VIRTUAL FULL-DUPLEX MULTIPLE-INPUT MULTIPLE-OUTPUT RELAYING IN THE PRESENCE OF INTER-RELAY INTERFERENCE

IGBAFE ORIKUMHI

UNIVERSITI TEKNOLOGI MALAYSIA

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To God Almighty, my dear family, friends and my lovely fiancée Juliet Ogele Yahaya.
Also, to my late aunt Tina Orikumhi your memories will always remain with us.

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ABSTRACT

Driven by the increasing demand for wireless broadband, low latency and power-efficient networks, multiple-input multiple-output (MIMO) full-duplex relaying (FDR) schemes have gained much attention in recent years. However, the performance of FDR schemes is impaired by sophisticated self-interference suppression techniques. As such, MIMO virtual FDR (VFDR) schemes have been considered as practical alternatives to recover spectral efficiency loss in half-duplex relays (HDR) without the need for sophisticated self-interference suppression algorithms. Successive relaying (SR) scheme is one of the VFDR techniques which uses a pair of HD relays that alternate between reception and retransmission of the source information to the destination. The performance of the SR based VFDR scheme is affected by inter-relay interference (IRI) due to the concurrent transmission of the source and relay nodes. The interference in VFDR schemes is conventionally treated as a degrading factor on the information decoding receivers resulting in the design of several interference avoidance and cancellation techniques. On the contrary, this thesis developed several VFDR schemes which exploit the interference to achieve performance improvement. In this study, interference management techniques, transmit/receive beamforming matrices, power allocation and joint optimisation algorithms were developed. First, a reliable MIMO VFDR scheme in the presence of IRI was designed, where the IRI was exploited for reliability improvements. The results showed significant reliability improvement over the existing schemes. Second, a joint power allocation for MIMO VFDR schemes under network power constraint was developed. The power allocation problem in the presence of IRI was formulated based on primal-dual algorithm. The results showed that the joint optimisation algorithm can efficiently utilise the network power when compared with the conventional approach. Third, simultaneous wireless information and power transfer (SWIPT) in MIMO VFDR system was proposed, where the transmit beamforming matrices which optimise the achievable rate and harvested energy at the relays were jointly designed. The results showed that the interference energy can be harnessed to improve the SWIPT system throughput. Finally, a joint optimisation of the power split and relay position in SWIPT MIMO VFDR network were investigated. Results showed that the joint optimisation of the power split and distance factors can greatly improve the system outage performance. The analytical and numerical results in the research showed that IRI can be exploited to improve the throughput, reliability and energy harvesting of a wireless communication system. The results also showed a minimum achievable rate improvement of 80% over the HDR schemes and a reliability of 100% over the FDR schemes.

