ROUTING IN MIMO WIRELESS X NETWORKS USING ALTERNATE RELAYING AND SIGNAL ALIGNMENT

by

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Submitted in partial fulfillment of the requirements
for the degree of Master of Applied Science

at

Dalhousie University
Halifax, Nova Scotia
December 2023

For Taliyah

you are a reminder of the beauty that exists in the world.

Table of Contents

List of Figures

Abstract

This thesis investigates the enhancement of Multiple-Input Multiple-Output (MIMO) wireless networks using an X-type topology with one-way data transfer. In this configuration, two nodes transmit data to two receivers, mimicking the structure of an 'X', with a single relay initially and then two relays at the intersecting point. Originally limited to a half-duplex operation due to the constraints of a solitary relay, our research aims to enable full-duplex system functionality by introducing two half-duplex relays that operate in alternate time slots. Our approach to achieving full-duplex capability and doubling the system throughput involves implementing advanced signal processing algorithms. These techniques include opportunistic listening, signal alignment, and refined antenna design algorithms at the system level. A key innovation in our study is the application of virtual MIMO processing at the receivers, which combines opportunistic listening and relay transmissions into a unified process. This is achieved by doubling the number of receive antennas only at the receivers. We apply concepts from physical layer network coding and signal alignment, alongside specialized precoding methods, adapted for the two-relay setup. The integration of these advanced transceiver and relay strategies results in a comprehensive solution for enhancing bandwidth efficiency and ensuring effective data transmission in contemporary wireless communication networks.

List of Abbreviations and Symbols Used

AF	amplify-and-forward
ANC	analog network coding
AWGN	additive white Gaussian noise
BC	broadcast
BER	bit error rate
BPSK	binary phase shift keying
CDMA	code division multiple access
CR	cognitive radio
CRN	cognitive radio network
CSI	channel state information
DF	decode-and-forward
FEC	forward error control
IA	interference alignment
IC	interference channel
i.i.d	independent identically distributed
MAC	medium access control
MAI	multiple access interference
MATLAB®	mathematical laboratory
MIMO	multiple-input multiple-output
MMSE	minimum mean square error
ML	maximum likelihood
MU-MIMO	multi-user multiple-input multiple-output
NC	network coding
PNC	physical network coding
PU	primary user
QAM	quadrature amplitude modulation
SA	signal alignment
SISO	single-input single-output

SNR	signal-to-noise ratio
SU	secondary user
TDMA	time division multiple access
TS(s)	time slot(s)
TSER	ternary symbol error rate
TWRC	two-way relay channel
WCDMA	wideband code division multiple access
WLAN	wireless local area network
WN	wireless network
WSN	wireless sensor network
XOR	exclusive or
ZF	zero-forcing

Acknowledgements

I would like to express my heartfelt gratitude to Dr. Ilow for his unwavering support and guidance throughout my thesis journey. Your expertise, patience, and encouragement have been instrumental in helping me navigate the challenges and complexities of this research. Your dedication to my success is greatly appreciated, and I am fortunate to have had the opportunity to work under your mentorship.

I would also like to extend my deepest thanks to my parents Jila Shams and Javad Hoseyni for their support, both emotional and academic. Your belief in me has been my constant motivation. I am profoundly grateful for your love and guidance.

My thanks go as well to Fahiq Kohistani. Your sacrifices did not go unnoticed and it is one of the root causes that made this academic achievement possible.

This thesis represents not only my hard work but also the collective efforts of all those who have supported me. Thank you for being a part of this significant milestone in my academic journey.

Chapter 1

Introduction

Digital wireless communication has revolutionized how we connect and share information. Within that field, Multiple-Input Multiple-Output (MIMO) systems have attracted increased attention due to their characteristics such as spatial diversity, increased capacity, and enhanced reliability [1, 2, 3]. These features are especially important today, as the major increase in wireless data traffic demands higher transmission rates and more robust systems. One of the early efforts in MIMO was oriented towards systems with direct communications between the transmitter and receiver. The work by Park et al. [1] and Behbahani et al. [2] showed the potential for these systems. Over time, relaying techniques were introduced to further boost system performance.

Relaying techniques, as demonstrated by Zhou et al. [3] and Su et al. [4], are used where direct links are weak or non-existent. However, there are numerous challenges in relaying strategies, e.g., achieving interference-free transmission while maintaining the intended spatial diversity [5, 6]. Alhumaidi et al. worked on alternate AF MIMO relaying systems that offered solutions to counter inter-relay interference [7, 8] and Rong et al. [9] proposed a framework to optimize linear nonregenerative multicarrier MIMO relay communication systems. These advancements saw significant improvements in both theory and mathematical modeling. Other important contributors to the field of MIMO systems include Brualdi [10], Serre [11], Coleman and Pothen [12], and Leon et al. [13].

Despite these advances, enormous challenges persist, especially with full-duplex systems [14, 15]. Work conducted by Chen et al. [16] and Park and Alouini [17] has helped optimize MIMO relaying, but there is still room for improvement, especially in terms of routing in full-duplex MIMO wireless networks. Rankov and Wittneben's work on spectral efficient protocols [18] and the capacity analysis by Shende et al. [19] highlight the potential of full-duplex systems.

The evolution of wireless communication systems has been strongly influenced by advancements in relay networks and MIMO systems. The development of efficient beamforming strategies, as investigated by [20], has played a critical role in enhancing the performance of two-way relay networks. These strategies are essential for realizing the full potential of MIMO systems in terms of throughput and signal quality.

The degrees of freedom in MIMO systems, especially in complex configurations like the MIMO Y Channel, are another important aspect of modern communication systems. In [21], the authors explore signal space alignment and its impact on network coding for optimizing the use of available spectral resources. In [22], the authors investigate the real-world applications and benefits of theoretical advancements in wireless network coding. XOR-based network coding techniques have revolutionized the way wireless networks handle data, leading to more efficient and robust communication systems. Furthermore, the spectral efficiency of relay channels in fading environments, as discussed by the authors in [23], highlights the challenges of maintaining high-quality communication in all conditions. These studies represent a significant body of work supporting the theoretical and practical advancements in relay networks and MIMO systems.

The present thesis aims to address some key research gaps in full-duplex MIMO wireless networks. Along with establishing a novel routing mechanism optimized for full-duplex systems, this research incorporates the principles of alternate relaying and signal alignment to ensure efficient and interference-free transmissions in X wireless networks. "X networks" are so-called due to their distinctive topology, which resembles the shape of the letter "X". This unique arrangement offers specific advantages for data routing and communication by providing redundancy and fault tolerance. These features make X networks a good choice for applications where robustness and efficient data transmission are essential. The remainder of Chapter 1 includes a review of fundamental principles that are investigated in this work, with more detailed explanations presented in Chapter 2. Section 1.10 provides a listing of the objectives and organization of this thesis.

1.1 Physical Layer Network Coding

In digital communication, the demand for high data rates, improved spectral efficiency, and reduced latency continues to grow. To address these challenges, researchers have introduced Physical Layer Network Coding (PLNC), which is a technique that enables simultaneous transmission and reception of information. This section explores the concept of PLNC, highlighting its significance, benefits, and applications in digital communication.

1.1.1 PLNC Overview and Key Features

1. Overview: Physical Layer Network Coding is a technique that allows network nodes to simultaneously transmit and receive information in a single wireless channel, merging the traditionally separate tasks of transmission and reception. By exploiting the characteristics of wireless channels, PLNC eliminates the need for traditional store-and-forward relaying protocols, leading to significant improvements in throughput and efficiency.

2. Key Features and Benefits: a) Simultaneous Transmission and Reception: PLNC enables network nodes to transmit their own data simultaneously while receiving data from other nodes. This simultaneous operation eliminates the need for separate time slots for transmission and reception, improving spectral efficiency and reducing latency. b) Two way Communication: PLNC utilizes full-duplex communication, allowing nodes to recover signals of interest without interference. This capability enhances the overall throughput and efficiency of the communication system. c) Enhanced Network Performance: By merging multiple transmission and reception in a single channel, PLNC reduces the number of transmissions and eliminates the need for multiple relaying, leading to improved network performance, reduced packet delays, and increased overall capacity.

In the conventional non-NC scheme (Fig. 1.1(a)), terminal A and terminal B each require one time slot to send a packet to the relay, and the relay needs two time slots to broadcast both packets. The exchange of two packets between the two terminals therefore necessitates four time slots.

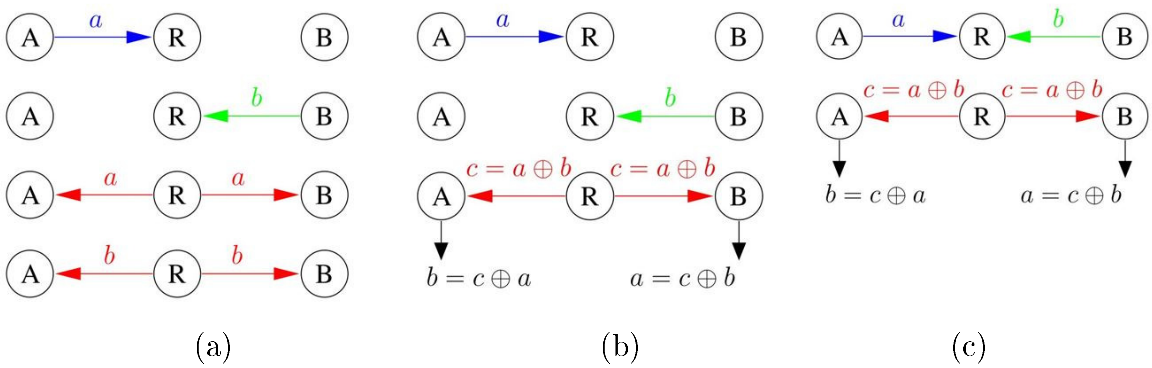

Figure 1.1: (a) Traditional non-NC vs. (b) Traditional NC vs. (c) PNC.

Figure 1.1(b) illustrates that this data exchange can be achieved in three time slots using network coding. After terminals send their packets independently to the relay in two time slots, the relay employs the NC technique, combining (exclusive OR [XOR] in bit level) the received two packets and broadcasting the combined packet in the third time slot. The terminals receive the same combined packet, but each of them can decode the packet using their own transmitted one.

Employing physical-layer network coding (PNC) or analog NC (ANC) allows the process of exchanging data between A and B in just two time slots, as shown in Fig. 1.1(c). Terminals A and B simultaneously transmit their packets to the relay, which performs over-the-air addition of the packets. The relay then re-broadcasts the mixed (or XORed representation of) packet it receives. The terminals recover their data of interest by XOR-ing the received data with their own data, similar to the NC technique.

1.1.2 PLNC Techniques

1. XOR-Based Network Coding: One of the techniques employed in PLNC is XOR-based network coding. In this technique, network nodes combine incoming signals using the XOR operation. The XORed result is then transmitted over the channel, allowing other nodes to extract the initially transmitted information through XOR operations. XOR-based network coding has been extensively studied and demonstrated to improve network performance.

2. Other Network Coding Schemes: While XOR-based network coding is commonly used, other more advanced network coding schemes have been proposed in PLNC. These schemes use linear or non-linear operations to perform network coding at the physical layer based on signal processing as opposed to bit processing in NC. The result is significant improvements in throughput, error resilience, and complexity reduction.

1.2 Half-Duplex and Full-Duplex Wireless Communication

Two fundamental transmission modes that play a crucial role in wireless communication are half-duplex and full-duplex. The following sections explore the concepts of half-duplex and full-duplex, highlighting their differences, advantages, and applications in digital wireless communication.

1.2.1 Half-Duplex Communication

1. Overview: Half-duplex communication refers to a transmission mode in which information can be sent or received, though not simultaneously. In a half-duplex system, the communication channel alternates between transmitting and receiving modes, allowing data to flow in one direction at a time. In the context of system operation in this thesis, the term *half-duplex system operation* is used to describe a scenario where the sender transmits only in alternate time slots. During the intervening slots when the sender is not active, it does not engage in listening and remains silent. In theory, this arrangement allows the sender to transmit continuously over time, using every other slot for transmission.

2. Key Features and Operation: a) Time-Division Duplex (TDD): Half-duplex communication uses the Time-Division Duplex (TDD) technique, where the available frequency band is divided into separate time slots. During one time slot, the transmitter sends data; during another, the receiver listens and receives data. This switching between transmit and receive modes allows half-duplex communication.

3. Advantages and Applications: a) Simplicity: Half-duplex communication systems are generally more straightforward in design and implementation than

full-duplex systems. This simplicity leads to cost savings, making half-duplex communication suitable for applications with limited resources or lower data rate requirements. b) Walkie-Talkies and Two-Way Radios: Half-duplex communication is commonly used in walkie-talkies and two-way radios, where users take turns speaking and listening. These devices typically operate in push-to-talk mode, allowing users to switch between transmit and receive modes.

1.2.2 Full-Duplex Communication

1. Overview: Full-duplex communication enables simultaneous transmission and reception of data in both directions within the same frequency band. Unlike half-duplex, full-duplex allows for concurrent bidirectional communication, opening up possibilities for higher throughput and increased efficiency. In the context of our work, *full-duplex operation* implies that senders are transmitting data continuously and receivers are receiving data at all times.

2. Key Features and Operation: a) Frequency-Division Duplex (FDD): Full-duplex communication typically uses the Frequency-Division Duplex (FDD) technique, where separate frequency bands are allocated for transmitting and receiving. This allocation enables simultaneous transmission and reception without interference. b) Self-Interference Cancellation: One of the critical challenges in full-duplex communication is managing self-interference caused by simultaneous transmission and reception. Sophisticated signal processing techniques and hardware designs are used to cancel or minimize self-interference, enabling successful full-duplex operation.

3. Advantages and Applications: a) Higher Throughput: Full-duplex communication offers the potential for significantly higher throughput compared to half-duplex. By enabling simultaneous transmission and reception, full-duplex systems maximize the utilization of available resources, leading to increased data rates and improved spectral efficiency. b) Wireless Local Area Networks (WLANs): Full-duplex communication has applications in WLANs, enhancing the overall network capacity, particularly in scenarios with high data traffic. Full-duplex WLANs can accommodate bidirectional data flows, allowing faster

file transfers and multimedia streaming. c) Cellular Networks: Full-duplex communication enables increased capacity and improved efficiency. Cellular networks can enhance spectral efficiency, reduce latency, and improve user experience by implementing full-duplex operation at base stations and user devices.

1.2.3 Hybrid-Duplex Communication

In specific scenarios, hybrid-duplex communication combines elements of both half-duplex and full-duplex modes.

In half-duplex communications, transmission, and reception occur on the same frequency channel, but not simultaneously. This means that devices can transmit or receive information on a channel at different times. When a device wants to transmit data, it first checks whether the channel is available. If it is, the device can transmit its data. However, if the channel is busy, the device must wait until it is available before transmitting. This method of communication is used in two-way radios, walkie-talkies, and some wireless sensor networks.

In full-duplex communication, transmission, and reception occur on different frequency channels, allowing for simultaneous transmission and reception of data. This means that devices can transmit and receive data at the same time without having to wait for the channel to become available. In full-duplex communication, the transmission and reception frequencies are separated by a frequency offset that allows them to be used simultaneously. This method of communication is commonly used in cellular networks, Wi-Fi networks, and other wireless communication systems.

The advantages of full-duplex communication include faster data transfer, improved network efficiency, and reduced latency. However, full-duplex communication also requires more complex hardware and signal-processing algorithms to reduce levels of self-interference, which can limit its practical application in specific scenarios. Overall, the choice between half-duplex and full-duplex communication depends on the application's specific requirements, such as the need for simultaneous transmission and reception, the available bandwidth, and the level of complexity and cost of the hardware and signal processing algorithms.

1.3 Half-Duplex Physical Layer Routing

Efficient routing in wireless digital communication is crucial to ensure reliable and timely data transmission. Half-duplex Physical Layer Routing (PLR), as investigated in this thesis, uses channel diversity and half-duplex constraints to enhance the performance of wireless networks [19]. The following sections explore the concept of half-duplex PLR, highlighting its significance, benefits, and applications in wireless digital communication.

1.3.1 Half-Duplex PLR Overview and Key Features

1. Overview: Half-duplex PLR is a routing technique that combines physical layer characteristics with routing and processing decisions to optimize data transmission in wireless networks. Instead of relying solely on network-layer routing protocols, half-duplex PLR uses wireless channel features, such as channel fading and spatial diversity, to improve network performance.

2. Key Features and Operation: a) Channel Diversity Exploitation: Half-duplex PLR takes advantage of channel diversity by selecting appropriate transmission paths based on the characteristics of wireless channels. By exploiting the fading nature of different channels, this approach maximizes the overall network throughput and minimize packet loss. b) Half-Duplex Constraint: Half-duplex PLR operates under the constraint that nodes can transmit or receive data at any given time, but not simultaneously. This constraint necessitates careful routing decisions to ensure efficient data transmission and minimize collisions.

3. Advantages and Benefits: a) Increased Network Throughput: Half-duplex PLR uses channel diversity to increase network throughput by dynamically selecting the best transmission paths. Utilizing multiple paths and choosing the most favorable ones based on channel conditions can lessen interference and improve overall network performance. b) Energy Efficiency: Half-duplex PLR can optimize energy consumption by selecting transmission paths that require lower energy expenditure. It can minimize energy consumption and prolong network lifetime by considering channel conditions and node capabilities.

1.4 MIMO and Virtual MIMO

The sections below present the main concepts of MIMO and its virtual counterpart, Virtual MIMO, highlighting their significance, benefits, and applications in digital communication.

1.4.1 MIMO Technology

1. Overview: MIMO technology utilizes multiple antennas at both the transmitter and receiver to improve system performance by exploiting the multipath propagation in wireless channels. By using the spatial domain, MIMO enables increased capacity, reliability, and data rates.

2. Key Features and Benefits: a) Spatial Multiplexing: MIMO allows the simultaneous transmission of multiple data streams, thereby increasing the data rate and spectral efficiency. This is achieved by transmitting independent data streams using different antennas, which are then received and decoded by corresponding antennas at the receiver. b) Diversity Gain: MIMO provides diversity gain by using the independent fading characteristics of multiple antennas. It lowers the effects of fading and improves the system's reliability and robustness. c) Beamforming: MIMO enables beamforming, which uses multiple antennas to focus the transmitted signal energy in a specific direction. This leads to improved signal quality, extended coverage, and reduced interference.

