coefficients g_i and h_i. The optimization of phase shifts is a critical aspect of RIS transmission models. Efficient algorithms are required to dynamically adjust ϕ_i in response to changes in the communication environment, such as the movement of users or variations in the channel conditions. This dynamic adjustment ensures that the RIS can continuously provide optimal performance by maintaining constructive interference at the receiver [28, 29].

3.3 Path Loss in RIS-Assisted Systems

Path loss is a crucial factor in RIS-assisted communication systems. The effective path loss in RIS-assisted systems is influenced by the distances between the transmitter, RIS, and receiver, as well as the configuration of the RIS elements. The path loss model for RIS can be derived based on the Friis transmission equation, taking into account the reflection coefficients of the RIS elements.

In this section, we present path loss models for RIS-enhanced wireless communication based on the work in [48, 49]. The standardized power radiation pattern is expressed as a function, denoted as $F(\theta, \varphi)$, within the spherical coordinate system, as depicted in (20). Here, θ and φ represent the elevation and azimuth angles, describing the orientation from the antenna to a specific transmitting/receiving direction [48],

$$F(\theta, \varphi) = \begin{cases} \cos\theta & \theta \in \left[0, \frac{\pi}{2}\right], \varphi \in [0, 2\pi] \\ 0 & \theta \in \left(\frac{\pi}{2}, \pi\right], \varphi \in [0, 2\pi]. \end{cases} \tag{20}$$

When a transmitter is considerably far from an antenna array, the spherical wave it produces can be approximated as a plane wave with the transmitter located in the far-field of the antenna array. The distinction between the far-field and near-field of the antenna array is established as $D = \frac{2A_D^2}{\lambda}$ [48]. In the given context, D represents the distance from the transmitter/receiver to the centre of the antenna array, A_D stands for the largest dimension of the antenna array, and λ denotes the wavelength.

Under far-field conditions, the elevation-azimuth angles from individual RIS elements to the transmitter and receivers, denoted by $\left(\theta_{n,m}^{t}, \varphi_{n,m}^{t}\right)$ and $\left(\theta_{n,m}^{r}, \varphi_{n,m}^{r}\right)$ (where the subscripts potentially represent the nth element in the mth row) can be approximated by the angles from the RIS centre to the transmitter and receivers, respectively, denoted by (θ_t, φ_t) and (θ_r, φ_r) Furthermore, if both the transmitting antenna and receiving antenna exhibit peak radiation in the direction pointing towards the centre of RIS, then in the far-field case, we can approximate $F^{tx}\left(\theta_{n,m}^{tx}, \varphi_{n,m}^{tx}\right) \approx 1$ and $F^{rx}\left(\theta_{n,m}^{rx}, \varphi_{n,m}^{rx}\right) \approx 1$ represent the radiation patterns of the transmitting and receiving antennas, respectively. With these simplifications, the joint normalized power radiation pattern in [48] can be simplified as

$$\begin{aligned} F_{\text{combine}}^{far-field} &= F^{tx}\left(\theta_{n,m}^{tx}, \varphi_{n,m}^{tx}\right) F^{RIS}\left(\theta_{n,m}^{t}, \varphi_{n,m}^{t}\right) \\ & F^{RIS}\left(\theta_{n,m}^{r}, \varphi_{n,m}^{r}\right) F^{rx}\left(\theta_{n,m}^{rx}, \varphi_{n,m}^{rx}\right) \\ &= F^{RIS}\left(\theta_t, \varphi_t\right) F^{RIS}\left(\theta_r, \varphi_r\right). \end{aligned} \tag{21}$$

Based on [24], consider a scenario where the amplitude of the reflection coefficient for all unit cells within RIS is uniform and denoted as A. The phase of these unit cells is optimized to maximize the received power for a specific user under far-field conditions. Subsequently, the reflection coefficient of each unit is adjusted to compensate for signal propagation delay, and the phase of the unit cells $\phi_{n,m}$ is set to $2\pi\left(d_t + d_r\right)/\lambda$. Utilizing the unit cell's normalized power radiation pattern as outlined in (20) and substituting $F^{RIS}\left(\theta_t, \varphi_t\right) = \cos\theta_t$ and $F^{RIS}\left(\theta_r, \varphi_r\right) = \cos\theta_r$, the overarching far-field expression from the reference [48] is further simplified to

$$P_{L_{\text{FF}}} = \frac{\left(G_t G_r M N d_x d_y\right)^2 \cos\theta_t \cos\theta_r A^2}{16\pi^2 \left(d_t d_r\right)^2}, \tag{22}$$

where d_t and d_r denote the distances between the transmitter and receiver antennas and the centre of RIS. M and N represent the quantities of surface elements, while dx and dy signify the dimensions of individual elements along the x and y axes, respectively.

Additionally, the RIS can dynamically adjust the reflection coefficients to optimize the signal strength at the receiver, even in the presence of obstacles or other environmental factors that may impact the direct non-line-of-sight (NLOS) path. This adaptability makes RIS a powerful tool in mitigating path loss and ensuring robust communication links [24].

3.3.1 SNR in RIS Systems

The SNR is a key performance metric in wireless communication systems. For RIS-assisted systems, the SNR can be optimized by configuring the phase shifts of the RIS elements to maximize the constructive interference at the receiver.

The SNR for an RIS-assisted system can be expressed as

$$SNR_{RIS} = \frac{P_t \left| \sum_{i=1}^{N} h_i \mathrm{e}^{j\phi_i} \right|^2}{N_0}, \tag{23}$$

where

1. P_t is the transmit power.
2. h_i is the channel coefficient between the i_{th} RIS element and the receiver.
3. ϕ_i is the channel coefficient between the i_{th} RIS element and the receiver.
4. N is the number of RIS elements.
5. N_0 is the noise at the receiver.

By optimizing the phase shifts ϕ_i, the summation term in the numerator can be maximized, leading to an enhanced SNR and improved communication performance. To achieve this, the phase shifts must be carefully chosen to align the phases of the signals reflected by the RIS elements. This alignment ensures that the reflected signals add constructively at the receiver, maximizing the received power and, consequently, the SNR. The optimal phase shift for the i_{th} element is given by

$$\phi_i^{opt} = -arg\left(g_i h_i\right). \tag{24}$$

In practical scenarios, the optimization of phase shifts is an ongoing process that must account for dynamic changes in the communication environment. Algorithms for real-time phase shift adjustment are essential to maintain optimal SNR levels. These algorithms rely on accurate and timely CSI to compute the optimal phase shifts for each RIS element.