ABSTRAK

Didorong oleh permintaan yang semakin meningkat terhadap jalur lebar wayarles, pendaman rendah dan rangkaian berkuasa cekap, geganti dupleks penuh (FDR) berbilang-input berbilang-output (MIMO) telah mendapat banyak perhatian kebelakangan ini. Bagaimanapun, prestasi skim FDR terjejas oleh penindasan gangguan diri yang kompleks. Oleh itu, MIMO FDR maya (VFDR) telah dipertimbangkan sebagai alternatif praktikal untuk mendapatkan semula kehilangan kecekapan spektrum dalam geganti dupleks separuh (HD) tanpa memerlukan algoritma penindasan gangguan kendiri yang rumit. Geganti berturut-turut (SR) adalah salah satu teknik VFDR yang menggunakan sepasang geganti HD silih-ganti antara penerimaan dengan penghantaran semula isyarat maklumat dari sumber ke destinasi. Prestasi skim VFDR berdasarkan SR terjejas oleh gangguan antara geganti (IRI) akibat penghantaran isyarat serentak dari sumber dan geganti. Gangguan dalam skim VFDR lazimnya dianggap sebagai faktor degradasi penerima penyahkodan informasi yang membawa kepada reka bentuk beberapa teknik penghindaran gangguan dan pembatalan gangguan. Sebaliknya, tesis ini membangunkan beberapa skim VFDR yang mengeksploitasi gangguan bagi mencapai peningkatan prestasi. Dalam kajian ini, teknik pengurusan gangguan, pembentukan alur penghantar/penerima, peruntukan kuasa dan algoritma pengoptimuman bersama telah direka. Pertama, satu skim MIMO VFDR yang boleh dipercayai dalam kehadiran IRI telah direka, iaitu IRI dimanfaatkan untuk penambahbaikan kebolehpercayaan. Hasil kajian menunjukkan peningkatan kebolehpercayaan yang memberangsangkan berbanding skim sedia ada. Kedua, satu peruntukan kuasa bersama untuk MIMO VFDR di bawah kekangan kuasa rangkaian telah dibangunkan. Masalah peruntukan kuasa dalam kehadiran IRI dirumus menggunakan algoritma *primal-dual*. Hasil kajian menunjukkan bahawa algoritma pengoptimuman bersama boleh menggunakan kuasa rangkaian secara cekap berbanding dengan pendekatan konvensional. Ketiga, pemindahan maklumat wayarles dan tenaga serentak (SWIPT) dalam sistem MIMO VFDR telah dicadangkan, iaitu matriks pembentukan alur penghantaran yang mengoptimumkan kadar yang dapat dicapai dan tenaga yang dituai telah direka bersama. Keputusan menunjukkan bahawa tenaga gangguan boleh dimanfaatkan untuk menambahbaik daya pemprosesan sistem SWIPT. Akhir sekali, pengoptimuman bersama pembahagian kuasa dan kedudukan geganti dalam rangkaian SWIPT MIMO VFDR telah dikaji. Hasil kajian menunjukkan bahawa pengoptimuman bersama faktor-faktor pembahagian kuasa dan kedudukan boleh menambahbaik secara ketara kebarangkalian gangguan sistem. Dapatan analisis dan dapatan berangka dalam kajian ini menunjukkan bahawa IRI boleh dimanfaatkan untuk meningkatkan daya pemprosesan, kebolehpercayaan dan penuaian tenaga dalam sistem perhubungan wayarles. Keputusan tersebut juga menunjukkan kadar minimum penambahbaikkan sebanyak 80% pada skim HDR dan kebolehpercayaan sebanyak 100% pada skim FDR.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AF	-	Amplify and Forward
APC	-	Aggregate Power Constraint
CDF	-	Cumulative Density Function
CSI	-	Channel State Information
CSIR	-	Channel State Information at the Receiver
CSIT	-	Channel State Information at the Transmitter
CVX	-	Convex Optimization
DF	-	Decode and Forward
DMT	-	Diversity-multiplexing Tradeoff
FD	-	Full-Duplex
FDD	-	Frequency Division Duplexing
HD	-	Half-Duplex
i.i.d	-	independent and identically distributed
IPC	-	Individual Power Constraint
IRI	-	Inter-Relay Interference
LTE-A	-	Long Term Evolution-Advanced
MCAS	-	Maximum Capacity Antenna Selection
MIMO	-	Multiple Input Multiple Output
MISO	-	Multiple Input Single Output
NOMA	-	Non-Orthogonal Multiple Access
OFDM	-	Orthogonal Frequency Division Multiplexing
PDF	-	Probability Density Function
QoS	-	Quality of Service
RAS	-	Random Antenna Selection
R-E Tradeoff	-	Rate-Energy Tradeoff
RF	-	Radio Frequency
SIC	-	Successive Interference Cancellation

SIMO	-	Single Input Multiple Output
SISO	-	Single Input Single Output
SINR	-	Signal to Interference and Noise Ratio
SNR	-	Signal to Noise Ratio
SR	-	Successive Relaying
SVD	-	Singular Value Decomposition
SWIPT	-	Simultaneous Wireless Information and Power Transfer
TDD	-	Time Division Duplexing
VFD	-	Virtual Full-Duplex
WiFi	-	Wireless Fidelity
WIT	-	Wireless Information Transfer
WPT	-	Wireless Power Transfer
ZF	-	Zero-Forcing
ZFBF	-	Zero-Forcing Beamforming