3. Applications of MIMO: MIMO technology is applied in various wireless communication systems, as explained below. a) Wireless LANs (Wi-Fi): MIMO is widely used in Wi-Fi standards (such as 802.11n, 802.11ac, and 802.11ax) to achieve higher data rates, better coverage, and improved overall performance. b) Cellular Networks: MIMO is used in 4G LTE and 5G cellular networks, as it enables higher data rates, increased capacity, and better spectral efficiency. c) Wireless Sensor Networks: MIMO can be employed in sensor networks to improve communication reliability and extend network coverage.

1.4.2 Virtual MIMO

Virtual MIMO is an innovative approach that uses multiple devices to create a virtual MIMO system, even in scenarios where physical MIMO hardware is unavailable. This approach is based on cooperative communication techniques that combine signals from multiple devices, as in traditional MIMO systems. In virtual MIMO, devices work collaboratively to enhance system performance, with each device acting as an individual antenna, transmitting its signal, while other devices receive and process these signals to improve reception quality. This technique offers benefits such as improved coverage and reliability by extending coverage range through cooperation, increased data rates through simultaneous transmission of multiple data streams, and the potential for localization and tracking applications by utilizing spatial information from multiple cooperating devices.

MIMO and virtual MIMO technologies have revolutionized digital communication by using the spatial dimension of wireless channels. MIMO offers higher data rates, improved reliability, and increased capacity, while virtual MIMO offers MIMO benefits without physical MIMO hardware. Both technologies can be applied across various wireless communication systems, driving advancements in Wi-Fi, cellular networks, and wireless sensor networks.

1.5 Single Link MIMO Processing

This section presents the mathematical underpinnings for signal recovery through matrix inversion (also called Zero-Forcing processing) in the single user (SU-MIMO) setup. In SU-MIMO, as visualized in Fig. 1.2, all the T transmit antennas are co-located at the single transmitter and all the R receive antennas are in the single receiver in the same location. The channel gain coefficients h_{ij} represent the channel gains from the j-th transmit antenna to the i-th receive antenna. The transmitted signal x_i from the i-th transmit antenna represents the data stream d_i.

The signal received on the i-th receive antenna is denoted by $Y_i(t)$. For R receive antennas, the received signals can be represented as $Y_1(t)$, $Y_2(t)$, $\ldots$, $Y_R(t)$. In our work, we use $R = T = N$ received signals to obtain the estimated transmitted signals $\tilde{x}_1(t)$, $\tilde{x}_2(t)$, $\ldots$, $\tilde{x}_N(t)$ from mixing in the channel.

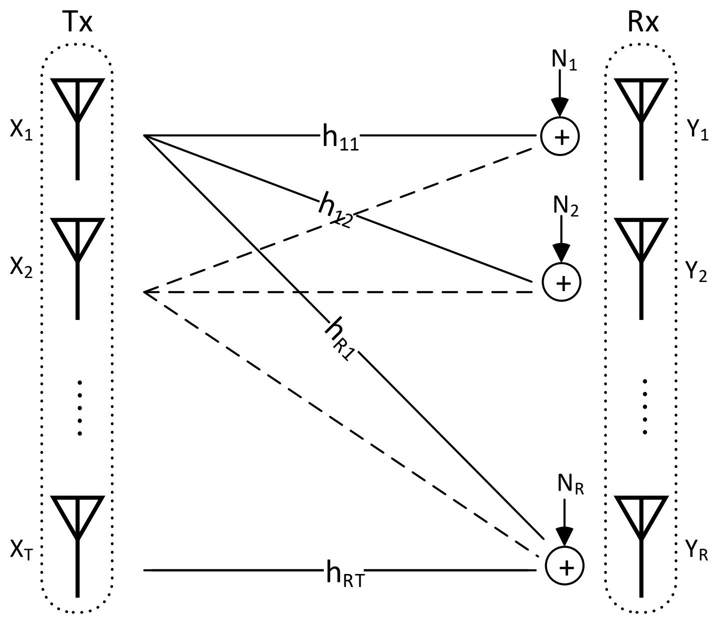

Figure 1.2: Single User MIMO Channel Model.

Once we have $\tilde{x}_1(t)$, $\tilde{x}_2(t)$, ..., $\tilde{x}_N(t)$, we recover at the receiver $d_1(t)$, $d_2(t)$, ..., $d_N(t)$, which are N spatial streams of data.

In single user MIMO, we have a single transmitter equipped with T antennas and a single receiver equipped with R antennas, as visualized in Figure 1.2. To cover N spatial streams so that each transmits from the j-th antenna, the transmitter would be able to send a data stream at the same time and in the same frequency band, ensuring that $T = R = N$.

If h_{ij} represents the channel gain from transmit antenna j to receive antenna i, then the signal $y_i(t)$ received on the i-th antenna is:

$$y_i(t) = \sum_{j=1}^{N} h_{ij}\tilde{x}_j(t) + n_i(t) \tag{1.1}$$

where n_i is the AWGN (Additive White Gaussian Noise) representing noise in the i-th antenna. We then have N received signals, and after dropping the time indexing, the matrix form representation for N-lines equation like in (1.1) is:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1N} \\ h_{21} & \cdots & h_{2N} \\ \vdots & \ddots & \vdots \\ h_{N1} & \cdots & h_{NN} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix} = \mathbf{H}_{N\times N} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix} \tag{1.2}$$

where $\mathbf{H}_{N\times N}$ is referred to as the channel gain matrix. If $\mathbf{H}_{N\times N}$ is invertible and $\mathbf{H}_{N\times N}$ knowledge is available at the receiver, using zero-forcing post-processing of receivers, the signal of interest about the N spatial data streams can be recovered from the received signals using matrix inversion, as follows:

$$\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \vdots \\ \hat{x}_N \end{bmatrix} = \mathbf{H}_{N\times N}^{-1} \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} + \mathbf{H}_{N\times N}^{-1} \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix} \tag{1.3}$$

This Z-F processing is used in this thesis in various configurations, despite its known problems such as noise enhancements. In addition to Single User MIMO link processing, we will work with transmit antennas being distributed between two senders (source and relay) and receive antennas being at the single destination, referred to as virtual MIMO.

1.6 MIMO X Channel Model

The MIMO X channel model represents a wireless communication scenario involving four users and a relay station. In this setup, there are four user nodes, denoted as A, B, X, and Y. These user nodes have one-way communications through a relay station R. This model enables concurrent communication between users in two primary phases: the Medium Access Control (MAC) phase and the Broadcast (BC) phase. As shown in 1.3, transmitter A wants to send data to receiver X, and transmitter B wants to send data to receiver Y. However, there is no line of sight between them, so the system uses a relay R to send data from A to X and from B to Y. A and Y, as well as B and X, have a line of sight and can engage in opportunistic listening, which we use in signal detection.

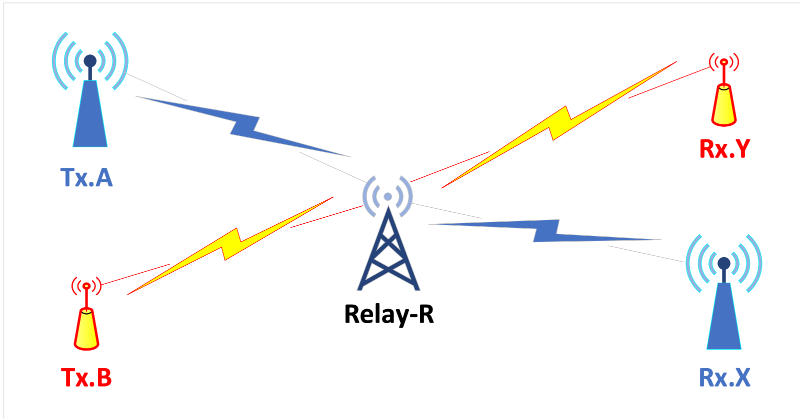

Figure 1.3: X Channel MIMO Model.

1.6.1 MAC Phase

During the MAC phase, the four users exchange messages. Each user processes its messages by utilizing carefully designed precoding vectors. These precoding vectors serve the purpose of aligning messages from the same source-destination pair within specific dimensions in the signal space. This alignment is important for ensuring efficient and organized communication. The aligned dimensions in this phase can be referred to as $\mathbf{D}_{ij}$, where i and j represent the source and destination user pairs, respectively. Achieving this alignment involves the multiplication of channel gain matrices $\mathbf{H}_{R,k}$ and corresponding precoding vectors $\mathbf{v}_{l,k}$, with k representing the relay station. These aligned dimensions guarantee that messages from each source user are transmitted to their destination users.

1.6.2 BC Phase

During the BC phase in a multi-user communication scenario, a relay station generates a composite signal that includes network-coded data from all four user pairs. This signal is broadcast to all users in a single time slot. To ensure that each user extracts only the required information from this broadcast, specific signal processing techniques are employed at the relay station. These techniques involve careful manipulation of the broadcast signal so that each user can decode their message, mainly through XOR operations. The process is similar to the MIMO X channel strategy but manages four users and a relay station. It eliminates unwanted signals at each user node, ensuring that only the necessary data are received.

In the MIMO X channel model, the extension to four users and a relay station allows for more complex bidirectional communication. The Multiple Access (MA) phase focuses on aligning and transmitting messages, while the BC phase enables simultaneous broadcasting. This ensures that each user receives only the data meant for them.

1.7 Alternate Relaying in SISO Wireless Communication

Wireless communication, is continuously evolving to meet the ever-increasing demand for improved network performance. In this section, we present the "Alternate Relaying Concept", which is an approach designed to enhance the efficiency and reliability of SISO wireless relay communication. Additionally, this concept aims to address conventional relay challenges, reduce latency, and optimize network resource utilization.

The Alternate Relaying Concept helps to mitigate the constraints usually associated with traditional half-duplex single relay systems, such as having to switch between transmit and receive modes. In the single relay, the Alternate Relaying Concept uses two half-duplex relays so that the source can continuously transmit and the destination can continuously receive. This approach enhances spectral efficiency, lowers latency, and improves overall network performance.

Single relay half-duplex operations are presented in Figure 1.1. As shown, the Alternate Relaying Concept involves allocating relay nodes to alternate between transmit and receive modes. Figure 1.4 illustrates a simplified alternate relay system operating in one-way mode, comprising a single transmitter (Tx), one receiver (Rx), and two relays, R_1 and R_2, operating in alternating time slots. During time slot n, R_2 is set to receive mode to accept data from transmitter A, while R_1 is in transmit mode, sending data to receiver X. In the subsequent time slot, $n + 1$, R_2 shifts to transmit mode and R_1 switches to receive mode. This setup allows the system to continuously transmit and receive data in every time slot.

In a multi-node network, each relay node switches between these modes in a synchronized manner. During the transmit phase, relay nodes forward data to the destination nodes. In alternately aligned time slots, this utilization of spatial diversity doubles the throughput over half-duplex relay. In the receive phase, the same relay nodes actively listen for incoming signals from the source nodes, ensuring readiness to receive data.

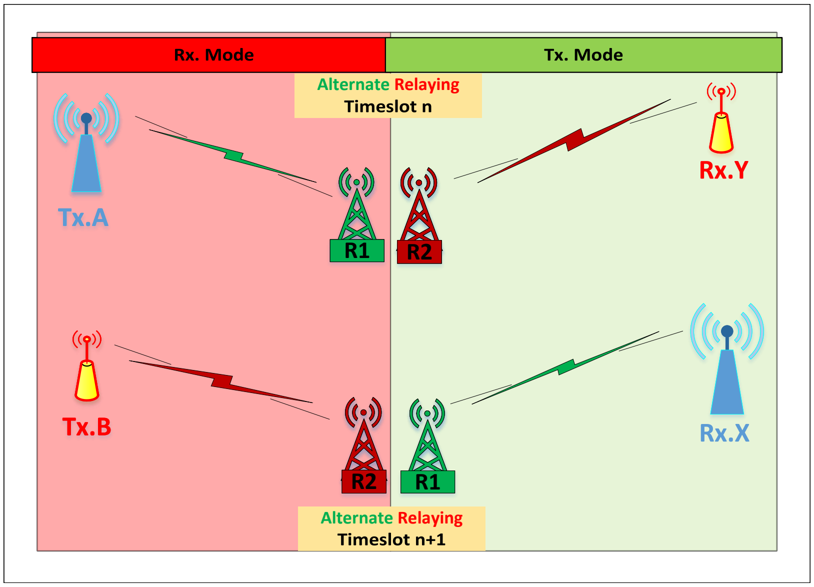

Figure 1.4: Alternate Relaying System.

Adopting the Alternate Relaying Concept has several advantages, such as:

- Enhanced Throughput: Simultaneous transmission and reception provides higher data rates and improved spectral efficiency.
- Reduced Latency: Relay nodes can respond to incoming data immediately, minimizing transmission delays and reducing end-to-end latency.
- Resource Efficiency: The concept optimizes relay node utilization, making better use of available network resources.
- Scalability: The Alternate Relaying Concept is adaptable to networks of varying sizes and complexities, ensuring scalability.

Despite these significant benefits, adopting the Alternate Relaying Concept also involves some challenges, including efficient interference management, synchronization mechanisms, and practical implementation issues. Future research in this area should prioritize the development of advanced interference cancellation techniques, synchronization methods, and real-world deployment strategies.

In conclusion, the Alternate Relaying Concept advances SISO wireless relay communication by strategically alternating relay nodes between transmit and receive modes. In so doing, it improves throughput, reduces latency, and enhances overall network performance. While challenges persist, research and development in this area (including the work conducted in the present thesis) shows the potential to realize the full benefits of this concept.

1.8 Signal Alignment and Preceding Matrices

In relay digital communication, precoding matrices play a crucial role in improving the reliability and capacity of the communication system by exploiting different signalling dimensions. Precoding involves applying a matrix operation at the transmitter to optimize the transmitted signals based on the channel conditions [24]. In this context, a precoding matrix is used to linearly transform the transmitted signals to achieve specific objectives, such as maximizing the signal power, minimizing interference, or increasing the diversity gain by multiplexing. Precoding is employed in relay communication systems to reduce interference. By using the channel state information (CSI) available at the transmitter, precoding matrices optimize the transmitted signals based on the channel characteristics.

Precoding matrices are used to achieve various objectives in relay digital communication, including Diversity Gain, Interference Mitigation, and Capacity Precoding, as explained below: a) Diversity Gain: Precoding can exploit channel diversity by applying appropriate matrix transformations. This enhances the robustness of the communication system against fading and improves the reliability of the transmitted signals. b) Interference Mitigation: Precoding matrices can minimize the interference caused by simultaneous transmissions or co-channel interference. Overall system performance is improved by shaping the transmitted signals to nullify or suppress interfering signals. c) Capacity Precoding techniques can increase the communication system's capacity by optimizing the transmitted signals. By exploiting the available degrees of freedom, such as multiple antennas or relays, precoding matrices can improve the achievable data rates.

Precoding techniques can also be used in relay communication, depending on the specific system requirements and objectives. Various precoding techniques are frequently employed in relay digital communication. Some commonly used precoding techniques include Zero-Forcing Precoding and Maximum Rate Transmission, as explained below: a) Zero-Forcing (ZF) Precoding: ZF precoding aims to eliminate interference at the receiver by designing the precoding matrix to ensure zero interference at specific antennas. ZF precoding can achieve interference-free transmission but may introduce noise enhancement. b) Maximum Ratio Transmission (MRT): MRT precoding maximizes the received signal power at the destination by aligning the transmitted signals with the channel's dominant eigenmodes. This technique uses the channel's spatial characteristics to maximize the received signal quality.

However, implementing precoding matrices in relay digital communication systems poses challenges, such as Channel Estimation and Complexity, as explained below: a) Channel Estimation: Accurate channel estimation is critical for designing effective precoding matrices. Estimating the channel state information at the transmitter and relay nodes may require dedicated pilot signals or feedback mechanisms. b) Complexity: Precoding techniques may involve complex matrix operations, which can increase the computational complexity and implementation overhead. Efficient algorithms and hardware architectures are necessary to handle the computational requirements.

For optimizing transmitted signals, precoding matrices are crucial in relay digital communication systems. These matrices are designed to achieve various objectives, such as enhancing diversity gain, lessening interference, and increasing capacity. With the advancement of precoding techniques, relay communication systems can achieve higher reliability, improved spectral efficiency, and increased data rates. However, the challenges of accurate channel estimation and complexity must be addressed to ensure efficient implementation of precoding matrices in practical relay digital communication systems.

1.9 Inter-Relay Interference (IRI) in Wireless Relay Communication

Inter-Relay Interference (IRI) is an ongoing issue in wireless relay communication, occurring when multiple relay nodes interfere with each other's transmissions. IRI degrades signal quality, lowers throughput, and impacts network performance. In our work, we focus on other aspects and do not directly address IRI. Some of the mitigation techniques are as follows:

- **Spatial Separation:** Deploy relay nodes further apart to reduce IRI.
- **Interference Coordination:** Synchronize relay transmissions using time, frequency, or power control.
- **Advanced Antennas:** Use smart or directional antennas to focus transmissions and minimize interference.
- **Network Coding:** Combine relay transmissions strategically to reduce IRI.
- **Cognitive Radio:** Dynamically adapt transmission parameters to avoid interference.

Although this thesis does not directly address IRI cancellation in the system under study, it does occur in our system, so deploying IRI mitigation techniques is an essential part of the proposed design.

1.10 Thesis Contributions and Outline

Our work fills a significant gap in the existing literature and provides a foundation for subsequent research in the field. The main contributions of this thesis are as follows:

1. **Methodological Framework**: Presents a mathematical framework that enables better signal alignment in a 2-D space at the relays, which has the potential to optimize the performance of MIMO Full-Duplex systems.
2. **Virtual MIMO Data Detection**: Introduces a novel approach for decoding received signals in a MIMO Full-Duplex system that utilizes the concept of Virtual MIMO and accounts for the time-varying nature of the full-duplex system.
3. **Null Space Data Separation and Detection**: Develops an innovative approach to separating and detecting signals in the null space. This provides an additional degree of freedom for improving performance and enhancing the system's resistance to co-channel interference.

4. **BER Performance**: Contributes to the literature by offering a comprehensive BER performance evaluation of MIMO Full-Duplex systems in AWGN channels, thus providing guidelines for future implementations.

Overview of Subsequent Chapters

In Chapter 2, we will explore the existing relay communication system, focusing on Physical-Layer Network Coding (PLNC) and opportunistic listening. The applied scenarios feature a single relay operating in half-duplex mode during even time slots, utilizing XORed representation of data from senders A and B.