3.4 Conclusion

RIS represent a transformative technology in wireless communication, offering significant potential to enhance signal propagation, reduce interference, and improve overall system performance. By leveraging advanced control of signal reflection and phase shifts, RIS can achieve superior SNR and BER compared to traditional systems. The mathematical models and numerical simulations presented in this section underscore the effectiveness of RIS in enhancing wireless communication. Practical implementation of RIS involves addressing challenges related to phase shift control, channel estimation, and hardware limitations, which are critical for realizing the full potential of this technology [50].

CHAPTER IV

QAM IMPERFECTIONS

4.1 Introduction to QAM Imperfections

QAM is a widely used modulation scheme in digital communication systems due to its high spectral efficiency. QAM conveys data by changing (modulating) the amplitude of two carrier waves. These two waves, usually sine and cosine waves, are out of phase by 90 degrees, hence the term "quadrature". The amplitude of each wave is modulated to represent the data signal. While QAM is powerful and efficient, it is susceptible to various imperfections that can degrade the performance of the communication system. These imperfections include frequency offset, phase offset, and symbol timing offset. Each of these imperfections arises due to different reasons and affects the communication system in unique ways.

4.1.1 Frequency Offset

Frequency offset is one of the most critical imperfections in QAM systems. It occurs when there is a discrepancy between the transmitter and receiver oscillator frequencies. This discrepancy can be due to several reasons, including oscillator mismatches, Doppler shifts caused by relative motion between the transmitter and receiver, and other environmental factors. When frequency offset occurs, it results in a rotation of the QAM constellation, which can cause symbol misinterpretation at the receiver. For instance, in a 16-QAM system, where each symbol represents 4 bits, even a small rotation can lead to significant errors. The impact of frequency offset is more pronounced at higher modulation orders, as the constellation points are closer together, making them more susceptible to errors. To mitigate frequency offset, various estimation and compensation techniques are employed. One popular method is the

Discrete Fourier Transform (DFT) estimator, which leverages the frequency domain representation of the received signal to estimate the offset. The DFT estimator is known for its computational efficiency and accuracy at moderate to high SNR.

4.2 Phase Offset

Phase offset occurs when there is a constant phase difference between the transmitted and received signals. This can be caused by oscillator phase noise, multipath propagation, or other channel impairments. Phase offset results in a uniform rotation of the QAM constellation, similar to frequency offset but typically on a smaller scale and with a fixed rotation angle. Phase offset can cause severe degradation in system performance, especially in high-order QAM systems. To address phase offset, channel estimation techniques such as the Least Squares (LS) method are used. The LS method estimates the channel coefficients by minimizing the sum of squared errors between the received and estimated signals. This technique assumes a flat-fading channel and simplifies the estimation process by treating the modulated symbols as real values.

4.2.1 Symbol Timing Offset

Symbol timing offset arises when there is a misalignment between the symbol rate of the transmitter and the sampling rate of the receiver. This misalignment can be caused by clock drift, propagation delays, or other synchronization issues. Symbol timing offset leads to inter-symbol interference (ISI), which degrades the performance of the communication system by causing symbols to overlap. To correct symbol timing offset, synchronization algorithms such as the Phase-Locked Loop (PLL) are employed. The PLL-based symbol timing synchronizer typically consists of a Timing Error Detector (TED), an interpolator, an interpolation controller, and a loop filter. These components work together to estimate and correct the timing error, ensuring that the received samples align with the symbol boundaries.

4.2.2 Advanced Techniques for Mitigating QAM Imperfections

In recent years, advanced techniques have been developed to mitigate QAM imperfections more effectively. These techniques often involve sophisticated signal processing algorithms and machine learning methods. For example, adaptive equalization algorithms can dynamically adjust the receiver parameters to compensate for time-varying channel conditions and imperfections. Machine learning algorithms can also be trained to identify and correct imperfections in real-time, improving the robustness of the communication system. Another advanced technique is the use of RIS. RIS can dynamically alter the propagation environment to improve signal quality and reduce the impact of imperfections. By intelligently reflecting and refracting the transmitted signals, RIS can enhance the received signal strength and reduce the effects of frequency, phase, and timing offsets.

4.3 Frequency Offset

4.3.1 Introduction to Frequency Offset

Frequency offset in QAM systems refers to the deviation of the carrier frequency of the received signal from the expected carrier frequency. This deviation can cause significant performance degradation in communication systems. The primary causes of frequency offset include oscillator mismatches and Doppler shifts. Oscillator mismatches occur due to the slight differences in the frequencies of the oscillators used in the transmitter and receiver. These differences, although small, can accumulate over time, leading to a significant offset. Doppler shifts, on the other hand, arise due to the relative motion between the transmitter and the receiver, commonly encountered in mobile communication systems. When frequency offset occurs, it causes a rotation of the QAM constellation, which can lead to incorrect symbol detection. For example, in a 16-QAM system, each symbol represents 4 bits. A rotation caused by frequency offset can make the receiver interpret the received symbols incorrectly, resulting in a higher bit error rate (BER). The impact of frequency offset is more severe in higher-order QAM systems, such as 64-QAM or 256-QAM, where the constellation points are closer together, making the system more susceptible to errors. To understand the impact of frequency offset, consider the received signal $r(t)$ with a frequency offset Δf as

$$r(t) = s(t)\mathrm{e}^{j2\pi\Delta f t}, \tag{25}$$

where $s(t)$ is the transmitted signal. The term $\mathrm{e}^{j2\pi\Delta f t}$ presents the frequency offset, which rotates the received signal in the complex plane. This rotation must be corrected to accurately recover the transmitted data.

The DFT estimator is a widely used method for CFO estimation and compensation. It calculates the DFT of the received signal and identifies a peak at the CFO frequency. The DFT estimator leverages the frequency domain representation of the received signal to estimate the offset. By analyzing the spectrum of the received signal, the CFO can be detected and corrected.CFO is a critical parameter in communication systems, affecting the performance of signal demodulation and decoding. Accurate estimation of the CFO is necessary for maintaining the integrity and quality of data transmission. This report details the first method of CFO estimation as outlined in the provided document.

4.3.2 Method Overview

The method for CFO estimation is versatile and can be applied to both small and large CFO values. This method requires a small frequency difference (delta f) between samples to achieve high-resolution estimation. The primary steps involved in this method are as follows

1. Pilot Signals: The method utilizes pilot signals embedded within the transmission to estimate the CFO. The number of pilot signals and the symbol time play

a crucial role in determining the resolution and the length of the data sequence.

2. Frequency Resolution: To achieve a good resolution in CFO estimation, the method requires small frequency differences between the samples. This ensures that even minor CFO values can be detected accurately.