LIST OF SYMBOLS

a	-	denote scalars
$\mathbf{A}$	-	boldface upper case letters denote matrices
$\mathbf{a}$	-	boldface lower case letters denote vectors
$\mathbf{A}^H$	-	Hermitian transpose of matrix $\mathbf{A}$
$\mathbf{A}^T$	-	transpose of matrix $\mathbf{A}$
$\mathbf{A}^\dagger$	-	pseudo inverse of matrix $\mathbf{A}$
$\\| \cdot \\|_F$	-	Frobenius norm
$\log_a(A)$	-	logarithm of A to base a
$E_A\{a\}$	-	expectation of a over the random variable of A
$[\mathbf{A}]_{i,j}$	-	(i,j)-th element of matrix $\mathbf{A}$
tr($\mathbf{A}$)	-	trace of matrix $\mathbf{A}$
exp(a)	-	exponent (a)
$[a]^+$	-	max (a or 0)
$\mathbb{N}^n$	-	$n \times n$ dimensional Hermitian matrix set
$\forall$	-	for all
$\preceq, \succeq$	-	componentwise inequality
$\in$	-	is an element of
A	-	set of A
$a \to \infty$	-	a tends to positive ∞
Pr(A)	-	probability of event A
a!	-	factorial of a
diag($\lambda_1, \lambda_2, ...$)	-	diagonal matrix with element $\lambda_1, \lambda_2, ...$
$C\mathcal{N}(\mu, \sigma^2)$	-	circular symmetric Gaussian random variable with mean μ and variance σ^2

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Current wireless communication systems promise high quality of service in voice and data communication. Other features such as massive number of connected devices, high mobility, low latency, reliability, resilience, security, long battery life and more have led to numerous research in the ongoing 5-th generation standardisation process [1]. Although several solutions have been provided in the 5-th generation standardisation process, several key issues are still being addressed. One key challenge of wireless communication is the cell edge coverage issue. When wireless signals are transmitted through space, the transmit power attenuates exponentially [2], leading to low data rates at the cell edge and shadowed environments. Among several solutions, the advantage of using relays to overcome the coverage hole and assist the network has been studied and the progress made so far can be found in the numerous research articles.

In recent and future wireless communications, relays have been adopted as one of the key technology to improve service coverage at the cell edge, eliminate dead spot, reduce energy consumption, enhance capacity and increase network reliability [3,4]. The advantages provided by relay networks have attracted interest in the wireless communication field. This has led to several research works aimed at studying the performance benefits in both dedicated and user-based relay networks. In general, relays can operate in half-duplex (HD) mode (transmit and receive in the orthogonal time slot or orthogonal frequencies) or full-duplex (FD) mode (simultaneously transmit and receive in the same time slot and frequencies).

However, the use of HD relays in 3rd Generation Partnership Project (3GPP) and Long Term Evolution-Advanced (LTE-A) is limited by HD constraint. This constraint describes the inability of a relay to transmit and receive simultaneously, consequently, a spectral efficiency loss of at least 50% is experienced, since extra dedicated bandwidth is always required for relaying transmission. On the other hand, FD relays have also been recently introduced in wireless networks, but their performance is limited by self-interference and loop back residual interference. The self-interference in FD relays exist due to the simultaneous reception and transmission on the same channel resulting in power leakage from the transmitter of the relay to its receiver, the interference from the transmitter could saturate its own receiver's analogue to digital converter. The isolation of transmitter and receiver chains in FD relaying are characterised with the self-interference or co-channel interference. Although several techniques have been proposed to combat the self-interference in FD relays [5], researchers have highlighted that a part of the self-interference could still exist in the system, such interference is referred to as residual self-interference. Due to the challenges in the use of FD relays especially in multi-antenna scenarios, the majority of research results are still based on the HD signal models, as they can be deployed in a more practical scenario. However, the challenge remains on how to overcome HD constraint in HD relays.