Sections 2.2, 2.3, and 2.4 investigate SISO and MIMO half-duplex operations. The chapter introduces a half-duplex wireless relay communication system operating in two time slots for communication between transmitters A and B, and receivers X and Y via relay R, designed for scenarios lacking line-of-sight. It provides details on operations in odd and even time slots, extending to MIMO configurations with spatial diversity and precoding techniques for enhanced performance and increased data rates. Mathematical formulas are also provided to describe signal propagation, interference cancellation, and data recovery processes. Signal representation emphasizes scalar signals x^A, x^B, y^X, and y^Y, and introduces yRR for relay reception and s^R for relay transmission.

In Chapter 3, a scenario is introduced where transmitters A and B use a single antenna to achieve continuous transmission by utilizing two relays with single antenna operating in half-duplex mode. In complementary time slots, relays transmit and receive, achieving a full-duplex operation as initially presented in Chapter 2, section 2.1. Additionally, Chapter 3 introduces a SISO full-duplex wireless relay communication system involving transmitters A and B, receivers X and Y, and relays R1 and R2. The objective is to transmit data from A to X and from B to Y through relays, considering non-line-of-sight conditions. The system employs Binary Phase Shift Keying (BPSK) modulation, and precoding is implemented to achieve unit channel gains at relays.

Section 3.1 discusses the theoretical foundation for the system's operation, which involves single antennas for transmitters A and B and relay R, and two antennas each for receivers X and Y. In this section, our design merges opportunistic listening and reception of relay data into a single phase virtual MIMO. This builds on the framework outlined in section 2.3, with adjustments to the number of receiving antennas at both receivers. Section 3.2 assesses the system's performance through simulation studies. The proposed system maintains the operation during the Medium Access base time slot, as explained in section 2.3, now incorporating two relays, R1 and R2. Like section 2.3, R1 receives data during odd time slots, while R2 receives Physical-Layer Network Coding (PLNC) data during even time slots. This configuration, with each element using only one antenna, doubles the system's throughput compared to the previous model.

In Chapter 4, we introduce system design and signal processing into the MIMO Full-Duplex Alternate Relays System Operation, building on concepts from previous chapters. This MIMO configuration features two transmit antennas at nodes A and B, two receive/transmit antennas at relays R_1 and R_2, and two receive antennas at nodes X and Y. The purpose in this design is to better utilize spatial diversity and obtain higher data rates. The system architecture and underlying assumptions are explained in subsequent subsections.

An important aspect of the full-duplex alternate relays system is its incorporation of the virtual MIMO technique. During odd time slots, transmitter A, relay R2, and receiver Y collaborate to form a 4×4 virtual MIMO configuration, from the perspective of receiver Y. Transmitter B, relay R1, and receiver X establish another 4×4 virtual MIMO structure. This is to replace opportunistic listening time slots in half-duplex operation. In the MAC phase, when A and B transmit continuously either to R_1 (in odd time slots) or to R_2 (in even time slots), the signal alignment is the same as in Chapter 2 but with specialized precoding matrices.

The virtual MIMO concept enables, during odd time slots, transmitter A and relay R2 to function as the MIMO transmitter with a total of four antennas (two each), while receiver Y, with four antennas, acts as the MIMO receiver. The roles are reversed in even time slots, involving transmitter B, relay R2, and receiver X. This dynamic configuration, involving the exchange of roles between relays R1 and R2, characterizes the full-duplex alternate relays system.

Chapter 2

Half-Duplex Operation of X Networks

This chapter examines the existing relay communication system and reviews work pertinent to our study. Specifically the chapter describes a half-duplex wireless relay communication system that operates in two time slots to enable communication between transmitters A and B and receivers X and Y, via a relay R. The system is designed for scenarios where there is no line of sight between A and X, and B and Y.

In our work, the signal from A can reach Y and the corresponding signal from B can reach X, where Y is the designated receiver for transmitter B. During odd time slots, transmitters A and B send precoded data to relay R while receivers X and Y listen to the transmitted signals. During even time slots, relay R uses the received precoded data from odd time slots to detect transmitted symbols, combining them and transmitting the combination to receivers X and Y. Receivers X and Y use opportunistic listening to recover the transmitted symbols from both transmitters and the relay.

The current research related to PLNC (Physical Layer Network Coding) and opportunistic listening focuses on scenarios where a single relay operates in a half-duplex mode, forwarding information during even time slots. It involves the XORed representation of the data received from senders A and B.

Section 2.2 examines SISO operations, specifically those involving sender A and B transmitting only one stream during the Medium Access Control (MAC) phase. Sections 2.3 and 2.4 explain the SISO and MIMO half-duplex, respectively, while section 2.4 presents a system description of MIMO configurations, where multiple antennas are used at each node. Additionally, it outlines the signal processing steps for odd and even time slots, including signal reception, precoding, decoding, and XOR operations.

2.1 Introduction

The proposed MIMO half-duplex relay communication system uses spatial diversity and precoding techniques to enhance system performance and increase data rates. The mathematical formulas express the signal propagation, interference cancellation, and data recovery processes within the system. The scalar signals sent from the sender's antenna at A and B are represented by x^A and x^B, respectively, and signals received by receivers X and Y are y^X and y^Y, respectively. Because our system has several different signals, the superscript in the signal description represents the nodes in our system model. Hence, y^R represents the signal received by the relay, while the signal transmitted by R is s^R.

The generic time index for transmitted and received signals is initially given in parentheses as (n). So, for instance, the signal received at R at n is $y^R(n)$. Later in the thesis, we drop the time index n for the sake of brevity. In this chapter, when we explain system operation, we may use time index o to represent odd time slots when transmitters A and B send the data and time index e to represent even time slots when the relay sends data.

2.2 Half-Duplex System Description

The half-duplex wireless relay communication system shown in Figure 2.1 consists of two transmitters, A and B, two receivers, X and Y, and one relay, R. The system's objective, which operates in two time slots, is to enable communication between A and X. B and Y do not have a direct communication path or are out of transmission range using the relay R. The system operates under the following combination options:

1. Line of sight does not exist between A and X or between B and Y.
2. Transmitter A sends a data stream a_1, where each data element can have a value of 0 or 1.
3. Transmitter B sends a data stream b_1, where each data element can have a value of 0 or 1.
4. Transmitter A maps the binary data to BPSK symbols $s^A(n)$, where 0 is translated to -1 and 1 is translated to $+1$ (see Appendix A for more details).

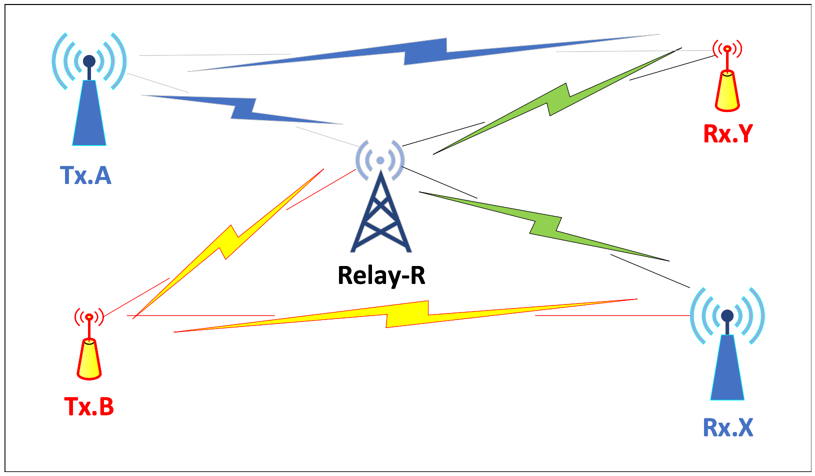

Figure 2.1: Single Relay Half-Duplex One-Way Data Transmission.

5. Transmitter B maps the binary data to BPSK symbols $s^B(n)$, where 0 is translated to -1 and 1 is translated to $+1$.

6. Transmitter A creates and transmits precoded data $x^A(n)$ from $s^A(n)$, as per (2.1):

$$x^A(n) = v^A \cdot s^A(n) \tag{2.1}$$

   Precoding is implemented to counteract the effects of channel loss.

7. Transmitter B creates and transmits precoded data $x^B(n)$ from $s^B(n)$:

$$x^B(n) = v^B \cdot s^B(n) \tag{2.2}$$

8. The precoding is used to achieve a channel gain equal to the one between the transmitter node and the receiver node:

$$h_{AR} \cdot v^A = h_{BR} \cdot v^B = 1 \tag{2.3}$$

   This equalization ensures that incoming signals from A and B reach the relay with uniform gain, enabling the relay to recover $c_1 = a_1 \oplus b_1$ for transmission. In the subscript, the first letter refers to the transmitter node and the second letter to the receiver node.

9. Receivers X and Y are in sight of B and A, respectively, and have opportunistic listening capabilities. They can receive unwanted data.

10. In odd time slots, transmitters A and B send their precoded data $x^A(n)$ and $x^B(n)$ to relay R simultaneously.

11. At the same time in odd time slots , receiver Y receives data from transmitter A, and receiver X receives data from transmitter B due to line of sight and opportunistic listening.

12. Relay R retrieves the $x^A(n) + x^B(n)$ representation of PLNC data by decoding $x^A(n)+x^B(n)$, resulting in $c_1 = a_1 \oplus b_1$. Subsequently, the relay transmits $s^R(n)$ the BPSK-modulated signal, which represents the data c_1.

13. Receiver X and receiver Y use opportunistic listening to receive the data transmitted by A and B in odd time slots. They also receive the relay's transmission in even time slots $s^R(n)$.

14. Receiver X recovers c_1 from $s^R(n)$ and b_1 from the opportunistic listening and then performs an XOR operation on these data to detect the transmitted data a_1:

$$a_1 = c_1 \oplus b_1 \tag{2.4}$$

15. Receiver Y recovers c_1 from $s^R(n)$ and a_1 from the opportunistic listening and then performs an XOR operation on these data to detect the transmitted data b_1:

$$b_1 = c_1 \oplus a_1 \tag{2.5}$$

2.3 SISO Half-Duplex System

2.3.1 System Configuration

A Single-Input Single-Output half-duplex communication system consists of two transmitters, A and B, two receivers, X and Y, and a single relay, R. This setup serves as a foundational model in wireless relay communication, providing insights into the dynamics of half-duplex communication. Transmitters A and B are the primary information sources responsible for data generation, transmission to their destinations, or relay through R. These transmitters play a key role in initializing and routing information. Receivers X and Y act as the system endpoints and are responsible for signal capture, demodulation, data decoding, and delivery to users or higher-level protocols. The performance of X and Y significantly influences overall system reliability and data integrity. The relay node R is an intermediary, receiving signals from A and B, processing them, and retransmitting them to their respective destinations.

2.3.2 Mathematical Preliminaries

The system consists of two transmitters (A and B), two receivers (X and Y), and one relay (R). It operates in half-duplex mode, meaning that the communication occurs in two different time slots: odd and even.

Odd Time Slots (MAC Phase)

In the MAC phase, two signals are received by the relay and two by the receivers x and y through the opportunistic listening taking place at the phase. The MAC phase refers to the events occurring from the relay perspective and opportunistic listening for receivers x and y.

$y^Y(n) = h_{AY} \cdot x^A(n) = h_{AY} \cdot v_a \cdot \hat{s}^A(n)$

$\hat{s}^A(n) = \frac{1}{h_{AY}} . \frac{1}{v_a} \cdot y^Y;$

hence, getting to $v_a = h_{AY}$

In the opportunistic listening phase in the receiver Y, we get $\hat{s}^A(n)$, and out of this, we get $a_1(n)$.

During odd time slots, the system functions as follows:

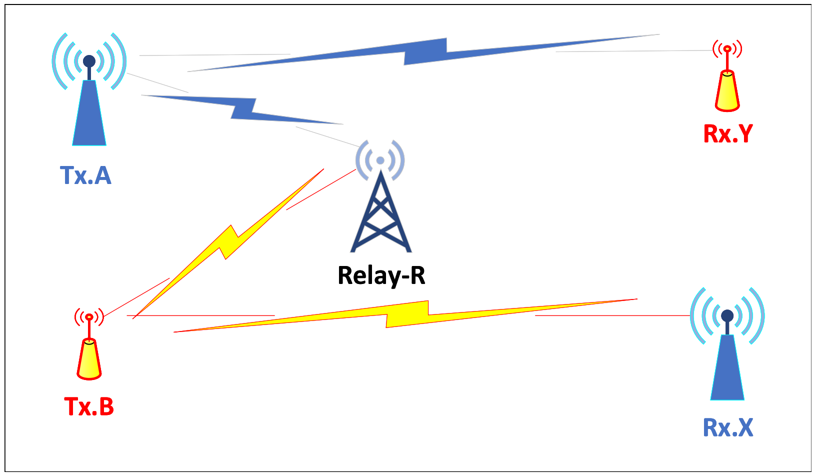

Figure 2.2: Single Relay Half-Duplex One-Way Data Transmission for Odd Time Slots.

Receiver Y

Receives data from transmitter A and additional noise:

$$y^Y(n) = h_{AY} \cdot x^A(n) + n^Y(n) \tag{2.6}$$

where h_{AY} is the channel gain, $x^A(n)$ is the transmitted signal from A, and n^Y is the noise at receiver Y.

Receiver X

Receives data from transmitter B and additional noise:

$$y^X(n) = h_{BX} \cdot x^B(n) + n^X(n) \tag{2.7}$$

where h_{BX} is the channel gain, $x^B(n)$ is the transmitted signal from B, and n^X is the noise at receiver X.

Relay R

Receives the sum:

$$y^R(n) = h_{AR} \cdot x^A(n) + h_{BR} \cdot x^B(n) \tag{2.8}$$

Even Time Slots (Broadcast Phase)

During even time slots, the system performs the following:

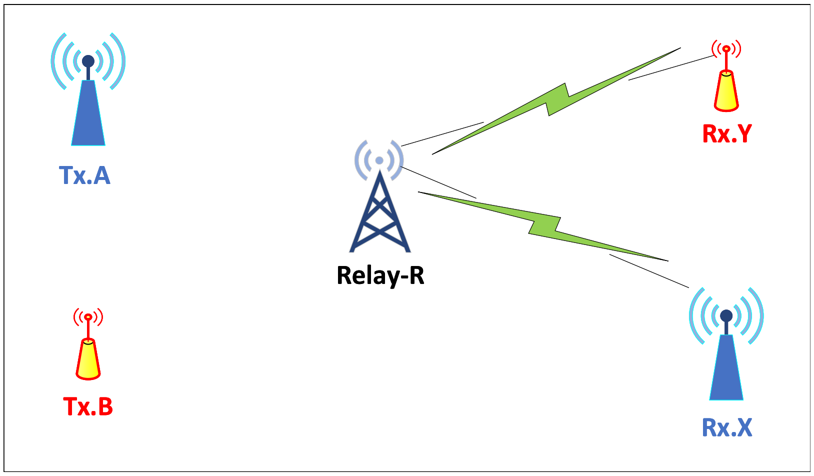

Figure 2.3: Single Relay Half-Duplex One-Way Data Transmission for Even Time Slots.

Relay R Operations

1. The relay recovers :

$$c_1 = a_1 \oplus b_1 \tag{2.9}$$

2. BPSK modulation:

   s^R represents the BPSK version of the transmitted signal, taking the value of 1 or -1. Here, the value of $s^R = 1$ corresponds to logical 1 in c_1, and the value of $s^R = -1$ corresponds to logical 0 in c_1.

3. Transmission:

$$y^X(n) = h_{RX} \cdot s^R(n) \tag{2.10}$$
$$y^Y(n) = h_{RY} \cdot s^R(n) \tag{2.11}$$

In the broadcast phase, where receiver Y receives $y^Y(n)$ by taking the inverse of h_{RY}, we recover $\hat{s}^R(n) = \frac{1}{h_{RY}} y^Y(n)$. Having $\hat{s}^R(n)$, we will get $c_1(n)$ from the receiver.

Using $c_1(n)$ during the broadcast phase and the a_1 that was received in the MAC phase through opportunistic listening, we can utilize the combined information to detect the desired data b_1.

Receiver X

In this process, X receives the relay's transmission plus noise:

$$y^X(n) = h_{RX} \cdot s^R(n) + n^X(n) \tag{2.12}$$

where h_{RX} is the channel gain, $s^R(n)$ is the relay's BPSK-modulated signal, and n^X is the noise at receiver X.

1. Recovering c_1:

$$c_1 = \text{function of } y^X(n) \tag{2.13}$$

2. XOR with b_1:

$$a_1 = c_1 \oplus b_1 \tag{2.14}$$

Receiver Y

The same process will be executed at the receiver Y.

2.4 MIMO Half-Duplex System

In this section, we extend the analysis of the previous SISO system to the MIMO case in half-duplex relay communication systems with opportunistic listening. The MIMO configuration involves multiple antennas at each transmitter and receiver, enabling the system to exploit spatial diversity and achieve higher data rates. The system architecture and combination options remain the same as described in the previous section.

In the MIMO version of the scheme presented in sections 2.1 to 2.3, we have two-bit streams a_1 and a_2 sent from A, and two-bit streams b_1 and b_2 sent from B. The bit streams a_1 and a_2 are represented after BPSK +1 and -1 mapping as s_1 and s_2. After the signals are processed through coding, they leave the two antennas at A are x_1 and x_2.

Similar notations apply to the signals at transmitter B. Because of the MIMO character of the system in this chapter, the signal leaving transmitter A is given through the variable

$$\mathbf{x}^A = \begin{bmatrix} x_1^A \\ x_2^A \end{bmatrix} \tag{2.15}$$

The boldfacing indicates that we are dealing with a column vector of size 2×1.

2.4.1 System Overview

- Transmitters A and B each send two spatial data streams, denoted by a_1, a_2 and b_1, b_2, respectively.
- Receivers X and Y each have two antennas and are able to receive the data using the MIMO concept.
- Transmitters A and B map the binary data to BPSK symbols.
- Relay R facilitates communication by receiving, decoding, and forwarding the signals.

