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ÉTUDE DU RELAIS FULL-DUPLEX DANS LES ENVIRONNEMENTS INTÉRIEURS

STUDY OF FULL-DUPLEX RELAY IN INDOOR ENVIRONMENTS

MÉMOIRE

PRÉSENTÉ

COMME EXIGENCE PARTIELLE

DE LA MAÎTRISE EN INGÉNIERIE

PAR

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DEDICATION

This work is dedicated to my family, Research director, friends, thesis committee, and the staff of the Université du Québec en Abitibi-Témiscamingue (UQAT), School of Engineering. The endless support I have received from all parties allowed me to complete this and without their help, I'd have given up long ago.

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LIST OF ABBREVIATIONS

3GPP	Third Generation Partnership Project
AF	Amplify-and-forward
AWGN	Additive white Gaussian noise
BER	Bit error rate
BF	Beamforming
BPSK	Binary phase-shift keying
CCI	Co-Channel Interference
CR	Cognitive Radio
CSI	Channel state information
D	Destination
dB	Decibels
DF	Decode-and-forward
DH	Dual-hop
FD	Full-duplex
FR	Full-rank
HD	Half-duplex
LI	Loopback Interference
LTE	Long Term Evaluation
LTE-A	Long Term Evaluation-Advance
LOS	Line of Sight
MMSE	Minimum Mean Square Error
MIMO	Multiple-input multiple-output
NLOS	Non-Line of Sight
NSP	Null Space Projection
OLOS	Obstructed Line Of Sight
QPSK	Quadrature phase-shift keying
R	Relay

S	Source
SPA	Space Projection Algorithm
SP	Subspace Projection
TSPA	Two Stage Projection Algorithm
SI	Self-Interference
SNR	Signal-to-noise ratio
WSN	Wireless Sensor Network
ZF	Zero-Forcing

ABSTRACT

Expanding the coverage of network with different techniques is necessity and demand of today's life. As the population increases, the demand for more solutions to give more capacity and to reach everyone on the whole world with network also increases. Recent studies have confirmed that interferences, such as co-channel interferences (CCIs) and self-interferences (SIs), have an enormous impact on wireless communication systems and can cause significant performance degradation. Relaying techniques, in which an origin node communicates to the destination node with the help of intermediate node, have been introduced as a cost-effective solution to address the ever growing need for high data rates and available services over the air. As such, it is crucial to design relay systems that can not only provide high spectral efficiency but also fully take advantage of the relay channel diversity.

With this objective in mind, this thesis investigates the SI's and CCI's cancellation techniques for Full-Duplex (FD) Amplify-and-Forward (AF) relay equipped Multiple-Input-Multiple-Output (MIMO) antenna system.

This thesis is concerned to develop an efficient SI cancellation algorithm for MIMO relays in the indoor wireless communication system. Transmit and receive simultaneously the same radio signal create an SI around the relay transceivers due to the loop-back signals. The main challenge of implementing FD-MIMO relay is to mitigate the performance deterioration induce or involve by the SI. This work presents an efficient algorithm for mitigating this SI by using Two Stage Projection Algorithm (TSPA) which consists of two steps called Null Space Projection (NSP) and Subspace Projection (SP) to reduce or cancel the SI. Simulation results show that the SI of the proposed method is efficiently minimize.

RÉSUMÉ

Élargir la couverture des services du réseau aux endroits difficiles et aux régions éloignées est un besoin de plus en plus nécessaire de nos vies quotidiennes actuelles et futures. L'augmentation de la population et la demande accrue de services et de solutions de communication requièrent l'augmentation de la capacité des moyens de communication tout en permettant une couverture plus efficiente et plus étendue des territoires et régions faiblement peuplées dans le Canada et dans monde. Des études récentes ont confirmé que des interférences comme les interférences dans le même canal (ICC) et les interférences mutuelles (SI) ont un impact énorme sur les systèmes de communication sans fil et peuvent entraîner une dégradation significative des performances. Les techniques de relayage, dans lesquelles une source émettrice communique avec un récepteur destinataire l'aide d'un nœud intermédiaire, ont été introduites comme des solutions pour répondre au besoin croissant de débits plus élevés et de couverture étendu pour les communications sans fil. En tant que tel, il est essentiel de concevoir des systèmes de relais capables non seulement d'offrir une grande efficacité spectrale du signal radio, mais aussi de bénéficier pleinement des facilités de la diversité antennaire. Pour répondre à cet objectif, ce mémoire présente une étude sur une technique originale de réduction et d'annulation des interférences induite par un relayage quasi instantané sur un même signal radio en utilisant les antennes multiples du relais. Transmettre et recevoir simultanément le même signal radio au niveau du relais, créent une auto-interférence en raison des signaux de bouclage. Le défi principal de la mise en œuvre du relais est d'atténuer et d'annuler la destruction ou la perte de l'information relayée. L'originalité de du travail réside dans la proposition d'un algorithme efficace utilisant une double projection l'une à l'entrée du relais et une autre à la sortie du relais. Les résultats obtenus démontrent une réduction significative des interférences comparativement à d'autres travaux.

CHAPTER 1

INTRODUCTION

Wireless communication is one of the very few inventions which has been able to shrink the world in an exceptional manner. The standards that define how wireless communication contrivances interact are expeditiously converging and will sanction the building of a global wireless network that will distribute a broad range of services.

Recent communication system operates over a wide variety of communication channels including a convoluted pair of wires, coaxial cable, optical fibers, and wireless channels. All practical channels introduce some distortion, noise, and interference. Wireless communication systems face incrementing challenges due to the ever-growing demand for high data rates and Feasible services over the air.

Modern wireless Communication is the fastest rising and most vibrant high-tech areas in the communication arena. Current wireless communication systems face increasing challenges for high data rates, reliable communications, coverage enhancements, and less power requirements. Multiple-input multiple outputs (MIMO) is an antenna system for communications in which antennas are used at both transmitter and receiver. Relays that receive and transmit the signal between the sources and destinations to increase the throughput extend coverage of communication links. MIMO relaying can be recognized as an effective candidate increase the data rate, provide reliable communication and enhance the wireless communication coverage. Cooperative FD-MIMO relaying scheme provides a promising technique to enhance coverage area, system reliability, the throughput of wireless communication system.

Cooperative relaying is a novel technique for wireless communications promising gains in throughput and energy efficiency. In cooperative relaying techniques, the relay nodes provide support in transmission from one node to another node. In [1-4], a cost-effective method has been proposed to fulfill some of the demands in the future wireless network system where there is no communication link between one nodes to another node or the link is weak. In particular, in the context of cellular networks, the adaptation of relay technology [5], the interface environment becomes increasingly complex.

The deployment of relay node has been shown to extend coverage, fill coverage hole, enhance reliability, and improve spectral efficiency per unit area. This can be achieved without installing high costly extra base stations, e.g., site acquisition and backhaul cost. As, relaying is one of the key features currently being considered in several wireless standards such as 3GPP, LTE, etc., it is essential for future wireless standards to have relay schemes that not only increase the reliability of the wireless network but also present a high spectral efficiency [6-7].

In the cooperative relaying communication system, due to the broadcast nature of wireless transmission, few nodes in the network link may listen to the transmitted signal from the source end. When a direct communication between the source and destination fails, the channel variations of those nodes keep a copy of the transmitted signal. This could help to re-transmit the source signal to the destination. The relay mainly can function in two different approaches: The Amplify-and-Forward (AF) relay and the Decode-and- Forward (DF) relay. The AF relay amplifies the received signal and then forwards it to the destination. The DF relay first decode and re-encode the received signal and then send it to the destination.

1.1. Research Problematic

In wireless communication system, interferences have a significant impact on a wireless system's performance, and it causes the performance degradation of the system. Interferences occur when unwanted signals interrupt wireless communication, including multipath propagation, shadowing, channel fading, Doppler shift, noise, path loss, and loopback self-inference etc. The multipath propagation loss and the loopback interference are the main reasons of performance degradation. The multipath propagation phenomenon that marks in wireless signals reaching the receiving antenna by non-line-of sight (NLOS). The effects of multipath comprise of constructive and damaging interference and phase shifting of the signal. In digital telecommunications, multipath can cause errors and affect the quality of communications. A relaying technique plays a vital role to overcome this problem. But it also suffers from loopback SIs, CCIs when the simultaneous data transmission and reception occurs in the same frequency channel.

1.2 SI Cancellation Techniques: A Review

This an ineluctable interrogation for SI cancellation techniques in full-duplex is what is the propagation characteristics of SI channel. Previously many scheme has been applied prior to low noise amplifier or analog-to-digital converter techniques. Proper SI cancelation techniques requires a clear understanding of SI channel propagation characteristics and modeling. The SI channel has diverse characteristics of propagation pf forward channel A few preliminary studies concerning propagation characterization of SI channel have been described. In [8], A FD relay SI channel are measured at 2.6GHz for outdoor-to-indoor communications. The measurement was done for two different cases: a solid relay and separate relay. Especially, for a separate relay scenario, relation of antenna suppression and separation distance is investigated. In [9], indoor mobile single-input-single output (SISO) SI channel propagation characteristics of a shared single omni-dipole antenna with circulator are studied, signifying that the corresponding SI channel power delay profile has three components: leakage path and reflection due to antenna port mismatch, space multipath due to surrounding environment. In [10], the SI channel and antenna suppression of SISO bandwidth in various circumstances are analyzed for ultra-wideband 3GHz to 10GHz. In [11], the authors are studied the performance of self-interference cancellation, where some parts are related to the SI channel characteristics. They are tried to find the environmental reflections limit cancellation performance that passive SI suppression can achieve. Authors in [12], assume that the SI channel is Ricean distributed and characterize K-factor for the SI channel prior to RF cancellation, after RF cancellation, and after digital baseband cancellation. However, little attention has been paid to MIMO FD SI channel. The FD SI cancelation technique can be implemented via digital and analog approach. For the digital approach, the transmit signal in digital baseband and properly reconstruct SI by adjusting the attenuation and phase accordingly. The reconstructed SI signal is converted/up-converted to RF analog domain, and combined with SI signal prior to low noise amplifier via a coupler [13-17]. For analog cancellation approach, one of the most widely used approaches is multi-tap structure, which is similar to analog FIR filter. In [19-20], authors propose a 12-tap Analog SI cancellation with variable attenuator and fixed delay line for shared single antenna circulator configuration, working with the wide bandwidth, 80MHz, and data rates used by the latest 802.11ac in the 2.4GHz spectrum. In addition, RF/Analog SI cancellation will introduce nonlinear distortion due to higher transmitted power, which effectively increases the receiver noise. Authors in [21, 22] try to solve this problem by proposing RF/Analog SI cancellation nonlinear suppression technology, in which the nonlinear distortion is modeled by memory polynomial. In the subsequent cancellation stages, the model estimations are subtracted instantaneously from the received signal containing nonlinear distortions. Also, the authors are conducted on AF relay system has ignored the CCIs in [22-26]. However, in practice, the system’s achievable performance is inevitably degraded by CCIs generated by external interfering sources. Moreover, in [27-35], the analyses are limited to interference model and proposed interference cancellation algorithms to reduce or cancel the interferences. Despite all of the approaches as mentioned above, complete cancellation of the interference signal has not been achieved to date.

1.2. *Contribution of Thesis*

In future wireless networks require relaying protocols that can fully exploit the channel as well as provide high spectral efficiency. Motivated by this fact, the objective of this thesis is to investigate the loopback interference around the relay and a mathematical method to analyze the performance of the relay system in the presence of inferences. We proposed a two-stage projection algorithm (TSPA) to cancel the loopback interference around the relay.

1.3. *Structure of Thesis*

The rest of the thesis is structured as follows:

Chapter 2 provides some background material and introduces important concepts which will be used throughout the thesis.

In the next chapter we introduce cooperative communications and outlines the used protocols as well as the different techniques.

Chapter 4 presents a mathematical analysis of dual-hop amplify-and-forward FD-MIMO relaying system in the presence of interferences. Moreover, in this chapter we discuss the proposed approach in detail to cancel the SI.

In chapter 5 the simulations are carried out and based on the proposed approach. The BER, SNR and performance metrics are also included in this chapter.

Finally, Chapter 6 concludes the thesis by reaffirming our contributions and further studies.

CHAPTER 2

WIRELESS COMMUNICATION

2.1. Introduction

Wireless communication systems are the fastest developing technologies in communications commerce over the past few decades due to the massive demand for mobile access. The first inauguration of wireless communications was back in 1895 when Guglielmo Marconi transmitted a three-dot Morse code for the letter 'S' over a distance of 3 kilometers using electromagnetic waves [36]. Then, wireless communication has gone through an outstanding development regarding combined circuitry and scientific advances to the complex networks which we have now. From satellite transmission, radio and television broadcast to the continuing development of 4G for mobile communications all stimulated by the never-ending quest for higher throughput, reliability, faster data transfer and cost efficiency. Exploiting the technical development in radio hardware and integrated circuits, which allow for the implementation of more complicated communication schemes, would require an evaluation of the fundamental performance restrictions of wireless networks [37].

The wireless network system can usually be observed as a set of links trying to communicate with each other. However, the broadcast nature of wireless channels, one may think of those links as a set of antennas distributed in the wireless system. Transmission between these antennas suffers from much degradation which inspires considerable research on how to effectively combat these adverse effects that impair signal transmission. Cooperative relaying is one of the techniques that could combat these problems. It is a unique technique for wireless communications systems, which helps to have promising gains in throughput and spectral efficiency. The simple idea of cooperative relaying is: A device transmits a signal to a destination. The third device listens to this transmission and relays the message to the target. Then the destination combines these received signal to improve decoding. Some of these channel problems will be outlined for a clearer understanding of the Cooperative Communication methodology [36,37].

2.2. Channel Impairments

The conditions or factors that degrade or disturb the communication between the source to destination is called channel impairments. We are going to discuss the channel impairments factors as given below:

2.2.1. Path Loss

In a wireless communication system, where a transmitter communicates with a receiver by sending an electromagnetic signal via a wireless medium, the strength of the signal attenuates as it traverses the medium and, thus, becomes weaker as the propagation distance increases. Beyond a certain distance, the attenuation becomes unacceptably great, and repeaters or amplifiers would be required to boost the signal at regular intervals. These problems are more complicated when there are more than one receivers, where the distance from the transmitter to receiver is variable [37]. The amount of degradation in the signal strength concerning the distance can be characterized by the ratio between the transmitted power, P_t and the received power, P_r which is denoted by [38]:

$$P_L = \frac{P_t}{P_r} \tag{2.3}$$

This ratio is used to quantify the effect of path loss, and the value may depend on the geographic environment as well as certain radio properties, such as the spaciousness of the environment, the transmission distance, the radio wavelength, heights of the transmitter and receiver, etc. The path loss is usually represented in decibels by:

$$P_L(db) = 10log_{10}\frac{P_t}{p_r} \tag{2.4}$$

Several path loss models exist, such as, the free space model, two-ray model, log-normal model, etc. [64].

2.2.2. Free Space Path Loss Model

In wireless communication networks, electromagnetic waves propagating through free space practice an attenuation or reduction in power density. This phenomenon is known as path loss and is caused by many factors which include absorption, diffraction, reflection, refraction, the distance between transmitter and receiver, height and location of the antenna, atmospheric conditions moisture in air and knife edge scenarios, including vegetation and trees.

For an ideal isotropic antenna, free space path loss could be calculated using the formula [37]:

$$\frac{P_t}{p_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{C^2} \tag{2.5}$$

Where:

P_t= signal power at the transmitting antenna

P_r= signal power at the receiving antenna

λ= carrier wavelength

f = carrier frequency

d = propagation distance between antennas

c = speed of light $(3 \times 10^8 m/s)$

Considering non-isotropic antennas where their gain is taken into consideration, the following equation is used:

$$\frac{P_t}{P_r} = \frac{(4\pi)^2}{G_r G_t}\frac{(d)^2}{\lambda} = \frac{(\lambda d)^2}{A_r A_t} = \frac{(Cd)^2}{f^2 A_r A_t} \tag{2.6}$$

Where:

G_t= gain of the transmitting antenna

G_r= gain of the receiving antenna

A_t = effective area of the transmitting antenna

A_r = effective area of the receiving antenna

From the above relation, the received signal power is contrariwise related to the distance between the source and the destination. It implies that the closer the receiver or relay to the source, the greater is the detected power of the signal [37]. Howsoever, real-life conditions are not "free space." Since the earth acts as a reflecting surface, other severe models may apply [38].

2.2.3. Shadow fading Model

In communication system, fading may either be due to multipath propagation, referred to as multipath induced fading, weather received signal strength fluctuation around the mean value due to radio signal blocking by buildings (outdoor), walls (indoor), and shadow from obstacles affecting the wave propagation, sometimes referred to as shadow fading. When the received signal shadowed by observations such as buildings, hills or walls, it results in variation of local mean received power.

$$P_r\,(dB) = \overline{P_r}(dB) + G_s$$

Where $\overline{P_r}(dB)$ is received signal power due to the path loss.

2.2.4. Multipath Propagation

In a mobile wireless communication system, a signal can be transmitted from source to destination through multiple reflective paths which are known as multipath propagation and is demonstrated in Figure 2.1. Multipath propagation causes instabilities in signal's amplitude, phase and angle of arrival creating multipath fading. The three (surface reflection, direct path, and bottom reflection) propagation mechanisms plays a role in the multipath fading:

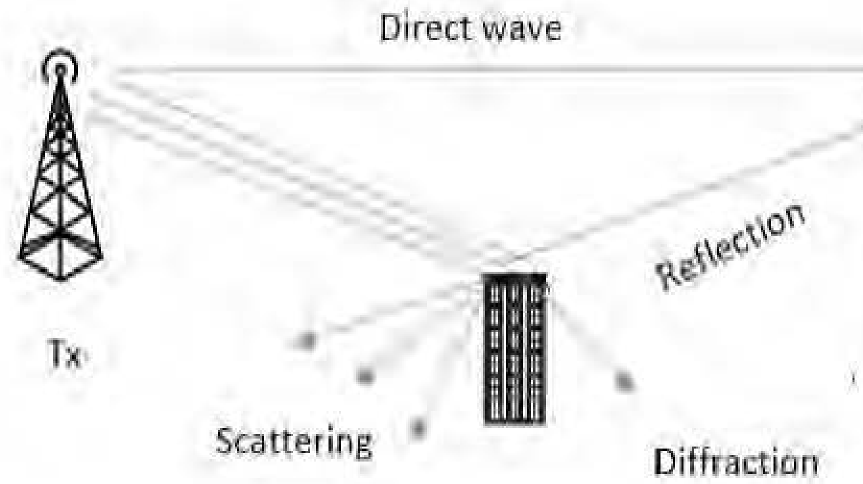


Fig.2.1: Illustration of multipath, reflection, refraction, scattering, diffraction of a radio wave

2.2.4.1.Reflection

It occurs when a propagating electromagnetic signal encounters a smooth surface that is large relative to the signal's wavelength. An indication of this is shown in Figure 2.1.

2.2.4.2.Diffraction

It occurs at the edge of a dense body which is larger compared to the signal's wavelength as indicated in Figure 2.1. It is termed shadowing for as much as the signal can reach the receiver even if it encounters a compact body

2.2.4.3.Scattering

It occurs when the propagating radio wave encounters a surface with dimensions on the order of the signal's wavelength or less and causes the incoming signal to spread out (scatter) into several weaker outgoings in all directions.

2.2.5. Doppler Effect

In wireless system, the Doppler Effect is the relative motion between the transmitter and the receiver causes Doppler shifts. Local scattering typically comes from many angles around the mobile. This scenario causes a range of Doppler shifts, known as the Doppler spectrum. The maximum Doppler shift corresponds to the local scattering components whose direction exactly opposes the mobile trajectory. Due to Doppler spread, fading effects can also be classified as fast fading and slow fading.

2.2.5.1. Fast Fading

It is a scenario where the channel impulse response changes rapidly within the symbol duration. It could also be described as a situation where coherence time of the canal, TD, is smaller than the symbol time of the transmitted signal. Here the channel imposes an amplitude and phase change which varies considerably over the term of use.

2.2.5.2. Slow Fading

Slow fading is the result of shadowing by buildings, mountains, hills and other objects. In this situation, the coherence time of the channel is large relative to the delay constraint of the canal. The channel imposes an amplitude and phase change that is roughly constant over the period of use.

2.2.6. Multipath Fading

Multipath fading is an attribute that needs to be taken into account when designing or developing a wireless system. In wireless Communication system, the signal will reach the receiver not only via the straight path but also as an outcome of reflections from objects such as buildings, hills, ground, water, etc. that are adjacent to the main path.

Multipath fading can affect wireless communications channels in two fundamental ways. This can give the way in which the effects of the multipath fading are mitigated.

2.2.6.1. Flat Fading

Flat fading or non-selective fading occurs when the bandwidth of the transmitted signal B is smaller than the coherence bandwidth of the canal resulting in a situation where all frequency components of the received signal differ in the same ratios simultaneously.

2.2.6.2. Frequency Selective Fading

It is experienced if the bandwidth of the signal is larger than the coherence bandwidth of the channel. De-correlated fading is thus experienced by the different frequency components of the signal.

2.3. Inter-Symbol Interference (ISI)

In wireless communication, ISI is a form of distortion of a signal in which one symbol interferences with subsequent symbols. It is an undesirable phenomenon as the earlier symbols have the similar effect as noise, thus making the communication less reliable. In exercise, communication channels have a limited bandwidth, and hence transmitted pulses are spread during transmission. This pulse spreading can result in an overlap of pulses over adjacent time slots, as shown in Figure 2.2. The signal overlap may lead to an error at the receiver. This phenomenon is referred to as Inter-Symbol Interference (ISI).

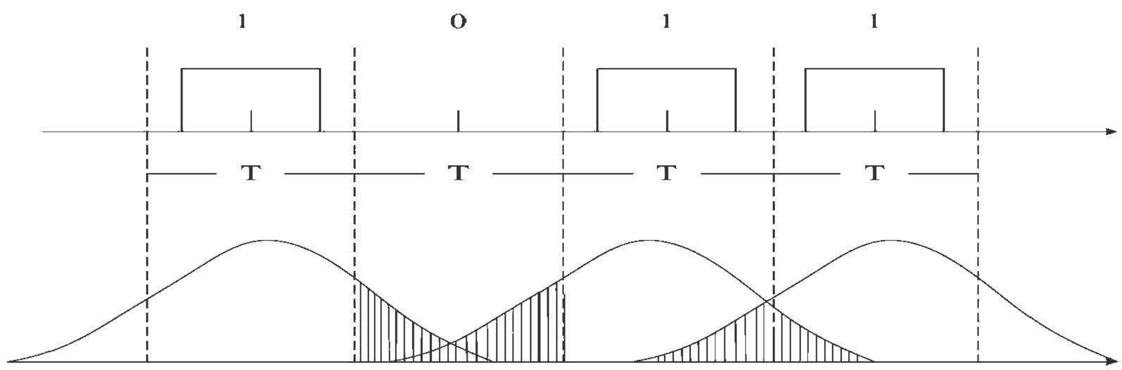


Fig.2.2: ISI in Digital Transmission

2.4. Channel State Information (CSI)

Channel state information (CSI) which represents the state of the communication link from the transmitter to the receiver. The CSI defines how a signal propagates from the source to the destination and signifies the mutual effect of, i.e., scattering, fading, and power delay with distance. The technique is called Channel estimation. The CSI makes it promising to adapt transmissions to current channel conditions, which is vital for attaining reliable communication with high data rates in multi-antenna systems.