Several schemes have been proposed to combat HD constraint in HD relaying networks [6], such as two-way relaying scheme [7], cognitive cooperative relaying scheme [8] and successive relaying (SR) scheme [9]. These schemes are termed virtual FD (VFD) relaying schemes, by exploiting these schemes the spectral efficiency loss in HD relays can be recovered and the system performance can be improved. VFD relaying achieves close to the performance limits of FD relaying by separating the reception and transmission of FD relaying either in space or time. Two-way relaying achieves VFD relaying modes by receiving and transmitting at least two streams of data in orthogonal time. In SR, two or more relays which are separated by space, alternate between reception and transmission of signals from the source to the destination. SR protocol is able to recover the losses in one-way HD relays if the relays are properly positioned and the inter-relay interference is properly managed. The improvement in spectral efficiency introduced by the SR relaying scheme has motivated its applications in multiple users and multiple antennas scenarios. Single-antenna SR networks have been broadly studied while only a few studies have been carried out on multi-antenna SR schemes which has motivated the study in this thesis.

Although several performance benefits can be achieved in cooperative schemes, it is important to note that the cooperating nodes or relays could be fixed node such as infrastructural relays or mobile nodes such as handheld devices (Mobile phones, tablets, laptops etc.). While the infrastructural relays can be connected to a power grid, handheld devices usually rely on batteries. The lifetime of battery-powered devices is limited and therefore requires energy replenishing. These mobile devices can be remotely charged by wireless power transfer while simultaneously receiving information from the same RF signal, which has motivated the study of simultaneous wireless information and power transfer (SWIPT) in this thesis.

The rest of this chapter is organised as follows. The problem background is presented in Section 1.1. The current state of the art related to this thesis is presented in Section 1.2. The problem statements are highlighted in Section 1.3. The objectives of this thesis are presented in Section 1.4. The scope of the thesis is presented in Section 1.5. The chapter is concluded with the contributions and organisation of the thesis in Section 1.6.

1.1 Problem Background

Wireless communication is evolving to meet the increasing quality of service (QoS) and bandwidth demands. As the demand for wireless broadband continues to increase, current and future wireless networks continue to promise reliable communication and data rate improvements [10]. To ensure reliable communication at the promised data rate between the user at the cell edge and the base station through a direct transmission can be very expensive, due to the transmission power required as the distance between the user and the base station increases. Relays can bridge this gap by improving the link quality, reliability and signal to noise ratio between the base station and the cell edge users. Although signal to noise ratio improvements can be achieved by employing relays, the use of HD relay still shows about 50% spectral efficiency losses which cannot be ignored for real-time applications such as video conferencing. VFD relaying schemes have been proposed as a possible solution to recover the losses due to HD constraint while providing an easier means of tackling the self-interference in FD relaying scheme. In addition, VFD relaying schemes provide means of increasing signal reliability and power efficiency.

As wireless signals travel from a source to the destination, its power decays exponentially. Several studies have shown that the use of relays in networks (either infrastructural or user enabled relays) can provide diversity gain and data rate improvements in cooperative communication [11, 12]. The diversity gain provides redundant paths for the signal to combat the effect of deep fade, thereby improving the user's capacity and QoS. Given the numerous benefits of cooperative communications, reliable and efficient algorithms are required to exploit these benefits.

In SR based VFD relaying scheme, two or more HD relays are implemented to mimic an FD relay. The participating relays alternate between reception and transmission to enable the source to transmit new messages to the destination continuously. However, due to the co-channel operation of the participating relays, the performance of the SR scheme can be degraded by inter-relay interference (IRI) [13]. In the existing SR schemes, the IRI is either avoided using interference avoidance techniques or cancelled out using successive interference cancellation (SIC) [14] while beamforming techniques have been applied in multiple antenna scenarios [15]. The cancellation or avoidance of the IRI can greatly improve the capacity of the SR scheme, but the full diversity provided by the SR scheme cannot be achieved. In general, IRI has always been considered as an unwanted signal in SR scheme. However, improving the reliability of user's information in wireless communication requires sending multiple copies of the same signal to the user, either in the frequency domain, time domain or spatial domain [16]. This thesis is motivated by the fact that the IRI can be decoded as shown by the successive interference cancellation schemes. However, instead of discarding the decoded IRI, it can be retransmitted to the user, thereby improving the user's signal reliability. Another motivating factor is, by improving the reliability of the user, beamforming and power allocation algorithms can be implemented to improve the network power allocations.