The MIMO half-duplex relay communication system consists of two transmitters (A and B) equipped with multiple antennas and two receivers (X and Y) that are also

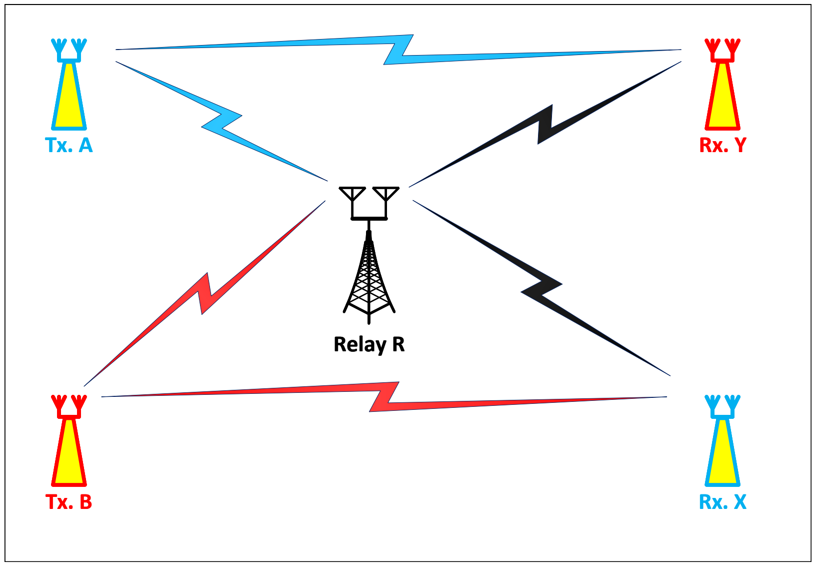

Figure 2.4: MIMO Single Relay Half-Duplex One-Way Data Transmission for Odd/Even Time Slots.

equipped with multiple antennas. The relay, R, has multiple antennas as well. The system operates in two time slots to enable communication between A and X and B and Y, utilizing the relay R.

The following combination options apply to the MIMO system:

1. A and B communicate with X and Y, respectively, where no line of sight exists between A and X or B and Y.

2. Transmitter A sends two data streams, denoted by a_1 and a_2, where each data element can have a value of 0 or 1.

3. Transmitter B sends two data streams, denoted by b_1 and b_2, where each data element can have a value of 0 or 1.

4. Transmitter A maps the binary data to BPSK symbols $\mathbf{s}^A$, where the vector component 0 is translated to -1 and 1 is translated to $+1$.

$$\mathbf{s}^A = \begin{bmatrix} s_1^A \\ s_2^A \end{bmatrix} \tag{2.16}$$

5. Transmitter B maps the binary data to BPSK symbols $\mathbf{s}^B$, where the vector component 0 is translated to -1 and 1 is translated to $+1$.

$$\mathbf{s}^B = \begin{bmatrix} s_1^B \\ s_2^B \end{bmatrix} \tag{2.17}$$

6. Transmitter A creates and transmits precoded data $\mathbf{x}^A$ from $\mathbf{s}^A$ using precoding matrix $\mathbf{V}^A_{2x2}$. where

$$\mathbf{x}^A = \mathbf{V}^A \cdot \mathbf{s}^A$$

7. Transmitter B creates and transmits precoded data $\mathbf{x}^B$ from $\mathbf{s}^B$ using precoding matrix $\mathbf{V}^B_{2x2}$. where

$$\mathbf{x}^B = \mathbf{V}^B \cdot \mathbf{s}^B$$

8. Precoding is used to exploit the spatial diversity and enhance the overall channel capacity.

9. Receivers X and Y have multiple antennas and employ opportunistic listening to receive data from A and B as well as the relay's transmission.

10. In odd time slots, transmitters A and B simultaneously send their precoded data $\mathbf{x}^A$ and $\mathbf{x}^B$ to the relay R.

11. Receiver Y $[a_1 \quad a_2]$ receives data from transmitter A and receiver X receives data $[a_1 \quad a_2]$ from transmitter B, due to line-of-sight and opportunistic listening.

12. Relay R receives the two data streams from A and B, which will comprise the vector format:

$$\mathbf{y}^R = \mathbf{H}_{AR} \cdot \mathbf{x}^A + \mathbf{H}_{BR} \cdot \mathbf{x}^B \tag{2.18}$$

    This is equivalent to (2.8) in SISO case. Based on y_1^R and y_2^R in $\mathbf{y}^R$, the relay recovers PLNC representations for c_1 and c_2 which are given by $c_1 = a_1 + b_1$ and $c_2 = a_2 + b_2$. How this is accomplished is discussed in detail in Section 2.4.3 and Appendix B.

13. In even time slots, relay R transmits $\mathbf{s}^R$ the BPSK representation of c_1 and c_2:

$$\mathbf{s}^R = \begin{bmatrix} s_1^R \\ s_2^R \end{bmatrix} \tag{2.19}$$

14. Knowing $[b_1, b_2]$ from step 11 (opportunistic listening in odd time slots) and from the relay's transmission receiving c_1 and c_2 in even time slots, receiver X calculates the data of interest as follows:

$$a_1 = c_1 \oplus b_1 \tag{2.20}$$

$$a_2 = c_2 \oplus b_2 \tag{2.21}$$

15. Knowing $[a_1, a_2]$ from step 11 (opportunistic listening in odd time slots) and from the relay's transmission receiving c_1 and c_2 in even time slots, receiver Y calculates the data of interest as follows:

$$b_1 = c_1 \oplus a_1 \tag{2.22}$$

$$b_2 = c_2 \oplus a_2 \tag{2.23}$$

The MIMO half-duplex relay communication system uses the advantages of spatial diversity and precoding techniques to enhance system performance. The utilization of multiple antennas at each transmitter and receiver, combined with the Decode-and-Forward strategy, enables efficient data transmission and reception, thereby improving the overall communication reliability and capacity.

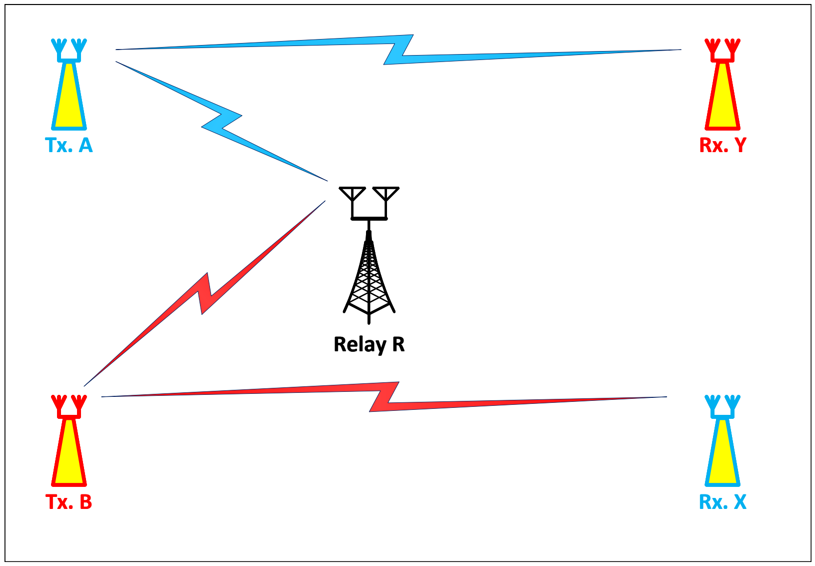

Figure 2.5: MIMO Single Relay Half-Duplex for Odd Time Slots.

2.4.2 Mathematical Preliminaries

This section presents more detailed explanation for MIMO half-duplex system operation.

Transmitter A

Transmitter A transmits two spatial bit streams, a_1 and a_2. Both are modulated using BPSK, where they are represented by -1 and +1:

$$s_1^A = \{-1, +1\} \text{ for } a_1 \tag{2.24}$$

$$s_2^A = \{-1, +1\} \text{ for } a_2 \tag{2.25}$$

Precoded data:
Precoding matrices are used to align transmitted data (a_1, a_2, b_1, b_2) along two spatial (MIMO) dimensions that the relay can recover using two receive antennas. With the precoding matrix V^A, the actual vector signal X^A leaving antennas at transmitter A is:

$$\mathbf{x}^A = \mathbf{V}^A \cdot \mathbf{s}^A \tag{2.26}$$

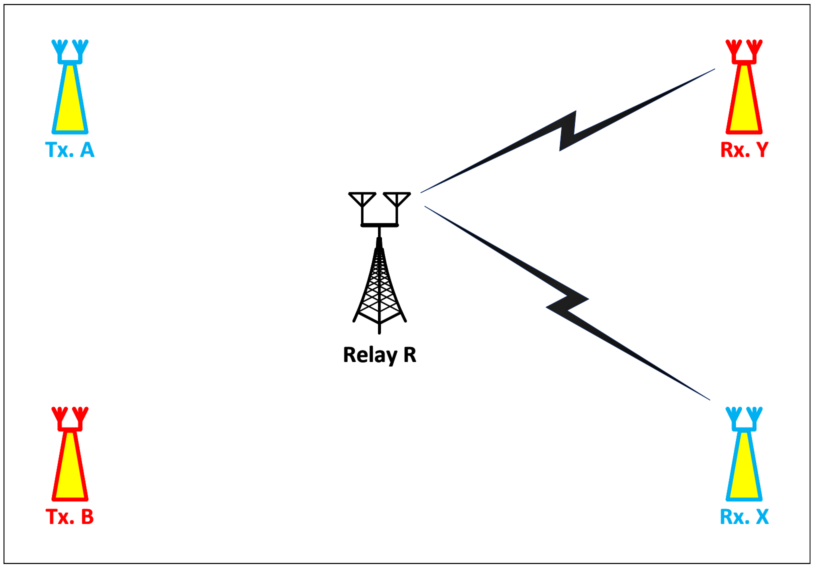

Figure 2.6: MIMO Single Relay Half-Duplex Even Time Slots.

$$\begin{bmatrix} x_1^A \\ x_2^A \end{bmatrix} = \begin{bmatrix} v_{11}^A & v_{12}^A \\ v_{21}^A & v_{22}^A \end{bmatrix} \cdot \begin{bmatrix} s_1^A \\ s_2^A \end{bmatrix} = \begin{bmatrix} \mathbf{v}_1^A & \vdots & \mathbf{v}_2^A \end{bmatrix} \cdot \begin{bmatrix} s_1^A \\ s_2^A \end{bmatrix} \tag{2.27}$$

Here, the symbol $\vdots$ denotes the concatenation of submatrixes. In this case, $\mathbf{v}_1^A$ is the first column and $\mathbf{v}_2^A$ is the second column of $\mathbf{V}^A$.

Transmitter B

Transmitter A transmits two spatial bit streams, b_1 and b_2. Both are modulated using BPSK, where they are represented by -1 and +1:

$$s_1^B = \{-1, +1\} \text{ for } b_1 \tag{2.28}$$

$$s_2^B = \{-1, +1\} \text{ for } b_2 \tag{2.29}$$

Precoded data: With the precoding matrix $\mathbf{V}^B$, the vector signal $\mathbf{x}^B$ leaving antennas at transmitter B is equivalently

$$\mathbf{x}^B = \mathbf{V}_{2\times 2}^B \cdot \mathbf{s}^B \tag{2.30}$$

$$\begin{bmatrix} x_1^B \\ x_2^B \end{bmatrix} = \begin{bmatrix} v_{11}^B & v_{12}^B \\ v_{21}^B & v_{22}^B \end{bmatrix} \cdot \begin{bmatrix} s_1^B \\ s_2^B \end{bmatrix} = \begin{bmatrix} \mathbf{v}_1^B & \vdots & \mathbf{v}_2^B \end{bmatrix} \cdot \begin{bmatrix} s_1^B \\ s_2^B \end{bmatrix} = s_1^B \cdot \mathbf{v}_1^B + s_2^B \cdot \mathbf{v}_2^B \tag{2.31}$$

2.4.3 Signal Received X, Y, and R in MAC Phase

In this system, transmitters A and B each send two spatial data streams, denoted as a_1, a_2, b_1, and b_2. These data streams are then mapped to BPSK symbols. Receivers X and Y, each equipped with two antennas, employ the MIMO concept to receive the transmitted signals.

Receiver X Opportunistic Listening

The received signal at receiver X, denoted as $\mathbf{y}^X$, is given by the multiplication of the channel matrix $\mathbf{H}_{BX}$ and the transmitted preprocessed symbols from transmitter B, along with the added channel noise term:

$$\begin{bmatrix} y_1^X \\ y_2^X \end{bmatrix} = \mathbf{H}_{BX} \cdot \begin{bmatrix} x_1^B \\ x_2^B \end{bmatrix} + \begin{bmatrix} n_1^X \\ n_2^X \end{bmatrix} \tag{2.32}$$

This can also be represented as:

$$\mathbf{y}^X = \mathbf{H}_{BX} \cdot \begin{bmatrix} x_1^B \\ x_2^B \end{bmatrix} + \mathbf{N}^X \tag{2.33}$$

where $\mathbf{H}_{BX}$ is the channel between transmitter B and receiver X and $\mathbf{N}^X$ denotes the channel noise. The received signals y_1^X and y_2^X through zero force processing after matrix inversion provides information about the transmitted data b_1 and b_2 .(step 11)

Receiver Y Opportunistic Listening

Receiver Y receives its signal, $\mathbf{y}^Y$, through the channel matrix $\mathbf{H}_{AY}$ from transmitter A:

$$\mathbf{y}^Y = \mathbf{H}_{AY} \cdot \begin{bmatrix} x_1^A \\ x_2^A \end{bmatrix} + \mathbf{N}^Y \tag{2.34}$$

The channel matrix $\mathbf{H}_{AY}$ characterizes the interaction between transmitter A and receiver Y, and the received signals y_1^Y and y_2^Y carry information about the transmitted data from A. For the sake of brevity, we omit the consideration of wireless channel noise so we can focus on the core aspects of the system. This simplification allows us to concentrate on the primary signal propagation and processing mechanisms, leading to a clearer understanding of the underlying principles.

Relay R

This section provides equations expressing the processing of received signals at relay R. To better understand signal processing, we deconstruct the equations step by step, starting with:

$$\mathbf{y}^R = \mathbf{H}_{AR} \cdot \mathbf{V}^A \cdot \begin{bmatrix} s_1^A \\ s_2^A \end{bmatrix} + \mathbf{H}_{BR} \cdot \mathbf{V}^B \cdot \begin{bmatrix} s_1^B \\ s_2^B \end{bmatrix}, \tag{2.35}$$

The received signal at relay R ($\mathbf{y}^R$) is derived from two components: the first represents transmitter A, and the second transmitter B.

If we expand (2.35) using (2.27) and (2.31) we get:

$$\begin{aligned} \mathbf{y}^R = {} & \mathbf{H}_{AR} \cdot \mathbf{v}_1^A \cdot s_1^A + \mathbf{H}_{AR} \cdot \mathbf{v}_2^A \cdot s_2^A \\ & + \mathbf{H}_{BR} \cdot \mathbf{v}_1^B \cdot s_1^B + \mathbf{H}_{BR} \cdot \mathbf{v}_2^B \cdot s_2^B. \end{aligned} \tag{2.36}$$

As shown, each term in the equation corresponds to the product of the channel matrix ($\mathbf{H}$) and the precoded vector ($\mathbf{v}$) for the respective transmitter and symbol.

Next, we introduce the matrices $\mathbf{D_1}'$, $\mathbf{D_1}''$, $\mathbf{D_2}'$, and $\mathbf{D_2}''$:

$$\mathbf{D_1}' = \mathbf{H}_{AR} \cdot \mathbf{v}_1^A, \tag{2.37}$$

$$\mathbf{D_1}'' = \mathbf{H}_{BR} \cdot \mathbf{v}_1^B, \tag{2.38}$$

$$\mathbf{D_2}' = \mathbf{H}_{AR} \cdot \mathbf{v}_2^A, \tag{2.39}$$

$$\mathbf{D_2}'' = \mathbf{H}_{BR} \cdot \mathbf{v}_2^B. \tag{2.40}$$

These matrices are the results of combining the channel matrices and the precoded vectors for each transmitter. With these matrices, $\mathbf{y}^R$ is represented as:

$$\mathbf{y}^R = s_1^A \cdot \mathbf{D_1}' + s_1^B \cdot \mathbf{D_1}'' + s_2^A \cdot \mathbf{D_2}' + s_2^B \cdot \mathbf{D_2}'' \tag{2.41}$$

However, because $\mathbf{y}^R$ is 2-D, we can only recover two signals at the relay in the MAC phase, and we want them to be $s_1^A + s_1^B$ and $s_2^A + s_2^B$. The reason for this is that the relay will be able to recover these two signals, $c_1 = a_1 \oplus b_1$ and $c_2 = a_2 \oplus b_2$. To accomplish this, we adjust the precoding matrices $\mathbf{v}_A$ and $\mathbf{v}_B$ so that we get:

$$\mathbf{D_1} = \mathbf{D_1}' = \mathbf{D_1}'', \tag{2.42}$$

$$\mathbf{D_2} = \mathbf{D_2}' = \mathbf{D_2}''. \tag{2.43}$$

The signal processing at the relay is thus enabled and we can decode and transmit the c_1 and c_2, which are the XORed data received from A and B data streams 1 and 2.

We can express the received signal $\mathbf{y}^R$ in (2.41) as a linear combination of the transmitted symbols:

$$\mathbf{y}^R = (s_1^A + s_1^B) \cdot \mathbf{D_1} + (s_2^A + s_2^B) \cdot \mathbf{D_2}. \tag{2.44}$$

We can also express it as:

$$\mathbf{y}^R = \begin{bmatrix} \mathbf{D_1} & \vdots & \mathbf{D_2} \end{bmatrix} \cdot \begin{bmatrix} s_1^A + s_1^B \\ s_2^A + s_2^B \end{bmatrix}. \tag{2.45}$$

Assuming that we know D_1 and D_2 at the relay, we can then recover through zero-forcing the ternary representation for c_1 and c_2, giving:

$$\begin{bmatrix} s_1^A + s_1^B \\ s_2^A + s_2^B \end{bmatrix} = \begin{bmatrix} \mathbf{D_1} & \vdots & \mathbf{D_2} \end{bmatrix}^{-1} .\mathbf{y^R} \tag{2.46}$$

This equation demonstrates how relay R both processes and combines the signals from transmitters A and B.

The recovery of $[s_1^A + s_1^B]$ and $[s_2^A + s_2^B]$ is discussed in detail in Appendix B. Specifically, we demonstrate how we can adjust $\mathbf{V}_A = [\mathbf{v}_1^A : \mathbf{v}_2^A]$ and $\mathbf{V}_B = [\mathbf{v}_1^B : \mathbf{v}_2^B]$, so that $\mathbf{D}_1' = \mathbf{D}_1''$ and $\mathbf{D}_2' = \mathbf{D}_2''$. We do this by adjusting signals in 2-D, so we can recover c_1 and c_2 from $[s_1^A + s_1^B]$ and $[s_2^A + s_2^B]$, respectively. Our aim is to have $\mathbf{D_1}' = \mathbf{D_1}''$ and $\mathbf{D_2}' = \mathbf{D_2}''$, in order for $\mathbf{D_1}' = \mathbf{D_1}''$ and $\mathbf{D_2}' = \mathbf{D_2}''$, we adjust v_1^A and v_1^B and v_2^A and v_2^B, so that by aligning signals in $2-D$, we can recover c_1 and c_2 in the relay.