3. Phase Calculation: The method involves calculating the phase shift induced by the CFO. By analyzing the phase difference between successive pilot symbols, the CFO can be estimated. The precise equation used for phase calculation is essential but is not specified in the provided extract.

This method is effective for a wide range of CFO values, from very small to very large. However, it is particularly noted that while the method can handle large CFO values, it might introduce some degree of resolution loss, making it less ideal for very small CFO values. Resolution and Data Length The method's resolution and the length of the data sequence are determined by the number of pilot symbols and the symbol time. A higher number of pilots and longer symbol times can improve the estimation accuracy. It is implied that after low-pass filtering (LPF), further processing steps are involved to refine the CFO estimation. The exact nature of these post-processing steps is critical for the final accuracy but is not detailed in the provided extract. For effective CFO estimation, it is suggested to remove high-frequency components from the signal. This helps in isolating the relevant frequency shifts caused by the CFO.

4.3.3 Detailed Method Description and Formulas

The core principle of CFO estimation involves measuring the phase shift between consecutive symbols or pilots. The frequency offset (Δf) can be estimated using the relationship between phase shift $(\Delta\theta)$ and the symbol duration (T_s) as

$$(\Delta f) = \frac{\Delta\theta}{2\pi T_s}, \tag{26}$$

where

- Δf is the estimated frequency offset.
- $\Delta\theta$ is the phase shift between consecutive symbols.
- T_s is the symbol duration.

The CFO influences the phase shift between symbols and can be expressed as

$$\Delta\theta = arg\left(\frac{P_{n+1}}{P_n}\right), \tag{27}$$

where

- P_{n+1} and P_n are the received pilot symbols at time n and $n+1$, respectively.
- arg represents the complex number's argument (phase angle).

Pilot symbols are critical in this estimation method. The document emphasizes the importance of the number of pilot symbols and their placement within the transmission sequence. A higher number of pilot symbols improves the resolution of CFO estimation. This indicates that increasing the number of pilots enhances the estimation resolution, making it easier to detect even small CFO values. After obtaining the initial CFO estimation, low-pass filtering is applied to remove high-frequency components that might introduce noise or interfere with the accuracy of the CFO estimation. The document mentions the necessity of LPF post-processing but does not provide specific filter parameters. The general purpose of LPF in this context is to smooth the estimated phase shifts and improve the robustness of the CFO estimation.

4.3.4 Conclusion

CFO estimation provides a robust approach to managing both small and large CFO values in communication systems. Its reliance on pilot symbols and phase calculations makes it a versatile method, though it requires careful consideration of sample frequency differences and post-processing steps to achieve optimal results. For scenarios involving very small CFO values, additional methods might be necessary to complement this approach. The detailed formulas and steps outlined in this report highlight the critical aspects of the CFO estimation, providing a comprehensive understanding of its implementation and potential advantages and limitations.

4.4 Phase Offset

Phase offset is a common issue in QAM systems, characterized by a constant phase difference between the transmitted and received signals. This difference can arise due to various factors, including mismatches in the transmitter and receiver oscillators, propagation delays, and multipath effects.

In practical communication systems, oscillators at the transmitter and receiver are not perfectly synchronized. Even slight differences in their frequencies can accumulate over time, resulting in a phase offset. Additionally, propagation delays, which occur as the signal travels from the transmitter to the receiver, can introduce phase shifts. Multipath propagation, where the signal takes multiple paths to reach the receiver, can further exacerbate phase offset issues.

4.4.1 Introduction to Phase Offset

The presence of phase offset leads to a rotation of the QAM constellation. In a simple QAM system, such as 4-QAM, this rotation might result in symbols being misinterpreted. For higher-order QAM systems, such as 16-QAM or 64-QAM, where constellation points are closer together, the impact of phase offset becomes more pronounced, leading to higher BER. Mathematically, if the transmitted signal is represented as $s(t) = I(t) + jQ(t)$, where $I(t)$ and $Q(t)$ are the in-phase and quadrature components respectively, the received signal with a phase offset θ can be expressed as

$$\left(I\left(t\right)+Q\left(t\right)\right)\mathrm{e}^{j\phi_i}. \tag{28}$$

This equation shows that the received signal $r(t)$ is the transmitted signal $s(t)$ rotated by an angle θ in the complex plane.

4.4.2 The Least Squares Method for Phase Offset Estimation

The LS method is a powerful statistical signal processing technique used to estimate and correct phase offset. It is widely used in digital communication systems for channel estimation and equalization. The LS method aims to find the channel coefficients that minimize the sum of the squared errors between the received signal and the estimated signal. The received signal in the presence of a channel h and noise $w[m]$ as

$$z\left[m\right]=h\left[m\right]*a\left[m\right]+w\left[m\right], \tag{29}$$

where $z\left[m\right]$ is the received signal, $h\left[m\right]$ is the channel tap, and $a\left[m\right]$ is the transmitted symbol. The objective of the LS method is to estimate the channel tap $h\left[m\right]$ by minimizing the error between the received signal and the estimated signal. To account for noise and other errors, the LS method formulates the problem as an optimization task as

$$min_{h[m]}\sum_{m=0}^{M-1}\left|z\left[m\right]h\left[m\right]*a\left[m\right]+w\left[m\right]\right|^2. \tag{30}$$

The LS solution can be derived by setting the derivative of the objective function concerning $h[m]$ to zero. This results in the following equation

$$\hat{h}\left[m\right]=\frac{\sum_{m=0}^{M-1}a\left[m\right]^{*}z\left[m\right]}{\sum_{m=0}^{M-1}\left|a\left[m\right]\right|^2}, \tag{31}$$

where $\hat{h}$ is the estimated channel tap, $a\left[m\right]^{*}$ denotes the complex conjugate of $a\left[m\right]$, and $\left|a\left[m\right]\right|^2$ is the magnitude squared of $a\left[m\right]$.

In the context of phase offset estimation, the LS method can be applied to estimate the phase shift introduced by the channel. By minimizing the error between the received and estimated signals, the LS method effectively compensates for the phase offset. Consider the received signal with a phase offset θ as

$$r\left[m\right] = s\left[m\right] \mathrm{e}^{j\phi_i} + w\left[m\right], \tag{32}$$

where $s\left[m\right]$ is the transmitted symbol and $w\left[m\right]$ is the noise. The goal is to estimate the phase offset θ that minimizes the error. By applying the LS method, we obtain the following estimate for the phase offset as

$$\hat{\theta} = \arg\left(\frac{\sum_{m=0}^{M-1} s\left[m\right]^{*} r\left[m\right]}{\sum_{m=0}^{M-1} \left|s\left[m\right]\right|^{2}}\right). \tag{33}$$

This estimate leverages the correlation between the transmitted and received signals to determine the phase offset.