To further improve the system performance, power efficiency is a vital design consideration. Although power allocation schemes have been widely studied in multiple input multiple output (MIMO) systems [17–19], the existing schemes cannot be directly applied to SR schemes where the IRI is exploited. This is due to the different power requirements from the source and inter-relay link. Uniform power allocation at each node has been generally adopted for ease of analysis and computation. Meanwhile, in MIMO systems, it has been shown that water filling power allocation is optimal. However, in a MIMO relay network, individual power allocation and aggregate power allocation have been shown to further improve the system power efficiency in one way relaying scheme [17] and can further be extended to SR schemes.

Attracted by the benefits of simultaneous wireless information and power transfer in replenishing the batteries of mobile users. Users cooperation can be encouraged if the mobile users who are serving as relays can harvest energy from the RF signals and use the harvested energy to forward the signal [20]. Recent studies in SWIPT have shown that several factors such as; increasing the number of relay receive antennas, relay positioning in the network and beamforming designs can help to improve energy harvesting efficiency at the relay. In FD relay networks, energy harvesting can be enhanced by utilising the self-interference [21], while energy harvesting utilising IRI in SR based VFD relaying scheme has not been explored. Note that SWIPT systems can be implemented with separate or co-located information decoders (ID) and energy harvesting (EH) receiver architecture. In the co-located SWIPT design, the ID and EH receivers possess the same channel coefficients from the source, while in the separate architecture the ID and EH receivers possess different channels coefficients from the source [22].

IRI has traditionally been assumed as a performance degrading factor to the ID receiver. However, this thesis exploits the IRI for energy harvesting and data rates improvements with respect to the relay distance and power split factor. The optimisation of relay position and power split factor have been widely investigated in several literatures, these two optimisations are usually studied separately [23, 24]. Given that the relay position and power split factor determines the path loss of the adjacent hop, this thesis studies the joint optimal relay position and power split parameter that minimises the end to end outage probability of the SR scheme with and without IRI.

1.2 State-of-the-Arts

The future 5-th generation (5G) network is currently being studied. A survey on 5G is presented in [25], where it is highlighted that the technology will operate within small cells. Hence, relays will play an important role in connecting several devices, small cells and the base station [26, 27]. Also as the cell size becomes smaller, the difference between the transmit and receive power in an FD relays network become smaller, therefore FD relays are currently being studied as the key technology to facilitate the implementation of 5G and beyond. The key issues with the FD relays are self-interference and the complexity in the design of the transmit and receive chains as the number of antennas increases [5]. Note that the future 5G network proposes to deliver high data rate by implementing a large number of antenna array known as massive multiple input multiple output (Massive MIMO).

SWIPT enabled relays are also currently being studied as they could be vital in the energy efficiency of battery-powered devices. The rate-energy (R-E) tradeoff of SWIPT systems for direct transmission has been studied in [22, 28]. In [29], practical receivers for SWIPT systems are investigated. The authors also defined the R-E tradeoff for single antenna system with power split and time switch architectures. The architectures are extended to MIMO receivers and the optimal beamforming matrices for MIMO broadcast SWIPT network are presented in [22], where the R-E tradeoff is also discussed.

However, with the current research activities and the issue with self-interference in FD relaying schemes, there is a need to develop relaying schemes that can fully mimic the FD relays with less sophisticated interference suppression techniques using HD relays while recovering the loss in spectral efficiency due to HD constraint. In addition, there is a need to consider the use of IRI in such network to improve the system reliability and enhance energy harvesting efficiency while encouraging cooperation between users. This is important as billions of devices are expected to be connected in 5G networks.

1.3 Problem Statement

Bandwidth is a limited resource and requires efficient utilisation. SR based VFD relaying schemes can efficiently utilise the limited bandwidth [30], but their performance is degraded by inter-relay interference [31]. Although interference avoidance and cancellation schemes have been proposed, they fail to exploit the full diversity provided by the SR based VFD scheme. Due to the inefficient utilisation of the diversity, the current SR based VFD relaying schemes exhibit poor outages and inefficient power allocation.