2.4.4 BC Phase Process

BC phase

During the BC phase, which occurs in even-numbered time slots, relay R transmits the BPSK-encoded signal vector $\mathbf{s}^R = \begin{bmatrix} s^{R1} \\ s^{R2} \end{bmatrix}$, corresponding to the data bits c_1 and c_2.

Receivers X and Y acquire the signals $\mathbf{y}^X$ and $\mathbf{y}^Y$, respectively, given by:

$$\mathbf{y}^X = \mathbf{H}_{RX}\mathbf{s}^R,$$
$$\mathbf{y}^Y = \mathbf{H}_{RY}\mathbf{s}^R.$$

Utilizing these received signals, receiver X and Y are capable of deducing c_1 and c_2. Using the matrix inverse $\mathbf{s}^R = \mathbf{H}^{-1} \cdot \mathbf{y}^Y$ and once we have $\mathbf{s}^R$, we can recover c_1 and c_2.

Additionally, receiver X combines the bits b_1 and b_2, obtained via opportunistic listening during the MAC phase (odd-numbered time slots) to retrieve the transmitted data from source A. The recovery can be expressed as follows:

$$a_1 = c_1 \oplus b_1,$$
$$a_2 = c_2 \oplus b_2,$$

where $\oplus$ is the XOR operation. Receiver Y conducts similar procedures to recover the transmitted data.

Chapter 3

Full Duplex Alternate Relay Operation of X Networks

3.1 Introduction

In this chapter, we explore the scenario where transmitters A and B are allowed to transmit continuously by using two relays operating in half-duplex mode in complementary time slots. This achieves a full-duplex operation of the system that was introduced in Chapter 2. Section 3.1 provides a theoretical basis for the system's operation when transmitters A and B, along with relay R, use a single antenna, while receivers X and Y continuously receive signals using two antennas each. This approach is similar to that presented in section 2.3, but with adjustments to the number of receiving antennas at both receiver X and receiver Y, and constitutes the first major contribution of this thesis. Section 3.2 evaluates the performance of the system through simulations.

In the proposed system, the operation during the Medium Access base time slot remains consistent with section 2.3, but now involves two relays, R1 and R2. Similar to section 2.3, R1 receives data from transmitters A and B during odd time slots, while R2 receives PLNC data from the same transmitters during even time slots. Both transmitters A and B, as well as relays R1 and R2, utilize one antenna each. This configuration enables transmitters A and B to send data during all time slots, doubling the system's throughput compared to the system described in section 2.3.

Additionally, this chapter discusses a Single-Input Single-Output full-duplex wireless relay communication system involving transmitters (A and B), receivers (X and Y), and relays (R1 and R2). The goal is to transmit data from A to X and from B to Y using relays, considering non-line-of-sight conditions. BPSK modulation is utilized and precoding is applied to achieve unit channel gains at relays. The system operates in time slots, each with several stages, as follows:

Time Slot 1:

Transmitters A and B send precoded data to relay R1. Relay R2 amplifies and forwards the combined data received from A and B in the previous time slot. Receiver Y detects data from A through line of sight and opportunistic listening. It also receives data from relay R2. Receiver X detects data from B and receives data from relay R2. Receivers X and Y perform BPSK demodulation and data recovery through XOR operations.

Time Slot 2:

Transmitters A and B send precoded data to relay R2. Relay R1 amplifies and forwards the combined data received from A and B in the previous time slot. Receiver Y detects data from A through line of sight and opportunistic listening. It also receives data from relay R1. Receiver X detects data from B and receives data from relay R1. Receivers X and Y perform BPSK demodulation and data recovery through XOR operations.

The system relies on virtual MIMO techniques, efficient signal processing, and relay amplification to achieve data transmission. The chapter highlights the process of transmission, reception, demodulation, and XOR operations to recover transmitted data across multiple time slots, accounting for the relay's role in enhancing communication. The proposed full-duplex relay system offers a reliable solution for non-line-of-sight scenarios in wireless communication.

3.2 One-Way Full-Duplex System Overview

In the proposed system, the operation in the MAC phase (odd time slots) is similar to that presented in section 2.3, except now we are working with two relays: R1 and R2. As in section 2.3, R_1 receives data from A and B in odd time slots, while R_2 receives PLNC data from A and B in even time slots. A, B, R_1, and R2 use one antenna. This allows A and B to send data in all time slots, doubling the throughput in the system compared to what was achievable in the corresponding system in section 2.3.

However, because X and Y in the modified system are losing the opportunity to receive directly from A and B, we initiate two antennas to receive the transmitted data from A and B all the time. This enables X and Y to obtain XORed representation of the replayed data and the original data for A and B initially received in the designated time slot. The signal received at X and Y is now represented as a column vector, which is represented through virtual MIMO reception. In the modified full-duplex system, signal vectors received at Y and X are represented in a virtual MIMO matrix format. The system equations can be rewritten as follows:

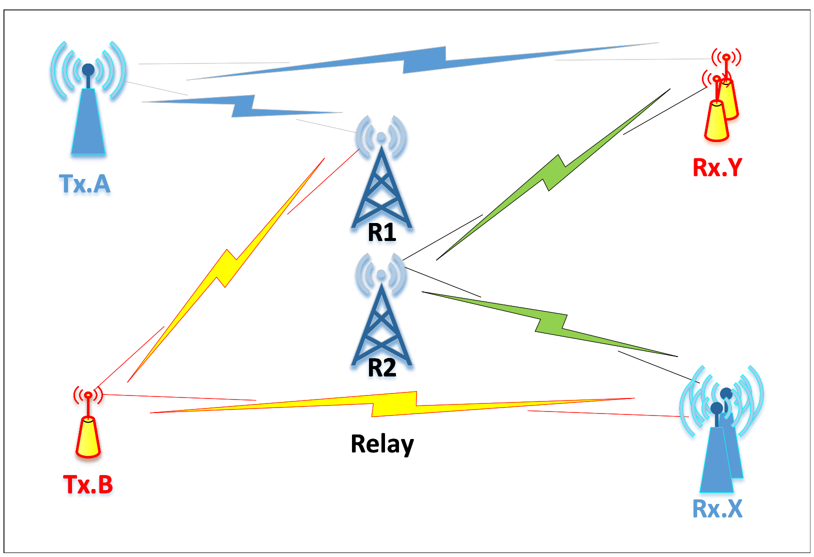

Figure 3.1: Dual Relay Full-Duplex One-Way Data Transmission for Odd Time Slots.

- $\mathbf{y}^Y$ is the received signal vector at Y, with components $y_1^Y(n)$ and $y_2^Y(n)$.
- $\mathbf{y}^X$ is the received signal vector at X, with components $y_1^X(n)$ and $y_2^X(n)$.

- $x^A(n)$ and $x^B(n)$ are the signals transmitted from transmitters A and B, respectively.
- $s^R(n)$ is the signal transmitted from the relay.
- $\mathbf{h}_{AY}$, $\mathbf{h}_{RY}$, $\mathbf{h}_{BX}$, and $\mathbf{h}_{RX}$ are channel gain matrices representing the respective channel gains.

This modified system still supports simultaneous transmission and reception, and it takes advantage of virtual MIMO techniques to improve system performance. The matrix representation allows for efficient computation and processing of signals, enhancing the system's throughput and spectral efficiency.

3.3 SISO Full-Duplex System Details

3.3.1 System Description

This system consists of two transmitting nodes (A and B), two receiving nodes (X and Y), and two relaying nodes (R_1 and R_2). The overall objective is to send information from A to X and B to Y, via full-duplex relays.

3.3.2 Modulation

Transmitters A and B and relay R are using Binary Phase Shift Keying (BPSK) to modulate their data streams. The corresponding mathematical representation for BPSK can be expressed as: s^A and s^B represents the BPSK version of the transmitted signal, taking the value of 1 or -1. Here, the value of $s = 1$ corresponds to logical 1, and the value of $s = -1$ corresponds to logical 0.

3.3.3 Relay Process

The relay R_1 operates in half-duplex mode. As described in section 2.2, it retrieves for bit streams the $s^A + s^B$ representation of PLNC data by decoding $s^A + s^B$, resulting in $c = a \oplus b$ for odd time slots when R_1 is listening. The relay then transmits s^R the BPSK-modulated signal, which represents the data c, since this is applicable for the operation of R_2, when R_2 is listening but in the even time slot. Both R_1 and R_2 recover c, R_1 in odd time slots and R_2 in even time slots.

Reception

Receivers X and Y can receive unwanted data but must process the signals through two time slots.

Time Slot 1

Transmitters A and B

Transmitters A and B send precoded data to relay R_1 simultaneously:

$$y^{R_1} = h_{AR_1} \cdot x^A(n) + h_{BR_1} \cdot x^B(n) \tag{3.1}$$

Relay R_2

Relay R_2 transmits $s^{R_2}(n-1)$ the BPSK-modulated signal, which represents the data $c(n-1)$, with " -1" referring to the previous time slot.

Virtual MIMO System at Receiver X

By incorporating the opportunistic listening and broadcast phases into one time slot, we get:

$$\mathbf{y}^X = \begin{bmatrix} y_1^X(n) \\ y_2^X(n) \end{bmatrix} = \mathbf{h}_{BX} \cdot x^B(n) + \mathbf{h}_{R_2X} \cdot s^{R_2}(n-1) \tag{3.2}$$

where $\mathbf{y}^X$, $\mathbf{h}_{BX}$, and $\mathbf{h}_{R_2X}$ are 2×1 column vectors. The term $\mathbf{h}_{BX} \cdot x^B(n)$ represents the opportunistic listening phase and the term $\mathbf{h}_{R_2X} \cdot s^{R_2}(n-1)$ represents the broadcast phase. Relation in (3.2) can be re-written as:

$$\mathbf{y}^X = \begin{bmatrix} y_1^X(n) \\ y_2^X(n) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{BX} & \vdots & \mathbf{h}_{R_2X} \end{bmatrix}_{2\times 2} \begin{bmatrix} x^B(n) \\ s^{R_2}(n-1) \end{bmatrix} \tag{3.3}$$

Resolving the above:

$$\begin{bmatrix} x^B(n) \\ s^{R_2}(n-1) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{BX} & \vdots & \mathbf{h}_{R_2X} \end{bmatrix}_{2\times 2}^{-1} \cdot \begin{bmatrix} y_1^Y(n) \\ y_2^Y(n) \end{bmatrix} \tag{3.4}$$

Out of $x^B(n)$, where $x^B(n) = V^B \cdot s_1^B$, we can obtain $s_1^B = \frac{1}{V_B} x^B(n)$ with the value ± 1 and detecting b_1. Out of the transmitted $s^{R_2}(n-1)$ binary representation, we get c_0, which is $a_0 \oplus b_0$ transmitted by R_1.

Virtual MIMO System at Receiver Y

$$\mathbf{y}^Y = \begin{bmatrix} y_1^Y(n) \\ y_2^Y(n) \end{bmatrix} = \mathbf{h}_{AY} \cdot x^A(n) + \mathbf{h}_{R_2Y} \cdot s^{R_2}(n-1) \tag{3.5}$$

$$\mathbf{y}^Y = \begin{bmatrix} y_1^Y(n) \\ y_2^Y(n) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{AY} & \vdots & \mathbf{h}_{R_2Y} \end{bmatrix}_{2\times 2} \begin{bmatrix} x^A(n) \\ s^{R_2}(n-1) \end{bmatrix} \tag{3.6}$$

Resolving the above:

$$\begin{bmatrix} x^A(n) \\ s^{R_2}(n-1) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{AY} & \vdots & \mathbf{h}_{R_2Y} \end{bmatrix}_{2\times 2}^{-1} \cdot \begin{bmatrix} y_1^Y(n) \\ y_2^Y(n) \end{bmatrix} \tag{3.7}$$

Demodulation and Data Recovery

Receivers X and Y perform BPSK demodulation and additional processing (e.g., saving data, performing XOR operations) to detect transmitted data in previous time slots. The operation involves XOR operations and handling multiple antennas, and it considers the system as virtual MIMO to fully recover the intended transmitted data streams.

Time Slot 2:

Transmitters A and B

Transmitters A and B send precoded data to relay R_2 simultaneously and the received signal here is:

$$y^{R_2} = h_{AR_2} \cdot x^A(n) + h_{BR_2} \cdot x^B(n) \tag{3.8}$$

After recovery of c_1 from ternary representation, later on R_2 is going to send BPSK representation of c_1 as s_{R_2}.

Relay R_1

Relay R_1 transmits $s^{R_1}(n)$ the BPSK-modulated signal, which represents the data $c(n)$ from the previous time slot.

Virtual MIMO System at Receiver X

$$\mathbf{y}^X = \begin{bmatrix} y_1^X(n+1) \\ y_2^X(n+1) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{BX} & \vdots & \mathbf{h}_{R_1X} \end{bmatrix}_{2\times 2} \begin{bmatrix} x^B(n+1) \\ s^{R_1}(n) \end{bmatrix} \tag{3.9}$$

Resolving the above:

$$\begin{bmatrix} x^B(n+1) \\ s^{R_1}(n) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{BX} & \vdots & \mathbf{h}_{R_1X} \end{bmatrix}_{2\times 2}^{-1} \cdot \begin{bmatrix} y_1^Y(n+1) \\ y_2^Y(n+1) \end{bmatrix} \tag{3.10}$$

Virtual MIMO System at Receiver Y

$$\mathbf{y}^Y = \begin{bmatrix} y_1^Y(n+1) \\ y_2^Y(n+1) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{AY} & \vdots & \mathbf{h}_{R_1Y} \end{bmatrix}_{2\times 2} \begin{bmatrix} x^A(n+1) \\ s^{R_1}(n) \end{bmatrix} \tag{3.11}$$

Resolving the above:

$$\begin{bmatrix} x^A(n+1) \\ s^{R_1}(n) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_{AY} & \vdots & \mathbf{h}_{R_1Y} \end{bmatrix}_{2\times 2}^{-1} \cdot \begin{bmatrix} y_1^Y(n+1) \\ y_2^Y(n+1) \end{bmatrix} \tag{3.12}$$

Which allows for the recovery of $a_1(n+1)$ and $c_1(n)$ in a single phase, creating a virtual 2×2 MIMO system. We refer to it as *virtual MIMO* because the single antenna at A and R2 are located at different places. It is considered a 2×2 MIMO system because, combined, A and R2 use two transmit antennas, and Y uses two receive antennas. This virtual MIMO setup effectively merges opportunistic listening and relay data recovery at receiver Y into one operation.

Demodulation and Data Recovery

Receivers X and Y perform BPSK demodulation and additional processing (e.g., saving data, performing XOR operations) to detect transmitted data in previous time slots. The operation involves XOR operations and handling multiple antennas, considering the system as virtual MIMO to fully recover the intended transmitted data streams.

Points:

1. As noted, the system has a one-time slot delay due to the utilization of the relay for conveying the data from the previous time slot.

2. This process can be extrapolated for other time slots by repeating similar operations and only changing the involved data signals and relay roles.

3.3.4 Full-Duplex System BER performance Evaluation in AWGN Channel

Bit Error Rate (BER) is a critical performance metric in digital communication systems, reflecting the fraction of bits transmitted that are erroneously received. To evaluate and compare the BER performance of half-duplex and full-duplex systems under Additive White Gaussian Noise (AWGN) conditions, MATLAB simulations were conducted. For the half-duplex system, the channel is utilized alternately for transmission and reception, limiting the communication to one direction at a time. The full-duplex system can simultaneously transmit and receive signals on the same frequency band, theoretically doubling the channel's efficiency.

In the MATLAB simulation, both systems were subjected to a range of Signal-to-Noise Ratio (SNR) values to examine their robustness against noise. BPSK modulation was employed for its simplicity and ability to provide a clear comparison between the systems' performances, as shown in 3.2. As expected, the BER for both systems decreased with increasing SNR, demonstrating improved performance at higher SNR values. However, the half-duplex system showed a longer delay due to time-sharing, which was not present in the full-duplex system.

In the simulation provided in 3.2, an ideal situation was assumed where perfect IRI cancellation is possible in the full-duplex system. This means that the transmitted signal does not interfere with the received signal at all. This idealization is why the BER performance for both half-duplex and full-duplex systems appeared the same. In a more realistic scenario, the performance of the full-duplex system would be degraded due to the IRI, unless IRI cancellation techniques were used. These techniques can be complex and may not achieve perfect cancellation, especially as the power of the transmitted signal becomes much larger than the power of the received signal, which is often the case in real-world communication systems.

To reflect a more realistic scenario in the simulation, the IRI effect would have to be modeled in the full-duplex system. This could involve adding an additional noise component to the received signal in the full-duplex system that represents the residual IRI after Self-Interference Cancellation (SIC) efforts, as shown in 3.3.

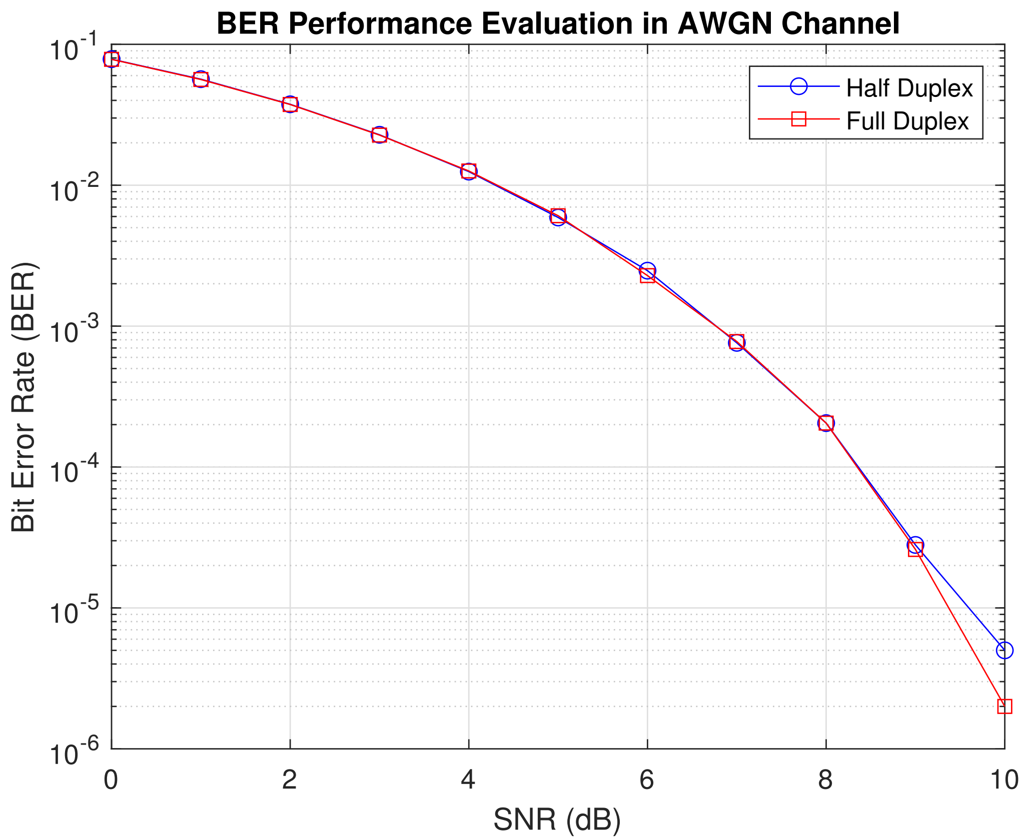

Figure 3.2: Full-Duplex and Half-Duplex BER vs SNR in AWGN.