2.5. CCI and Feedback

In mobile networks, frequency reuse introduces CCI to the wireless communication system. In a more realistic analysis, it is important to consider CCI effect on the relay constructed communication system. This CCI issue is experienced in both the relay and the destination. Also, in practice, CSI is not perfect. Therefore, it is important to study the systems with imperfect CSI.

2.6. Communication Channel

To design a communication scheme, all issues which may affect the propagation of the signal must be considered. Hence, there is a need to investigate the effects of fading and noise on mobile channels. Some typical communication channels are introduced in the following sub-section.

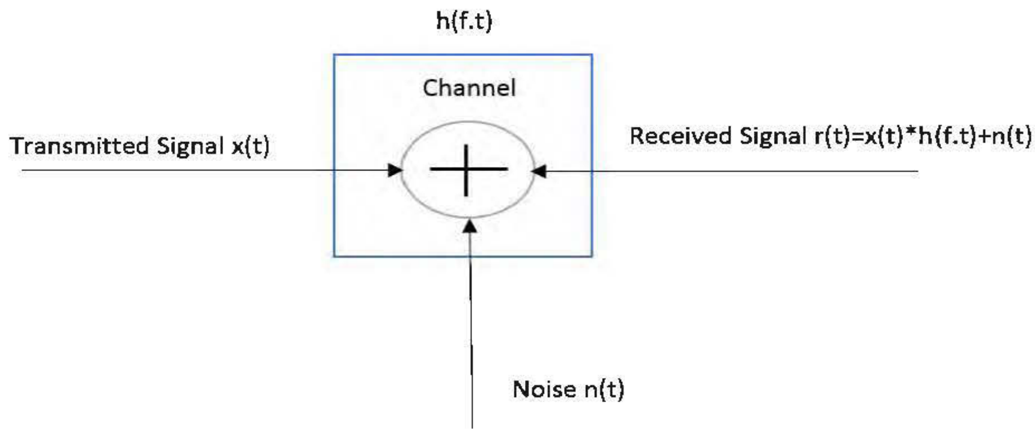


Figure 2.3: The additive noise channel

2.6.1. Additive White Gaussian Noise (AWGN) Channel

In this channel, the only impairment that encounters the propagation of the transmitted signal is the thermal noise, which associated with the physical channel itself, as well as the electronics at, or between, transmitter and receiver. In AWGN channel the signal is demeaned by white noise which has constant spectral density and a Gaussian distribution of amplitude. In this model $h(f.t)$ is always assumed to be $\delta(f.t)$.

2.7. Stationary Channel Model

2.7.1. Rayleigh Fading Channel Model

In this model, channel is considered stationary. This type of fading occurs when there are multiple indirect paths between transmitters and receivers and no clear dominant path, such as an LOS path. It represents a worst-case scenario. It could be dealt with analytically by providing insights into performance characteristics that can be used in challenging environments, such as downtown urban settings. A Rayleigh random variable R has the probability distribution:

$$PR(r) = \frac{2r}{\sigma} * exp\left(\frac{-r^2}{\Omega}\right)$$

Where $\sigma = E(R^2)$

2.7.2. Rician Fading Channel Model

In this model, channel is considered stationary which means that $h(f.t) = h(f)$ for t. Rician fading describes a situation where there is a direct LOS path in addition to several indirect multipath signals and the distribution is found to be Rician. The pdf of such function is given by:

$$PR(r) = \frac{r}{\sigma^2} * exp\left(\frac{-(r^2 + A^2)}{2\sigma^2}\right) I_0\left(\frac{Ar}{\sigma^2}\right), r \geq 0, A \geq 0$$

Where σ^2 is the variance of the in-phase and quadrature components. A is the amplitude of the signal of the dominant path and I_0 is the zero-order modified Bessel function of the first kind.

It is often applicable in indoor environments, smaller cells or more open outdoor environments. The channels can be characterized by a parameter K, defined as follows:

$$K = \frac{Power\ in\ the\ dominant\ path}{Power\ in\ the\ scattered\ path}$$

When K = 0, the channel is experiencing Rayleigh fading (i.e., numerator is zero) and when

K = ∞ the channel is experiencing AWGN (i.e., denominator is zero) [38].

2.7.3. Nakagami-m Fading Chamıel Model

Stationary channel also considered in this model where $h(f.t) = h(f)$ for $t.$ Nakagami-m Fading often applies to land-mobile, scintillating ionospheric and indoor-mobile links. The PDF of Nakagami-m is given by:

$$f_X(x) = \frac{2m^m x^{2m-1}}{\Omega^m \Gamma(m)} * exp - \frac{mx^2}{\Omega} \qquad x \geq 0 \qquad (2.7)$$

Where m is the Nakagami-m fading parameter in range of $\frac{1}{2} \leq m \leq \infty$ and $\Gamma(.)$ is the gamma function defined as:

$$\Gamma(m) = \int_0^\infty x^{m-1} e^{-x} dx$$

In the special case m = 1, Rayleigh fading is recovered from (2.7). For m > 1, the fluctuations of the signal strength reduce compared to Rayleigh fading.

2.8. MIMO Communication System

A MIMO scheme uses multiple antennas at both the transmitter and receiver to improve the communication system performance by use of diversity and multiplexing techniques. MIMO system is a cost effective and it provides higher spectral efficiency, improve throughput capacity, and advances the reliability, and improved resistance to interference [39].

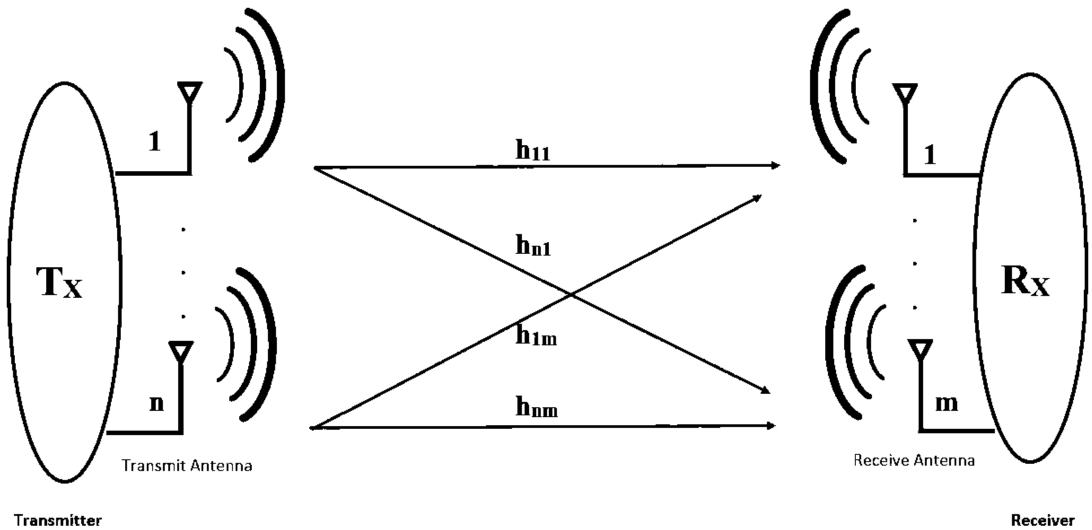


Figure 2.4: MIMO Communication system.

There are three key MIMO techniques that have been proposed in the literature, such as, precoding, spatial multiplexing, and diversity coding. Precoding is a technique that uses the knowledge of CSI at the transmitter and the receiver to design precoder for multi-stream beamforming. In a situation where CSI is not available at the transmitter, diversity coding can be used to achieve better diversity gain like MRC system. In diversity coding method, the signal is transmitted by applying space-time coding at the transmitter.

A Basic MIMO system is illustrated in Figure 2.4. This MIMO system consists of n transmit antennas and m received antennas. The channel between the i th receive antenna and the jth transmit antenna is denoted as h_{ij} . Therefore, received signal can be modeled as:

$$y = H_x + n \tag{2.8}$$

Where y is the received signal vector, x transmitted signal vector, n is the noise vector and H is the channel matrix where each (i, j) component represent the h_{ij} .

2.9. Signal Encoding Technique

2.9.1. BPSK Modulation

BPSK is a simple form of phase shift keying which uses two phases, each separated by 180°. This modulation technique is the most robust of all PSKs since it requires the maximal level of noise or distortion to commit the demodulator achieve a wrong decision. However, it only modulates at 1bit/symbol which makes it quite unsuitable for high data-rate applications in limited bandwidth cases. The demodulator is usually unable to tell which constellation point is which when there is an arbitrary phase-shift introduced by the communications channel thus data is often differentially encoded before modulation [40].

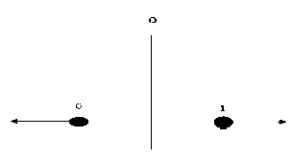


Figure 2.5: Signal constellation diagram for BPSK

The BER of BPSK in AWGN can be written as:

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \quad or \quad P_b = \frac{1}{2}erf_c\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{2.9}$$

Since there is only one bit per symbol, this is also the symbol error rate.

Where:

- E_b = Energy-per-bit
- E_s = Energy-per-symbol = nE_b with n bits per symbol
- T_b = Bit duration
- T_s = Symbol duration
- $\frac{N_0}{2}$= Noise power spectral density (W/Hz)
- P_b= Probability of bit-error

- S_b = Symbol of bit b

2.9.2. QPSK Modulation

QPSK modulation technique uses four points on the constellation diagram, equispaced around a circle with all phases and can encipher two bits per symbol. When analyzed mathematically, it can be shown that BPSK can be used to twofold the information rate compared with a BPSK scheme while maintaining the same bandwidth of the signal or to retain the data rate of BPSK but halving the bandwidth needed. Due to bandwidth limitations, QPSK has an advantage because it transmits twice the data rate in a given bandwidth than BPSK does at the same BER. The only demerit is that QPSK transmitters and receivers are quite complicated thus more expensive. Contrasting encoded QPSK is often used in practice to counter the phase ambiguity problems at the receiving end [41].

As a result, the probability of bit-error for QPSK is the same as for BPSK:

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

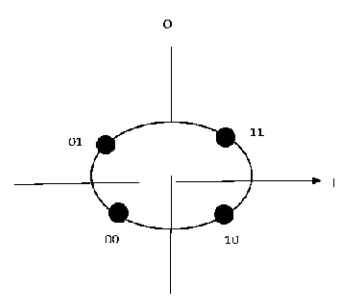


Figure 2.6: Signal constellation diagram for QPSK

However, to achieve the same bit-error probability as BPSK, QPSK uses twice the power (since two bits are transmitted simultaneously). The symbol error rate is given by:

$$P = 1 - (1 - P_b)^2$$
$$= 2Q\left(\sqrt{\frac{E_S}{N_0}}\right) - Q^2\left(\sqrt{\frac{E_S}{N_0}}\right) \quad (2.10)$$

If the SNR is high (as is compulsory for practical QPSK systems) the probability of symbol error may be approximated as:

$$P_S \approx 2Q\left(\sqrt{\frac{E_S}{N_0}}\right) \quad (2.11)$$

CHAPTER 3

RELAY AND COOPERATIVE COMMUNICATION

3.1. *Introduction*

The progress of wireless communications from analog to digital led to the enhancement of early propagation models, which provided information about power, to also consider time and delay information. Further consideration of the space domain either with space diversity or smart antennas or, nowadays, MIMO systems has also pushed the evolution of propagation modeling toward more complex spatiotemporal considerations. In wireless communication, users often suffer from channel fading where the signal attenuation varies significantly over the transmission. This can be overcome using proper diversity methods such as spatial, temporal, and frequency diversity. Achieving same collaboration between distributed relay nodes that help to establish a communication link between an origin transmitting node and a destination receiving node. Several theoretical studies have been carried out on cooperative communication, and these studies suggest that cooperation required less transmitted power at the origin and the relay node. It makes cooperative diversity is interference less and a power efficient communication method. Also, it enhances the coverage and the throughput of the system [42-45].

In this work, we study dual hop transmission, which is a three-node network consisting of a source, a destination, and a relay. Figure 3.1 illustrates a simple schematic of the dual hop communication system. Here, fading channels source-relay, relay-destination, and source-destination are denoted as h_{sr},h_{rd} and h_{sd}, respectively. For this system, received signal at the relay node can be obtained as: [46].

$$y_{sr} = \sqrt{P_s} h_{sr} x + n_r$$

Where P_s is the average transmit power at the source, x is the signal transmitted at the source and n_r is the noise at the relay.

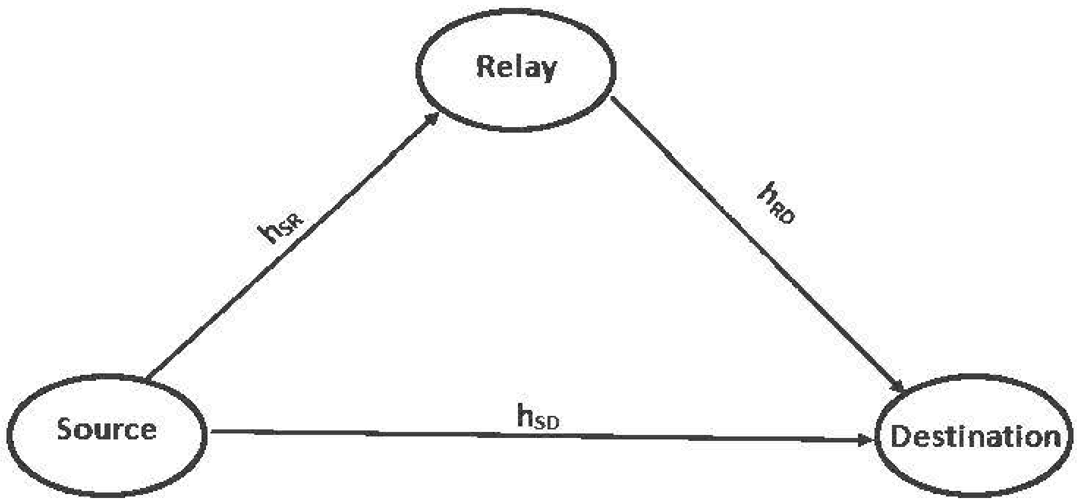


Figure 3.1: Dual-hop relay communication.

Dual hop system can be classified into two broad categories, depending on how the receive signal processing is done at the relay node. This can be split in two sub-groups regenerative (decode-and-forward) and non-regenerative (amplify-and-forward) systems.

3.2. *Relay Function*

Right up till the present time, the limit of the general relay channel alongside its ideal relay functions are obscure. Thus, several relay functions have been proposed in the literature. Due to practical constraint, relay operating in the literature are causal, i.e., the signal transmitted by the relay at a given time can only be a function of previously received signals. Basic relay functions include decode-and-forward (DF), compress-and- forward (CF), and amplify-and-forward (AF).

3.2.1. Amplify and forward (AAF)

In AF, the relay nodes receive the signal and forwards amplified signal to the destination node. AF gives substantial gains with using simpler signal processing. Not only AF can be employed in practice, but it also has lower implementation loss, simpler implementation method, and very cost effective.

AF relaying scheme is illustrated in Figure 3.2 [47]. In the AF relaying system, $\boldsymbol{h}_{sd}, \boldsymbol{h}_{sr}, and\ h_{rd}$ to indicate the channel coefficient of the source-to-destination link, the source-to-relay link, and the relay-to-destination link. The received signal y_{sr} at the relay node is subject to an amplification factor G before forwarding it to the destination node. The received signal $\boldsymbol{y}_{rd}$ at the destination is given by equation:

$$\boldsymbol{y}_{rd} = G\sqrt{P_R}h_{rd}y_{sr} + \boldsymbol{n}_r \tag{3.1}$$

Where G is the complex channel gain between relay and receiver. P_R is the average transmit power at the relay.

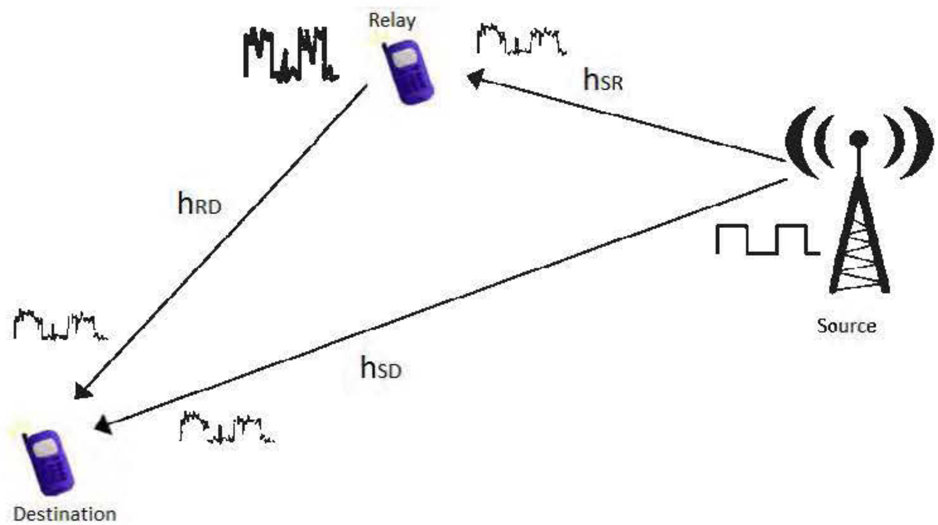


Figure 3.2: Amplify and forward relaying system [72]

The AF relaying scheme can be classified into two categories based on the availability of the channel station information (CSI) at the relay node, i.e., CSI assisted AF relaying and fixed gain AF relaying. The CSI assisted scheme adopts channel measurements to compensate the instantaneous fading amplitudes of the source-relay link. The fixed gain scheme, in contrast, amplifies and forwards the received signal with a fixed gain, which may either rely on average CSI information (i.e., semi-blind) or be CSI independent (i.e., blind relays) and such approach results in reduced processing overheads and implementation complexity at the relay. On the other hand, co-channel interference (CCI), caused by aggressive reuse of frequency in a cellular system, can dramatically degrade the performance of the system [48].

3.2.2. Decode and Forward (DAF)

In a DF relay scheme as shown in figure 3.3 [45], Decoding is the reverse of encoding. It converts encoded data communication transmissions and files to their original states. The received signal is decoded and re-encoded (y_{sr}) to estimate x. Then the estimated signal $\hat{x}$ is forwarded to the destination to complete the transmission. This signal estimation can be carried out in symbol by symbol or by the entire code word by considering the system required performance and complexity at the relay. The received signal y_{rd} at the destination can be obtained as:

$$y_{rd} = \sqrt{P_R} h_{rd} \hat{x} + n_d \tag{3.2}$$

Where P_r is the average transmit power at the relay and n_d is the noise at the destination.

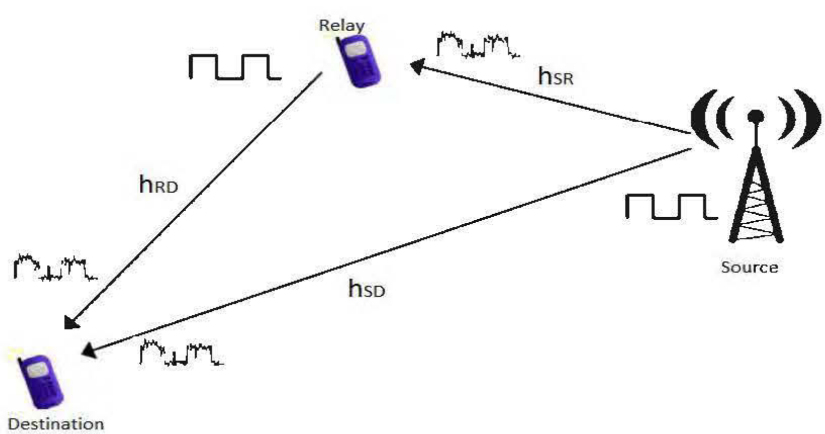


Figure 3.3: Decode and forward relaying system [72]

3.2.3. Compressed and Forward (CAF)

The compress-and-forward (CF) scheme allows the relay station to compress the received signal from the source node and forward it to the destination without decoding the signal where Wyner-Ziv coding can be used for optimum compression. The Wyner–Ziv coding scheme is obtained by adding a quantizer and a de-quantizer to the Slepian–Wolf coding scheme. Therefore, a Wyner–Ziv coder design could focus on the quantizer and corresponding reconstruction method design.

3.3. Half-Duplex Relay

Van der Meulen in 1971 [48] was first introduced the relay channel. Later, in the similar work of [47], Cover and Gamal laid the foundation to the information-theoretic understanding of the relay channel. Earlier theoretical works assumed that the relay could operate in full-duplex (FD) mode, i.e., the reay can transmit and receive data at the same time over the same frequency band [49-53]. This assumption was believed to be impractical due to the vast difference in transmitting and receive signal powers levels, which results in self-interference. Thus, motivated by wireless scenarios, the focus on the relay channel was shifted to half-duplex (HD) operation.

Pioneer works on HD were relaying focused on dual-hop strategies, e.g., [54-57]. In HD protocols, data is transmitted from source to destination through the relay in two phases as shown in figure 3.4. In the first step, the node of origin N1 sends to the relay R, whereas the relay communication to the destination node N2. For the 3GPP next generation mobile communication systems, the dual-hop strategies can be easily implemented in practice to improve the network coverage of the network [30].

The half-duplex relay uses two main rules in transmission one is non-orthogonal, and the other is two-way. In two-way protocol, a cooperation composed of two-time slots: during the first time slot, the source communicates with the relays and destination. In second time slot, when only the relays communicate with the destination, the protocol is called as orthogonal or two-way. On the contrary, the protocol is not orthogonal when the both source and relays communicate with the destination. As shown in figure 3.4, the non- orthogonal relay does not send back the data, but it keeps it on forwarding. Node S_1 sends data to both relay and the S_2 node in the first phase, in blue (Continuous) line on Fig 3.4, while in the second phase, red (dot) line, the relay and S_1 nodes send the data to the S_2 node or destination again. Two way, on the other hand, guarantees the success of transmission in two ways. The first phase is the sending path from S_1 node to S_2 node through the relay where the second one is the opposite path from S_2 to S_1 node through the same relay node [59].

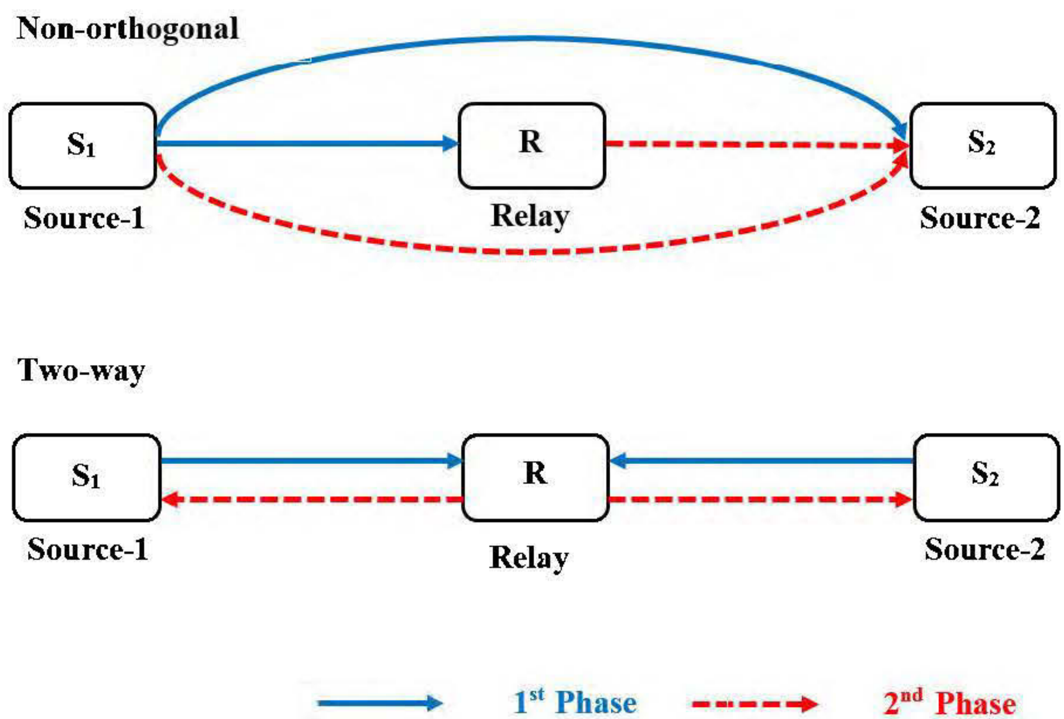


Fig. 3.4. HD Relay Protocols

In the protocols discussed above, node S_1 wants to communicate to node S_2 via the relay, i.e., information flows from S_1 to S_2 $(S_1 \rightarrow S_2)$. These protocols can thus be broadly relegated as one-way (OW) relaying schemes.