The interference cancellation and avoidance techniques also show significant losses in terms of achievable rates and energy harvesting in SWIPT systems. Based on the current studies SWIPT systems can thrive if the amount of harvested energy is sufficiently high [21, 32]. By using properly designed beamforming and interference mitigation techniques, the performance of the VFD relaying systems can be improved with information decoding relay receivers only or with SWIPT enabled relay receiver nodes. In addition, the VFD relaying scheme with only information decoding receivers stand to gain from exploiting interference to improve the diversity-multiplexing tradeoff, outage probability, efficient network power utilisation and achievable rates, while the VFD relaying scheme with SWIPT enabled relay receivers can exploit IRI to improve the amount of harvested energy, achievable rates, R-E tradeoff and outage probability with optimised beamforming and covariance matrices.

The development of new VFD relaying schemes in the presence of inter-relay interference is crucial to overcoming the sophisticated interference cancellation techniques in FD relays [33, 34]. The development is also crucial in 5G wireless communication networks with billion of connected devices [35–37], where the systems have to learn to cope with interference [38]. To this end, this thesis investigates the effect of IRI in SR based VFD relaying network with emphasis on the user data rate, outage probability, diversity and multiplexing tradeoff, energy harvesting, R-E tradeoff etc. These problems will be addressed by answering the following research questions.

1. How can inter-relay interference be exploited to improve the achievable throughput and reliability of the user?
2. How can power allocation improve the end to end system performance in terms of throughput and outage probability in the presence of IRI?
3. How can IRI be exploited to improve the achievable rate and energy harvesting in SWIPT networks?
4. What are the optimal power split and distance factors for a SWIPT VFD relaying network that minimise the end to end outage probability?

In summary, it is observed that the inter-relay interference which has conventionally been assumed as a degrading factor in VFD relaying schemes, can be exploited by proper interference mitigation and beamforming techniques to improve VFD relaying system performance.

1.4 Objective of Research

This thesis aims to demonstrate the use of inter-relay interference in enhancing system reliability, improving the system data rate and improving the power efficiency in VFD relaying systems. Based on the aforementioned aims, the main objectives of this thesis are presented in the following paragraphs.

1. The first objective is to propose a reliable MIMO virtual FD relaying scheme in the presence of inter-relay interference.

2. The second objective is to propose an efficient power allocation scheme in a MIMO VFD relaying network to improve the system capacity and outage performance in the presence of IRI.

3. The third objective is to design the source transmit beamforming matrices which optimise the information rate at the ID receiver and the energy harvesting at the EH receiver for a MIMO VFD SWIPT relaying system, where the system is implemented with separate information decoding and energy harvesting receivers in the presence of IRI.

4. The final objective is to design the optimal power allocation to the ID and EH receivers and the optimal relay position for a simultaneous wireless information and power transfer enabled MIMO VFD relaying scheme, where the scheme is implemented with co-located information decoders and energy harvesters in the presence of IRI.

In summary, HD relays exhibit a spectral efficiency loss of about 50% since they require addition time or frequency resource. On the other hand, FD relaying schemes requires sophisticated self-interference suppression algorithms. This thesis presents VFD relaying schemes to bridge the gap between the HD and FD relaying schemes using HD relays in the presence of IRI. Unlike the existing schemes, this thesis proposes VFD relaying schemes to recover the spectral efficiency loss in HD relaying networks, while achieving the performance of FD relaying schemes with less sophisticated interference mitigation techniques. In addition, the research aims to exploit the IRI for system improvements in terms of capacity, reliability, energy harvesting etc.

1.5 Scope of Work

The scope of this thesis includes developing receive and transmit beamforming matrix for multiple antenna VFD relaying system in the presence of IRI. Relay transmit antenna selection algorithm will be implemented to reduce the dimension of IRI. The scope is limited to numerical and analytical simulations of the proposed schemes. The user analysis in terms of capacity, outage probability, energy harvesting, power optimisation and relay position optimisation will be addressed. The research also focuses only on the physical layer. The performance analysis will be evaluated using MATLAB simulator, while convex optimisation tools such as CVX and Nsolve in Mathematical will be used for optimisation algorithms. The scenarios of interest are listed as follows.