3.3.5 Full Duplex System End to End Channel Capacity

Channel capacity, as articulated by the Shannon-Hartley theorem, represents the maximum data rate achievable over a noisy channel. The MATLAB simulations calculated this theoretical limit for both Half-Duplex and Full-Duplex systems over a range of SNR values. For the Half-Duplex system, the channel capacity was effectively halved due to the time division for transmission and reception. In contrast, the Full-Duplex system's capacity was not subject to this division, assuming perfect IRI cancellation. The simulations revealed that the Full-Duplex system has the potential to double the channel capacity compared to the Half-Duplex system under ideal conditions as shown in 3.4. This capacity enhancement is attributable to the Full-Duplex system's ability to concurrently use the channel for both transmission and reception.

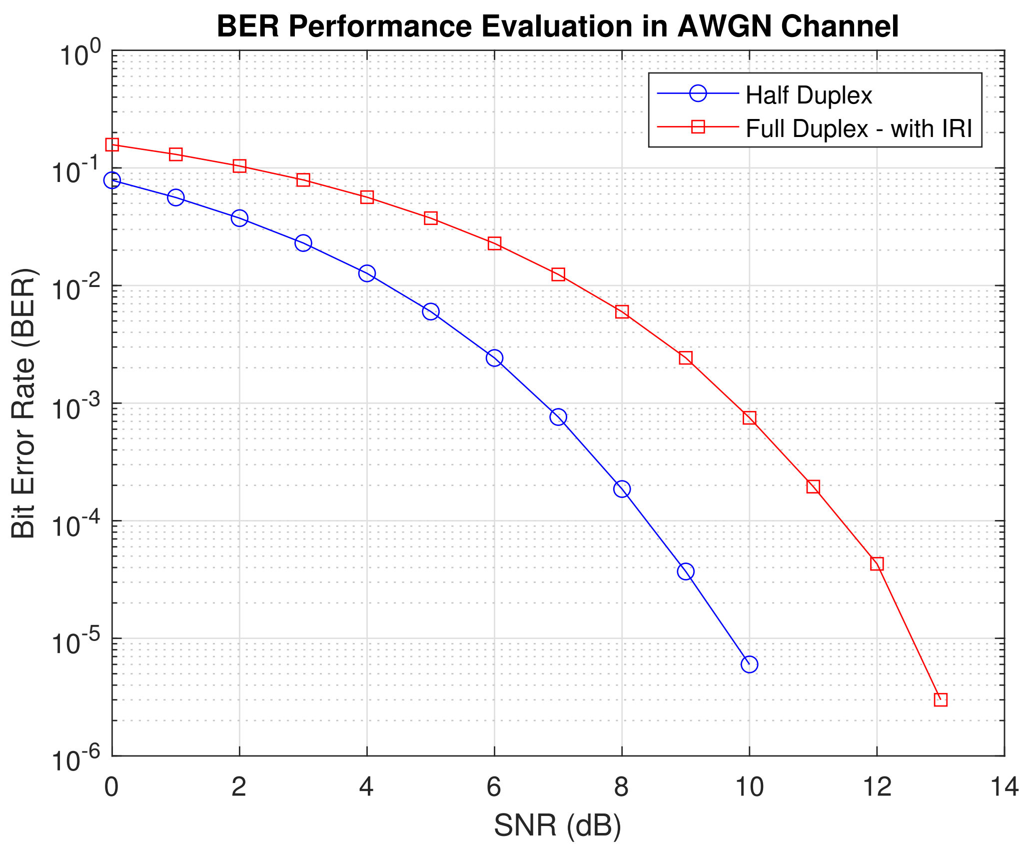

Figure 3.3: Full-Duplex and Half-Duplex BER vs SNR in AWGN Practical Scenarios.

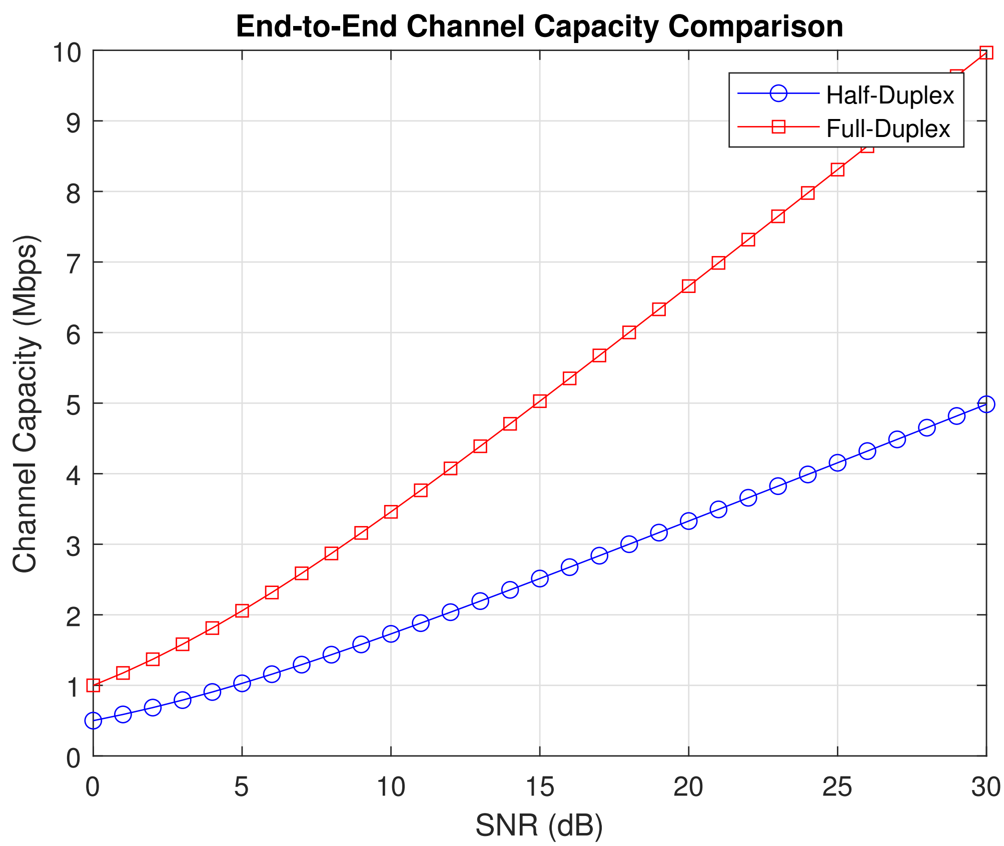

Figure 3.4: Full Duplex and Half Duplex Channel Capacity vs SNR in AWGN

Chapter 4

MIMO Full Duplex Alternate Relays Operation of X Networks

4.1 MIMO Full Duplex Alternate Relays System

In this section, we analyse a MIMO Full-Duplex Alternate Relays System. This MIMO configuration has multiple antennas at both the transmitters and receivers and takes advantage of the spatial diversity by improving reliability and obtaining higher data rates. The system architecture and assumptions are discussed in the following subsections.

A key feature of the full-duplex alternate relays system is the use of the virtual MIMO technique. In time slot one, transmitter A, relay R_2, and receiver Y together form a 4x4 virtual MIMO configuration. At the same time, transmitter B, relay R_2, and receiver X form another 4x4 virtual MIMO structure. The scenario is similar to time slot two, but with the involvement of relay R_1 instead of R_2. Using the virtual MIMO concept, during odd time slots, transmitter A and relay R_2 serve as the MIMO transmitter with a total of four antennas (two each). Receiver Y, which has four antennas, functions as the MIMO receiver. Similarly, transmitter B, along with relay R_2, becomes the MIMO transmitter for receiver X. For even time slots, the configuration mirrors the above, but with relays R_1 and R_2 exchanging roles.

4.1.1 System Overview

Transmitters A and B each send two spatial data streams, denoted by a_1, a_2 and b_1, b_2, respectively. Receivers X and Y each have four antennas and are capable of receiving data using MIMO techniques. Transmitters A and B map the binary data to BPSK symbols. The system employs two relays, R_1 and R_2, which alternate between receiving and transmitting modes in odd and even time slots. In each time slot, 4x4 virtual MIMO is formed between the transmitters, one relay, and one receiver. In odd time slots, R_1 is in receiving mode, capturing data from A and B. Meanwhile,

R_2 is in transmitting mode, forwarding data to X and Y. In even time slots, R_2 is in receiving mode, capturing data from A and B, and R_1 is in transmitting mode, forwarding data to X and Y. Transmitter A sends two data streams a_1 and a_2, where each data element can have a value of 0 or 1. The binary data is mapped to BPSK symbols, leading to:

$$\mathbf{s}^A = \begin{bmatrix} s_1^A \\ s_2^A \end{bmatrix}$$

Similarly, for transmitter B:

$$\mathbf{s}^B = \begin{bmatrix} s_1^B \\ s_2^B \end{bmatrix}$$

The transmitted precoded data from A and B are:

$$\mathbf{x}^A = \mathbf{V}^A \cdot \mathbf{s}^A$$

$$\mathbf{x}^B = \mathbf{V}^B \cdot \mathbf{s}^B$$

This is similar to what we discussed in Section 2.4, but in this chapter, A is sending continuously, alternating between R_1 and R_2. Therefore, the precoding matrix V^A will be adjusted in odd time slots according to the channel condition for A to R_1 (denoted as H_{AR_1}), and in even time slots, it will be adjusted according to A to R_2.

4.1.2 Time Slot Operations

Odd Time Slots

In odd time slots, R_1 receives the two data streams from A and B:

$$\mathbf{y}^{R_1} = \mathbf{H}_{AR_1} \cdot \mathbf{x}^A + \mathbf{H}_{BR_1} \cdot \mathbf{s}^B$$

This is the basis to recover $c_1(n)$ and $c_2(n)$ at R_1 at the same time.

R_2 transmits $\mathbf{s}^{R_2}$:

$$\mathbf{s}^{R_2} = \begin{bmatrix} s_1^{R_2} \\ s_2^{R_2} \end{bmatrix}$$

Which is in BPSK representation for c_1 and c_2 aligned.

Even Time Slots

In even time slots, R_2 receives the two data streams from A and B:

$$\mathbf{y}^{R_2} = \mathbf{H}_{AR_2} \cdot \mathbf{x}^A + \mathbf{H}_{BR_2} \cdot \mathbf{s}^B$$

If align conditions are met, $\mathbf{y}^{R_2}$ is used for recovering c_1 and c_2.
In even time slots, R_1 transmits $\mathbf{s}^{R_1}$:

$$\mathbf{s}^{R_1} = \begin{bmatrix} s_1^{R_1} \\ s_2^{R_1} \end{bmatrix}$$

BPSK representation for c_1 and c_2.

4.1.3 Virtual MIMO

In each time slot, a 4x4 virtual MIMO system is formed between the transmitters, one of the relays, and one of the receivers. This is made possible due to the use of multiple antennas at each node, allowing for increased channel capacity and spatial diversity.

For odd time slots, the following virtual MIMO configurations are:

(i) Two transmit antennas on each of A and R_2, and

(ii) four receive antennas at Y.

$$\text{System 1: } A, R_2, Y \quad \Rightarrow \quad 4 \times 4 \text{ Virtual MIMO}$$

(i) Two transmit antennas on each of B and R_2, and

(ii) four receive antennas at X.

$$\text{System 2: } B, R_2, X \quad \Rightarrow \quad 4 \times 4 \text{ Virtual MIMO}$$

For even time slots, the following virtual MIMO configurations are:

$$\text{System 3: } A, R_1, Y \quad \Rightarrow \quad 4 \times 4 \text{ Virtual MIMO}$$

$$\text{System 4: } B, R_1, X \quad \Rightarrow \quad 4 \times 4 \text{ Virtual MIMO}$$

As in the half-duplex case, noise is omitted for the sake of simplicity, allowing the focus to be on signal propagation and processing mechanisms.

4.1.4 Mathematical Preliminaries for Full-Duplex System

4.1.5 Transmission Scheme

Transmitter A transmits two spatial bit streams, a_1 and a_2. Both are modulated using BPSK, where they are represented by -1 and +1:

$$s_1^A = \{-1, +1\} \text{ for } a_1 \tag{4.1}$$

$$s_2^A = \{-1, +1\} \text{ for } a_2 \tag{4.2}$$

Precoded data for full-duplex system:

$$\mathbf{x}^A = \mathbf{V}^A \cdot \mathbf{s}^A \tag{4.3}$$

Transmitter B transmits two spatial bit streams denoted as b_1 and b_2. Both are modulated using BPSK, where they are represented by -1 and +1.

$$s_1^B = \{-1, +1\} \text{ for } b_1 \tag{4.4}$$

$$s_2^B = \{-1, +1\} \text{ for } b_2 \tag{4.5}$$

Precoded data for full-duplex system:

$$\mathbf{x}^B = \mathbf{V}^B \cdot \mathbf{s}^B \tag{4.6}$$

4.1.6 Signal Received at R_1 and R_2 in MAC Phase for Full-Duplex System

In the full-duplex system, transmitters A and B each send two spatial data streams. These streams are then mapped to BPSK symbols. Relays R_1 and R_2, each equipped with two antennas, use the MIMO concept to receive and transmit the signals simultaneously.

Relay R_1 Full-Duplex Reception

The received signal at relay R_1, denoted as $\mathbf{y}^{R_1}$, is given by:

$$\mathbf{y}^{R_1} = \mathbf{H}_{AR_1} \cdot \mathbf{x}^A + \mathbf{H}_{BR_1} \cdot \mathbf{s}^B \tag{4.7}$$

Relay R_2 Full-Duplex Reception

The received signal at relay R_2, denoted as $\mathbf{y}^{R_2}$, is given by:

$$\mathbf{y}^{R_2} = \mathbf{H}_{AR_2} \cdot \mathbf{x}^A + \mathbf{H}_{BR_2} \cdot \mathbf{s}^B \tag{4.8}$$

Here, $\mathbf{H}_{AR_1}$ and $\mathbf{H}_{AR_2}$ represent the channels between transmitter A and relays R_1 and R_2, respectively. Similarly, $\mathbf{H}_{BR_1}$ and $\mathbf{H}_{BR_2}$ represent the channels between transmitter B and relays R_1 and R_2, respectively. The received symbols at R_1 and R_2 provide information about the transmitted data after passing through the channel. (See Appendices B and C.)

4.1.7 Signal Received at X and Y in Full-Duplex MAC Phase with Time Slots

In this full-duplex system with time slot-based relay operation, the received signals at receivers X and Y differ based on the time slot due to the alternating roles of R_1 and R_2.

Receiver X

The received signals at receiver X are:

During Odd Time Slots:

$$\mathbf{y}^X_{\text{odd}} = \mathbf{H}_{BX} \cdot \mathbf{x}^B + \mathbf{H}_{R2X} \cdot \mathbf{s}^{R2} \tag{4.9}$$

During Even Time Slots:

$$\mathbf{y}^X_{\text{even}} = \mathbf{H}_{BX} \cdot \mathbf{x}^B + \mathbf{H}_{R1X} \cdot \mathbf{s}^{R1} \tag{4.10}$$

Receiver Y

The received signals at receiver Y are:

During Odd Time Slots:

$$\mathbf{y}^Y_{\text{odd}} = \mathbf{H}_{AY} \cdot \mathbf{x}^A + \mathbf{H}_{R2Y} \cdot \mathbf{s}^{R2} \tag{4.11}$$

During Even Time Slots:

$$\mathbf{y}^Y_{\text{even}} = \mathbf{H}_{AY} \cdot \mathbf{x}^A + \mathbf{H}_{R1Y} \cdot \mathbf{s}^{R1} \tag{4.12}$$

In these equations, $\mathbf{H}_{BX}$, $\mathbf{H}_{AY}$, $\mathbf{H}_{R1X}$, $\mathbf{H}_{R1Y}$, $\mathbf{H}_{R2X}$, and $\mathbf{H}_{R2Y}$ represent the channel matrices for the corresponding transmitter-receiver pairs.

4.1.8 System Diagrams and Operations

Odd Time Slots

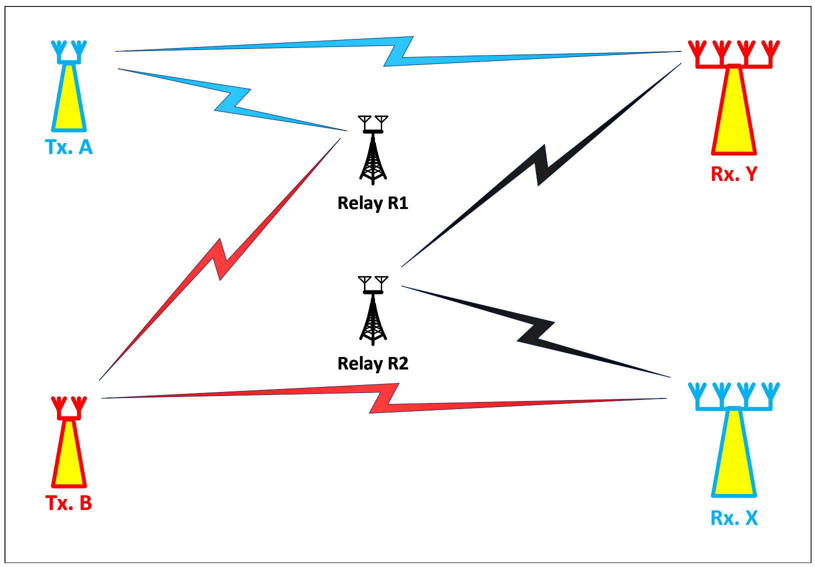

Figure 4.1: MIMO Full-Duplex Alternate Relays System: Odd Time Slots.