3.4. *Full-Duplex Relay*

From the above discussion, we can see that half-duplex constraint of the relay has a significant impact on spectral efficiency on relay protocols. Full-Duplex (FD) wireless operation for this part has been shown to be practicable through a novel combination of self-interference (SI) mitigation scheme [60-64]. In particular, to avoid saturating the receiver front end, several techniques before analog-to-digital conversion have been proposed. For instance, basic analog cancellation methods include antenna separation [60-62], orientation [60] and directionality [65]. Despite these advances in cancellation techniques, the self-interference remains a challenge as it cannot be completely mitigated in practice. As such, different from earlier information theoretical works, the self-interference must be explicitly taken into account when assessing, designing and analyzing FD protocols.

Similar to HD schemes, FD protocols can be classified depending on whether the direct source-destination link is used or not in transmission. In fact, the idea of cooperative relaying can be traced back to the works of van der Meulen and Cover in [48,49], respectively, which make use of the direct link for FD communication. Specifically, in FD relaying schemes, the source transmits to the relay and the destination, while the relay simultaneously receives the signal from the source and transmits to the destination, as shown in Fig. 3.5. Similar to their HD counterparts, FD dual-hop relaying has two main limitations when the direct connection is not under heavy shadowing. First, although the source is allowed to transmit continuously, the rate of the FD dual-hop scheme might be degraded due to the self-interference created at the destination node from the direct link. Furthermore, this protocol does not provide any diversity benefits. Thus, as in the HD scenario, cooperative FD techniques that make use of the direct link for transmission might be able to offer data rate and diversity advantages.

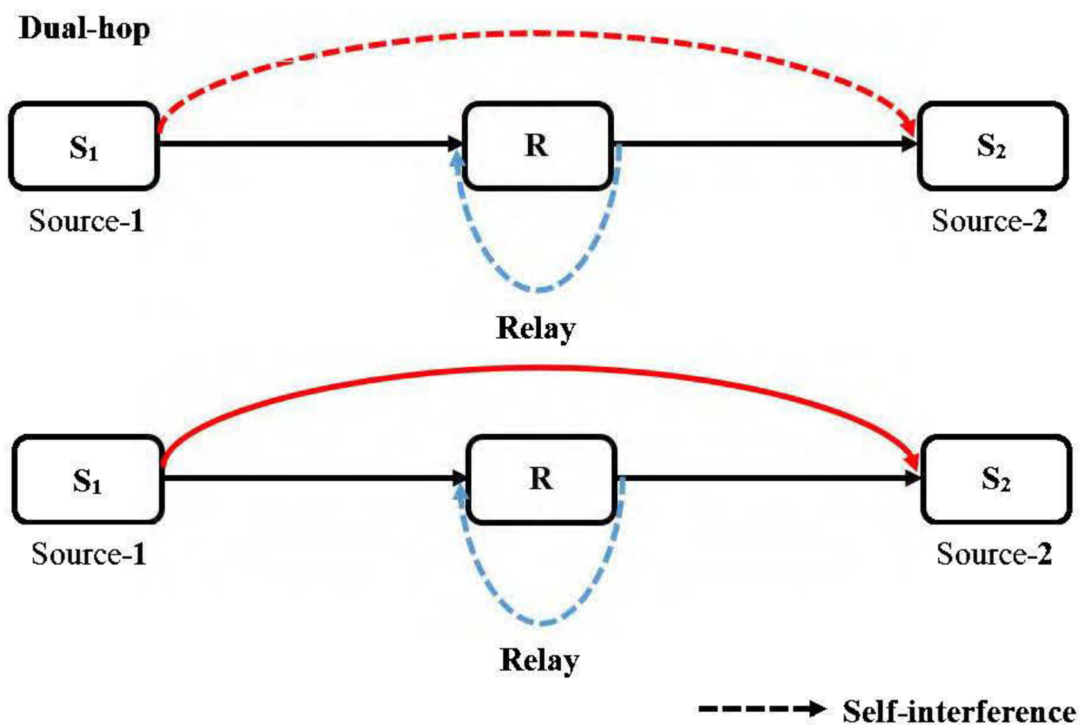


Fig.3.5. FD Relay Protocols

It is important to note that for both FD protocols in Fig. 3.5, the potential gains of FD relaying might not be realizable due to the level of residual self-interference at the relay node. Hence, the ideal FD schemes previously proposed in the literature need to be re- analyzed under such scenario.

3.5. Cooperative VS Relaying Communications

The concept of cooperative relaying is a promising means to counteract the effects of small-scale fading. It builds on the idea of cooperative diversity and exploits alternative communication paths by getting assistance from other nodes in the area of sender and receiver of a currently exaggerated communication link. These additional nodes act then as relays, i.e., a dedicated or temporarily chosen wireless node that helps in forwarding information from a source node to a destination node. The relayed information flow as a result of this creates a communication path concurrent to the direct communication flow from source to destination or communication via other relays. The relay channel model includes a source node, a relay node, and a destination node, as shown in Figure 3.1.

The work in [52], was based on the analysis of the capacity of a three-node network consisting of a source, a relay, and a receiver. The assumption was that all links function in the same frequency band. Therefore, the system could be decomposed into a broadcast channel concerning the source and a multiple access channels concerning the destination. While mostly analyzed capacity in an AWGN channel, the motivation now is more on the concept of diversity in a fading channel. Secondly, in work on the relay channel, the relay's sole aim is to aid the main channel, whereas, in cooperative communication, the total system resources are fixed, and users act both as information sources as well as relays [67]. Therefore, although the historical importance of the first works on relay channel is indisputable, recent work in cooperation has taken a somewhat different emphasis [68].

3.6. MIMO Relaying

The MIMO relaying is fascinating research direction that can optimally make use of the main resources of wireless fading channel, and attain the benefits of both MIMO and cooperative communication. We investigate the MIMO relaying systems in our study, such as two stage projection based FD amplify and forward MIMO relying.

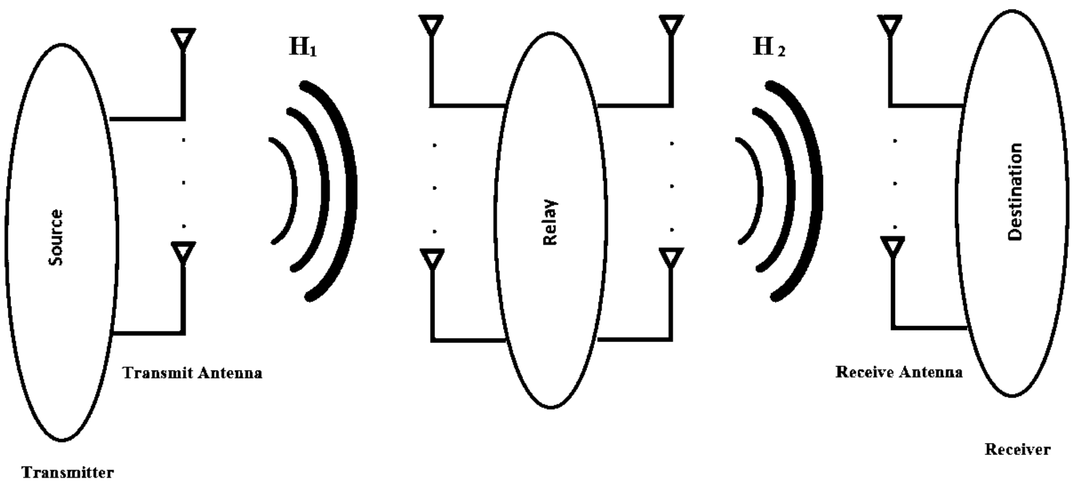


Fig. 3.6: MIMO cooperative communication system.

Two stage projection algorithms based FD-MIMO relaying systems can be used to improve the link reliability when a self-Interference is present between the source and transmitter. In this case, it is important to have multiple antenna at the transmitter to apply two stage projection. The receiver (relay, destination) can be either single antenna or multiple antenna. In chapter 4, we discuss further on two stage projection based FD-MIMO relaying system.

CHAPTER 4

PROPOSED FD-MIMO RELAY

4.1. Introduction

This chapter focuses on relay self-interference cancellation via two-stage projection. The projection algorithm applied through this chapter depending on the matrix rank.

The interference creates in the relay node when the unwanted signal sources are added to the primary signal, and it is the main reason for the signal corruption. In relaying communication, signal travel from a source to a destination is decidedly affected by the interference generated by other devices. In this way, if devices in the zone of the receiver transmit at the same time and on the same frequency, their signals interfere at the receiver with the useful signal from the sender and thus block appropriate reception. The CCI cause high error rates, and this has a vast destructive impact on the system performance. In general, CCI in a relaying system can be considered either at the relay, destination or both relay and destination node. As mentioned previously, most of the existing works are based on zero-forcing, minimum mean error square and null space projection. Though, in wireless communication networks, the interferences signals can cause different involvement attenuation, particularly in cellular networks. This main constraint motivated current study to derive a new mathematical analysis of a realistic situation. This model considers an AF relay system over Rayleigh fading channels in the presence of interferences at relay node. Therefore, the system model considered in this chapter is adequate for indoor wireless communication.

The main contribution of this thesis work is that a new mathematical method for accurate and efficient cancellation of SI around the relay, evaluate the bit error rate performance of amplify and forward FD-MIMO relays system for different modulation scheme.

4.2. The Relay System Model

Consider a three-link dual-hop amplifies and forward (AF) relaying system in the indoor wireless system. AF relay protocol is defined for cooperative relay communication, i.e., it improves the performance of the wireless communication system. AF relay amplifies its received signal and maintaining fixed average transmit power. In our relay system model, AF is employed because it requires relatively simple signal processing.

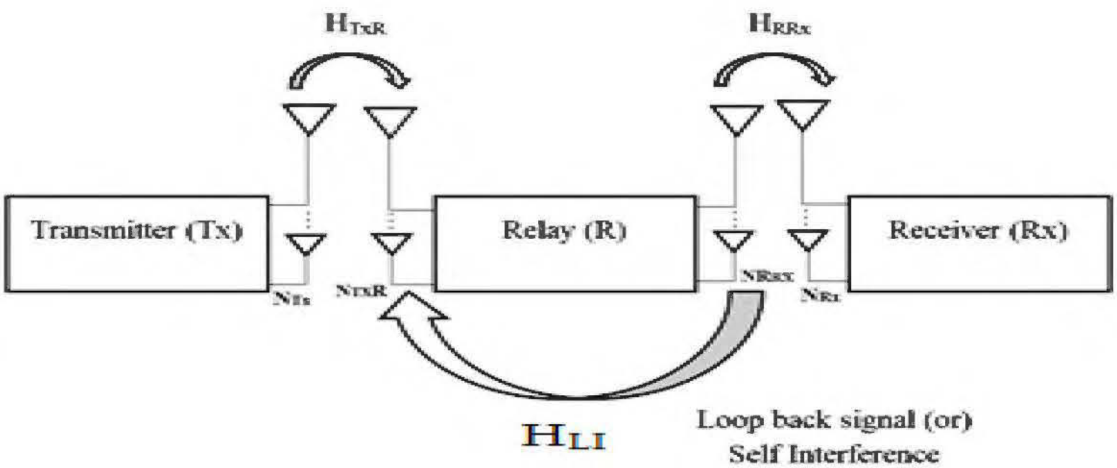


Fig.4.1: Two-hop relay model.

The relay model includes Transmitter(T_x), Relay (R) and Receiver (R_x) nodes shown in Fig.4.1. The transmitter node is equipped with a set of N_{Tx} antennas whereas the receiver node has N_{Rx} antennas. The relay node is equipped with two sets of antennas. The first set, have (N_R)antennas and is dedicated to receiving meanwhile the second set include (N_T)transmit antennas.

We define $H_{TxR} \in \mathbb{C}^{N_R \times N_{Tx}}$and $H_{RRx} \in \mathbb{C}^{N_{Rx} \times N_T}$ which represent respectively the MIMO complex channel matrices from the transmitter to relay node and from the relay node to a receiver. The signal vector $x(n)$ defined as a complex vector $x(n) \in \mathbb{C}^{N_{Tx} \times 1}$, transmitted by the source node. The complex signal vectors $r(n)$ and$t(n)$, stated as $r(n) \in \mathbb{C}^{N_R \times 1}$and $t(n) \in \mathbb{C}^{N_T \times 1}$, denote the received and transmitted signal at the relay node respectively. H_{LI} is the loopback self-interference signal which reduces the channel capacity from the transmission to reception and makes the relay system unstable in FD MIMO. The self-interference complex channel matrix, induce by the relay, is denoted by $H_{LI} \in \mathbb{C}^{N_R \times N_T}$, as shown in figure 4.1.

4.3. Proposed Two Stage Projection Approach

Proposed two stage projection algorithm (TSPA) consist of null space projection (NSP) and subspace projection (SP).

4.3.1. Projection

A projection matrix P is a $n \times n$ square matrix that gives a vector space projection from $\mathbb{R}^n$ to a subspace w. The columns of P are the projections of the standard basis vectors, and w is the image of P. A square matrix P is a projection matrix if and only if $P^2 = P$. An orthogonal projection is a projection for which the range and the null space are orthogonal subspaces. A projection is orthogonal if and only if it is self-ad-joint, which means that, in the context of real vector spaces, the associated matrix is symmetric relative to an orthonormal basis:$p = P^*$. Where P^* denoted as ad-joint matrix of P. The projection randomly selects the 'closet' subspace onto the matrix. For example, a linear system like $Ax = b$ which does not have a solution, may be approximated by a linear system $Ax = \acute{b}$ for which there does exist a solution and where the vector $\acute{b}$ is chosen so that it is close to b.

4.3.2. Null Space Projection (NSP)

Null space projections are distinct by their null space and the origin vectors used to describe their range. When these base vectors are orthogonal to the null space, then the projection is an orthogonal projection and where one projects a vector, onto a subspace and the vector in the subspace which is "closest" to the same vector. An example, in NSP the spatial receive and transmit filters are selected such that the transceivers receives and transmits in different subspace i.e., transmit beams are projected to the null-space of the loopback SI channel combined with the receive filters and vice versa.

4.3.2. Subspace Projection (SP)

The subspace is known as the column space of the matrix A. Subspace consists of all possible values of the vector x. It is precisely the subspace of K^n spanned by the column vectors of A. The row space of a matrix is the subspace spanned by its row vectors. When one projects a vector v onto a subspace, the vector in the subspace which is “closest” to v. The simplest case is of course if the vector is already in the subspace, then the projection of onto the subspace is the vector itself.

According to the multipath propagation, proposed scheme splits into two cases.

4.3.4. Flat Channel Case

In this case, the multipath parameter of the channel d is smaller than signal symbol time *(Ts)*, which means that the one symbol will interfere mainly with itself. The signal received by the relay is expressed as,

$$r(n) = H_{TxR}x(n) + H_{LI}t(n) + w(n) \tag{4.1}$$

Where $w(n) \in \mathbb{C}^{N_R \times 1}$denote an additive white Gaussian noise (AWGN) and $H_{LI}t(n)$ is the loopback interference signal received by the relay. Where $t(n)$ is the transmitted signal in the relay.

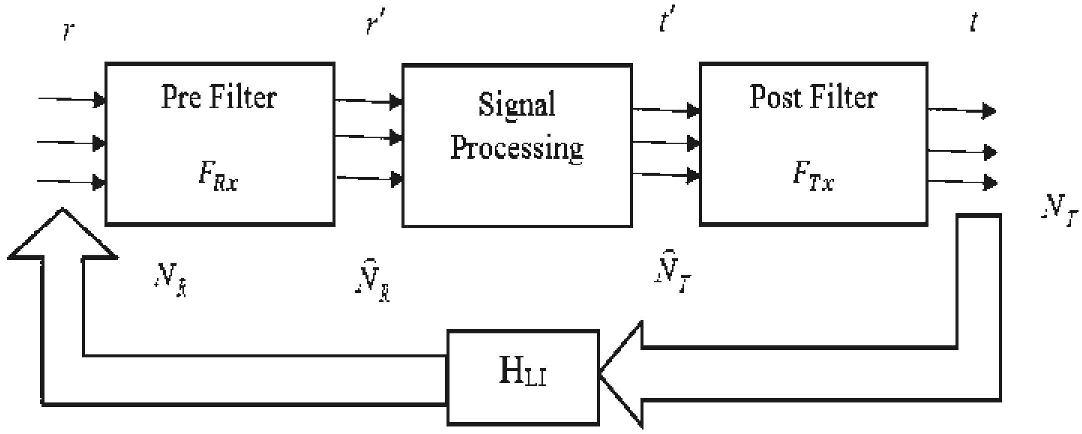


Fig. 4.2: Relay loopback interfernce cacellation by using TSPA scheme.

A pre-projection filter, which is called the loop back signal suppression filter denoted by $F_{Rx}$and defined as $F_{Rx} \in \mathbb{C}^{N_R \times \hat{N}_R}$ and post filter which is called transmit weight filer F_{Tx} defined by $F_{Tx} \in \mathbb{C}^{\hat{N}_T \times N_T}$ are depicted in fig.4.5. Without loss of generality, we can assume that $\hat{N}_R \leq N_R$ and $\hat{N}_T \leq N_T$ because the end to end communication cannot improve by the increasing the number of dimensions. The output signal of the pre-filter $r'(n) \in \mathbb{C}^{\hat{N}_R \times 1}$ and the input signal of the post filter $t'(n) \in \mathbb{C}^{N_T \times 1}$.

Now, the output of the pre-filter $r'(n)$ with loop back interference can be written as,

$$r'(n) = \{F_{Rx}(H_{TxR}\,x(n) + w(n))\} + \{F_{Rx}H_{LI}F_{Tx}\acute{t}(n)\} \tag{4.2}$$

In equation 4.2, the first part represents the desired signal exposed to white Gaussian noise and the second part is channel loopback interference.

As shown in fig. 4.2, relay used two adaptive filters, pre-filter F_{Rx} and post filter F_{Tx} to respectively process the input and output signal in order to cancel the SI. Which means that both filters will collaborate to define the right message to send with a view to suppressing the channel loopback interference. To achieve this goal, according to equation 4.2, the second part should be zero (cf. equation 4.3) is a necessary and sufficient condition to optimize both adaptive filter weights.

$$F_{Rx}H_{LI}F_{Tx} = 0 \tag{4.3}$$

4.3.5. Selective Frequency Case

For this case, the maximum multipath d induced by the channel loopback is more than one-time Ts duration. The number of subsequent symbols that interfere with one symbol, denoted by L, is estimated by equation 4.4.

$$L = \left\lceil \frac{d+\frac{T_S}{2}}{T_S} \right\rceil \tag{4.4}$$

Now, according to the model in fig.4.3 and due to the inter symbol interference the output signal $\acute{r}(n)$ is rewritten as,

$$\acute{r}(n) = \left\{F_{Rx}\left(H_{TxR}x(n) + w(n)\right)\right\} + \{F_{Rx}H_{LI}T(n)\} \tag{4.5}$$

Where $T(n) = [t_1(n) \quad t_2(n) \quad t_{N_T}(n)]^T$ is an array of relay out coming signals, one per transmitting antenna and defined as:

$$t(n) = [t_i(n) \quad t_i(n-1) \quad \cdots \quad t_i(n-L+1)] \tag{4.6}$$

The $t_i(j)$ is the transmit signal by the i th relay antenna at sample time j. The output of the post filter relay node is,

$$t(n) = F_{Tx}t'(n) \tag{4.7}$$

Where $t'(n)$ indicated the input signal of the post filter. Let, $t'(n) = [t'_1(n), \quad t'_2(n), \quad \cdots \quad t'_{\widehat{N}_T}(n)]$

Substitute equation (4.7) in equation (4.5) we get,

$$r'(n) = \left\{F_{Rx}\left(H_{TxR}x(n) + w(n)\right)\right\} + \left\{F_{Rx}H_{LI}\tilde{G}T\acute{}(n)\right\} \tag{4.8}$$

Where $T'(n) = \left[\acute{t}_1(n) \quad \acute{t}_2(n) \quad \cdots \quad \acute{t}_{\widehat{N}_T}\right]^T$ and $\tilde{G}$ is the diagonal matrix of the adaptive filters.

P is the permutation matrix used to go to diagonalizable space.

Where, $\tilde{G} = P^{-1}diag(F_{Tx}; L)$, $P = \begin{bmatrix} diag(Y_1; L) \\ diag(Y_2; L) \\ \vdots \\ diag(Y_L; L) \end{bmatrix}$

In the case, where $L = 1,2,\ldots$, which mean that d is smaller than Ts i.e., the channel is selective frequency, *the* $F_{Rx}$and F_{Tx}filters can be adapted using equation 4.6 as:

$$F_{Rx}H_{LI}P^{-}diag(F_{Tx};L) = 0 \tag{4.9}$$

When $L \geq 1$, then equation (4.9) is rewritten as,

$$F_{Rx}[H_{L,1}, \quad H_{L,2}, \quad \cdots \quad H_{L,L}]diag(F_{Tx};L) = 0 \tag{4.10}$$

To achieve the sufficient condition of equation 4.7 is,

$$F_{Rx}H_{LI} = 0 \qquad and \qquad \left[H_{L,1}^{T}, \quad H_{L,2}^{T}, \quad \cdots \quad H_{L,L}^{T}\right]^{T}F_{Tx} = 0 \tag{4.11}$$

Where, $F_{Rx}$is the pre-space projection filter, F_{Rx} project the row space of H_{LI} to the null space of H_{LI}. Similar with F_{Tx}, F_{Tx} is the null space of$\left[H_{L,1}^{T}, \quad H_{L,2}^{T}, \quad \cdots \quad H_{L,L}^{T}\right]^{T}$.

4.3.6. Null Space projection (NSP) with short rank loop interference matrix.

When the matrix is not of full rank that is the row or column matrix is not linearly independent then solution of (4.11), when the adaptive pre and post filters F_{Rx} and F_{Tx}, cannot be zero matrices, then.

$$0 < rf(H_{LI}) < N_R \; and \; 0 < rf(H) < N_T \tag{4.12}$$

Where, *rf* the rank function given the dimension of the vector space generated by matrix columns. The rank of a matrix would be zero only if the matrix had its elements equal to zero.