4.4.3 Conclusion

Phase offset is a significant impairment in QAM systems that can degrade communication performance. The LS method provides a robust and accurate technique for phase offset estimation by minimizing the sum of squared errors between the received and estimated signals. Despite its computational complexity and assumptions, the LS method remains a widely used approach in digital communication systems. By understanding and addressing phase offset, communication systems can achieve lower BER and improved reliability. The integration of the LS method with other synchronization techniques further enhances its performance, making it a valuable tool for modern communication systems. As communication technologies continue to evolve, ongoing research and development will be essential to refine and optimize phase offset estimation methods.

4.5 Symbol Timing Offset

4.5.1 Introduction to Symbol Timing Offset

Symbol timing offset occurs when there is a misalignment between the transmitted symbol rate and the receiver's sampling rate. This misalignment can lead to intersymbol interference (ISI) and degrade system performance. Symbol timing offset can be caused by clock drift, propagation delays, or other synchronization issues. In practical communication systems, the receiver must synchronize its sampling times with the transmitted symbols to accurately decode the received signal. Consider a received signal with a timing offset τ as

$$r(t) = s(t - \tau). \tag{34}$$

The timing offset τ causes the symbols to be sampled at incorrect times, resulting in ISI. This ISI occurs because the signal components from adjacent symbols overlap, making it difficult for the receiver to distinguish between them. The symbol timing synchronizer uses a Phase-Locked Loop (PLL) algorithm to adjust the receiver's sampling instants to align with the transmitted symbols. The PLL-based symbol timing synchronizer consists of four main components

1. Timing Error Detector (TED)

2. Interpolator

3. Interpolation Controller

4. Loop Filter

These processes work together to estimate the timing error and adjust the sampling instants accordingly.

4.5.2 Timing Error Detector (TED)

The TED estimates the timing error by comparing the in-phase (I) and quadrature (Q) components of the input signals. The TED produces an error signal that indicates whether the sampling instants are too early or too late. One common method for timing error detection is the Mueller-Muller algorithm, which is decision-directed and operates on the I and Q components. The Mueller-Muller TED computes the timing error as

$$e_k = I_k \cdot (Q_{k-1} - Q_{k+1}) + Q_k \cdot (I_{k-1} - I_{k+1}), \tag{35}$$

where I_k and Q_k are the in-phase and quadrature components of the k-th sample, respectively. The TED output e_k is used to adjust the sampling instants.

Another method is the Gardner TED, which is non-data-aided and uses the mid-point of the symbols to estimate the timing error as

$$e_k = (r_k - r_{k-2}) \cdot r_{k-1}, \tag{36}$$

where r_k is the k-th received sample. The Gardner TED is robust to noise and does not require knowledge of the transmitted symbols.

4.5.3 Interpolator

The interpolator adjusts the positions of the samples to align with the symbol boundaries. It is adaptive and determines the time delay from fixed-rate samples of the matched filter output. The interpolator uses the timing error estimate from the TED to decide how much adjustment is needed for each sample.

There are various interpolation techniques, including linear interpolation, polynomial interpolation, and spline interpolation. Linear interpolation is the simplest and fastest method, but it may not provide sufficient accuracy for high-precision applications. Polynomial and spline interpolation offers higher accuracy but at the cost of increased computational complexity.

For linear interpolation, the interpolated sample $r_{\text{int}}(t)$ can be computed as

$$r_{\text{int}}(t) = r(t_0) + (t - t_0) \cdot \frac{r(t_1) - r(t_0)}{t_1 - t_0}, \tag{37}$$

where t_0 and t_1 are the sampling instants before and after the desired time t.

4.5.4 Loop Filter

The interpolation controller adjusts the interpolation factor to ensure that the output samples align with the symbol boundaries. The interpolation factor is adjusted based on the timing error estimate from the TED. The interpolation controller determines the fraction of samples between two symbol transitions and adjusts the sampling instants accordingly.

The loop filter smooths the timing error estimate to generate a control signal for the interpolation controller. The loop filter must be designed to ensure stability and fast convergence of the timing synchronizer. A common loop filter design is the proportional-integral (PI) filter, which combines proportional and integral control to provide a balance between responsiveness and stability.

The PI filter output can be expressed as

$$v(t) = K_p \cdot e(t) + K_i \int e(t)\, dt, \tag{38}$$

where $e(t)$ is the timing error, K_p is the proportional gain, and K_i is the integral gain. The proportional term provides a direct response to the timing error, while the integral term accumulates the error over time to eliminate steady-state errors.

Optimizing the loop filter parameters is crucial for achieving the desired performance of the timing synchronizer. The loop gain K_p and phase margin ϕ_m of the filter must be carefully adjusted to balance stability and convergence speed. Increasing the loop gain improves the convergence speed but may lead to instability if the gain is too high. Conversely, reducing the loop gain enhances stability but slows down the convergence.

To optimize the loop filter parameters, one can use techniques such as root locus analysis and Bode plot analysis. These techniques help analyze the stability and frequency response of the loop filter, allowing for fine-tuning of the parameters.

4.5.5 Numerical Example

To illustrate the operation of the symbol timing synchronizer, consider a simple example with a 16-QAM system. Assume the transmitted symbols $a[m]$ are

$$a[m] = [1 + j, 1 - j, -1 + j, -1 - j], \tag{39}$$

The received signal $r[m]$ with a timing offset $\tau = 0.2T$ (where T is the symbol period) can be expressed as

$$r[m] = s[m - 0.2T] + w[m], \tag{40}$$

where $s[m]$ is the transmitted symbol and $w[m]$ is the noise.

1. **Timing Error Detection**: Using the Mueller-Muller TED, the timing error for each sample is computed. For example, if the in-phase and quadrature components are

$$I[m] = [1, 0.7, -1, -0.7], \tag{41}$$

$$Q[m] = [1, -0.7, 1, -0.7], \tag{42}$$

The timing error e_k can be calculated as

$$e_k = I_k \cdot (Q_{k-1} - Q_{k+1}) + Q_k \cdot (I_{k-1} - I_{k+1}). \tag{43}$$

2. **Interpolation**: The interpolator adjusts the sample positions based on the timing error. If the linear interpolation method is used, the interpolated sample at $t = 0.8T$ can be computed as

$$r_{\text{int}}(0.8T) = r(0.7T) + (0.8T - 0.7T) \cdot \frac{r(0.9T) - r(0.7T)}{0.9T - 0.7T}. \tag{44}$$

3. **Interpolation Control**: The interpolation controller updates the interpolation factor based on the timing error estimate, ensuring that the output samples align with the symbol boundaries.