In odd time slots, as depicted in Figure 4.1, relay R_1 is in the receiving mode. It receives signals from transmitters A and B. Simultaneously, relay R_2 is in the transmitting mode, forwarding the processed signals from the previous time slot to receivers X and Y.

Even Time Slots

In even time slots, as shown in Figure 4.2, the roles of the relays are reversed compared to odd time slots. Here, relay R_2 is in the receiving mode, capturing signals from transmitters A and B, while relay R_1 is in the transmitting mode, sending the processed signals to receivers X and Y.

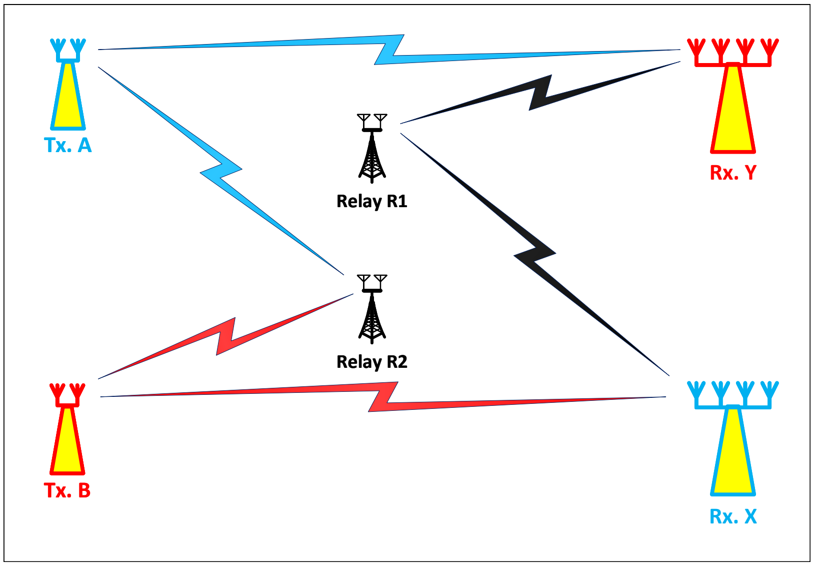

Figure 4.2: MIMO Full-Duplex Alternate Relays System: Even Time Slots.

4.1.9 Relay Operations

The operation of relays R_1 and R_2 in the full-duplex system is similar to their counterparts in the half-duplex system, though with some differences due to the full-duplex nature.

Relay R_1

In odd time slots, relay R_1 is in received mode. It receives data streams from both A and B and processes them similarly to the half-duplex relay. The received signals are represented as:

$$\mathbf{y}^{R_1} = \mathbf{H}_{AR_1} \cdot \mathbf{x}^A + \mathbf{H}_{BR_1} \cdot \mathbf{x}^B$$

In even time slots, relay R_1 switches to transmitt mode, forwarding the data it received in the last even time slot. The forwarded data is processed through the same techniques of data detection, modulation, and transmission as in the half-duplex system.

Relay R_2

In even time slots, relay R_2 is in receiving mode. It captures data streams from A and B and performs data detection, demodulation, and decoding, similar to the half-duplex relay. The received signals at R_2 can be described as:

$$\mathbf{y}^{R_2} = \mathbf{H}_{AR_2} \cdot \mathbf{x}^A + \mathbf{H}_{BR_2} \cdot \mathbf{x}^B$$

In odd time slots, relay R_2 switches to transmitting mode, forwarding the data it received in the last even time slot, after appropriate processing.

4.1.10 Bit-Level Operations at Relays

Both R_1 and R_2 employ a Decode-and-Forward strategy, which involves decoding the received signal to retrieve the original data bits, followed by re-encoding them for transmission.

Relay R_1

Even Time Slots: In transmitting mode, R_1 forwards the decoded and re-encoded bits c_1 and c_2 that it received in the previous odd time slot.

The transmitted signals are:

$$\mathbf{s}^{R_1} = \begin{bmatrix} s_1^{R_1} \\ s_2^{R_1} \end{bmatrix}$$

where $s_1^{R_1}$ and $s_2^{R_1}$ are BPSK representations of c_1 and c_2.

Even Time Slots: In receiving mode, R_1 decodes the received signals y_{R1} to obtain $c_1 = a_1 \oplus b_1$ and $c_2 = a_2 \oplus b_2$. R_1 and can directly determine c_1 and c_2 based on the aggregated signal level, giving $c_1, c_2 = 0$ for $y_{R1} \in \{2, -2\}$ and $c_1, c_2 = 1$ for $y_{R1} = 0$.

Relay R_2

Even Time Slots: In receiving mode, R_2 performs similar decoding and XOR operations as R_1 to produce c_1 and c_2 from the received signals.

Odd Time Slots: In transmitting mode, R_2 forwards the re-encoded bits c_1 and c_2. The transmitted signals are:

$$\mathbf{s}^{R_2} = \begin{bmatrix} s_1^{R_2} \\ s_2^{R_2} \end{bmatrix}$$

where $s_1^{R_2}$ and $s_2^{R_2}$ are BPSK representations of c_1 and c_2.

2-D Space Signal Alignment in Relays R_1 and R_2

This section discusses the equations governing how the received signals are processed at relays R_1 and R_2, starting with the equation for R_1:

$$\mathbf{y}^{R_1} = \mathbf{H}_{AR_1} \cdot \mathbf{V}^A \cdot \begin{bmatrix} s_1^A \\ s_2^A \end{bmatrix} + \mathbf{H}_{BR_1} \cdot \mathbf{V}^B \cdot \begin{bmatrix} s_1^B \\ s_2^B \end{bmatrix}. \tag{4.13}$$

and for R_2:

$$\mathbf{y}^{R_2} = \mathbf{H}_{AR_2} \cdot \mathbf{V}^A \cdot \begin{bmatrix} s_1^A \\ s_2^A \end{bmatrix} + \mathbf{H}_{BR_2} \cdot \mathbf{V}^B \cdot \begin{bmatrix} s_1^B \\ s_2^B \end{bmatrix}. \tag{4.14}$$

In both equations, the first term shows the influence of transmitter A and the second the influence of transmitter B.

Similar to the half-duplex case, matrices $\mathbf{D_1}'$, $\mathbf{D_1}''$, $\mathbf{D_2}'$, and $\mathbf{D_2}''$ are introduced for each relay, which are the results of combining the channel matrices and the precoded vectors for each transmitter, as follows:

For R_1, we have:

$$\mathbf{D_1}'_{R1} = \mathbf{H}_{AR_1} \cdot \mathbf{v}_1^A, \tag{4.15}$$

$$\mathbf{D_1}''_{R1} = \mathbf{H}_{BR_1} \cdot \mathbf{v}_1^B, \tag{4.16}$$

$$\mathbf{D_2}'_{R1} = \mathbf{H}_{AR_1} \cdot \mathbf{v}_2^A, \tag{4.17}$$

$$\mathbf{D_2}''_{R1} = \mathbf{H}_{BR_1} \cdot \mathbf{v}_2^B. \tag{4.18}$$

and for R_2, we have:

$$\mathbf{D_1}'_{R2} = \mathbf{H}_{AR_2} \cdot \mathbf{v}_1^A, \tag{4.19}$$

$$\mathbf{D_1}''_{R2} = \mathbf{H}_{BR_2} \cdot \mathbf{v}_1^B, \tag{4.20}$$

$$\mathbf{D_2}'_{R2} = \mathbf{H}_{AR_2} \cdot \mathbf{v}_2^A, \tag{4.21}$$

$$\mathbf{D_2}''_{R2} = \mathbf{H}_{BR_2} \cdot \mathbf{v}_2^B. \tag{4.22}$$

Similar to the half-duplex case, we want to align the signals in 2-D space to recover c_1 and c_2 at each relay in their corresponding receive time slots (odd for R_1 and even for R_2). Therefore, we adjust $\mathbf{V}^A$ and $\mathbf{V}^B$ such that:

$$\mathbf{D_1}'_{R1} = \mathbf{D_1}''_{R1}, \quad \mathbf{D_2}'_{R1} = \mathbf{D_2}''_{R1}, \tag{4.23}$$

$$\mathbf{D_1}'_{R2} = \mathbf{D_1}''_{R2}, \quad \mathbf{D_2}'_{R2} = \mathbf{D_2}''_{R2}. \tag{4.24}$$

For each relay, we can then represent the received signal $\mathbf{y}^R$ as a linear combination of the transmitted symbols:

$$\mathbf{y}^{R_1} = (s_1^A + s_1^B) \cdot \mathbf{D_1}_{R1} + (s_2^A + s_2^B) \cdot \mathbf{D_2}_{R1}, \tag{4.25}$$

$$\mathbf{y}^{R_2} = (s_1^A + s_1^B) \cdot \mathbf{D_1}_{R2} + (s_2^A + s_2^B) \cdot \mathbf{D_2}_{R2}. \tag{4.26}$$

Finally, the relay can recover c_1 and c_2 by using the inverse of the effective channel matrix:

$$\begin{bmatrix} s_1^A + s_1^B \\ s_2^A + s_2^B \end{bmatrix}^{R1} = \begin{bmatrix} \mathbf{D_1}_{R1} \vdots\ \mathbf{D_2}_{R1} \end{bmatrix}_{R1}^{-1} \cdot \mathbf{y}^{R_1}, \tag{4.27}$$

$$\begin{bmatrix} s_1^A + s_1^B \\ s_2^A + s_2^B \end{bmatrix}^{R2} = \begin{bmatrix} \mathbf{D_1}_{R2} \vdots\ \mathbf{D_2}_{R2} \end{bmatrix}_{R2}^{-1} \cdot \mathbf{y}^{R_2}. \tag{4.28}$$

Relay R_1 recovers c_1 and c_2 in the odd time slots, and R_2 recovers c_1 and c_2 in the even time slots, so that in the following time slot they could transmit BPSK representation (s_{R1} and s_{R2}) of c_1 and c_2.

Virtual MIMO Data Detection for MIMO Full-Duplex System

The MIMO system involves matrices to represent the multiple antennas at each node. For simplification, we assume 2×2 MIMO, meaning two antennas at each transmitter and receiver.

Odd Time Slots (n is odd)

Receiver X: In odd time slots (n is odd), receiver X receives signals from transmitter B and relay R_2. The received signal can be modeled as:

$$\mathbf{y}_{\text{odd}}^{X}(n) = \mathbf{H}_{BX}\mathbf{x}^{B}(n) + \mathbf{H}_{R_2X}\mathbf{s}^{R_2}(n-1) \tag{4.29}$$

Here, $\mathbf{y}_{\text{odd}}^{X}(n)$ represents the received signal at receiver X during odd time slots. The term $\mathbf{H}_{BX}\mathbf{x}^{B}(n)$ is the contribution from transmitter B, and $\mathbf{H}_{R_2X}\mathbf{s}_{R_2}(n-1)$ is the contribution from relay R_2. To decode the data at receiver X, we can solve the following equation:

$$\begin{bmatrix} \mathbf{x}^{B}(n) \\ \mathbf{s}^{R_2}(n-1) \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{BX} \vdots \ \mathbf{H}_{R_2X} \end{bmatrix}^{-1} \mathbf{y}_{\text{odd}}^{X}(n) \tag{4.30}$$

Receiver Y: Similarly, for receiver Y in odd time slots, the received signal is:

$$\mathbf{y}_{\text{odd}}^{Y}(n) = \mathbf{H}_{AY}\mathbf{x}^{A}(n) + \mathbf{H}_{R_2Y}\mathbf{s}^{R_2}(n-1) \tag{4.31}$$

To decode the data at receiver Y, we solve:

$$\begin{bmatrix} \mathbf{x}^{A}(n) \\ \mathbf{s}^{R_2}(n-1) \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{AY} \vdots \ \mathbf{H}_{R_2Y} \end{bmatrix}^{-1} \mathbf{y}_{\text{odd}}^{Y}(n) \tag{4.32}$$

Even Time Slots (n is even)

Receiver X: In even time slots (n is even), receiver X receives signals from transmitter B and relay R_1:

$$\mathbf{y}^{X}_{\text{even}}(n) = \mathbf{H}_{BX}\mathbf{x}^{B}(n) + \mathbf{H}_{R_1X}\mathbf{s}^{R_1}(n-1) \tag{4.33}$$

Data decoding at receiver X:

$$\begin{bmatrix} \mathbf{x}^{B}(n) \\ \mathbf{s}^{R_1}(n-1) \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{BX} \vdots \ \mathbf{H}_{R_1X} \end{bmatrix}^{-1} \mathbf{y}^{X}_{\text{even}}(n) \tag{4.34}$$

Receiver Y: For Receiver Y during even time slots:

$$\mathbf{y}^{Y}_{\text{even}}(n) = \mathbf{H}_{AY}\mathbf{x}^{A}(n) + \mathbf{H}_{R_1Y}\mathbf{s}^{R_1}(n-1) \tag{4.35}$$

Data decoding at Receiver Y:

$$\begin{bmatrix} \mathbf{x}^{A}(n) \\ \mathbf{s}^{R_1}(n-1) \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{AY} \vdots \ \mathbf{H}_{R_1Y} \end{bmatrix}^{-1} \mathbf{y}^{Y}_{\text{even}}(n) \tag{4.36}$$

This section has provided a mathematical framework for understanding the signal reception and data decoding processes in a MIMO full-duplex system. By considering both odd and even time slots, we accounted for the time-varying nature of the full-duplex system. The mathematical models are crucial for understanding how multiple antennas can be used in a full-duplex setting to enhance system performance.

4.2 MIMO Full Duplex System BER performance Evaluation in AWGN Channel

The simulation evaluates and compares the Bit Error Rate (BER) performance of MIMO half-duplex and full-duplex wireless relay systems under AWGN channel conditions in a MATLAB environment. The configuration has two transmit (Tx) and two receive (Rx) antennas and uses BPSK modulation. The noise is modeled as AWGN.

4.2.1 Results and Discussion

The simulation results presented in Figure 4.4 illustrate the BER performance of both half-duplex and full-duplex MIMO systems across the SNR range. As shown, the BER decreases with increasing SNR for both systems, demonstrating that higher SNR leads to improved signal quality and lower bit error rates. The full-duplex system had marginally worse BER performance compared to the half-duplex system. This can be attributed to alternate relaying noise. Overall, the simulation provided valuable insights into the BER performance of MIMO half-duplex and full-duplex systems under AWGN conditions. The findings suggest that the trade-off for enhanced throughput is an increased BER, which can be mitigated by boosting the power and SNR. These insights are important for designing and optimizing MIMO wireless full duplex relay systems in real-world communication scenarios.

4.3 Full-Duplex System End-to-End Channel Capacity

This section presents a MATLAB-based simulation aimed at comparing the end-to-end channel capacities of MIMO full-duplex and MIMO half-duplex systems. The simulation is structured to provide insights into how each system performs under different SNR conditions in an AWGN channel. The primary objective is to show the potential throughput advantages of full-duplex over half-duplex in MIMO configurations.

4.3.1 Results and Discussion

The simulation results illustrated in 4.3 show a distinct advantage in channel capacity for the full-duplex system across all SNR values. As expected, the full-duplex system consistently outperformed the half-duplex system, revealing its potential for higher throughput in practical scenarios. A key observation was the rate at which the capacity increased with SNR in the full-duplex system compared to the half-duplex. This difference became more pronounced at higher SNR values, indicating the significant potential of full-duplex systems in high SNR environments.

However, it is worth noting that simulation 4.4 was conducted under idealized conditions, primarily the assumption of an AWGN channel without fading. In real-world scenarios, factors like multipath fading, interference, and hardware limitations can significantly influence the performance of these systems.

4.3.2 Conclusion

The simulation provided valuable insights into the capacity benefits of MIMO full-duplex systems over their half-duplex counterparts. These findings suggest that full-duplex systems, despite their increased complexity, offer the potential to enhance the throughput of wireless communication systems, especially in environments with high SNR. Further research that incorporates more realistic channel models and system impairments would help to better understand the practical implications of these results.

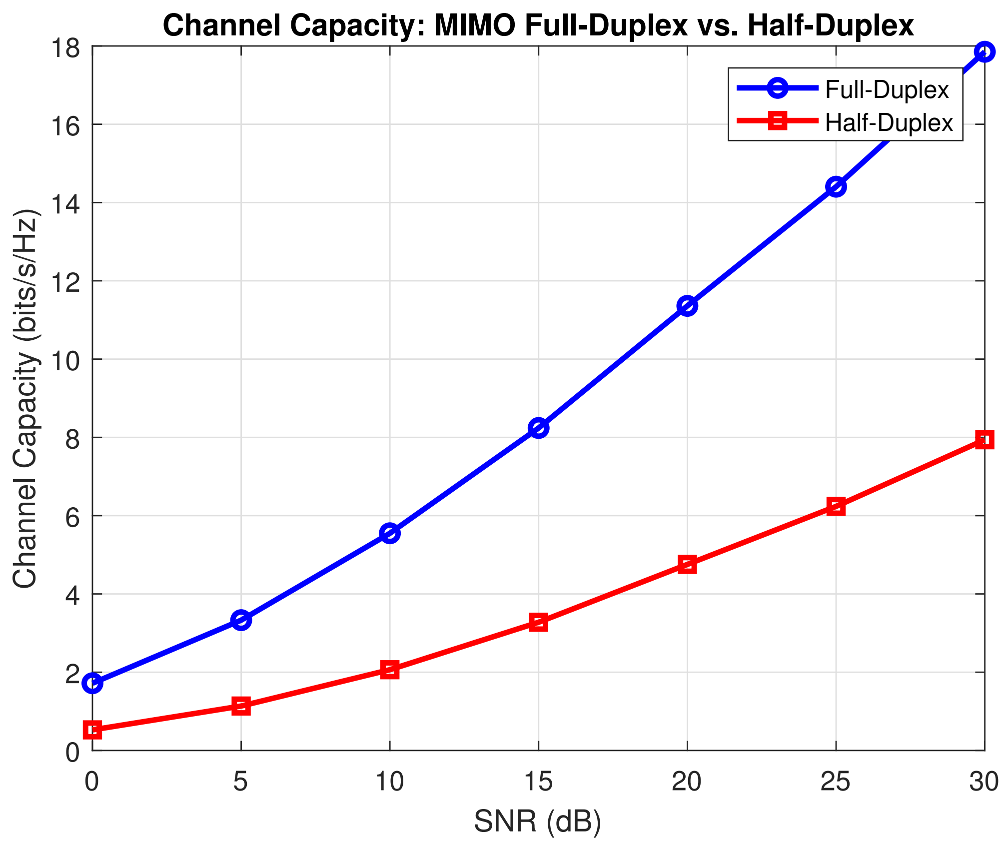

Figure 4.3: MIMO Full-Duplex and Half-Duplex Channel Capacity vs SNR in AWGN.