If a matrix had even one non-zero element, its minimum rank would be one. $H = \left[H_{L,1}^{T}, \quad H_{L,2}^{T}, \quad \cdots \quad H_{L,L}^{T}\right]^{T}$. $[\,]^{T}$ is the transpose of H. It means that only when the H_L or the H is not linearly independent matrix or not full rank the non-zero solution of equation (4.14) exist. With Zero Forcing algorithm, a solution of null space projection as,

$$F_{Rx} = I - H_{LI}H_{LI}^{+} \tag{4.13}$$

$$F_{Tx} = I - HH^{+} \tag{4.14}$$

Where $[.]^{+}$ is the Moore-Penrose pseudo-inverse and I is the identity matrix.

4.3.7. Subspace Projection Partly Cancelling Interference (SSPCI) with Full Rank (FR) Matrix

A matrix is of full rank when each of the rows and columns of the matrix is linearly independent is called full rank matrix. The second algorithm is called Subspace Projection Partly cancelling Interference (SPPCI). When the H_L and H are FR, as

$$r(H_{LI}) = N_{Rx}; \qquad r(H) = N_{Tx} \tag{4.15}$$

We could just suppress the loop interference at the row space of H_{LI} or the column space of H. Choose the smaller positive integers C_1, C_2, D_1 and D_2 are defines the range for each order and it is a small positive integer to satisfy both (4.16) and (4.17) equation.

$$r([H_{L,m_1}, \quad H_{L,m_2}, \quad \cdots, \quad H_{L,m_{D_1}}]) = N_R - C_1 \tag{4.16}$$

$$r\left([H_{L,n_1}^T, \quad H_{L,n_2}^T, \quad \cdots, \quad H_{L,n_{D_2}}^T]^T\right) = N_T - C_1 \tag{4.17}$$

Where m_i , $n_i \in [1, \quad 2, \quad \cdots, \quad L]$ we have the subspace

$$H_1 = [H_{L,m_1,}, \quad H_{L,m_2}, \quad \cdots, \quad H_{L,m_{D_1}}] \tag{4.18}$$

$$H_2 = [H_{L,n_1}^T, \quad H_{L,n_2}^T, \quad \cdots, \quad H_{L,n_{D_2}}^T]^T \tag{4.19}$$

For designing the filters separately, the row space of F_{Rx} should be in the subspace space and F_{Tx} is in the null space. Let H_1^+ denote the Moore-Penrose pseudoinverse of H_1 for which $H_1 H_1^+ H_1 = H_1$ by definition. Then project the loop interference to the complementary space of H_1 or H_2 and the loop interference in space of H_1 or H_2 is cancelled by,

$$F_{Rx} = I - H_1 H_1^+ \tag{4.20}$$

$$F_{Tx} = I - H_2 {H_2}^{+} \tag{4.21}$$

The nonlinearity of $f(.)$ provides more degrees of choice to design the adaptive filters F_{Rx} and F_{Tx}. We can have two cases for relay transmitted signal. The Decode and Forward (DF) MIMO relay case, according to equation 4.22 where DF relay process the signal and regenerate source data streams, and the Amplify and Forward (AF) relay, according to equation 4.23, where the signal is forwarded after some basic processing.

The $F_{Rx}$and F_{Tx} have the equivalent function in AF relays, so they can be combined into one filter which would only mitigate the interference. The nonlinearity of $f(.)$ provide more degrees of freedom for designing the $F_{Rx}$and F_{Tx} jointly, the loop interference suppression filter pairs are in the DF relays for suppressing the loop interferences for both cases.

$$t(n) = F_{Rx} f\left(F_{Rx}\big(r(n)\big) - w(n)\right) \tag{4.22}$$

$$t(n) = F_{Tx} F_{Rx}\big(r(n) + w(n)\big) \tag{4.23}$$

CHAPTER 5

RESULTS AND ANALYSIS

This chapter is based solely on the presentation of the simulation results for SI cancellation technique in amplify-and-forward FD-MIMO relay. In the simulation, we consider stationary Rayleigh fading channel for indoor wireless communication. From the simulation results, we can see that proposed TSP algorithm can able to cancel or remove the loopback interference around the relay node, where's the other conventional method, i.e., MMSE, ZF cannot be able to mitigate the SI completely.

5.1. Bit Error Rate (BER)

The performance of a wireless channel is measured at the physical level by bit-error-rate (BER), block-error-rate, symbol-error-rate, or probability of outage. BER is ascertained as the percentage of bits that have errors due to noise, distortion or interference relative to the total number of bits received in a transmission. Calculating this is dependent on the signal encoding technique used as will be emphasized later in the respective parts. The bit error rate can be representing into a simple formula:

$$Bit\ Error\ Rate, BER = \frac{Number\ of\ errors}{Total\ number\ of\ bits\ sent}$$

5.2. Signal-to-Noise Ratio (SNR)

Signal-to-Noise-Ratio is defined as the power ratio between a signal (desired information) and the noise (unwanted signal). In this thesis the relation between the SI, BER and SNR is:

$$SNR = \frac{S}{N}; \quad N = W_n + SI$$

Where N is the noise, W_n is the white noise and SI is the self-interference.

5.3. BER performance with BPSK Modulation

Fig.5.1. illustrates that the bit error rate (BER) of the relay is a function of the signal-to-noise ratio (SNR). Subspace projection (blue curve) decreases SNR almost 13dB than the no suppression (green) curve and the subspace projection applied for the full rank SI channel matrix. When the SI channel matrix is not of full rank, the null space projection has been applied and it decreases the SNR of 2dB comparing to subspace projection and 16 dB SNR comparing no suppression curve. So, from the simulation curves we can see that even the rank of loop interference matrix is full, it is possible to eliminate the loop interference by jointly design receive and transmit space projection filter.

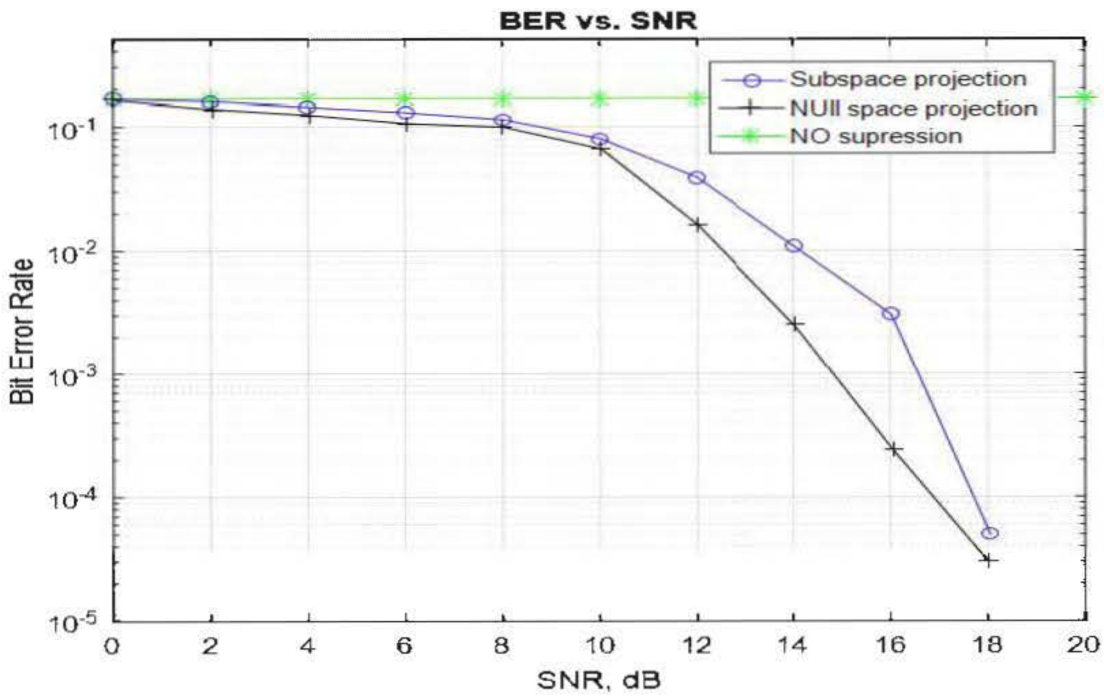


Fig.5.1. Bit Error Rate VS Signal to Noise Ratio for flat channel with BPSK modulation

Fig. 5.2 shows that the bit error rate (BER) of the relay is a function of the signal-to-noise ratio (SNR). The simulation shows that even when the delay is greater than the one time symbol, i.e., the channel is in selective frequency fading, it is possible to eliminate the most of the loopback interference by cooperatively design receive and transmit space projection filter. In simulation, the SNR value literally reduces because of the high silectivity of channel. The Nullspace projection (NSP) can entirely mitigate the known and partly unknown component of the self-interference and the subspace projection filter where's the Subspace projection (SP) mitigate the known part when the channel is in selective, and the value is higher the T_s duration. The proposed TSPA able to minimize the SI when the channel is in high selective frequency fading, i.e., the delay or the number of path increases and apparently greater than the time duration as shown in fig. 5.3.

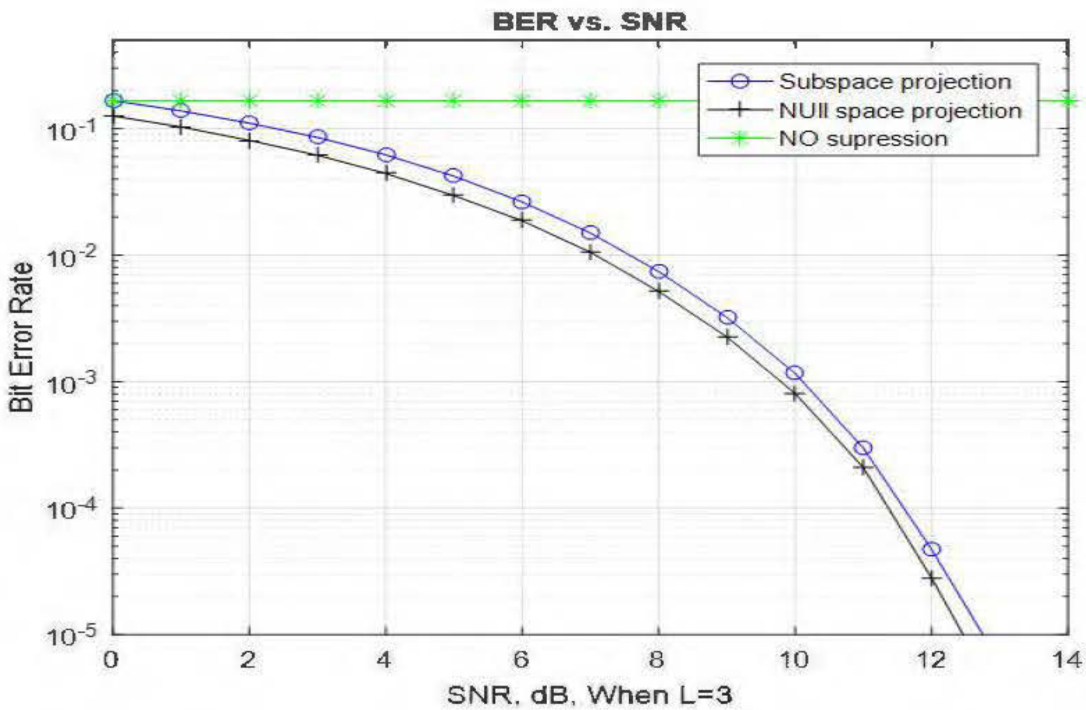


Fig.5.2. Bit Error Rate VS Signal to Noise Ratio for selective frequency channel with BPSK modulation

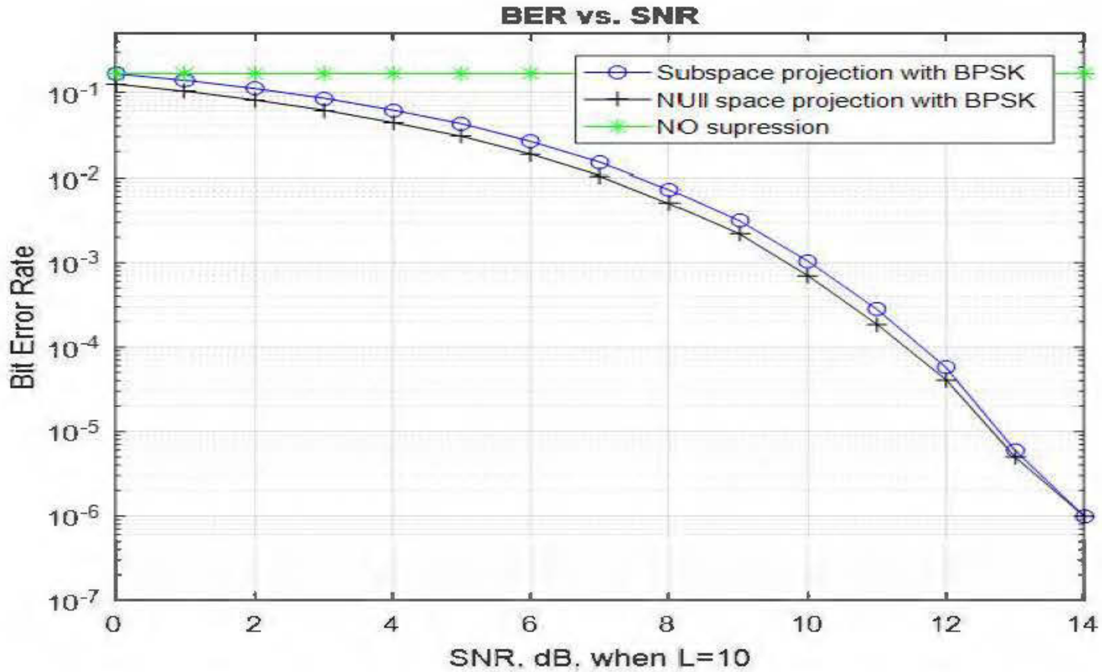


Fig.5.3. Bit Error Rate VS Signal to Noise Ratio for high selective frequency channel with BPSK modulation

Fig. 5.4. Compared the BER performance of the Zero forcing (ZF), Minimum Mean Square Error (MMSE) and proposed two stage projection (TSPA) algorithm. For a given level of BER, ZF and MMSE curves, indicate a requested SNR slightly inferior in proposed TSPA method with the maximum deference of 6.5dB and 2dB respectively. Keeping in mind that, proposed scheme decreases the SNR and increase the signal strength. According to the simulated curve, the BER performance of MMSE is better than ZF technique. However, our proposed TSPA gives better BER Performance than conventional MMSE and ZF technique. From the comparison, we can see that our proposed scheme TSPA can cancel the self-interference more than 60% than other existing conventional LI suppression method.

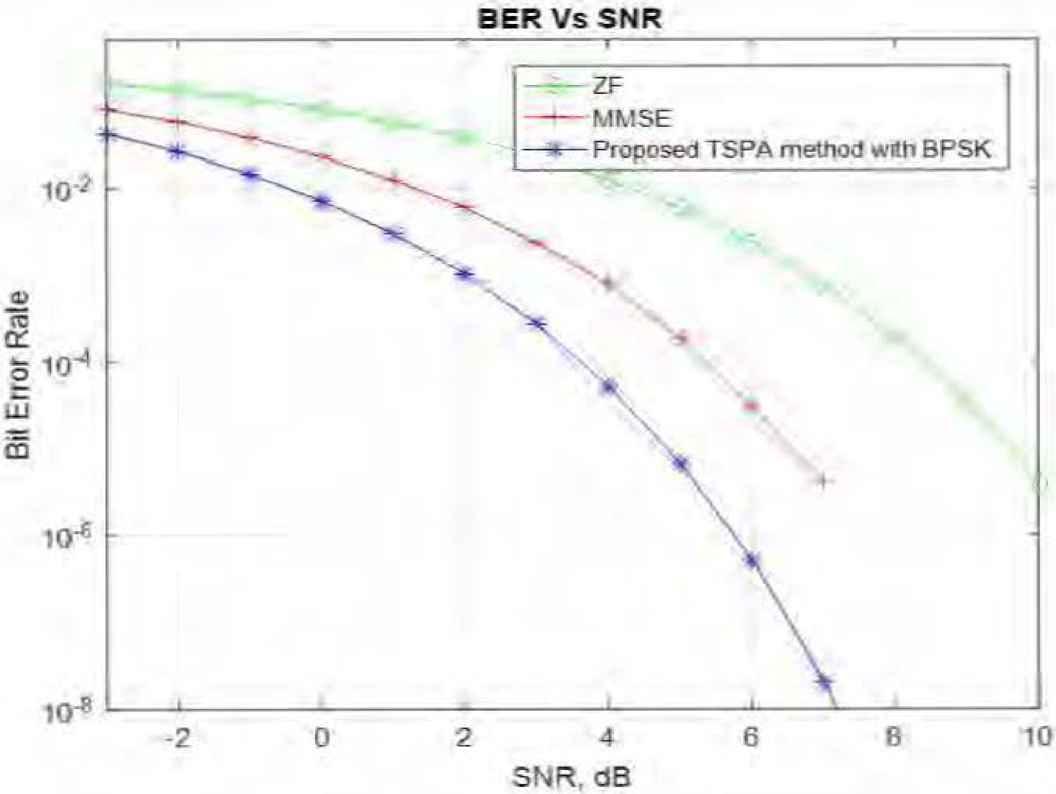
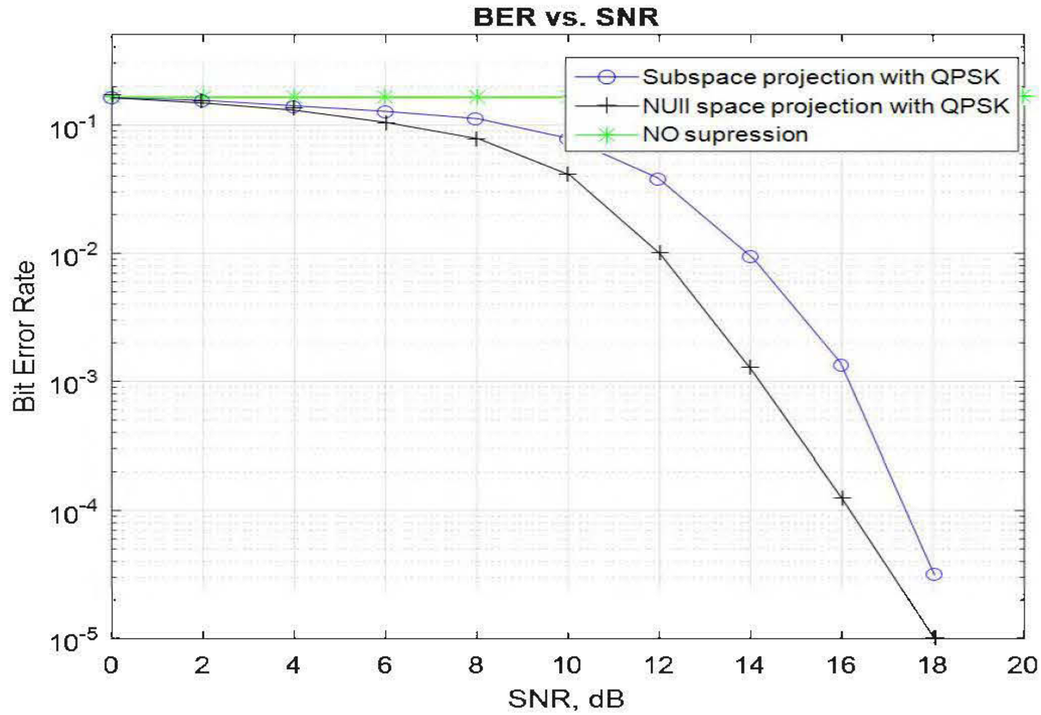


Fig.5.4. Compare to ZF, MMSE and Proposed TSPA with BPSK modulation Scheme

5.4. BER performance with QPSK Modulation

Fig.5.5. shows that the BER of the relay is a function of the signal-to-noise ratio (SNR). Since the SI channel matrix is not of full rank, the BER performance of null space projection is better than subspace projection and the improvement between them is 5 dB at BER 10^{-3}. So, we could say that even the rank of loop interference matrix is full, it's possible to eliminate the loop interference entirely by jointly design receive and transmit space projection filter.



5.5: Bit Error Rate VS Signal to Noise Ratio for flat channel with QPSK modulation

Fig.5.6 shows that the BER of the relay is a function of the signal-to-noise ratio (SNR). When the number of path is three the simulation shows that even when the delay is greater than the one-time symbol, it is possible to eliminate most of the loopback interference by cooperatively design receive and transmit space projection filter. The Null space projection (NSP) can entirely mitigate the known and partly unidentified element of the self-interference and the subspace projection filter where's the Subspace projection (SP) reduce the known part when the number L is three time the T_s duration. The TSPA also able to cancel the SI, when the channel is in high selective frequency fading that means the number of path L is ten times the time duration and the results shown in fig. 5.7.

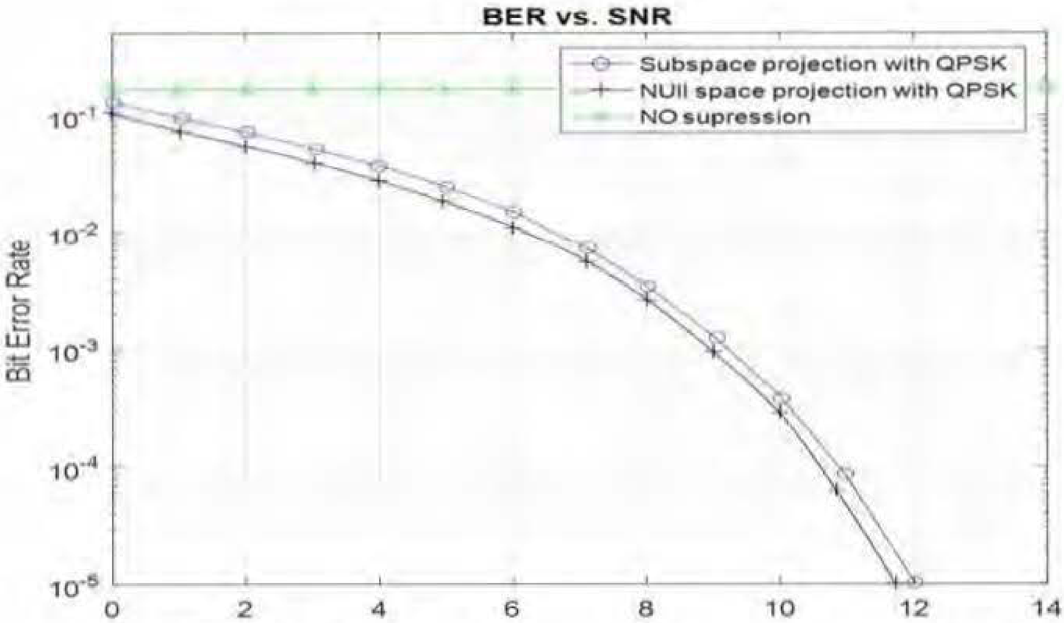


Fig.5.6: Bit Error Rate VS Signal to Noise Ratio for selective frequency channel with QPSK modulation, L=3

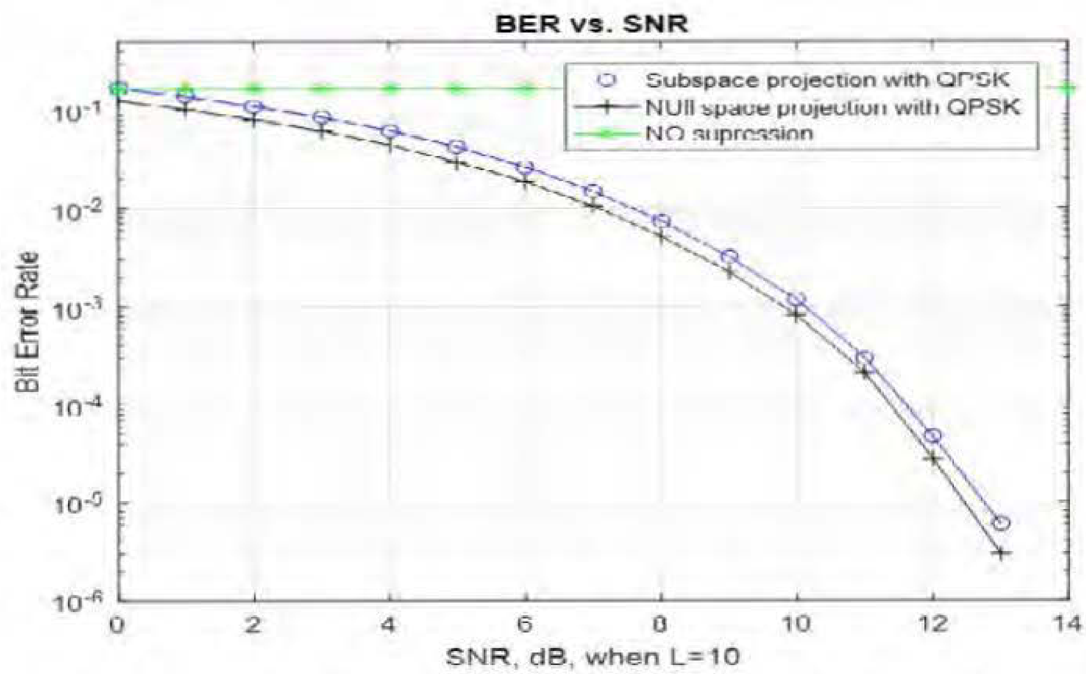


Fig.5.7. Bit Error Rate VS Signal to Noise Ratio for high selective frequency channel with QPSK modulation

Fig. 5. 8. Compared the BER performance of the Zero forcing (ZF), Minimum Mean Square Error (MMSE) and proposed two stage projection (TSPA) with BPSK and QPSK modulation scheme. The simulation shows that the Proposed method with both modulation gives exceptional BER performance than conventional MMSE and ZF method. However, proposed TSPA with four phase QPSK gives better BER Performance than proposed TSPA with BPSK. At BER 10^{-4} the improvement between BPSK and QPSK proposed method is approximately 2dB. From the comparison, we=- can see that our proposed scheme (TSPA) with QPSK can mitigate the self-interference more than 70% than other existing conventional LI suppression method.