4. **Loop Filtering**: The loop filter smooths the timing error estimate, generating a control signal for the interpolation controller. The PI filter output is computed as

$$v(t) = K_p \cdot e(t) + K_i \int e(t)\,dt, \tag{45}$$

where K_p and K_i are chosen to balance responsiveness and stability.

The performance of the symbol timing synchronizer can be evaluated using metrics such as timing error variance, bit error rate (BER), and convergence speed. The timing error variance quantifies the deviation of the sampling instants from the ideal symbol boundaries. A lower timing error variance indicates better synchronization. The BER measures the accuracy of symbol detection, with a lower BER indicating better performance. Convergence speed refers to the time it takes for the timing synchronizer to achieve stable synchronization. Faster convergence speeds are desirable for real-time communication systems.

4.5.6 Conclusion

The symbol timing synchronizer is a critical component in digital communication systems, ensuring accurate alignment of the receiver's sampling instants with the

Table 1: Symbol Timing Synchronizer Performance Metrics

Metric	**Description**
Timing Error Variance	Deviation of sampling instants from symbol boundaries
Bit Error Rate (BER)	Accuracy of symbol detection
Convergence Speed	Time to achieve stable synchronization

transmitted symbols. The PLL-based algorithm, consisting of the Timing Error Detector (TED), interpolator, interpolation controller, and loop filter, provides a robust solution for symbol timing synchronization.

By addressing symbol timing offset, communication systems can achieve lower bit error rates and improved overall performance. The choice of interpolation technique and optimization of loop filter parameters are key factors in the effectiveness of the timing synchronizer. As communication technologies continue to evolve, ongoing research and development will be essential to refine and enhance symbol timing synchronization techniques, ensuring reliable and high-performance communication systems [51].

CHAPTER V

PERFORMANCE ANALYSIS

5.1 Introduction

The performance of wireless communication systems is critical to ensure reliable and efficient data transmission. In recent years, RIS have emerged as a revolutionary technology, capable of dynamically manipulating electromagnetic waves to enhance signal propagation and reception. This chapter delves into a comprehensive performance analysis of RIS-assisted systems, juxtaposed with traditional relay-assisted systems employing AF and DF protocols. The focus is on the Bit Error Rate (BER) performance of these systems under various scenarios and conditions, derived from rigorous simulations. Furthermore, this analysis will consider the impact of QAM imperfections [51], including frequency offset, phase offset, and symbol timing offset, which are pivotal in real-world communication systems.

Wireless communication systems are the backbone of modern connectivity, supporting a myriad of applications from mobile communications to internet services. The advent of RIS technology presents an innovative approach to improving these systems. RIS consist of large arrays of passive elements that can reflect and refract incoming signals in a controlled manner, thereby optimizing the propagation environment. This capability makes RIS a promising candidate for future wireless networks, potentially replacing or augmenting traditional relay systems [3, 4].

Relay systems have been a cornerstone in enhancing wireless communication by extending coverage and improving signal quality. AF and DF are two primary relaying techniques used in these systems. In AF relaying, the relay node amplifies the received signal and retransmits it to the destination, without decoding the signal. This method is relatively simple and requires minimal processing power at the relay. In contrast, DF relaying involves decoding the received signal at the relay, re-encoding it, and then transmitting it to the destination. While DF relaying can mitigate noise and errors introduced in the first transmission hop, it requires more complex processing and introduces a delay due to the decoding and encoding process [43].

This chapter will explore the performance of these three systems RIS-assisted, AF relay-assisted, and DF relay-assisted—through [44, 45, 46] a series of simulations. The simulations are conducted under three distinct scenarios to provide a comprehensive understanding of the system's performance under varying conditions. The distances between the source (S), relay (R), and destination (D) nodes are varied to reflect different practical deployment scenarios.

5.1.1 Key Scenarios and Parameters

In evaluating the performance of the RIS-assisted, AF relay-assisted, and DF relay-assisted systems, three distinct scenarios were considered to reflect practical deployment conditions

1. Scenario 1: $d_{SR} = 180$ m and $d_{RD} = 20$ m In this scenario, the source and relay are placed far apart, while the relay and destination are close. This setup is typical in urban environments where relays are deployed to enhance coverage in areas with poor direct line-of-sight between the source and destination. The significant distance between the source and relay necessitates robust signal propagation mechanisms to ensure effective communication.

2. Scenario 2: $d_{SR} = 100$ m and $d_{RD} = 100$ m This scenario represents an equidistant setup where the source, relay, and destination form a linear chain with equal distances between each pair of nodes. Such configurations are common in suburban areas where relays are strategically positioned to extend the coverage of a base station evenly. The balanced distances facilitate a symmetrical

analysis of the relay systems' performance.

3. Scenario 3: $d_{SR} = 20$ m and $d_{RD} = 180$ m Here, the source is close to the relay, and the relay is far from the destination. This scenario is relevant in rural or remote areas where a relay is used to bridge a significant distance to the destination. The proximity of the source and relay ensures strong signal reception at the relay, while the long relay-to-destination distance tests the relay's capability to maintain signal integrity over extended ranges.

The modulation schemes employed in the simulations were Binary Phase-Shift Keying (BPSK) and 4-QAM. BPSK, known for its simplicity and robustness, is suitable for low-data-rate applications and offers resilience against noise. In contrast, 4-QAM provides higher data rates by transmitting two bits per symbol but is more susceptible to noise and other impairments [6, 29].

5.2 Comparative Analysis of BER with MATLAB Figures

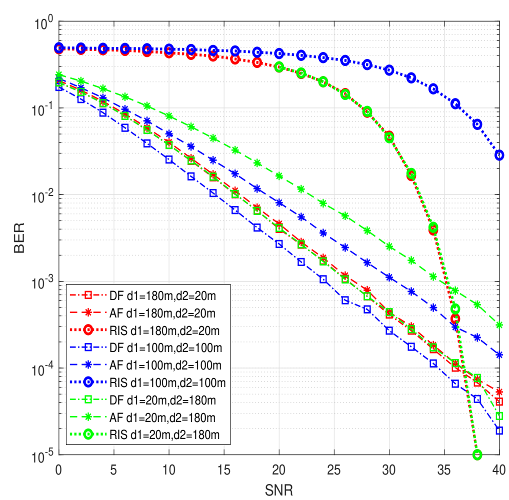

Figure 3: AF/DF vs 324-RIS for 4.25 GHz with BPSK

Observation: The MATLAB Fig. 3 reveals that the RIS-assisted system outperforms AF and DF relay systems after the number of RIS elements exceeds 324 and the SNR is greater than 35 dB. This performance advantage is attributed to the RIS's ability to manipulate the propagation environment dynamically, enhancing signal strength and reducing interference. However, the RIS advantage diminishes when positioned at the midpoint between the source and destination. This reduction in performance is primarily due to increased path loss, as the RIS must account for the combined distances between the transmitter to RIS and RIS to the receiver.