1. Perfect channel state information (CSI) is assumed in this thesis.
2. A four-node network with a single source, single destination and two HD decode and forward relays are considered.
3. The direct link between the source and the destination is assumed to be weak and disconnected.
4. The relays are assumed to be information decoding receivers in both Chapters 4 and 5.
5. The relays are assumed to be separate information decoding and energy harvesting receivers in Chapter 6.
6. The relays are assumed to be integrated information decoding and energy harvesting receivers in Chapter 7.

The following are beyond the scope of this thesis.

1. The performance of the proposed scheme in 5G networks.
2. The performance of the scheme in frequency selective and fast fading channels.
3. The RF power consumption at the nodes.

4. The performance of the proposed scheme in multiple relays greater than two.

1.6 Contributions and Organisation of the Thesis

The main contributions of this thesis are summarised as follows,

- In Chapter 4, a system which exploits IRI in MIMO VFD relaying network is proposed. The IRI is managed by the use of relay transmit antenna selections and relay receive beamforming matrix. The proposed scheme jointly decodes the source and the IRI symbols at the relay receiver, a superposition of the decoded symbols are transmitted to the destination. Analytical and numerical results are provided to validate the performance of the proposed scheme. The analytical and numerical results show that the proposed scheme can achieve the full diversity provided by SR scheme while maintaining the multiplexing gain of the FD relaying scheme. The results also show that the proposed scheme can outperform conventional SR based VFD relaying scheme in terms of outage probability, diversity and multiplexing gain even in the presence of IRI.
- Power allocation optimisation for MIMO VFD relaying scheme under network power constraint is proposed in Chapter 5. Individual power constraint at each antenna and the aggregate power constraint at each node are addressed. A joint power allocation problem under network power constraint is also formulated as a convex optimisation problem. The formulated problem is addressed using the low complexity and high computational efficient Lagrangian primal-dual optimisation algorithm [39]. Due to the effect of the IRI power on the relay receiver, an iterative algorithm is presented to address the joint power allocation problem. The results justify the achieved improvements in capacity and outage probability of the proposed scheme.

- A MIMO VFD relaying scheme with separate information decoding and energy harvesting receivers is proposed in Chapter 6. The source and relay transmit beamforming matrix are designed for a VFD relaying scheme with separate information decoding and energy harvesting receivers. The harvested energy at the relay of the proposed scheme is used to forward the relay decoded message to the destination. The results show that by properly designing the precoding matrices for the separate information decoding and energy harvesting receivers, the end to end capacity of the VFD relaying scheme can be improved. In addition, it is shown that EH receivers can rely on interference sources to improve the amount of harvested energy.
- A MIMO VFD relaying scheme with co-located information decoding and energy harvesting receivers is proposed in Chapter 7. The R-E tradeoff for co-located receivers of the proposed scheme is presented. The optimal power split factor for a fixed relay distance factor, the optimal distance factor for a fixed power split factor as well as the optimal joint power and distance factors which minimise the end to end outage probability are also studied. The results show that inter-relay interference can improve the R-E tradeoff of the SWIPT VFD relaying scheme. In addition, the joint optimisation of the power split and distance factors improves the outage performance of the system compared to the conventional schemes where the distance or the power allocation factors are optimised separately.

In summary, this thesis proposes new techniques of handling inter-relay interference in a MIMO VFD relay system. The proposed schemes employ beamforming, power allocation, antenna selection, energy harvesting to achieve improved performance. The proposed schemes are able to achieve better throughput, outage probability, power efficiency, diversity and reliability.

The rest of the thesis is organised as follows. In Chapter 2, related works are investigated and presented in a literature review. Chapter 3 presents the research methodology. In Chapter 4, the proposed reliable virtual FD relaying scheme in the presence of inter-relay interference is discussed. Chapter 5 presents the proposed joint power allocation for decode and forward (DF) concatenated MIMO VFD relaying scheme under network power constraint. In Chapter 6, the proposed wireless information and power transfer in MIMO virtual FD relaying system is discussed. The power split and relay position optimisation for SWIPT MIMO virtual FD relaying network are studied in Chapter 7. Finally, the conclusions of the thesis and suggestions on the future works are given in Chapter 8.

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