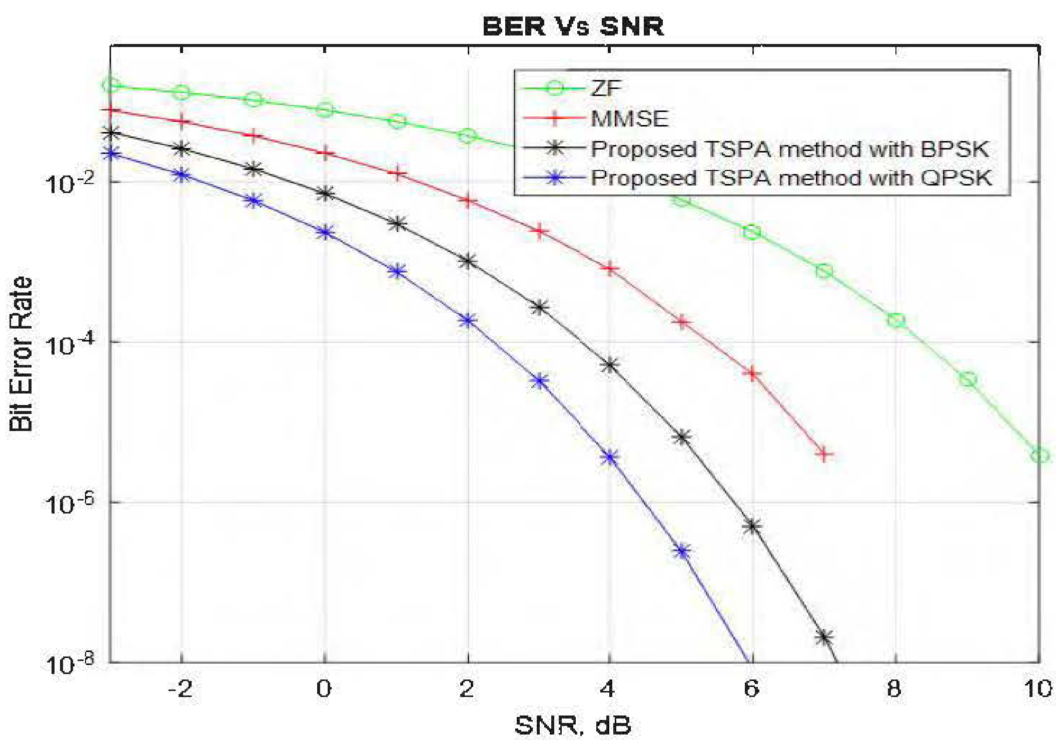


Fig. 5.8: Compare to ZF, MMSE and Proposed TSPA with BPSK & QPSK Scheme

5.5. *Results Analysis*

To cancel the self-interference in the relay node, we used TSPA methods which can able to cancel the SI effectively around the relay. TSPA works in two stages, in the first step null space projection (NSP) canceling the SI when the loopback channel matrix is not of full rank and when the loopback channel matrix is of full rank, in the second stage subspace projection (SP) canceling the SI. Many works [65-68] have been presented based on SI cancellation technique by using either null space projection or subspace projection methods, while the complete cancellation has not been achieved to date. In this work, both null space and subspace projections are involved in canceling the SI. From figure 5.4 and 5.8 we can see that our proposed TSPA method outperforms the conventional zero-forcing (ZF) and minimum mean square error (MMSE) methods. The improvement of our proposed scheme over conventional ZF and MMSE because the projection always selects the best projection point to apply the projection method. Normally, ZF applies the inverse of the channel frequency response to the received signal, to restore the signal after the channel. However, we do not need to select best point to apply this method in the channel where the MMSE designs the filter to minimize $E[|e|2]$, where e is the error signal, which is the filter output minus the transmitted signal. The performance in [69-71], the conventional MMSE and ZF approach are significantly poorer for an increase in the SNR because it does not exploit the capability of the mobile stations to perform self-interference cancellation. The main advantage of TSPA over the conventional method is that TSPA can able to cancel the SI in two stages entirely and it improves the self-interference cancellation at least 70% than other existing conventional methods.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1. Conclusion

The study presented in this thesis has focused on the problems and challenges of relaying technique in the presence of interferences. Interference generated by the relay node because of external interfering sources, loopback interferences, and the signal propagates from source to relay and relay to the destination. In this study, our main aim was to cancel or remove the SI around the relay. In this task, we defined a mathematical method that produces precise and simplified expressions for canceling the SI.

Chapter 2 presented relevant background theories wireless communication required in this thesis including channel impairments, flat and selective frequency fading, signal encoding techniques with their statistics behaviors. The literature review in Chapter 3, presented a discussion on principle relay cooperative systems.

Chapter 4 addresses the SI cancellation algorithm for FD-MIMO relays in the indoor wireless communication system. Where, the same signal transmits and receives at the same time on the same frequency create self-interference around the relay transceivers due to the loopback signals. The SI cancellation is attained efficiently by using a proposed TSPA. We observed the performance for the channel propagation conditions related to its flatness. As a result, two modulation scheme BPSK and QPSK provide significant cancellation of SI. Subspace projection has better system stability and cancels the loopback SI by reducing the BER significantly. The second stage null space project supports and increases this enhancement at least by 50% for multipath path propagation channel. The proposed method outperforms the existing ZF and MMSE method.

In chapter 5 is based solely on the presentation of the simulation results and discussion for SI cancellation technique in amplify-and-forward FD-MIMO relay..

6.2. Future Work

Perspective work of this thesis involves observing the effect of changing the number of relay antennas, the number of relays in harsh environments for the stationary and non-stationary channel model.

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Self-Interference Mitigation in Two-Hop Relay Using Two Stage Projection Algorithms

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Abstract— **This paper develops an efficient Self-Interference (SI) mitigation algorithm for Multiple-Input and Multiple-Output (MIMO) for Full-Duplex (FD) relays in the indoor wireless communication system. The relayed signal create an SI around the relay transceivers due to the loop-back (LI) signals. The main challenge of implementing FD-MIMO relay is to mitigate the performance degradation induced by the SI. This paper presents an efficient algorithm using Two Stage Projection Algorithm (TSPA) to reduce or remove the SI. The simulation results show that the proposed method minimize efficiently the SI.**

Keywords—*Dual-hop relays; Self-Interference; two Stage Projection Algorithm (TSPA); null space projection (NSP); subspace projection (SP); MIMO.*

I. Introduction

Relaying is a promising technique to provide lower transmit powers, higher throughput and enhance the coverage in the future wireless communication system. The FD-MIMO relay provides a promising approach to wireless communication systems, and it can improve 3GPP association in the technical specification of 5G mobile wireless communication system [1]. MIMO relay technology is a cost-effective approach since it can extend the coverage of the wireless system, provide higher spectral efficiency, improve network throughput by offering cooperative diversity and enhance the communication system capacity [2] [3].

Nowadays, MIMO is the favorable technology for next generation wireless communication system to provide a wide coverage area, increased system capacity and high spectral efficiency. The MIMO links are furnished with antenna arrays between both transmitter and receiver sides to maintain a high efficient multi-stream between the end-to-end antennas of the communication link [4].

The relay approaches can be, also grouped into two broad categories, named as half-duplex (HD) and full-duplex (FD) relays. The FD methods are defined as a transceiver's ability to transmit and receive the same signal at the same time. Whereas, the HD relays require two orthogonal signals to achieve a single end-to-end link through a relay node. In the communication schemes, the FD relay is valuable in several anticipated features such as less delay, high efficiency, high security and improving access layer utility function [5]. Recently the FD relays are considered for infeasible inherent SI because FD enabled communication schemes are beneficial for many desired aspects (i.e., lower delay and higher efficiency, etc.). Thereby the exploiting specialized mitigation techniques were added in FD communications [6].

FD relays have been presented in an efficient short range application. According to the relay theory concept, SI signal is produced from the loopback (LI) signal. This signal has followed some signs such as high dynamic range of receiver or transmitter, faultless awareness of the SI path [7]. Hence the FD relay can receive the desired signals from the source end; while concurrently communicate the signals to the stage of destination. This ability gives the better results in decreasing the essential time slots on end-to-end communication and ignore the latency [8] [9].

The critical challenge to support FD relays is to resolve by suppression or cancellation SI induced by the LI signal in the relay node. According to several works [10], [11], there are three main categories to suppress this SI: passive suppression (PS), analog cancellation (AC), and digital cancellation (DC). The majority of PS approaches rely on antenna design and placement to suppress the SI. They use intrinsic antenna parameters such as placement, directivity or polarization to keep isolation or space orthogonality around the relay to break the loop-back interference. The PS is better suited for a millimeter wave communication system where antenna separation is easy to achieve and may reach high SI suppression, for example, it may remove more than 40 dB interferences in 60 GHz band. In the AC approaches, the basic idea is to estimate and remove, at the analog RF stage, the SI signal received by the relay node. In [12], analog circuit domain cancellation technique purposes to mitigate the SI in the analog receive chain circuitry the DC. Unlike all the previous approaches, the DC approaches deferred SI processing to the digital RF level, in the form of digital SI canceler or receive beamforming. The digital SI canceler requires accurate estimation of residual SI to ensure that a small noise is introduced due errors estimation and signal distortion. Meanwhile, receive beamforming approaches are supported only by MIMO systems. In [13] presents the SI suppression strategies by FD-MIMO relay applying using antenna selection technique. They also discussed the conventional LI suppression scheme. Conventionally, LI could be suppressed by using ZF and MMSE estimation filter. Authors in [14] proposed null space projection and minimum mean square error filters for spatial loop interference suppression as well as discuss shortly how to combine them with time-domain cancellation. Despite all these approaches, complete mitigation of the SI signal has not been achieved to date.

In this paper, we proposed new algorithm stated to as the Two Stage Projection (TSPA) algorithm. TSPA consist of Null space projection (NSP) and Subspace Projection (SP) algorithm which can employ in the position when loop back (LI) channel matrix is of full rank. So, in this situation, we design a receive and transmit filters combined with zero forcing (ZF) and also considered the multipath propagation of the LI signal. If the loop channel matrix is not of full rank, the NSP algorithm projected to cancel the loop back signal. SP algorithm primarily used to make the receive filter orthogonal to one subspace and the transmit filter orthogonal to another one to cancel the desired loop interference.

The paper is structured as follows: In section II, we introduce the system model of the two-hop relay. In section III, we present the proposed approach. Results and analysis has been introduced in section IV and the paper is concluded in section V.

II. System Model

In this section, we provide a mathematical model of a relay station with SI occurrence and mitigation. A 3-node dual-hop amplifies and forward (AF) relaying system in the indoor wireless system is considered. AF relay always used for cooperative communication to improve the performance of the wireless system. AF relay amplifies its received signal and maintaining fixed average transmit power. In our system model, AF is employed because it requires relatively simple signal processing. The proposed technique considered for the two-hop relaying model.

The model includes Transmitter(T_x), Relay (R)and Receiver (R_x) nodes shown in Fig.1. The transmitter node is equipped with a set of NT_x antennas whereas the receiver node has NR_x antennas. The relay node is equipped with two sets of antennas. The first set, have NR antennas and is dedicated to receiving meanwhile the second set include NT transmit antennas.

We define $H_{TxR} \in \mathbb{C}^{N_R \times N_{Tx}}$and $H_{RRx} \in \mathbb{C}^{N_{Rx} \times N_T}$ which represent the MIMO complex channel matrices respectively from the transmitter to relay node and from the relay node to a receiver. The signal vector $x(n)$ defined as a complex vector$x(n) \in \mathbb{C}^{N_{Tx} \times 1}$, transmitted by the source node. The complex signal vectors $r(n)$ and$t(n)$, stated as $r(n) \in \mathbb{C}^{N_R \times 1}$and $t(n) \in \mathbb{C}^{N_T \times 1}$, denote respectively the received and transmitted signal at the relay node. H_{LI} is the SI signal which

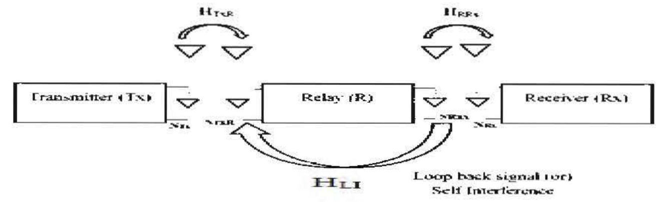

Fig. 1. Two-hop relay model.

reduces the channel capacity from the transmission to reception and makes the relay system unstable in FD-MIMO. The self-interference complex channel matrix, introduced by the relay, is denoted by $H_{LI} \in \mathbb{C}^{N_R \times N_T}$, as shown in fig. 1.

Time symbol (T_s) is the rate at which a signal is modulated, and it is a function of the symbol rate. i.e. for BPSK bit rate is equal to symbol rate(T_s). Since BPSK transmit one bit per symbol, and the symbol rate is $\frac{1}{T}$, BPSK can transmit $\frac{1}{T}$bits per second. The delay (d) is a measure of the multipath richness of a communications channel. In Fig.2. the signal power of each multipath is plotted against their respective propagation delays and it indicates how a transmitted pulse gets received at the receiver with different signal strength as it travels through a multipath channel with different propagation delays$(\tau_0, \tau_1 \; and \; \tau_2)$. The delay is mostly used in the characterization of wireless channels, but it also applies to any other multipath channel. According to the multipath delay of channel (d) and the time symbol of the signal(T_s), we can single out two cases. In both following situations, d will denote the maximum multipath time delay of the channel.

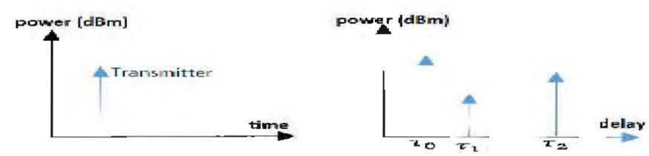

Fig. 2. Power delay profile.

A. *First case* $(d < T_s)$

In this case, the multipath parameter of the channel d is smaller than signal symbol time (T_s), which means that the one symbol will interfere mainly with itself. The signal received by the relay is expressed as,

$$r(n) = H_{TxR}x(n) + H_{LI}t(n) + w(n) \tag{1}$$

Where $w(n) \in \mathbb{C}^{N_R \times 1}$denote an additive white Gaussian noise (AWGN) and $H_{LI}t(n)$ is the loopback interference signal received by the relay. Where $t(n)$ is the transmitted signal in the relay.

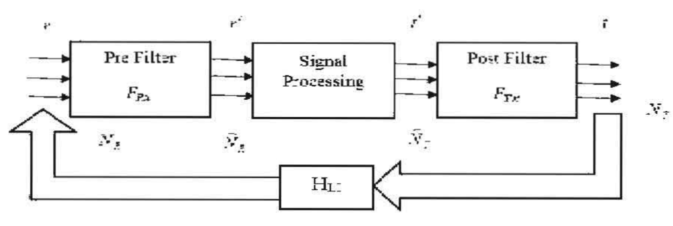

Fig. 3. Relay with loop back signal cancellation.

A pre-projection filter, which is called the LI signal suppression filter denoted by $F_{Rx}$and defined as $F_{Rx} \in \mathbb{C}^{N_R \times \widehat{N}_R}$ and post-filter which is called transmit weight filer F_{Tx} defined by $F_{Tx} \in \mathbb{C}^{\widehat{N}_T \times N_T}$ are depicted in fig.3. $\widehat{N}_R$ and $\widehat{N}_T$ are the received and transmit signal of the signal processor. Without loss of generality we can assume that $\widehat{N}_R \leq N_R$ and $\widehat{N}_T \leq N_T$ because the end to end communication cannot improve by the increasing the number of dimensions. The output signal of the pre- filter $r'(n) \in \mathbb{C}^{\widehat{N}_R \times 1}$ and the input signal of the post filter $t'(n) \in \mathbb{C}^{N_T \times 1}$.

Now, the output of the pre-filter $r'(n)$ with loop back interference can be written as,

$$r'^{(n)} = \{F_{Rx}(H_{TxR}x(n) + w(n))\} + \{F_{Rx}H_{LI}F_{Tx}\acute{t}(n)\} \qquad (2)$$

In equation 2, the first part represent the desired signal exposed to white Gaussian noise and the second part is channel loop back interference.

As shown in fig. 3, relay used two adaptive filters, pre filter F_{Rx} and post filter F_{Tx} to respectively process the input and output signal in order to cancel the SI. Which means that both filters will collaborate to define the right signal to send in order to suppress the channel loopback interference. To achieve this goal, according to equation 2, the second part should be zero (cf. equation 3) is a necessary and sufficient condition to optimize both adaptive filter weights.

$$F_{Rx}H_{LI}F_{Tx} = 0 \qquad (3)$$

B. Second case $(d > T_s)$

For this case, the maximum multipath d induced by the channel LI is more than one time T_s duration. The number of subsequent symbols that interfere with one symbol, denoted by L, is estimated by equation 4.

$$L = \left\lceil \frac{d+\frac{T_S}{2}}{T_S} \right\rceil \qquad (4)$$

The loop channel matrix $H_{LI} \in \mathbb{C}^{N_{RX} x (N_{TX} \cdot L)}$ can be written as

$$H_{LI} = \begin{bmatrix} H_{11} & H_{12} \cdots & H_{1N_{TX}} \\ H_{21} & H_{22} \cdots \ddots & H_{2N_{TX}} \\ \vdots & \vdots & \vdots \\ H_{N_{RX}1} & H_{N_{RX}2} & H_{N_{RX}N_{TX}} \end{bmatrix}$$

(5)

Where H_{ij} $\mathbb{C}^{1XL}$is the sub channel vector from the i th transmit antenna to the j th receive antenna of the relay. Now, according to the model in fig.3 and due to the inter symbol interference the output signal $\acute{r}(n)$ is again presented as,

$$\acute{r}(n) = \{F_{Rx}(H_{TxR}x(n) + w(n))\} + \{F_{Rx}H_{LI}T(n)\} \qquad (6)$$

Where $T(n) = [t_1(n) \quad t_2(n) \quad t_{N_T}(n)]^T$ is an array of relay out coming signals, one per transmitting antenna and defined as:

$$t(n) = [t_i(n) \quad t_i(n-1) \quad \cdots \quad t_i(n-L+1)] \qquad (7)$$

The $t_i(j)$ is the transmit signal by the ith relay antenna at sample time j. The output of the post filter relay node is,

$$t(n) = F_{Tx}t'(n) \qquad (8)$$

Where $t'(n)$ indicated the input signal of the post filter.

Let, $t'(n) = [t'_1(n), \quad t'_2(n), \quad \cdots \quad t'_{\widehat{N}_T}(n)]$

III. Proposed Approach

In this section, we showed the mathematical solution aspects of proposed algorithm. Substitute equation (8) in equation (6) we get,

$$r'(n) = \{F_{Rx}(H_{TxR}x(n) + w(n))\} + \{F_{Rx}H_{LI}\tilde{G}T\acute{}(n)\}$$

(9)

Where $T'(n) = [\acute{t}_1(n) \quad \acute{t}_2(n) \quad \cdots \quad \acute{t}_{\widehat{N}_T}]^T$and $\tilde{G}$ is the diagonal matrix of the adaptive filters.

P is the permutation matrix used to go to diagonalizable space.

$$\text{Where,} \tilde{G} = P^{-1}diag(F_{Tx}; L), P = \begin{bmatrix} diag(Y_1; L) \\ diag(Y_2; L) \\ \vdots \\ diag(Y_L; L) \end{bmatrix}$$

Diag(Y, L) is the diagonal matrix with L diagonal components Y; diag(Y) is the diagonal matrix with diagonal components of each element of row vector Y.

In the case where is L= 1, which mean that d is smaller than Ts, the F_{Rx} and F_{Tx}filters can be adapted using equation 3 as:

$$F_{Rx}H_{LI}P^{-1}diag(F_{Tx}; L) = 0 \qquad (10)$$

When L=1, then equation (10) is rewritten as,

$$F_{Rx}[H_{L,1}, \quad H_{L,2}, \quad \dots \quad H_{L,L}]diag(F_{Tx}; L) = 0 \qquad (11)$$

$$\text{Where } H_{LI,K} = \begin{pmatrix} h_{11,k} & \cdots & h_{1N_T,k} \\ \vdots & \ddots & \vdots \\ h_{N_R1,k} & \cdots & h_{N_RN_T,k} \end{pmatrix}$$

Where $h_{ij,k}$is the k th value of the row vector H_{ij} in equation (5). H_{LI} denoted by row space vector and H is denoted by column space vector. To achieve the sufficient condition of equation 10 is,

$$F_{Rx}H_{LI} = 0 \text{ and } [H_{L,1}^T, \quad H_{L,2}^T, \quad \dots \quad H_{L,L}^T]^T F_{Tx} = 0 \qquad (12)$$

Where, $F_{Rx}$is the pre space projection filter, F_{Rx} project the row space of H_{LI} to the null space of H_{LI}. Similar with F_{Tx}, F_{Tx} is the null space of $[H_{L,1}^T, \quad H_{L,2}^T, \quad \dots \quad H_{L,L}^T]^T$.