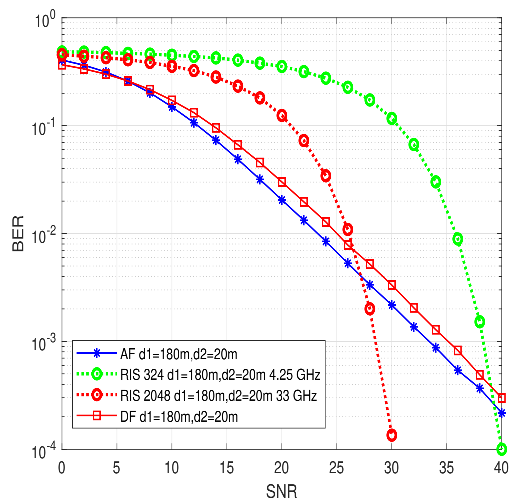

Figure 4: AF/DF vs RIS according to midpoint positioning with 4-QAM coherent system.

Observation: The MATLAB Fig. 4 highlights the significant impact of increasing the number of reflecting elements on the BER at positions near the receiver. For 2048 elements, the RIS-assisted system operates efficiently at a higher carrier frequency, demonstrating RIS' adaptability to different operational frequencies. This comparison underscores the substantial improvement in performance with the increase in RIS elements, particularly when the RIS is positioned near the receiver. The enhanced performance is due to the RIS's ability to focus and direct the signal more effectively, minimizing path loss and maximizing signal strength [7, 44].

5.3 Path Loss Considerations and Far-Field Analysis

Path loss is a crucial factor influencing the performance of wireless communication systems. The study provides detailed path loss (PL) calculations for RIS-enhanced systems, indicating that performance can vary significantly based on the positioning of RIS relative to the transmitter and receiver.

5.3.1 Far-Field Formula for RIS

The distinction between far-field and near-field is determined by

$$D = \frac{2A_D^2}{\lambda}, \tag{46}$$

where D is the distance from the transmitter/receiver to the center of the antenna array, A_D is the largest dimension of the antenna array, and λ is the wavelength. When RIS elements are within the far-field, the spherical wave can be approximated as a plane wave, simplifying the analysis.

5.3.2 Path Loss Formula in Far-Field

The path loss formula in the far-field can calculated as

$$P_{L_{\mathrm{FF}}} = \frac{(G_t G_r M N d_x d_y)^2 \cos\theta_t \cos\theta_r A^2}{16\pi^2 (d_t d_r)^2}, \tag{47}$$

where d_t and d_r are the distances from the transmitter and receiver to the RIS centre, M and N are the numbers of RIS elements along the x and y axes, and d_x and d_y are the dimensions of the RIS elements. This formula indicates that path loss is higher when the RIS is positioned in the middle, leading to performance degradation observed in the MATLAB figure (Fig. 3). The combined distance in path loss calculations for RIS-aided systems can result in higher path loss compared to relay-aided systems, especially when the RIS is positioned at the midpoint.

Unlike relay systems, where the signal is actively processed and amplified, the path loss for RIS-aided systems considers both the distances between the transmitter to RIS and between RIS to the receiver. This combined distance can lead to higher path loss, particularly when the RIS is positioned in the middle. In contrast, AF relay systems experience less degradation at this point due to the active amplification of the signal, which helps mitigate some of the path loss effects [24].

5.3.3 Conclusion

The performance analysis reveals several key insights

RIS-Assisted Systems These systems demonstrated superior performance with increasing RIS elements, particularly in high SNR scenarios and specific positional arrangements. However, performance degradation occurs at the midpoint due to the combined path loss from the transmitter to RIS and RIS to the receiver. The ability of RIS to dynamically manipulate the signal propagation environment offers significant advantages, but optimal placement is crucial to minimize path loss effects.

Relay Systems (AF and DF) These systems showed consistent performance across different scenarios, with AF relay systems experiencing less degradation at the midpoint compared to RIS systems. The active signal processing and amplification in AF relays help maintain signal integrity over longer distances, making them more robust in certain deployment conditions.

The MATLAB figures provide critical visual insights into the performance comparison, reinforcing the numerical results and highlighting the effectiveness of RIS technology in enhancing wireless communication performance. Future research could focus on optimizing RIS placement to further mitigate path loss effects and enhance overall system efficiency. Additionally, the impact of QAM imperfections—such as frequency offset, phase offset, and symbol timing offset—on system performance will be explored in subsequent sections to provide a more comprehensive analysis. These factors are critical in real-world scenarios, where perfect synchronization and signal alignment are challenging to achieve, and their impact on BER and overall system performance must be thoroughly understood [24].

5.4 QAM Imperfection Analysis

5.4.1 Figure Frequency Offset in RIS

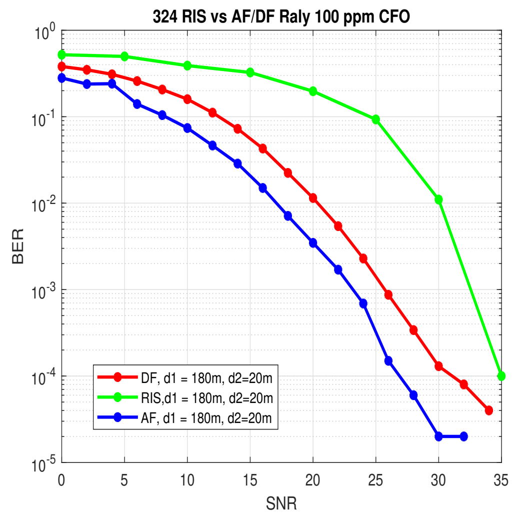

Figure 5: AF/DF vs RIS comparison with 100 ppm CFO.

Title and Description

- **Title**: Frequency Offset in RIS
- **Description**: This figure illustrates the frequency offset in RIS systems, emphasizing how deviations in frequency can impact signal quality.

Axes Information

- **X-Axis**: SNR (dB)
- **Y-Axis**: BER

Data Analysis

- **Trends**: The frequency offset graph displays how the signal frequency deviates over time or under various conditions.