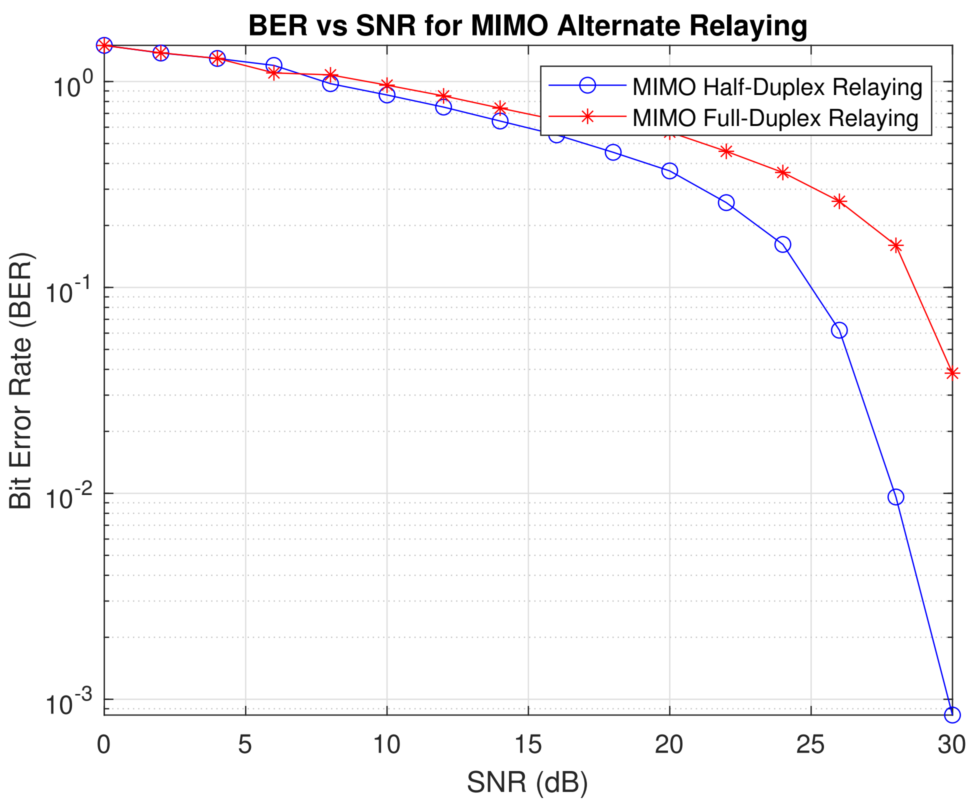

Figure 4.4: MIMO Full-Duplex and Half-Duplex BER vs SNR in AWGN.

Chapter 5

Conclusion

5.1 Summary and Conclusion

This thesis analyzed MIMO full-duplex systems, focusing on signal processing at relays and virtual MIMO data detection for MIMO full-duplex systems. In Chapter 3, we demonstrated the underlying principles of MIMO systems and their operations in full-duplex mode, looking at how precoding techniques and SVD-based optimization can be applied to increase spectral efficiency and reduce interference. Chapter 4 investigated the mathematical frameworks governing signal alignment and reception in 2-D spaces at relays R_1 and R_2. The equations were formulated to understand how signals from multiple transmitters can be aligned in a 2-D space for better reception.

5.2 Contributions

Before highlighting specifics, the uniqueness of the research problem should be stressed, along with the methodologies developed to address it. Our work fills a significant gap in the existing literature and provides a foundation for subsequent research in the field.

1. **Methodological Framework**: Presented a mathematical framework that enables better signal alignment in a 2-D space at the relays, which has the potential to optimize the performance of MIMO full-duplex systems.

2. **Virtual MIMO Data Detection**: Introduced a novel approach to decoding received signals in a MIMO full-duplex system that utilizes the concept of virtual MIMO and accounts for the time-varying nature of the full-duplex system.

3. **Null Space Data Separation and Detection**: Developed an innovative approach to separating and detecting signals in the null space. This offers

an additional degree of freedom for improving performance and enhances the system's resistance to co-channel interference.

4. **BER Performance**: Contributed to the literature by offering a comprehensive BER performance evaluation of MIMO full-duplex systems in AWGN channels, thus providing guidelines for future implementations.

5.3 Future Work

While the scope of this thesis is comprehensive, it does not encompass all potential challenges and solutions in MIMO full-duplex systems. Future work should aim to build on the foundational methodologies and insights presented here and could include the following:

1. **Extension to 3-D Space**: The concept of signal alignment in a 2-D space could be extended to 3-D space for further improvement in system performance.
2. **Machine Learning for Optimization**: Machine-learning techniques could be employed for dynamic optimization of the precoding matrices $\mathbf{V}^A$ and $\mathbf{V}^B$.
3. **Real-world Implementation**: The present study focuses mainly on theoretical analysis, but future work could involve real-world implementations and measurements to validate the mathematical models and optimizations proposed.
4. **Inclusion of More Antennas**: Our work considered a 2×2 MIMO system; extending this to $M \times N$ antennas could offer further system benefits.
5. **Other Channel Models**: The BER performance evaluation could be extended to different channel models, such as Rayleigh and Rician, for a broader analysis.

Appendix A

Analysis of BPSK Modulated Signals and XOR Operation in Simultaneous Transmission

The purpose of this appendix is to explain the ternary (3-level) representation for the received signal at the relay with signal alignment, and how this ternary signal is remapped at the relay into the bit representation of $c_1 = a_1 + b_1$.

In analyzing the BPSK modulated signals, we get the following.

For a_1:

$$a_1 = 0 \implies x_1^a = \cos(2\pi f_c t)$$
$$a_1 = 1 \implies x_1^a = -\cos(2\pi f_c t)$$

Similarly, for b_1:

$$b_1 = 0 \implies x_1^b = \cos(2\pi f_c t)$$
$$b_1 = 1 \implies x_1^b = -\cos(2\pi f_c t)$$

The combined transmitted signal y_R in relation to a_1 and b_1 is:

$$a_1 = 0, b_1 = 0 \implies y_R = 2\cos(2\pi f_c t)$$
$$a_1 = 0, b_1 = 1 \text{ or } a_1 = 1, b_1 = 0 \implies y_R = 0$$
$$a_1 = 1, b_1 = 1 \implies y_R = -2\cos(2\pi f_c t)$$

For the XOR operation on a_1 and b_1, we get:

$$a_1 = 0, b_1 = 0 \implies c = 0$$
$$a_1 = 0, b_1 = 1 \implies c = 1$$
$$a_1 = 1, b_1 = 0 \implies c = 1$$
$$a_1 = 1, b_1 = 1 \implies c = 0$$

For the correspondence between the results of the XOR operation and y_R, we get:

$$\begin{aligned} c = 0 &\implies y_R \in \{2\cos(2\pi f_c t), -2\cos(2\pi f_c t)\} \\ c = 1 &\implies y_R = 0 \end{aligned}$$

This establishes the consistent relation

$$c = a_1 \oplus b_1 \tag{A.1}$$

for all scenarios of the BPSK modulated signals x_1^a and x_1^b.

Appendix B

Data Detection in the Relays

Relays R_1 and R_2

This appendix provides details on the equations that govern the processing of received signals at relays R_1 and R_2. To gain a better understanding of the signal processing, we break down the equations systematically, as follows.

For R_1:

$$\mathbf{y}^{R_1} = \mathbf{H}_{AR_1} \cdot \mathbf{V}^A \cdot \begin{bmatrix} s_1^A \\ s_2^A \end{bmatrix} + \mathbf{H}_{BR_1} \cdot \mathbf{V}^B \cdot \begin{bmatrix} s_1^B \\ s_2^B \end{bmatrix}. \tag{B.1}$$

and for R_2:

$$\mathbf{y}^{R_2} = \mathbf{H}_{AR_2} \cdot \mathbf{V}^A \cdot \begin{bmatrix} s_1^A \\ s_2^A \end{bmatrix} + \mathbf{H}_{BR_2} \cdot \mathbf{V}^B \cdot \begin{bmatrix} s_1^B \\ s_2^B \end{bmatrix}. \tag{B.2}$$

Where when transmitting to different relays, A and B are using different precoding matrices. In both equations, the first term captures the influence of transmitter A and the second term represents the impact of transmitter B.

Similar to the half-duplex case, we introduce matrices $\mathbf{D_1}'$, $\mathbf{D_1}''$, $\mathbf{D_2}'$, and $\mathbf{D_2}''$ for each relay, which are the results of combining the channel matrices and the precoded vectors for each transmitter.

For R_1:

$$\mathbf{D_1}'_{R1} = \mathbf{H}_{AR_1} \cdot \mathbf{v}_{1R1}^A, \tag{B.3}$$

$$\mathbf{D_1}''_{R1} = \mathbf{H}_{BR_1} \cdot \mathbf{v}_{1R1}^B, \tag{B.4}$$

$$\mathbf{D_2}'_{R1} = \mathbf{H}_{AR_1} \cdot \mathbf{v}_{2R1}^A, \tag{B.5}$$

$$\mathbf{D_2}''_{R1} = \mathbf{H}_{BR_1} \cdot \mathbf{v}_{2R1}^B. \tag{B.6}$$

and for R_2:

$$\mathbf{D_1}'_{R2} = \mathbf{H}_{AR_2} \cdot \mathbf{v}^A_{1R2}, \tag{B.7}$$

$$\mathbf{D_1}''_{R2} = \mathbf{H}_{BR_2} \cdot \mathbf{v}^B_{1R2}, \tag{B.8}$$

$$\mathbf{D_2}'_{R2} = \mathbf{H}_{AR_2} \cdot \mathbf{v}^A_{2R2}, \tag{B.9}$$

$$\mathbf{D_2}''_{R2} = \mathbf{H}_{BR_2} \cdot \mathbf{v}^B_{2R2}. \tag{B.10}$$

Similar to the half-duplex case, we want to align the signals in 2-D space to recover c_1 and c_2 at each relay. Therefore, we adjust $\mathbf{V}^A_{R1}$ and $\mathbf{V}^B_{R1}$ as well as $\mathbf{V}^A_{R2}$ and $\mathbf{V}^B_{R2}$such that:

$$\mathbf{D_1}'_{R1} = \mathbf{D_1}''_{R1}, \quad \mathbf{D_2}'_{R1} = \mathbf{D_2}''_{R1}, \tag{B.11}$$

$$\mathbf{D_1}'_{R2} = \mathbf{D_1}''_{R2}, \quad \mathbf{D_2}'_{R2} = \mathbf{D_2}''_{R2}. \tag{B.12}$$

In their corresponding time slots for each relay for each relay, we can then represent the received signal $\mathbf{y}^{R1}$ and $\mathbf{y}^{R2}$ as a linear combination of the transmitted symbols:

$$\mathbf{y}^{R_1} = (s^A_1 + s^B_1) \cdot \mathbf{D_1}_{R1} + (s^A_2 + s^B_2) \cdot \mathbf{D_2}_{R1}, \tag{B.13}$$

$$\mathbf{y}^{R_2} = (s^A_1 + s^B_1) \cdot \mathbf{D_1}_{R2} + (s^A_2 + s^B_2) \cdot \mathbf{D_2}_{R2}. \tag{B.14}$$

Finally, the relays in their respective time slots can recover c_1 and c_2 by using the inverse of the effective channel matrix:

$$\begin{bmatrix} s^A_1 + s^B_1 \\ s^A_2 + s^B_2 \end{bmatrix}_{R1} = \begin{bmatrix} \mathbf{D_1}_{R1} & \vdots & \mathbf{D_2}_{R1} \end{bmatrix}^{-1}_{R1} \cdot \mathbf{y}^{R_1}, \tag{B.15}$$

$$\begin{bmatrix} s^A_1 + s^B_1 \\ s^A_2 + s^B_2 \end{bmatrix}_{R2} = \begin{bmatrix} \mathbf{D_1}_{R2} & \vdots & \mathbf{D_2}_{R2} \end{bmatrix}^{-1}_{R2} \cdot \mathbf{y}^{R_2}. \tag{B.16}$$

Appendix C

Null Space Concept

In order to find solutions for $\mathbf{v}_1^A$ and $\mathbf{v}_1^B$ in terms of $\mathbf{H}_{AR}$ and $\mathbf{H}_{BR}$, we can satisfy the matrix relation as:

$$\mathbf{H_{AR}}.\mathbf{v}_1^A = \mathbf{H_{BR}}.\mathbf{v}_1^B \tag{C.1}$$

which can also be written as:

$$\begin{bmatrix}\mathbf{H_{AR}} & \vdots & -\mathbf{H_{BR}}\end{bmatrix} \cdot \begin{bmatrix}\mathbf{v}_1^A \\ \mathbf{v}_1^B\end{bmatrix} = \begin{bmatrix}0 \\ 0\end{bmatrix} \tag{C.2}$$

where the matrix $\begin{bmatrix}\mathbf{H_{AR}} & \vdots & -\mathbf{H_{BR}}\end{bmatrix}$ has the dimensions 2×4.
We also need to find $\mathbf{v}_2^A$ and $\mathbf{v}_2^B$ to satisfy:

$$\mathbf{H_{AR}}\mathbf{v}_2^A = \mathbf{H_{BR}}\mathbf{v}_2^B \tag{C.3}$$

which can be written as

$$\begin{bmatrix}\mathbf{H_{AR}} & \vdots & -\mathbf{H_{BR}}\end{bmatrix} \begin{bmatrix}\mathbf{v}_2^A \\ \mathbf{v}_2^B\end{bmatrix} = \begin{bmatrix}0 \\ 0\end{bmatrix} \tag{C.4}$$

Next, we introduce the row vectors $\mathbf{a}$ and $\mathbf{b}$, as follows:

$$\begin{bmatrix}\mathbf{H}_{AR} & \vdots & \mathbf{H}_{BR}\end{bmatrix} = \begin{bmatrix}\mathbf{a} \\ \cdots \\ \mathbf{b}\end{bmatrix} \tag{C.5}$$

Where $\mathbf{a}$ and $\mathbf{b}$ have dimensions of 1×4 and $\begin{bmatrix}\mathbf{a} \\ \cdots \\ \mathbf{b}\end{bmatrix}$ represents the stacking of the row vectors.

We now introduce vectors P and Q:
Vectors **a** and **b** in 4-D can be expressed as linear combinations of two vectors, **P** and **Q**:

$$\mathbf{P} = \begin{bmatrix} \mathbf{v_1^A} \\ \mathbf{v_1^B} \end{bmatrix} \tag{C.6}$$

$$\mathbf{Q} = \begin{bmatrix} \mathbf{v_2^A} \\ \mathbf{v_2^B} \end{bmatrix} \tag{C.7}$$

Vectors **P** and **Q** are of size 4×1 (because $\mathbf{v}_1^A$ and $\mathbf{v}_1^B$ are of size 2×1). With these definitions of **a**, **b**, **P** and **Q** in the 4-D space, the relations in(C.2) and (C.5)can be rewritten as:

$$\begin{aligned} \mathbf{a} \cdot \mathbf{P} &= 0 \\ \mathbf{b} \cdot \mathbf{P} &= 0 \\ \mathbf{a} \cdot \mathbf{Q} &= 0 \\ \mathbf{b} \cdot \mathbf{Q} &= 0 \end{aligned} \tag{C.8}$$

Original requirement in (C.2) requires solving two linear homogeneous equations for four unknowns in vector $[v_1^A \; v_1^B]$, Which now is going to be interpreted as finding the null space (vector **P**) for the matrix

$$[\mathbf{H_{AR}} : -\mathbf{H_{BR}}]$$

The requirement in (C.3) is going to be interpreted as finding another null space for the same matrix

$$[\mathbf{H_{AR}} : -\mathbf{H_{BR}}].$$

Knowing **a** and **b** (channel gain coefficients), the objective is to find **P** and **Q** satisfying C.8. This is feasible because there are four orthogonal vectors in 4-D, and we can always form **P** and **Q** orthogonal to **a** and **b** (**a** and **b** define a 2-D plane, and there are two orthogonal vectors in 4-D to this plane). The null space of a matrix is a subspace of the vector space in which the matrix operates. It consists of all vectors that, when multiplied by the matrix, result in the zero vector.

For a matrix D, the null space, denoted as null(D), is defined as:

$$\text{null}(D) = \{\mathbf{x} \mid D\mathbf{x} = \mathbf{0}\} \tag{C.9}$$

Here, $\mathbf{x}$ represents a vector and $\mathbf{0}$ is the zero vector in the appropriate vector space. The null space can be characterized as the set of all solutions to the homogeneous equation $D\mathbf{x} = \mathbf{0}$, where $\mathbf{0}$ is a zero vector of appropriate dimensions. In practical terms, finding the null space is essential in solving systems of linear equations and understanding the linear independence of vectors. It helps determine the solutions to underdetermined systems and is a fundamental concept in linear algebra.

Consider the following 2x4 matrix:

$$D = \begin{bmatrix} \mathbf{a} \\ \mathbf{b} \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_3 & a_4 \\ b_1 & b_2 & b_3 & b_4 \end{bmatrix} \tag{C.10}$$

We want to find the null space of matrix D, which is the set of all vectors $\mathbf{x}$ such that $D\mathbf{x} = \mathbf{0}$, where $\mathbf{0}$ is the zero vector. In other words, we're looking for solutions to the equation:

$$D\mathbf{x} = \mathbf{0} \tag{C.11}$$

To find the null space, we set up the augmented matrix $[D|\mathbf{0}]$ and perform Gaussian elimination to row-reduce it to echelon form. The specific coefficients $a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4$ will determine the properties of the null space.

The null space of matrix D will consist of vectors in the form:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{C.12}$$

where x_1, x_2, x_3, and x_4 can be any real numbers, and $a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4$ are parameters representing the coefficients in matrix D. The specific values of

$a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4$ will determine the equations and properties of the null space. To find the null space for $[\mathbf{H_{AR}} : -\mathbf{H_{BR}}]$ in this thesis, we used the MATLAB function `null`.

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