A. NSP with short rank loop interference matrix.

The solution of (12), when the adaptive pre and post filters F_{Rx} and F_{Tx}, cannot be zero matrices, then.

$$0 < rf(H_{LI}) < N_R \text{ and } 0 < rf(H) < N_T \tag{13}$$

Where, the rank function rf gives the dimension of the vector space generated by matrix columns. The rank of a matrix would be zero only if the matrix had its elements equal to zero. If a matrix had even one non-zero element, its minimum rank would be one. $H = [H_{L,1}^T, \; H_{L,2}^T, \; \dots \; H_{L,L}^T]^T$. It means that only when the H_L or the H is not linearly independent matrix or not full rank the non-zero solution of equation (12) exist. With Zero Forcing algorithm, a solution of null space projection as,

$$F_{Rx} = I - H_{LI}H_{LI}^+ \tag{14}$$

$$F_{Tx} = I - HH^+ \tag{15}$$

Where $(.)^+$ is the Moore-Penrose pseudo-inverse and I is the identity matrix.

B. Subspace Projection Partly Cancelling Interference (SSPCI) with Full Rank Matrix

The second algorithm is called Subspace Projection Partly cancelling Interference (SPPCI). When the H_L and H are full rank, as

$$r(H_{LI}) = N_{Rx}; r(H) = N_{Tx} \tag{16}$$

We could just suppress the loop interference at the row space of H_{LI} or the column space of H. Choose the smaller positive integers C_1, C_2, D_1 *and* D_2 to satisfy both (17) and (18) equation.

$$r([H_{L,m_1}, \; H_{L,m_2}, \; \cdots, \; H_{L,m_{D_1}}]) = N_R - C_1 \tag{17}$$

$$r\left([H_{L,n_1}^T, \; H_{L,n_2}^T, \; \cdots, \; H_{L,n_{D_2}}^T]^T\right) = N_T - C_2 \tag{18}$$

Where m_i, $n_i \in [1, \; 2, \; \cdots, \; L]$ we have the subspace

$$H_1 = [H_{L,m_1}, \; H_{L,m_2}, \; \cdots, \; H_{L,m_{D_1}}] \tag{19}$$

$$H_2 = [H_{L,n_1}^T, \; H_{L,n_2}^T, \; \cdots, \; H_{L,n_{D_2}}^T]^T \tag{20}$$

Then project the loop interference to the complementary space of H_1 or H_2 and the loop interference in space of H_1 or H_2 is cancelled by,

$$F_{Rx} = I - H_1 H_1^+ \tag{21}$$

$$F_{Tx} = I - H_2 {H_2}^+ \tag{22}$$

The nonlinearity of $f(.)$ provide more degrees of choice to design the adaptive filters FR_x and F_{Tx}. We can have two cases for relay transmitted signal. The Decode and Forward (DF) MIMO relay case, according to equation 23 where DF relay process the signal and regenerate source data streams, and the AF relay, according to equation 24, where the signal is forwarded after some basic processing.

The F_{Rx} and F_{Tx} have the equivalent function in AF relays, so they can be combined into one filter which would only mitigate the interference partly. The nonlinearity of $f(.)$ provide more degrees of freedom for designing the F_{Rx} and F_{Tx} jointly, the loop interference suppression filter pairs are effective in the DF relays for completely suppressing the loop interference

$$t(n) = F_{Rx} f\left(F_{Rx}(r(n)) - w(n)\right) \tag{23}$$

$$t(n) = F_{Tx} F_{Rx}(r(n) + w(n)) \tag{24}$$

IV. Result and Disussion

The proposed model and TSPA approach are simulated with MATLAB software. The full-duplex MIMO relay is equipped with 6 antennas, three for each side (NR= NT= 3 antennas). The BPSK modulation is considered. The loop back channel is independent Rayleigh fading channel because a close estimation of attenuation due to the multipath fading in wireless channels can be made by relay fading where the no line of sight component present and is normalized as $\|H_{LI}\| = N_R N_T$

We evaluated the Bit Error Rate (BER) according to different Signal to Noise Ratio (SNR) for both condition, i.e., when the delay is less than the time symbol and delay is greater than time symbol. The relation between the SI, BER and SNR is

$$SNR = \frac{S}{N}; N = W_n + SI$$

Where N is the noise, W_n is the white noise and SI is the self-interference.

Fig.4. shows that the BER of the relay is a function of the signal-to-noise ratio (SNR). The simulation shows that even the rank of loop interference matrix is full, it's possible to eliminate the loop interference entirely by jointly design a receive and transmit space projection filter.

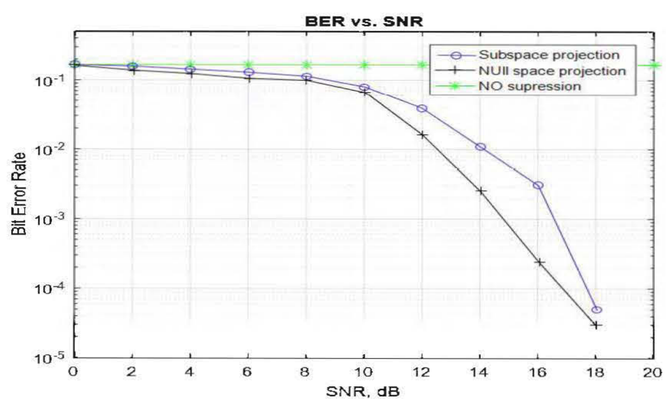

Fig.4. Bit Error Rate VS Signal to Noise Ratio, when $(d \langle T_s)$

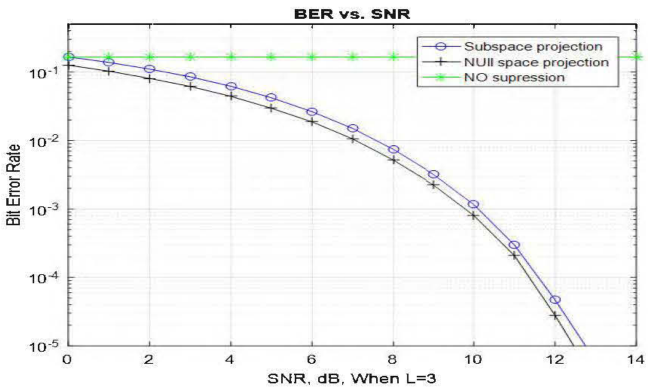

Fig.5. Bit Error Rate VS Signal to Noise Ratio, when L=3

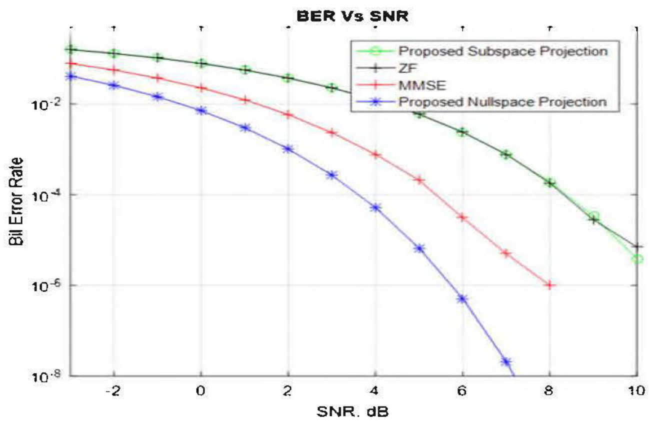

Fig.6. Bit Error Rate VS Signal to Noise Ration Compare to ZF, MMSE and Proposed Scheme

Fig.5. Shows that the BER of the relay is a function of the signal-to-noise ratio (SNR). The simulation shows that even when the delay is greater than the one time symbol, it is possible to eliminate the most of the loop back interference by cooperatively design receive and transmit space projection filter. The Null space projection (SPA) can entirely mitigate the known and partly unknown component of the self-interference and the subspace projection filter where's the Subspace projection (SP) reduce the known part when the number L is three time the Ts duration.

Fig. 6 compared the BER performance of the Zero forcing (ZF), Minimum Mean Square Error (MMSE) and proposed two stage projection. The simulation shows that the BER curve of MMSE, in red color, is better than ZF and proposed subspace projection. However, Proposed Two Stage Projection (TSPA) gives better BER Performance than MMSE and ZF. From the comparison, we can see that our proposed scheme (TSPA) can mitigate the self-interference 70% more than other existing conventional loop back suppression method.

V. Conclusion

This paper proposed an efficient Self-Interference cancellation algorithm for FD-MIMO relays in indoor wireless systems. Our primary concern was to mitigate the relay SI. The SI mitigation is achieved by using TSPA. It consists of two stages called NSP and SP. We observed the simulation for two conditions related to the symbol time duration and the maximum delay of the multipath channel where the relay is deployed. As preliminary results, two space projection scheme gives better and significant cancellation of SI. Subspace projection has better system stability, and it may cancel the loop back by reducing the BER significantly. The second stage null space project support and increase this enhancement at least by 50% for multipath and one path propagation channel. As future work, the number of relay antenna changing effect in harsh environments will be considered.

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Outage Probability Full Duplex Relay in OLOS Underground Mine Environments

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Abstract— **Expanding the coverage of network with different techniques is necessity and demand of today's life. As the population increases the demand for more solutions to give more capacity and to reach everyone on the whole world with network increases. This paper considers the design of dual-hop full-duplex (FD) Multiple-Input Multiple-Output (MIMO) Relay for workers in the underground mine tunnel area, with an obstructed line of sight OLOS conditions, where the relay is equipped with two antenuas, while the source and destination are armed with a single antenua. This paper aims to investigate the outage probability performance when the communication channel is obstructed by a vehicle in a mine tunnel. In this case, the radio signal is obstructed, and no communication is possible, we proposed an investigative relay, installed around that vehicle, with scheme Zero-Forcing Beam-Forming (ZFBF) to avoid obstruction and enable communication again. The simulation results show that the proposed scheme can efficiently minimize the outage probability.**

Keywords—*FD Relay, Amplify and forward (AF), Co-channel Interference (CCI), MIMO, Zero-Forcing Beamforming (ZFBF), Outage Probability.*

I. Introduction

Cooperative communication through MIMO relaying is an effective measure to ensure reliability, extend the network coverage, high spectral efficiency and provide high throughput [1]. In recent times, FD mode relaying have gained much attention and have been intensively studied, as these systems use the same time and channel from the relay station to the destination, without duplex loss. According to FD systems, it is capable of doubling the spectral efficiency when compared to the Half-Duplex (HD) networks. Unfortunately, the performance in practical systems is severely deteriorated by the intrinsic self-interference (SI) and the CCI from the other concurrent transmitter [2]. Nowadays, FD wireless communication received significant attention from both academia and industry due to its potentiality of double the spectral efficiency of the existing wireless communication systems [3]-[5].

Wireless communication conveys a significant role in underground mines to ensure the safety, security, and industry. The underground mine surroundings are way more different than usual surroundings. So, the wireless communication may not suitably work or more inadequate communication between the source and destination in underground mines because of its harsh environments [7]. We used the relay technique in order to improve the communication link between the source and destination. The relayed transmission is a promising technique for improving the quality of wireless communication. The FD relay arranges for a promising approach to a wireless communication system, and it can advance the technical specification of 5G mobile wireless communication system [8].

In the FD technique, relay forwarding the data simultaneously when any source node, N1 or N2, send data. The key challenge if FD relay, is to avoid or reduce interferences induced by the relay transmitting. Figure 1 shows the two main approaches used to support FD technique [8]-[10].

In both approaches, the relay node is set up in the middle between nodes (N1 and N2) and it takes data radio signal from one node, amplifies it and sends it to the other node. In dual-hop approach, it is same as a projection carried from one point to another point and got elevated by the midpoint to take it to the other part. Meanwhile, in a cooperative approach, the data is sent directly from the end node to other and indirectly through the relay.

Both configurations require line of sight between end nodes in order to complete the transmission, while dual hop will carry the data and triangulate to reach the desired position.

The formation of CCI, caused by simultaneous used of the radio signal by relay and end nodes, gives the system instability or unsteadiness. Thus, many research designs for FD systems were proposed and studied to overwhelm the challenges. Outage probability of FD-MIMO single user relying systems investigated for end-to-end communication in [4].

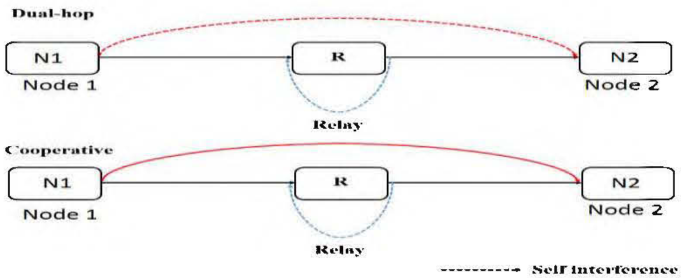

Fig. 1. FD Relay Protocol

In [6], Massive MIMO was applied in FD relaying systems to facilitate (SI) suppression and to improve the spectral efficiency and in [7] where the suboptimal downlink beamformer was designed to improve the system throughput. In this paper, we investigate the viable solutions to get these CCI impact on the original radio signal reduced or eliminated for the particular case of underground mine obstructed line of sight (OLOS), where big mining vehicles can play the role of full or partial obstructers in narrow tunnels of mine.

The paper is structured as follows: In section II, we present the problem statement. Section III, The proposed approach. In part IV, results and discussion and the paper is concluded in section V..

PROBLEM STATEMENT

Path Loss

Path loss is the reduction in the power density of an electromagnetic wave as it propagates through space. Path loss is an utmost component in the analysis and design of the link budget of a telecommunication system.

This term is commonly utilized in wireless communications and signal propagation. Path loss may be due to many effects, such as free-space loss, refraction, diffraction, reflection, aperture-medium coupling loss, and absorption. Path loss moreover has an impact on terrain contours, environment, propagation medium, the space within the reception and the transmission, and the height of location of antennas. Generally, for wireless communication amount of path loss that occurs for a transmitted signal can be tenacious from Friis transmission formula.

$$P_r = P_t + G_t + G_r + 20log10\left(\frac{\lambda}{4\pi R}\right)$$

The gain of the units dB, and units of power in dBm or dBW. Where P_t and P_r are the antenna powers, Gt and Gr are the antenna gains (concerning an isotropic radiator) of the transmitting and receiving antennas respectively, is the wavelength, and R is the distance between the antennas.

A. Multipath Loss

It is well known that multipath delay spread in the wireless channel limits data rates due to transmission errors caused by inter-symbol interference (ISI).Multipath loss can happen when an antenna receives a transmitted information that is the sum of the desired line-of-sight (LOS) information and non-line-of-sight (NLOS) signals. (NLOS signals are caused by reflections off of structures and diffraction off of obstacles.)

Multipath Signal Propagation

Wireless communication in the mining industry has removed the limitations imposed by wired communication; it has brought along a new set of challenges. Probably the most significant challenges in underground wireless communication are unreliable and unpredictable wireless link. Multipath propagation is a widespread phenomenon in signal transmission over wireless channels. A signal transmitted over multipath channels is subject to reflection, diffraction, and refraction. An accurate and applicable channel model is needed to predict the wireless propagation characteristics in underground mines.

B.Fading

In wireless communications, fading is a deflection of the attenuation that bearer -modulated signal experience over certain generation media. The fading may change with time, geographical situation and fixed radio frequency, and is often modeled as a desultory process. The Fading channel is a communication channel that experiences are fading. In the wireless scheme, fading even may either be due to a multipath extension, referred to as multipath induced fading, or due to shadowing from obstacle affecting the wave propagation, sometimes referred to as shadow fading.

C. Noise

In the underground mine, noise due the maneuver of mining equipment's reduces the signal superiority. Noise added to the signal either externally or internally which reduces the coverage range of the communication system. The leading noise sources in mines are rail motors, electric motors, power line and lighting systems. Performance of a communication system is affected due to environmental noise. The noise caused by different appliances, cable lines, electric motors and mining equipment are in the frequency bands in which underground communication devices operate [11].

Machinary Obstruction Loss

Large machines like generators /motors are used for sourcing the electrical installation like trolleys, blowers, lighting, exhaust fans, etcetera. Obstruction loss will occur if the area of these devices is comparable to the wavelength of the signal.

In figure 2, shows communication problems in underground mines tunnel. Here, mobile-1 can communicate with an access point without face any problem, but it cannot directly communicate with mobile-2 because of obstructed line-of-sight (OLOS). To overcome this issue we typically used a relay in between the source and destination. However, there is two communication scenario, i.e., mobile-1 to access point and mobile-1 to mobile-2.

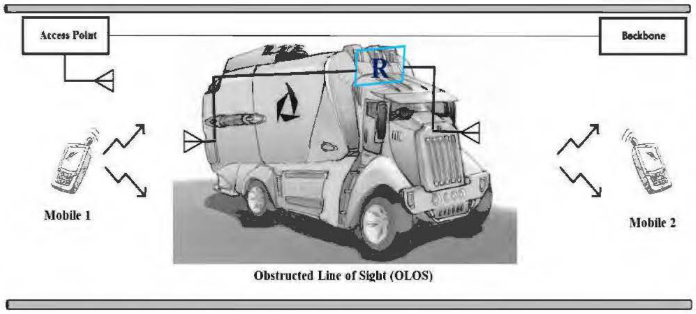

Fig. 2. Communication Problem in Underground mine tunnel.

For, mobile-1 to access point communication, it doesn't need the relay to be enabled, and for the mobile-1 to mobile-2 communication, the relay must need to be activated to build communication between them.

To proceed forward with the question of today fig.2 shows the problem one can face during a transmission process. If a source is in a mine tunnel and the destination is ahead of it but in between there is the vehicle that is obstructed in the channel the transmission may send wrong data or worse no communication at all. Not the statement here may seem to be simple enough but to answer it various techniques have been thought and implemented. Consider this vehicle as a co-channel interference, interfering with the proper communication of the signals. Now, this co-channel interference can be dealt with schemes like Maximum Ratio Combining, Zero Forcing or Minimum mean-square error. We used of zero forcing because it is easy to understand and easy to implement with almost 100 percent accuracy of minimizing the CCI.

PROPOSED APPROACH

The problem ahead has to be solved using relay channels so that the data can travel efficiently. The relay channel has its perks, but it also attenuates in undesired fashion. In the wireless communication arrangements relating to relays, it is must to improvise and recalibrate the systems in use nowadays. The link between the two servers wherever they are should be reliable and secure with complete coverage. It has to be done through various techniques, using relays and its varieties are one of them. Relay, itself can be used in numerous ways and could possess many distinct behaviors. The one we use and propose is to use the relay in amplifying and forward (AF) protocol due to the reason of its easy accessibility and low costs. AF systems do one job repeatedly, that is to send the received data forward with a scaled version. As our task here is to send the data complete and whole to the destination, it is obligatory to make the data received by relay as prominent as one system can offer. Now the relay may create their problems to the system one of them is the creation of the resistance named as co-channel interference. One cannot merely take the impact of this interference out of the equation. As a result, the signals deviate from the original track and go more extensive than they should go. It breaks the strength of the original signal, and the data can even get lost. One way to concentrate these signal is by using beamforming (BF) process. The BF gives shape to the signal so that it can transverse in the physical entity without getting dispersed. It has done through sending the same input from as many antennas of the device as it offers. Now, this BF can be categorized by the way they are used, and one that stands out is precoding. It supports multiple streams of data to be transmitted from the number of the antenna the system has. There are three most popular methods to get this BF reduce or eliminate the interference created by the relay channel itself. One named maximal ratio combining, which adds the signals from both the channels. It then makes the gain of all channels relational to the root mean square of signal and inversely relational to the square of the mean noise in that channel. The other is a minimum mean square error; it is also a pre-coder used to calculate the mean square of the values of the channel and find the minimal error between the two channels. Where we used the last technique in this paper named zero-forcing (ZF). The ZF or null steering is a way to compensate delays of receiving signals. The weighted array of signals is added with a carefully chosen compensating appropriate values. Now when this method is employed, and operational the outage probability was calculated and plotted the parameters of the performance analysis of the channel.

So the start of the program states to know the power given to the system and number of the antenna in the three stages of communication. These antennas are kept same for the simplicity of the project and its understanding. So the number of inputs and outputs namely number of the antenna at source (NS), Number of the antenna at the destination (ND). Number of the antenna at the relay to transmit (NR_t) and number of the antenna at the relay to receive (NR_r) are the number of the antennas. The source and destination add a vectors ts and td respectively whose mean square norm equals to 1. It is because of the destination does not know the way the channel behaves. The three channels namely HRR i.e., CCI, HSR (Source to Relay) and HRD (Relay to Destination) is configured that have a Rayleigh channel characteristics. Now, these vectors when passed through the channel they produce values hRD (Channel relay to destination) and hSR (Channel source to relay). These values are used later to find the input signal at the relay using formula, $rIN = hSR.* xS + HRR\,(WT.* xR) + nRR$ and the received value in Relay with $rR = (WR' * hSR * xS + WR' * HRR\,(WT * xR) + WR' * nRR)'$ formula. Here WR is the matrix the relay add in to the received signal and WT is the matrix it loads in to the transmitted signal. The value nRR is the noise and attenuation added to the signals in the channels, and the xS is the original data along with xR the received data. The values here are used as a random variable in the code line. The covariance at the relay and its probability when it is the destination and when it is the source is also calculated with the formulas given in [12]-[13].

RESULT AND DISCUSSION

Outage probability is the probability that the momentary source to destination (S-D) signal-to-noise-ratio (SNR) falls below an aimed SNR. In this work, based on the FD-MIMO relaying system outage occurs a communication failure in one of two links, i.e., source to relay (S to R) or relay to the destination (R-D).The simulation set up follows the proposed approach provide in section III. We considered a dual-hop (DH) relay and observed the simulation for both hops.

PARAMETERS

Name of the Parameters	HSR	HRR	HRD
Power	0.6 kw (Max 1 kw)	0.6 kw (Max 1 kw)	0.6 kw (Max 1 kw)
Number of antennas	2	2	2
Sample rate	250000	50000	250000
Maximum Doppler Shift	130	130	130

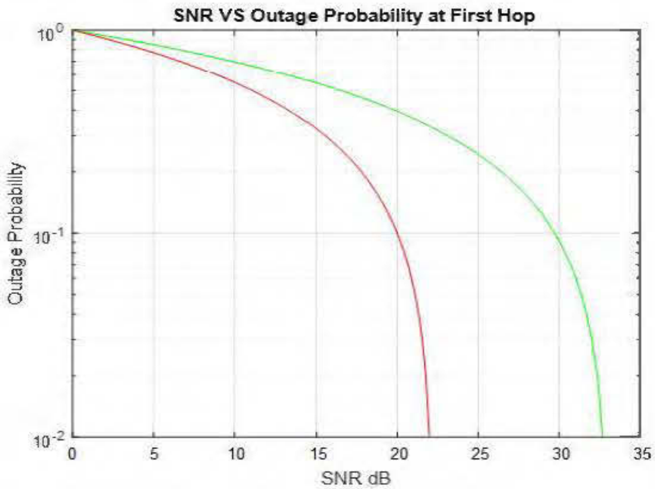

Fig. 3. The Outage Probability of the Channel in First hop

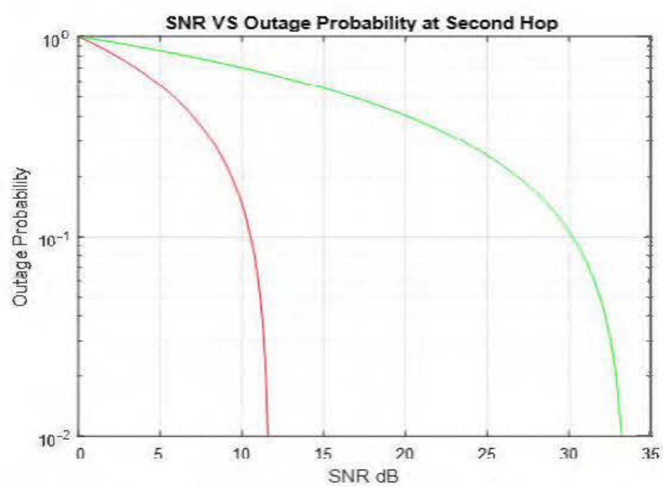

Fig. 4.The Outage Probability of the Channel in Second hop

Fig. 3 and Fig. 4 shows the simulation results for receive and transmit ZF based precoding design with the dual-hop relay. The results clearly show the decrease in outage probability as the SNR increases. The red is the outage probability given thought the relay while green is the link from source. Now the advantages of Zero Forcing here is the maximum probability of outage the SNR decrease in the system with relay installed in between the two locations notably the source and destination. In [12] shows the outage probability of the dual-hop AF relaying system with the ZF/MRT for multiple antennas at the relay and single antenna at source and destination. For OLOS underground mine environments we get the better outage performance with ZFBE comparing to ZF/MRT scheme.