- **Observations**: Significant deviations observed in the QAM signal constellation indicate the presence of imperfections, such as amplitude and phase noise, that can detrimentally impact signal integrity. These distortions can lead to increased bit error rates and reduced system capacity. While the CFO performance of the RIS system closely approximates that of traditional AF/DF relay systems when considering QAM offset estimations, the figure reveals a more pronounced sensitivity of the RIS system to QAM imperfections in terms of CFO. This suggests that the impact of QAM-related impairments on the overall system performance is amplified in RIS-based communication systems. Consequently, effective mitigation strategies for QAM imperfections are essential to optimize the performance and reliability of these systems.

- **Implications**: These frequency offset imperfections can cause inter-symbol interference in QAM, which detrimentally affects data transmission quality.

5.4.2 Figure Symbol Timing in RIS vs AF/DF Relay with 4.25GHz

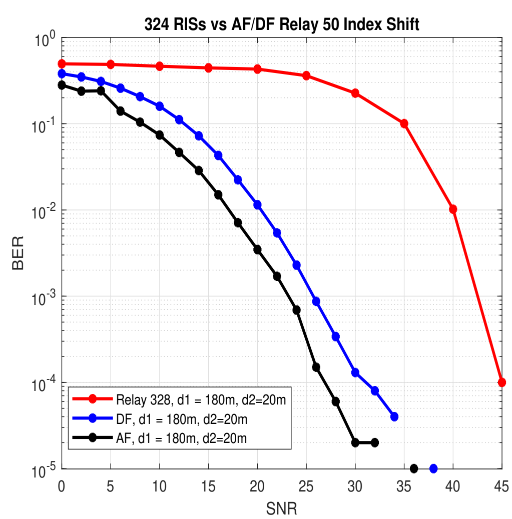

Figure 6: AF/DF vs RIS comparison with symbol timing offset.

Title and Description

- **Title**: Symbol Timing in RIS at 30dB and 4.25GHz

- **Description**: This figure depicts the accuracy of symbol timing in RIS systems under an SNR of 30dB and a frequency of 4.25GHz, showcasing timing synchronization performance.

Axes Information

- **X-Axis**: SNR (dB)

- **Y-Axis**: BER

Data Analysis

- **Trends**: The symbol timing plot demonstrates the precision with which the RIS maintains symbol timing.

- **Observations**: Variations in symbol timing within the QAM signal are indicative of timing jitter and other imperfections that can adversely affect signal quality. These timing discrepancies introduce inter-symbol interference (ISI), which can degrade system performance by increasing bit error rates. When comparing the impact of symbol timing offset on RIS and traditional AF/DF relay systems, based on CFO and QAM offset estimations, the figure reveals a more pronounced performance degradation for the RIS system. This suggests that RIS systems are more sensitive to symbol timing imperfections compared to their relay-aided counterparts. Consequently, effective timing synchronization techniques are crucial to mitigate the negative effects of symbol timing offset on RIS-based communication systems.

- **Implications**: Imperfect symbol timing in QAM can lead to errors during symbol demodulation, thereby reducing the reliability of the communication system.

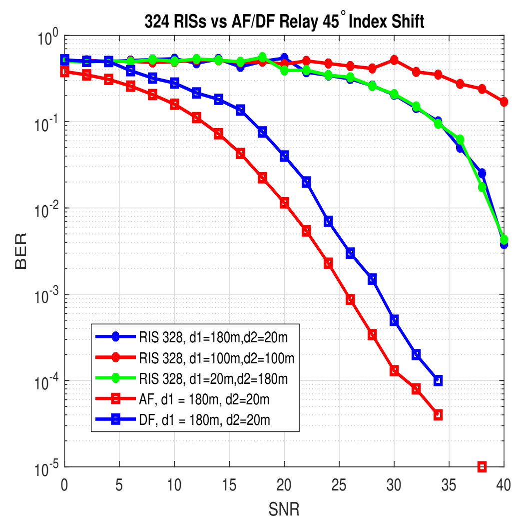

Figure 7: AF/DF vs RIS comparison with 45^o phase offset.

5.4.3 Figure Phase Response of RIS Under Three Conditions

Title and Description

- **Title**: Phase Response of RIS Under Three Conditions
- **Description**: This figure illustrates the phase response of RIS systems under three distinct conditions, showing how the phase changes and adapts accordingly.

Axes Information

- **X-Axis**: SNR (dB)
- **Y-Axis**: BER

Data Analysis

- **Trends**: The phase response graph reveals how the phase varies over time or under different conditions.
- **Observations**: Significant phase deviations observed in the QAM signal constellation indicate the presence of phase noise and other impairments that can

compromise signal integrity. These phase errors can lead to increased bit error rates and reduced system performance. Notably, the RIS system exhibits the most severe performance degradation due to phase offset compared to traditional AF/DF relay systems when considering other offset estimations. This suggests a higher sensitivity of RIS systems to phase imperfections. However, it's important to note that the RIS system demonstrates performance characteristics similar to those of an ideal QAM system in terms of CFO, highlighting the system's resilience to this specific impairment.

- **Implications**: Phase imperfections can induce phase noise in QAM, leading to distortions in the constellation points and degrading overall signal quality.

5.5 *Comparative Analysis RIS vs. Relay Techniques in Terms of QAM Imperfections*

5.5.1 Frequency Offset

- **RIS** Frequency offset imperfections in RIS can be significant due to the reconfigurable nature and varying conditions of the intelligent surfaces.

- **Relay Techniques** Traditional relay techniques generally exhibit more stable frequency characteristics due to fixed hardware and less dynamic conditions.

5.5.2 Symbol Timing

- **RIS** Symbol timing imperfections in RIS may arise from dynamic surface adjustments, causing timing jitter and inaccuracies.

- **Relay Techniques** Relay techniques typically maintain more stable timing characteristics due to fixed and well-established signal processing methods.

5.5.3 Phase Response

- **RIS** Phase imperfections in RIS are prominent due to the adaptive nature of the surfaces, resulting in phase noise and constellation distortions in QAM.

- **Relay Techniques** Relay techniques usually display more stable phase characteristics, thereby reducing phase noise and enhancing QAM signal integrity.

5.5.4 Conclusion

- **RIS Advantages** RIS offers flexibility and dynamic reconfiguration, which can be advantageous in specific scenarios. However, it introduces imperfections in frequency offset, symbol timing, and phase response, affecting QAM signal quality.

- **Relay Advantages** Traditional relay techniques provide more stable and predictable signal characteristics, resulting in superior QAM performance in terms of frequency stability, symbol timing accuracy, and phase noise reduction.

This comparison highlights the trade-offs between RIS and relay techniques, particularly concerning QAM signal imperfections. Relay techniques may be preferable for applications requiring high QAM fidelity, whereas RIS offers flexibility and adaptability benefits [51].

CHAPTER VI

CONCLUSIONS

6.1 Introduction

The comparative assessment of RIS and relaying techniques with QAM imperfections presented in this thesis offers a nuanced understanding of the potential and limitations of these emerging technologies in modern wireless communication systems. The findings underscore the transformative impact of RIS technology on enhancing signal propagation, mitigating channel impairments, and improving overall system performance [44, 45, 46].

Wireless communication systems are the backbone of the modern digital world, enabling a myriad of applications from simple voice calls to complex data transfers supporting the IoT and smart city infrastructure. As the demand for higher data rates, better signal quality, and broader coverage grows, traditional cellular and wireless network architectures face significant challenges. These challenges include capacity limitations, signal degradation, and coverage gaps, particularly in rural or geographically challenging areas and at higher frequencies such as millimeter waves (mmWave). Innovative solutions are required to address these issues and ensure the efficient and reliable transmission of information [28, 29].

6.1.1 RIS

RIS represent a cutting-edge approach to addressing these challenges. RIS consists of large arrays of passive, low-cost, and programmable reflecting elements, often referred to as meta-atoms or meta-elements. Each element can independently adjust the phase and amplitude of the incident electromagnetic waves. By collectively tuning these elements, RIS can shape the reflected wavefronts to achieve desired communication objectives, such as enhancing signal strength at the receiver, mitigating interference, or redirecting signals to avoid obstacles.

The fundamental principle behind RIS operation is its ability to dynamically control the propagation environment. Traditional wireless communication systems are often constrained by the fixed nature of the physical environment, leading to suboptimal signal transmission and reception. In contrast, RIS technology uses reconfigurable passive elements that can dynamically adjust their electromagnetic responses, thereby shaping the propagation environment to enhance signal quality, coverage, and overall system capacity [8, 9, 10].

6.1.2 Relaying Techniques

Relaying techniques, such as AF and DF, have been extensively employed to extend coverage and improve the reliability of wireless communication. In AF relaying, the relay node amplifies the received signal before retransmitting it, while in DF relaying, the relay node decodes the received signal, processes it, and then retransmits it. These techniques exploit the broadcast nature of wireless signals and create a virtual antenna array through cooperating nodes, thereby improving coverage and reliability. However, these methods also introduce additional complexity and potential delays due to the active signal processing involved [34, 35].

6.1.3 QAM Imperfections

QAM is a widely used modulation scheme in digital communication systems due to its high spectral efficiency. However, QAM systems are susceptible to various imperfections that can degrade performance. These imperfections include CFO, Timing Offset, and Phase Noise. CFO occurs when there is a discrepancy between the transmitter and receiver oscillator frequencies, leading to a rotation of the QAM constellation and potential symbol misinterpretation. Timing Offset is the misalignment of symbol timing between the transmitter and receiver, resulting in ISI. Phase Noise refers to random phase fluctuations in the transmitted signal, causing distorted constellation points.

Traditional relaying techniques like AF and DF address signal weakness but can introduce additional noise and distortions. RIS technology, on the other hand, offers a promising alternative by intelligently reflecting signals. This approach can potentially mitigate channel impairments without introducing noise amplification [51].

6.1.4 Comparative Analysis

The core of this thesis is a comparative analysis between RIS-enhanced dual-hop transmission schemes and conventional relaying techniques, specifically AF and DF. The comparison is based on key performance metrics such as BER and path loss. The findings convincingly demonstrate that RIS-assisted communication outperforms traditional relaying methods in terms of BER performance. Notably, DF relays consistently outperform AF relays in both far-field and near-field scenarios when coupled with RIS technology. This observation underscores the efficacy of RIS in facilitating line-of-sight (LOS) communication systems.

The research presented in this thesis employs a comprehensive model to analyze the impact of RIS configurations, including surface element positioning and quantity, on BER performance. Various scenarios, from modest deployments to large-scale applications with 2048 elements for mmWave and 328 elements for Wi-Fi bandwidth, are considered. This detailed analysis provides valuable insights into the scaling behavior of RIS technology for different deployment scenarios and frequency bands [25].

6.1.5 Energy Efficiency and Cost-Effectiveness

One of the significant advantages of RIS technology is its energy efficiency. Unlike traditional active components, RIS are passive devices that do not require continuous power for signal processing, making them highly energy-efficient. This characteristic is particularly valuable in scenarios where power resources are limited, such as in remote sensing applications or the deployment of sustainable communication networks. Furthermore, the integration of RIS into existing infrastructure offers a cost-effective solution for enhancing network performance without extensive modifications.

6.1.6 Potential Applications

The potential applications of RIS technology are vast and varied. In cellular networks, RIS can enhance coverage in urban areas with high building density by mitigating signal blockages and enhancing coverage in shadowed regions. In WLANs (Wi-Fi), RIS can optimize signal propagation within indoor environments, directing signals towards areas with poor coverage and enhancing signal strength. In satellite communications, RIS can improve signal propagation through the atmosphere and mitigate the effects of attenuation, leading to better performance in satellite-based services such as internet connectivity and global positioning systems (GPS). In IoT networks, RIS can ensure consistent connectivity and performance in challenging environments with varying propagation conditions.

6.2 Future Research Directions

The findings of this thesis open several avenues for future research and development. Advanced optimization algorithms that leverage machine learning techniques could be developed to predict and adapt to changing channel conditions more effectively. Integrating RIS technology with other emerging technologies, such as mmWave communication, massive MIMO, and IoT, could unlock new possibilities for enhancing network capacity, coverage, and efficiency. Experimental validation in real-world scenarios is essential to corroborate the theoretical and simulation-based findings. Security and privacy considerations related to RIS deployment should be explored to protect against potential vulnerabilities. Finally, the development of standardization and regulatory frameworks will be crucial to ensure interoperability and facilitate widespread adoption.

6.3 Conclusion

In conclusion, this thesis provides a thorough exploration of the potential and limitations of RIS and relaying techniques in modern wireless communication systems. The findings highlight the superior performance of RIS in mitigating channel impairments and improving BER, demonstrating its promise for revolutionizing wireless communication. As wireless systems evolve towards 5G and beyond, RIS technology, coupled with ongoing research and development, will play a pivotal role in addressing the growing demands for high data rates, low latency, and reliable connectivity. The insights gained from this research provide a solid foundation for the continued exploration and optimization of RIS technology, paving the way for the next generation of wireless communication systems [26, 27].

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