CONCLUSION

In this paper, we considered full-duplex dual-hop amplify-and-forward MIMO relay to investigated the outage probability performance of communication channel in OLOS underground mine environment. The zero forcing beamforming (ZFBE) is added in order to make the signals travel or triangulate in OLOS with a more significant probability and lesser SNR's, and the simulation result shows the improved CCI suppressed performance in both hops. The paper used the knowledge of signal communication processes and network theory which explains the ways a channel can affect the output of the system to the destination. In future work, the expected result is to state right balance between relay enabling and disabling operation for OLOS and LOS.

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FD-MIMO Relay Self-Interference Cancellation Using Space Projection Algorithms

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Abstract— **In this paper, self-interference (SI) cancellation algorithm based on Space Projection Algorithm (SPA) is proposed for Full-Duplex (FD) Multiple-Input Multiple-Ontput (MIMO) relays in an indoor wireless communication system. The simultaneous transmission and reception of the same radio signal imply a SI around the relay transceiver. The principal challenge of implementing the FD-MIMO relay is to this interference and increase the relaying capacity. To reach this aims, an efficient algorithm using SPA filters is designed and validated by simulation. The results of proposed method ontperform the exiting works in term of BER for the QPSK modulation.**

Keywords—FD relay; Self-Interference; Space Projection Algorithm; null space projection (NSP); subspace projection (SP); QPSK; MIMO.

I. INTRODUCTION

FD communication system has acquired much for its capability of simultaneously transmitting and receiving on the same signal at the same time [1]. The MIMO relay technology is a cost-effective approach since it can extend the coverage of the wireless system, provide higher spectral efficiency, improve network throughput by offering cooperative diversity and enhance the communication system capacity [2]. MIMO is the auspicious technology for the next-generation wireless communication system to provide a broad coverage area, incremented system capacity, and high spectral efficiency. The MIMO links are furnished with antenna arrays between both transmitter and receiver sides to maintain a high efficient multi-stream between the cessation-to-end antennas of the communication link [3] [4].

The relay approaches can be, also grouped into two broad categories, named as half-duplex (HD) and full-duplex (FD) relays. The FD methods are defined as a transceiver's ability to transmit and receive the same signal at the same time. Whereas, the HD relays require two orthogonal signals to achieve a single end-to-end link through a relay node. In the communication schemes, the FD relay is valuable in several anticipated features such as less delay, high efficiency, high security and improving access layer utility function [5]. Recently the FD relays are considered for infeasible inherent SI because FD enabled communication schemes are beneficial for many desired aspects. However, due to simultaneous transmission and reception, the self-interference (SI) caused by the coupling effect of the transmitted signal at relay receiver become a rigorous issue in FD MIMO relay system. Consequently, the SI suppression in FD relay system is considered as an essential technique to ascertain the reliable transmission [6].

FD relays have been presented in an efficient short range application. According to the relay theory concept, SI signal is produced from the loopback (LI) signal. This signal has followed some signs such as high dynamic range of receiver or transmitter, faultless awareness of the SI path [7]. Hence the FD relay can receive the desired signals from the source end, while concurrently communicate the signals to the stage of destination. This ability gives the better results in decreasing the essential time slots on end-to-end communication and ignore the latency [8] [9].

The critical challenge to support FD relays is to resolve by suppression or cancellation SI induced by the loopback (LI) signal in the relay node. According to several works [10], [11], there are three main categories to suppress this SI: passive suppression (PS), analog cancellation (AC), and digital cancellation (DC). The majority of PS approaches rely on antenna design and placement to suppress the SI. They use intrinsic antenna parameters such as placement, directivity or polarization to keep isolation or space orthogonality around the relay to break the loop-back interference. The PS is better suited for a millimeter wave communication system where antenna separation is easy to achieve and may reach high SI suppression, for example, it may remove more than 40 dB interferences in 60 GHz band. In the AC approaches, the basic idea is to estimate and remove, at the analog RF stage, the SI signal received by the relay node. In [12], analog circuit domain cancellation technique purposes to mitigate the SI in the analog receive chain circuitry the DC. Unlike all the previous approaches, the DC approaches deferred SI processing to the digital RF level, in the form of digital SI canceler or receive beamforming. The digital SI canceler requires accurate estimation of residual SI to ensure that a small noise is introduced due errors estimation and signal distortion. Meanwhile, receive beamforming approaches are

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supported only by MIMO systems. In [13] presents the SI suppression strategies by FD-MIMO relay applying using antenna selection technique. They also discussed the conventional LI suppression scheme. Conventionally, LI could be suppressed by using zero forcing (ZF) and minimum mean square error (MMSE) estimation filter. Authors in [14] [15], proposed null space projection and minimum mean square error filters for spatial loop interference suppression as well as discuss shortly how to combine them with time-domain cancellation. Despite all these approaches, complete cancellation of the SI signal has not been achieved to date.

In this paper, we proposed new algorithm stated to as the Two Stage Projection (TSPA) algorithm. TSPA consist of Null space projection (NSP) and Subspace Projection (SP) algorithm which can employ in the position when loopback (LI) channel matrix is of full rank. So, in this situation, we design receive and transmit filters combined with zero forcing (ZF) and also considered the multipath propagation of the LI signal. If the loop channel matrix is not of full rank, the NSP algorithm projected to cancel the loopback signal. SP algorithm primarily used to make the receive filter orthogonal to one subspace and the transmit filter orthogonal to another one to cancel the desired loop interference.

However, our paper is structured as follows: In section II, we introduce the system model of the two-hop relay. In section III, we present the proposed approach. Results and analysis has been introduced in section IV and the paper is concluded in section V.

II. System Model

In this section, we provide a mathematical model of a relay station with SI occurrence and cancellation. A 3-node dual-hop amplifies and forward (AF) relaying system in the indoor wireless system is considered. AF relay always used for cooperative communication to improve the performance of the wireless system. AF relay amplifies its received signal and maintaining fixed average transmit power. In our system model, AF is employed because it requires relatively simple signal processing. The proposed technique considered for the two-hop relaying model.

The model includes Transmitter(T_x), Relay (R)and Receiver (R_x) nodes shown in Fig.1. The transmitter node is equipped with a set of NT_x antennas whereas the receiver node has NR_x antennas. The relay node is equipped with two sets of antennas. The first set, have NR antennas and is dedicated to receiving meanwhile the second set include NT transmit antennas.

We define $H_{TxR} \in \mathbb{C}^{N_R \times N_{Tx}}$and $H_{RRx} \in \mathbb{C}^{N_{Rx} \times N_T}$ which represent the MIMO complex channel matrices respectively from the transmitter to relay node and from the relay node to a receiver. The signal vector $x(n)$ defined as a complex vector$x(n) \in \mathbb{C}^{N_{Tx} \times 1}$, transmitted by the source node. The complex signal vectors $r(n)$ and$t(n)$, stated as $r(n) \in \mathbb{C}^{N_R \times 1}$and $t(n) \in \mathbb{C}^{N_T \times 1}$, denote respectively the received and transmitted signal at the relay node. H_{LI} is the SI signal, which

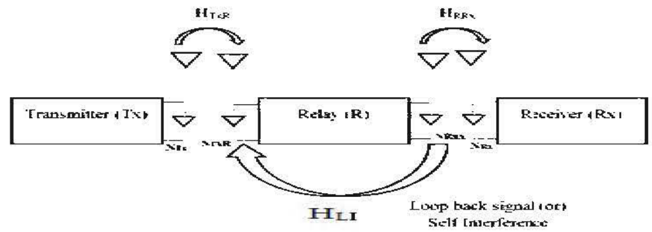

Fig. 4. Two-hop relay model.

reduces the channel capacity from the transmission to reception and makes the relay system unstable in FD-MIMO. The self-interference complex channel matrix, introduced by the relay, is denoted by $H_{LI} \in \mathbb{C}^{N_R \times N_T}$, as shown in fig. 1.

Time symbol (T_s) is the rate at which a signal is modulated, and it is a function of the symbol rate. i.e. for QPSK bit rate is $= \frac{2}{T_s}$ .Since QPSK transmit two bit per symbol, and the symbol rate is $\frac{1}{T}$, QPSK can transmit 2 bits per second. The delay (d) is a measure of the multipath richness of a communications channel. In Fig.2. the signal power of each multipath is plotted against their respective propagation delays and it indicates how a transmitted pulse gets received at the receiver with different signal strength as it travels through a multipath channel with different propagation delays(τ_0 , τ_1 *and* τ_2). The delay is mostly used in the characterization of wireless channels, but it also applies to any other multipath channel. According to the multipath delay of channel (d) and the time symbol of the signal(T_s), we can single out two cases. In both following situations, d will denote the maximum multi-path time delay of the channel.

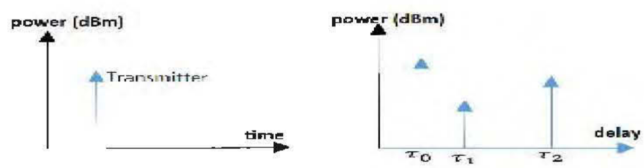

Fig. 5. Power delay profile (PDP).

a. *First case* $(d < T_s)$

In this case, the multipath parameter of the channel d is smaller than signal symbol time (T_s), which means that the one symbol will interfere mainly with itself. The signal received by the relay is expressed as,

$$r(n) = H_{TxR}x(n) + H_{LI}t(n) + w(n) \tag{1}$$

Where $w(n) \in \mathbb{C}^{N_R \times 1}$denote an additive white Gaussian noise (AWGN) and $H_{LI}t(n)$ is the loopback interference signal received by the relay. Where $t(n)$ is the transmitted signal in the relay.

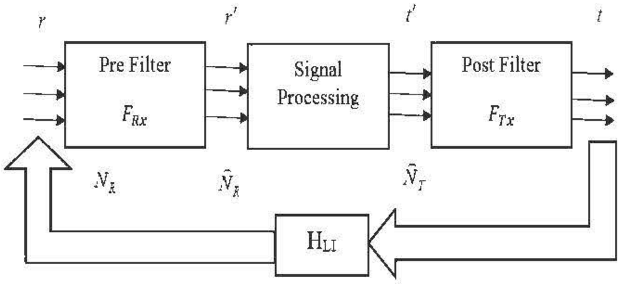

Fig. 6. Relay with loop back signal cancellation.

A pre-projection filter, which is called the LI signal suppression filter denoted by $F_{Rx}$and defined as $F_{Rx} \in \mathbb{C}^{N_R \times \hat{N}_R}$ and post-filter which is called transmit weight filer F_{Tx} defined by $F_{Tx} \in \mathbb{C}^{\hat{N}_T \times N_T}$ are depicted in fig.3. $\hat{N}_R$ and $\hat{N}_T$ are the received and transmit signal of the signal processor. Without loss of generality we can assume that $\hat{N}_R \leq N_R$ and $\hat{N}_T \leq N_T$ because the end to end communication cannot improve by the increasing the number of dimensions. The output signal of the pre- filter $r'(n) \in \mathbb{C}^{\hat{N}_R \times 1}$ and the input signal of the post filter $t'(n) \in \mathbb{C}^{N_T \times 1}$.

Now, the output of the pre-filter $r'(n)$ with loop back interference can be written as,

$$r'(n) = \{F_{Rx}(H_{TxR}x(n) + w(n))\} + \{F_{Rx}H_{LI}F_{Tx}\acute{t}(n)\} \quad (2)$$

In equation 2, the first part represent the desired signal exposed to white Gaussian noise and the second part is channel loop back interference.

As shown in fig. 3, relay used two adaptive filters, pre filter F_{Rx} and post filter F_{Tx} to respectively process the input and output signal in order to cancel the SI. Which means that both filters will collaborate to define the right signal to send in order to suppress the channel loopback interference. To achieve this goal, according to equation 2, the second part should be zero (cf. equation 3) is a necessary and sufficient condition to optimize both adaptive filter weights.

$$F_{Rx}H_{LI}F_{Tx} = 0 \quad (3)$$

b. Second case $(d > T_s)$

For this case, the maximum multipath d induced by the channel LI is more than one time T_s duration. The number of subsequent symbols that interfere with one symbol, denoted by L, is estimated by equation 4.

$$L = \left\lceil \frac{d+\frac{T_s}{2}}{T_s} \right\rceil \quad (4)$$

The loop channel matrix $H_{LI} \in \mathbb{C}^{N_{RX} x\,(N_{TX}.L)}$ can be written as

$$H_{LI} = \begin{bmatrix} H_{11} & H_{12} \cdots & H_{1N_{TX}} \\ H_{21} & H_{22} \cdots \ddots & H_{2N_{TX}} \\ \vdots & \vdots & \vdots \\ H_{N_{RX}1} & H_{N_{RX}2} & H_{N_{RX}N_{TX}} \end{bmatrix}$$

(5)

Where $H_{ij}\, \mathbb{C}^{1XL}$is the sub channel vector from the i th transmit antenna to the j th receive antenna of the relay. Now, according to the model in fig.3 and due to the inter symbol interference the output signal $\acute{r}(n)$ is again presented as,

$$\acute{r}(n) = \{F_{Rx}(H_{TxR}x(n) + w(n))\} + \{F_{Rx}H_{LI}T(n)\} \quad (6)$$

Where $T(n) = [t_1(n) \quad t_2(n) \quad t_{N_T}(n)]^T$ is an array of relay out coming signals, one per transmitting antenna and defined as:

$$t(n) = [t_i(n) \quad t_i(n-1) \quad \cdots \quad t_i(n-L+1)] \quad (7)$$

The $t_i(j)$ is the transmit signal by the ith relay antenna at sample time j. The output of the post filter relay node is,

$$t(n) = F_{Tx}t'(n)$$

(8)

Where $t'(n)$ indicated the input signal of the post filter.

Let, $t'(n) = [t'_1(n), \quad t'_2(n), \quad \cdots \quad t'_{\hat{N}_T}(n)]$

III. PROPOSED APPROACH

In this section, we showed the mathematical solution aspects of proposed algorithm. Substitute equation (8) in equation (6) we get,

$$r'(n) = \{F_{Rx}(H_{TxR}x(n) + w(n))\} + \{F_{Rx}H_{LI}\tilde{G}T(\acute{n})\} \quad (9)$$

Where $T'(n) = [t_1(n) \quad t_2(n) \quad \cdots \quad t_{\hat{N}_T}]^T$ and $\tilde{G}$ is the diagonal matrix of the adaptive filters.

P is the permutation matrix used to go to diagonalizable space.

Where, $\tilde{G} = P^{-1} diag(F_{Tx}; L)$, $P = \begin{bmatrix} diag(Y_1; L) \\ diag(Y_2; L) \\ \vdots \\ diag(Y_L; L) \end{bmatrix}$

diag(Y, L) is the diagonal matrix with L diagonal components Y; diag(Y) is the diagonal matrix with diagonal components of each element of row vector Y.

In the case where is L= 1, which mean that d is smaller than Ts, the F_{Rx} and F_{Tx}filters can be adapted using equation 3 as:

$$F_{Rx} H_{LI} P^{-1}{}_{diag}(F_{Tx}; L) = 0 \quad (10)$$

When L=1, then equation (10) is rewritten as,

$$F_{Rx}[H_{L,1}, \quad H_{L,2}, \quad \dots \quad H_{L,L}] diag(F_{Tx}; L) = 0 \quad (11)$$

Where $H_{LI,K} = \begin{pmatrix} h_{11,k} & \cdots & h_{1N_T,k} \\ \vdots & \ddots & \vdots \\ h_{N_R1,k} & \cdots & h_{N_RN_T,k} \end{pmatrix}$

Where $h_{ij,k}$is the k th value of the row vector H_{ij} in equation (5). H_{LI} denoted by row space vector and H is denoted by column space vector. To achieve the sufficient condition of equation 10 is,

$$F_{Rx} H_{LI} = 0 \text{ and } [H_{L,1}^T, \quad H_{L,2}^T, \quad \dots \quad H_{L,L}^T]^T F_{Tx} = 0 \quad (12)$$

Where, $F_{Rx}$is the pre space projection filter, F_{Rx} project the row space of H_{LI} to the null space of H_{LI}. Similar with F_{Tx}, F_{Tx} is the null space of $[H_{L,1}^T, \quad H_{L,2}^T, \quad \dots \quad H_{L,L}^T]^T$.

A. NSP with short rank loop interference matrix.

The solution of (12), when the adaptive pre and post filters F_{Rx} and F_{Tx}, cannot be zero matrices, then.

$$0 < rf(H_{LI}) < N_R \text{ and } 0 < rf(H) < N_T \quad (13)$$

Where, the rank function rf gives the dimension of the vector space generated by matrix columns. The rank of a matrix would be zero only if the matrix had its elements equal to zero. If a matrix had even one non-zero element, its minimum rank would be one. $H = [H_{L,1}^T, \quad H_{L,2}^T, \quad \dots \quad H_{L,L}^T]^T$. It means that only when the H_L or the H is not linearly independent matrix or not full rank the non-zero solution of equation (12) exist. With Zero Forcing algorithm, a solution of null space projection as,

$$F_{Rx} = I - H_{LI} H_{LI}^+ \quad (14)$$

$$F_{Tx} = I - HH^+ \quad (15)$$

Where $(.)^+$ is the Moore-Penrose pseudo-inverse and I is the identity matrix.

B. Subspace Projection Partly Cancelling Interference (SSPCI) with Full Rank Matrix

The second algorithm is called Subspace Projection Partly cancelling Interference (SPPCI). When the H_L and H are full rank, as

$$r(H_{LI}) = N_{Rx}; r(H) = N_{Tx} \quad (16)$$

We could just suppress the loop interference at the row space of H_{LI} or the column space of H. Choose the smaller positive integers C_1, C_2, D_1 *and* D_2 to satisfy both (17) and (18) equation.

$$r([H_{L,m_1}, \quad H_{L,m_2}, \quad \cdots, \quad H_{L,m_{D_1}}]) = N_R - C_1 \quad (17)$$

$$r\left([H_{L,n_1}^T, \quad H_{L,n_2}^T, \quad \cdots, \quad H_{L,n_{D_2}}^T]^T\right) = N_T - C_2 \quad (18)$$

Where m_i, $n_i \in [1, \quad 2, \quad \cdots, \quad L]$ we have the subspace

$$H_1 = [H_{L,m_1}, \quad H_{L,m_2}, \quad \cdots, \quad H_{L,m_{D_1}}] \quad (19)$$

$$H_2 = [H_{L,n_1}^T, \quad H_{L,n_2}^T, \quad \cdots, \quad H_{L,n_{D_2}}^T]^T \quad (20)$$

Then project the loop interference to the complementary space of H_1 or H_2 and the loop interference in space of H_1 or H_2 is cancelled by,

$$F_{Rx} = I - H_1 H_1^+ \quad (21)$$

$$F_{Tx} = I - H_2 {H_2}^{+} \tag{22}$$

The nonlinearity of $f(.)$ provide more degrees of choice to design the adaptive filters FR_x and F_{Tx}. We can have two cases for relay transmitted signal. The Decode and Forward (DF) MIMO relay case, according to equation 23 where DF relay process the signal and regenerate source data streams, and the AF relay, according to equation 24, where the signal is forwarded after some basic processing.

The F_{Rx} and F_{Tx} have the equivalent function in AF relays, so they can be combined into one filter which would only mitigate the interference partly. The nonlinearity of $f(.)$ provide more degrees of freedom for designing the $F_{Rx}$and F_{Tx} jointly, the loop interference suppression filter pairs are effective in the DF relays for completely suppressing the loop interference

$$t(n) = F_{Rx} f\left(F_{Rx}(r(n)) - w(n)\right) \tag{23}$$

$$t(n) = F_{Tx} F_{Rx}(r(n) + w(n)) \tag{24}$$

IV. Result and Disussion

The proposed model and TSPA approach are simulated with MATLAB software. The full-duplex MIMO relay is equipped with 6 antennas, three for each side (NR= NT= 3 antennas). The four phase QPSK modulation is considered. The loop back channel is independent Rayleigh fading channel because a close estimation of attenuation due to the multipath fading in wireless channels can be made by relay fading, where the no line of sight component present and is normalized as $\|H_{LI}\| = N_R N_T$.

We evaluated the Bit Error Rate (BER) according to different Signal to Noise Ratio (SNR) for both condition, i.e., when the delay is less than the time symbol and delay is greater than time symbol. The relation between the SI, BER and SNR is

$$SNR = \frac{S}{N}; N = W_n + SI$$

Where N is the noise, W_n is the white noise and SI is the self-interference.

Fig.4. shows that the BER of the relay is a function of the signal-to-noise ratio (SNR). The simulation shows that even the rank of loop interference matrix is full, it's possible to eliminate the loop interference entirely by jointly design receive and transmit space projection filter.

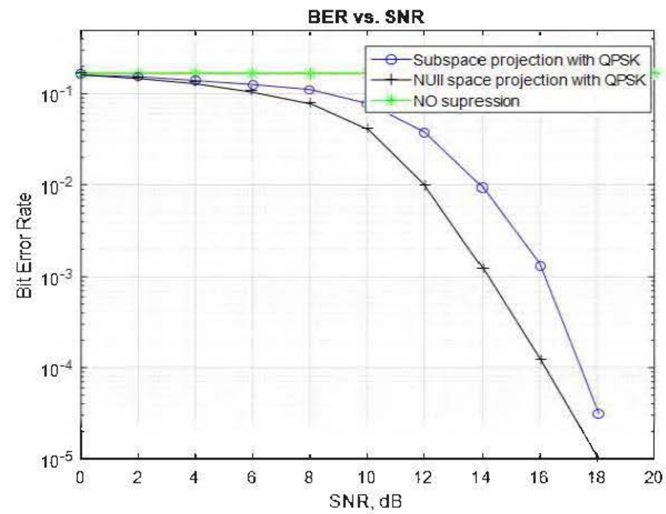

Fig.4. Bit Error Rate VS Signal to Noise Ratio, when $(d \langle T_s)$

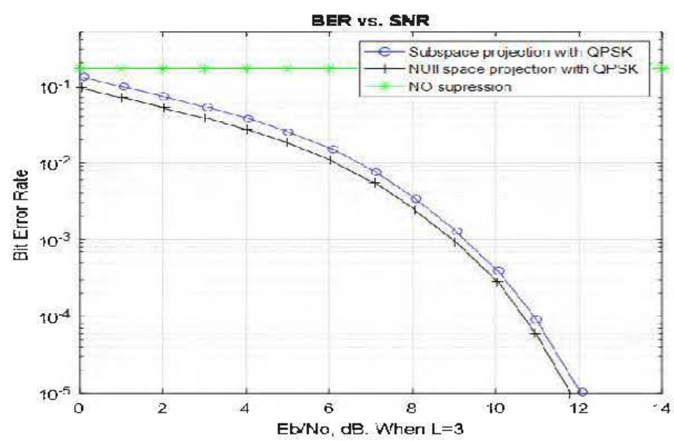

Fig.5. Bit Error Rate VS Signal to Noise Ratio, when L=3

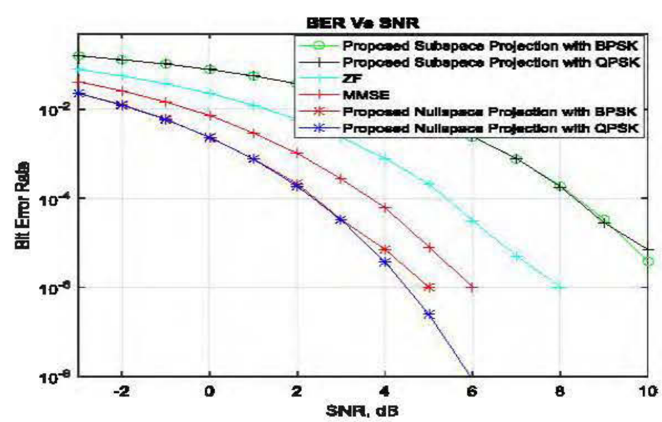

Fig.6. Bit Error Rate VS Signal to Noise Ration Compare to ZF, MMSE and Proposed Scheme

Fig.5. shows that the BER of the relay is a function of the signal-to-noise ratio (SNR). The simulation shows that even when the delay is greater than the one-time symbol, it is possible to eliminate the most of the loop back interference by cooperatively design receive and transmit space projection filter. The Null space projection (SPA) can entirely mitigate the known and partly unknown component of the self-interference and the subspace projection filter where's the Subspace projection (SP) reduce the known part when the number L is three time the T_s duration.

Fig. 6 compared the BER performance of the Zero forcing (ZF), Minimum Mean Square Error (MMSE) and proposed two stage projection with BPSK and QPSK modulation. The simulation shows that the BER performance of MMSE and ZF gives performance than proposed subspace algorithm with BPSK and QPSK. However, Proposed Two Stage Projection (TSPA) with four phase QPSK gives better BER Performance than MMSE, ZF and proposed two stage algorithm with BPSK. From the comparison, we can see that our proposed scheme (TSPA) with QPSK can mitigate the self-interference more than 70% than other existing conventional LI suppression method.

V. Conclusion

This article develops the FD-MIMO relays SI cancellation model for the indoor wireless communication systems. The significant self-interface cancellation is achieved by using SPA with QPSK modulation, where SPA consists of two space projection filters. In multipath channel, simulation results give better and significant cancellation of SI for QPSK modulation and outperform existing works. The first space projection filter reduces effectively the BER where the second one bring a significant enhancement, at least by 60%, in multipath propagation channel conditions. In the next step of this work, we are going to perform this operation for harsh environment such as underground mine.

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Outage Probability Performance Using Space Projection Algorithm in FD-MIMO Relay

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Abstract— **This paper investigates the performance of Full-Duplex (FD) Multiple-Input Multiple-Output (MIMO) relays in an indoor wireless communication system. The FD-MIMO system use Amplify-and-Forward (AF) approach to reduce interferences around relay and increase throughput capacity between both ends of the link. At the relay level, a major issue is to minimize the self-interference (SI) generated by a simultaneous receiving and transmitting of the same signal. To address SI interferences, we proposed a space projection algorithm (SPA) involving Null-space projection (NSP) and subspace projection (SP) algorithms. The simulation results reveal that the proposed SPA minimized the loop interferences and boosted up the link capacity.**

Keywords—*Full-Duplex, Amplify and forward (AF), Self-interference, Multiple-Input Multiple-Output, Space projection algorithm, Null space projection, Sub space projection.*

I. Introduction

In wireless communication system, relays are used to improve the data rate between the source and destination. The resulting three-node (S-R-D) channel is known as the relay channel. The relay can be installed where the source and destination cannot communicate each other directly, hence the need for intermediate nodes to relay and also it is known as the two-hop relay channel [1]-[2]. The MIMO relay technology is a cost-effective approach since it can extend the coverage of the wireless system, provide higher spectral efficiency, improve network throughput by offering cooperative diversity and enhance the communication system capacity [3]. MIMO is the promising technology for the next-generation wireless communication system to provide a broad coverage area, incremented system capacity, and high spectral efficiency. The MIMO links are furnished with antenna arrays between both transmitter and receiver sides to maintain a high efficient multi-stream between the cessation-to-end antennas of the communication link.

The relay approaches can be, also grouped into two broad categories, named as half-duplex (HD) and full-duplex (FD) relays. The FD methods are defined as a transceiver's ability to transmit and receive the same signal at the same time. Whereas, the HD relays require two orthogonal signals to achieve a single end-to-end link through a relay node. In the communication schemes, the FD relay is valuable in several anticipated features such as less delay, high efficiency, high security and improving access layer utility function [4]. Consequently, FD relays are impaired by SI, which is the interference caused by the relays transmit signal to the relay's received signal and oppositely, HD entirely avoids the SI [5]. However, due to the simultaneous transmission and reception, how to deal with the intense loop-back signal from transmitting to the receive antennas at FD relay becomes one of the critical challenges to be tackled [6]. In the existing work, the LI signal is repeatedly treated as harmful SI and needs to be significantly suppressed beforehand [7]–[9].

To support FD relays, suppression or cancellation of induced SI is needed. According to several works [10], [11], there are three main categories to suppress this SI: passive suppression (PS), analog cancellation (AC), and digital cancellation (DC). The majority of PS approaches rely on antenna design and placement to suppress the SI. However, these methods are too laborious to mitigate the high SI impeccably. The most commonly used method is DC cancellation, i.e., after the analog-to-digital converter (ADC), the limited dynamic range of the ADC induces significant quantization error that is not cancellable, and such SI will pointedly reduce the system performance. In [12], the authors implemented an FD relay testbed in OFDM systems, where the signal forwarded by the FD relay can be practically combined at the destination with the signal transmitted from the source in the direct link; where SI is still required to be canceled efficiently at the FD relay. In [13], presents the SI suppression strategies by FD-MIMO relay applying using antenna selection technique. They also discussed the conventional LI suppression scheme. Conventionally, LI could be suppressed by using ZF and MMSE estimation filter. Authors in [14] [15], proposed null space projection and minimum mean square error filters for spatial loop interference suppression as well as discuss promptly how to combine them with time-domain cancellation. Despite all these approaches, complete removal of the SI signal has not been achieved to date.

In this paper, we proposed new algorithm stated to as the Space Projection (SPA) algorithm. SPA consist of Null space projection (NSP) and Subspace Projection (SP) algorithm which can employ in the position when loop back channel matrix is of full rank. So, in this situation, we design receive and transmit filters combined with zero forcing (ZF) and also considered the multipath propagation of the loopback signal. If the loop channel matrix is not of full rank, the NSP algorithm projected to cancel the loop back signal. SP algorithm primarily used to make the receive filter orthogonal to one subspace and the transmit filter orthogonal to another one to cancel the desired loop interference.

The paper is structured as follows: In section II, we introduce the system model of the two-hop relay. In section III, we present the proposed approach. Results and analysis has been introduced in section IV and the paper is concluded in section V.

II. System Model

In this section, we provide a mathematical model of a relay station with SI occurrence and cancellation. A 3-node dual-hop amplifies and forward (AF) relaying system in the indoor wireless system is considered. AF relay always used for cooperative communication to improve the performance of the wireless system. AF relay amplifies its received signal and maintaining fixed average transmit power. In our system model, AF is employed because it requires relatively simple signal processing. The proposed technique considered for the two-hop relaying model.

We define $H_{TxR} \in \mathbb{C}^{N_R \times N_{Tx}}$ and $H_{RRx} \in \mathbb{C}^{N_{Rx} \times N_T}$ which represent the MIMO complex channel matrices respectively from the transmitter to relay node and from the relay node to a receiver. The signal vector $x(n)$ defined as a complex vector $x(n) \in \mathbb{C}^{N_{Tx} \times 1}$, transmitted by the source node. The complex signal vectors $r(n)$ and $t(n)$, stated as $r(n) \in \mathbb{C}^{N_R \times 1}$ and $t(n) \in \mathbb{C}^{N_T \times 1}$, denote respectively the received and transmitted signal at the relay node. H_{LI} is the SI signal which reduces the channel capacity from the transmission to reception and makes the relay system unstable in FD-MIMO. The self-interference complex channel matrix, introduced by the relay, is denoted by $H_{LI} \in \mathbb{C}^{N_R \times N_T}$, as shown in fig. 1.

According to the multipath delay of channel (d) and the time symbol of the signal (T_s), we can single out two cases. In both following situations, d will denote the maximum multipath time delay of the channel.

a. *First case* $(d < T_s)$

In this case, the multipath parameter of the channel d is smaller than signal symbol time (T_s), which means that the one symbol will interfere mainly with itself. The signal received by the relay is expressed as,

$$r(n) = H_{TxR}x(n) + H_{LI}t(n) + w(n) \quad (1)$$

Where $w(n) \in \mathbb{C}^{N_R \times 1}$ denote an additive white Gaussian noise (AWGN) and $H_{LI}t(n)$ is the loopback interference signal received by the relay. Where $t(n)$ is the transmitted signal in the relay. A pre-projection filter, which is called the LI signal suppression filter denoted by F_{Rx} and defined as $F_{Rx} \in \mathbb{C}^{N_R \times \widehat{N}_R}$ and post-filter which is called transmit weight filer F_{Tx} defined by $F_{Tx} \in \mathbb{C}^{\widehat{N}_T \times N_T}$ are depicted in fig.2. . $\widehat{N}_R$ and $\widehat{N}_T$ are the received and transmit signal of the signal processor. Without loss of generality we can assume that $\widehat{N}_R \le N_R$ and $\widehat{N}_T \le N_T$ because the end to end communication cannot improve by the increasing the number of dimensions. The output signal of the pre- filter $r'(n) \in \mathbb{C}^{\widehat{N}_R \times 1}$ and the input signal of the post filter $t'(n) \in \mathbb{C}^{N_T \times 1}$.

Now, the output of the pre-filter $r'(n)$ with loop back interference can be written as,

$$r'(n) = \{F_{Rx}(H_{TxR}x(n) + w(n))\} + \{F_{Rx}H_{LI}F_{Tx}\acute{t}(n)\} \quad (2)$$

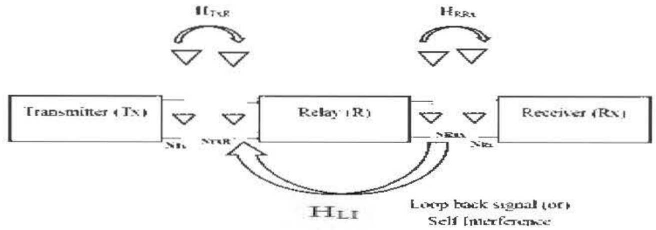

Fig. 7. Two-hop relay model.

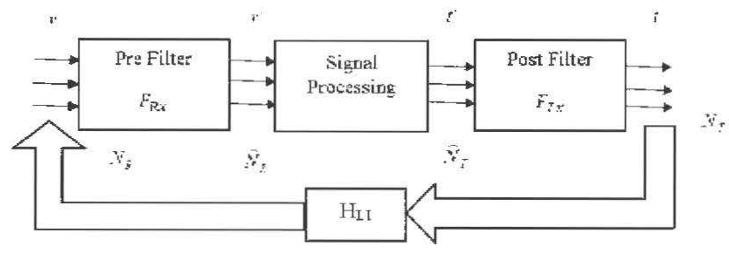

Fig. 8. Relay with loop back signal cancellation.

In equation 2, the first part represent the desired signal exposed to white Gaussian noise and the second part is channel loop back interference.

As shown in fig. 3, relay used two adaptive filters, pre filter F_{Rx} and post filter F_{Tx} to respectively process the input and output signal in order to cancel the SI. Which means that both filters will collaborate to define the right signal to send in order to suppress the channel loopback interference. To achieve this goal, according to equation 2, the second part should be zero (cf. equation 3) is a necessary and sufficient condition to optimize both adaptive filter weights.

$$F_{Rx}H_{LI}F_{Tx} = 0 \quad (3)$$

b. *Second case* $(d > T_s)$

For this case, the maximum multipath d induced by the channel LI is more than one time T_s duration. The number of subsequent symbols that interfere with one symbol, denoted by L, is estimated by equation 4.

$$L = \left\lceil \frac{d+\frac{T_S}{2}}{T_S} \right\rceil \quad (4)$$

The loop channel matrix $H_{LI} \in \mathbb{C}^{N_{RX}x\,(N_{TX}\cdot L)}$ can be written as

Where $H_{ij}\, \mathbb{C}^{1XL}$is the sub channel vector from the i th transmit antenna to the j th receive antenna of the relay. Now, according to the model in fig.3 and due to the inter symbol interference the output signal $\acute{r}(n)$ is again presented as,

$$\acute{r}(n) = \{F_{Rx}(H_{TxR}x(n) + w(n))\} + \{F_{Rx}H_{LI}T(n)\} \quad (5)$$

Where $T(n) = [t_1(n) \quad t_2(n) \quad t_{N_T}(n)]^T$ is an array of relay out coming signals, one per transmitting antenna and defined as:

$$t(n) = [t_i(n) \quad t_i(n-1) \quad \cdots \quad t_i(n-L+1)] \quad (6)$$

The $t_i(j)$ is the transmit signal by the ith relay antenna at sample time j. The output of the post filter relay node is,

$$t(n) = F_{Tx}t'(n) \quad (7)$$

Where $t'(n)$ indicated the input signal of the post filter.

Let, $t'(n) = [t'_1(n), \quad t'_2(n), \quad \cdots \quad t'_{\hat{N}_T}(n)]$

III. Proposed Approach

In this section, we showed the mathematical solution aspects of proposed algorithm. Substitute equation (7) in equation (5) we get,

$$r'(n) = \{F_{Rx}(H_{TxR}x(n) + w(n))\} + \{F_{Rx}H_{LI}\tilde{G}\acute{T}(n)\} \quad (8)$$

Where $T'(n) = \left[\acute{t}_1(n) \quad \acute{t}_2(n) \quad \cdots \quad \acute{t}_{\hat{N}_T}\right]^T$and $\tilde{G}$ is the diagonal matrix of the adaptive filters.

P is the permutation matrix used to go to diagonalizable space.

Where,$\tilde{G} = P^{-1}diag(F_{Tx}; L)$, $P = \begin{bmatrix} diag(Y_1; L) \\ diag(Y_2; L) \\ \vdots \\ diag(Y_L; L) \end{bmatrix}$

Diag(Y, L) is the diagonal matrix with L diagonal components Y; diag(Y) is the diagonal matrix with diagonal components of each element of row vector Y.

In the case where is L= 1, which mean that d is smaller than *Ts,* the F_{Rx} and F_{Tx}filters can be adapted using equation 3 as:

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When L=1, then equation (10) is rewritten as,

$$F_{Rx}[H_{L,1}, \quad H_{L,2}, \quad \ldots \quad H_{L,L}]diag(F_{Tx}; L) = 0 \quad (10)$$

Where $H_{LI,K} = \begin{pmatrix} h_{11,k} & \cdots & h_{1N_T,k} \\ \vdots & \ddots & \vdots \\ h_{N_R1,k} & \cdots & h_{N_RN_T,k} \end{pmatrix}$

Where $h_{ij,k}$is the k th value of the row vector H_{ij} in equation (5). H_{LI} denoted by row space vector and *H* is denoted by column space vector. To achieve the sufficient condition of equation 10 is,

$$F_{Rx}H_{LI} = 0 \text{ and } \left[H^T_{L,1}, \quad H^T_{L,2}, \quad \ldots \quad H^T_{L,L}\right]^T F_{Tx} = 0 \quad (11)$$

Where, $F_{Rx}$is the pre space projection filter, F_{Rx} project the row space of H_{LI} to the null space of H_{LI}. Similar with F_{Tx}, F_{Tx} is the null space of $\left[H^T_{L,1}, \quad H^T_{L,2}, \quad \ldots \quad H^T_{L,L}\right]^T$.

A. NSP with short rank loop interference matrix.

The solution of (12), when the adaptive pre and post filters F_{Rx} and F_{Tx}, cannot be zero matrices, then.

$$0 < rf(H_{LI}) < N_R \text{ and } 0 < rf(H) < N_T \quad (12)$$

Where, the rank function rf gives the dimension of the vector space generated by matrix columns. The rank of a matrix would be zero only if the matrix had its elements equal to zero. If a matrix had even one non-zero element, its minimum rank would be one. $H = \left[H_{L,1}^T, \quad H_{L,2}^T, \quad \dots \quad H_{L,L}^T\right]^T$. It means that only when the H_L or the H is not linearly independent matrix or not full rank the non-zero solution of equation (11) exist. With Zero Forcing algorithm, a solution of null space projection as,

$$F_{Rx} = I - H_{LI}H_{LI}^{+} \tag{13}$$

$$F_{Tx} = I - HH^{+} \tag{14}$$

Where $(.)^{+}$ is the Moore-Penrose pseudo-inverse and I is the identity matrix.

B. Subspace Projection Partly Cancelling Interference (SSPCI) with Full Rank Matrix

The second algorithm is called Subspace Projection Partly cancelling Interference (SPPCI). When the H_L and H are full rank, as

$$r(H_{LI}) = N_{Rx}; r(H) = N_{Tx} \tag{15}$$

We could just suppress the loop interference at the row space of H_{LI} or the column space of H. Choose the smaller positive integers $C_1, C_2, D_1 \; and \; D_2$ to satisfy both (16) and (17) equation.

$$r\left(\left[H_{L,m_1}, \quad H_{L,m_2}, \quad \cdots, \quad H_{L,m_{D_1}}\right]\right) = N_R - C_1 \tag{16}$$

$$r\left(\left[H_{L,n_1}^T, \quad H_{L,n_2}^T, \quad \cdots, \quad H_{L,n_{D_2}}^T\right]^T\right) = N_T - C_2 \tag{17}$$

Where m_i, $n_i \in [1, \quad 2, \quad \cdots, \quad L]$ we have the subspace

$$H_1 = \left[H_{L,m_1}, \quad H_{L,m_2}, \quad \cdots, \quad H_{L,m_{D_1}}\right] \tag{18}$$

$$H_2 = \left[H_{L,n_1}^T, \quad H_{L,n_2}^T, \quad \cdots, \quad H_{L,n_{D_2}}^T\right]^T \tag{19}$$

Then project the loop interference to the complementary space of H_1 or H_2 and the loop interference in space of H_1 or H_2 is cancelled by,

$$F_{Rx} = I - H_1H_1^{+} \tag{20}$$

$$F_{Tx} = I - H_2{H_2}^{+} \tag{21}$$

The nonlinearity of $f(.)$ provide more degrees of choice to design the adaptive filters FR_x and F_{Tx}. We can have two cases for relay transmitted signal. The Decode and Forward (DF) MIMO relay case, according to equation 22 where DF relay process the signal and regenerate source data streams, and the AF relay, according to equation 23, where the signal is forwarded after some basic processing.

The F_{Rx} and F_{Tx} have the equivalent function in AF relays, so they can be combined into one filter which would only mitigate the interference partly. The nonlinearity of $f(.)$ provide more degrees of freedom for designing the $F_{Rx}$and F_{Tx} jointly, the loop interference suppression filter pairs are effective in the DF relays for completely suppressing the loop interference

$$t(n) = F_{Rx}f\left(F_{Rx}\big(r(n)\big) - w(n)\right) \tag{22}$$

$$t(n) = F_{Tx}F_{Rx}\big(r(n) + w(n)\big) \tag{23}$$

IV. RESULT AND DISUSSION

The proposed model and TSPA approach are simulated with MATLAB software. The full-duplex MIMO relay is equipped with 6 antennas, three for each side (NR= NT= 3 antennas). The four phase BPSK modulation is considered. The LI channel is independent Rayleigh fading channel because a close estimation of attenuation due to the multipath fading in wireless channels can be made by relay fading where the no line of sight component present and is normalized as $\|H_{LI}\| = N_RN_T$.

We evaluated the outage probability performance according to different Signal to Noise Ratio (SNR) for the direct line and without direct line.

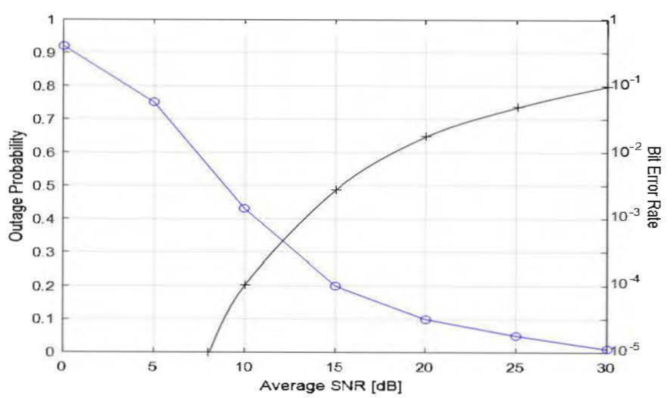

Fig.4. Outage probability vs Avg. SNR vs BER without relay (Direct Line)

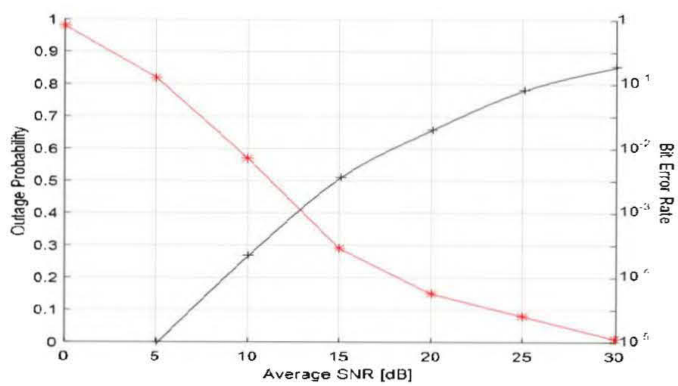

Fig.5. Outage probability vs Avg. SNR vs BER with relay (Without direct Line)

Fig. 5. and fig. 4. Show the outage probability and bit error rate of one link with and without using of our proposed relay. The simulation illustrated that the outage probability with the direct link has achieved the exact distribution of effective SNR at the receiver and improve the BER. Also, it has achieved effective SNR at the receiver with relay (without direct link) and effectively minimized the BER. From the above figures, we can see that in both cases the loopback self-interference has compensated efficiently by using SPA algorithm.

V. Conclusion

We investigated the performance of amplify and forward FD-MIMO relaying scheme in the presence of loopback self-interference. We proposed a space projection algorithm (SPA) to mitigate the SI and reduce the outage probability and BER. The simulation results show that even when the SI channel matrix is of full rank, it's possible to thoroughly and promptly cancel the interferences using the right space projection filter. The SPA suppresses the SI by increasing SNR significantly and reduce the BER.

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