TWO-PATH SUCCESSIVE RELAYING SCHEMES IN THE PRESENCE OF INTER-RELAY INTERFERENCE

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To my parents, brother, family and friends.

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ABSTRACT

Relaying is a promising technique to improve wireless network performance. A conventional relay transmits and receives signals in two orthogonal channels due to half duplex constraint of wireless network. This results in inefficient use of spectral resources. Two-Path Successive Relaying (TPSR) has been proposed to recover loss in spectral efficiency. However, the performance of TPSR is degraded by Inter-Relay Interference (IRI). This thesis investigates the performance of TPSR affected by IRI and proposes several schemes to improve relaying reliability, throughput and secrecy. Simulations revealed that the existing TPSR could perform worse than the conventional Half Duplex Relaying (HDR) scheme. Opportunistic TPSR schemes are proposed to improve the capacity performance. Several relay pair selection criteria are developed to ensure the selection of the best performing relay pair. Adaptive schemes which dynamically switch between TPSR and conventional HDR are proposed to further improve the performance. Simulation and analytical results show that the proposed schemes can achieve up to 45% ergodic capacity improvement and lower outage probability compared to baseline schemes, while achieving the maximum diversity and multiplexing tradeoff of the multi-input single-output channel. In addition, this thesis proposes secrecy TPSR schemes to protect secrecy of wireless transmission from eavesdropper. The use of two relays in the proposed schemes deliver more robust secrecy transmission while the use of scheduled jamming signals improves secrecy rate. Simulation and analytical results reveal that the proposed schemes can achieve up to 62% ergodic secrecy capacity improvement and quadratically lower intercept and secrecy outage probabilities if compared to existing schemes. Overall, this thesis demonstrates that the proposed TPSR schemes are able to deliver performance improvement in terms of throughput, reliability and secrecy in the presence of IRI.

ABSTRAK

Penggegantian adalah satu teknik yang menjanjikan peningkatan kepada prestasi rangkaian wayarles. Geganti konvensional menghantar dan menerima isyarat dalam dua ortogon saluran kerana kekangan separuh dupleks. Ini menyebabkan penggunaan sumber spektrum yang tidak cekap. Penggegantian Dwi-Laluan Berturutan (TPSR) telah dikemukakan untuk memulihkan kehilangan dalam kecekapan spektrum. Walau bagaimanapun, TPSR mengalami kemerosotan prestasi disebabkan oleh isyarat gangguan antara geganti (IRI). Tesis ini mengkaji prestasi TPSR yang terjejas oleh IRI dan mencadangkan beberapa skema untuk meningkatkan kebolehpercayaan, kelajuan dan kerahsiaan. Kajian simulasi menunjukkan bahawa skema TPSR yang sedia ada menunjukkan prestasi lebih teruk daripada skema Penggegantian Separuh Dupleks (HDR) konvensional. Skema-skema TPSR oportunistik dicadangkan untuk meningkatkan prestasi kapasiti dalam senario IRI. Beberapa kriteria pemilihan pasangan geganti dibangunkan untuk memastikan pasangan geganti yang dipilih menyampaikan prestasi yang terbaik. Skema-skema penyesuaian yang dinamik bertukar antara skema TPSR dan skema HDR konvensional telah dicadangkan untuk meningkatkan lagi prestasi. Keputusan simulasi dan analisis menunjukkan bahawa skema-skema yang dicadangkan menyampaikan peningkatan sehingga 45% dalam kapasiti ergodik dan kebarangkalian gangguan yang lebih rendah berbanding skema-skema yang sedia ada, manakala mencapai kepelbagaian dan pemultipleksan yang maksimum bagi saluran berbilang-input tunggal-output. Di samping itu, tesis ini mencadangkan skema-skema TPSR kerahsiaan untuk melindungi keselamatan penghantaran wayarles. Skema-skema menggunakan dua geganti dicadangkan dalam tesis ini untuk memastikan penghantaran kerahsiaan yang lebih mantap manakala penggunaan isyarat penyesakan berjadual dapat meningkatkan kadar kerahsiaan. Keputusan simulasi dan analisis menunjukkan bahawa skema-skema kerahsiaan yang dicadangkan boleh mencapai peningkatan sehingga 62% dalam kapasiti kerahsiaan ergodik serta kebarangkalian memintas dan kerahsiaan gangguan yang secara kuadratiknya lebih rendah berbanding dengan skema-skema sedia ada. Secara keseluruhan, tesis ini menunjukkan bahawa skema-skema TPSR yang dicadangkan mampu mencapai peningkatan prestasi daripada segi kebolehpercayaan, kelajuan dan kerahsiaan dalam senario kewujudan isyarat gangguan antara geganti.

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LIST OF ABBREVIATIONS

5G	-	Fifth Generation
ADC	-	Analog-to-Digital Converter
AF	-	Amplify-and-Forward
CDF	-	Cumulative Density Function
CSI	-	Channel State Information
IoT	-	Internet of Things
HDR	-	Half-Duplex Relaying
RF	-	Radio Frequency
TPSR	-	Two-Path Successive Relaying
IC	-	Successive Interference Cancellation
DF	-	Decode-and-Forward
DMT	-	Diversity and Multiplexing Tradeoff
FDR	-	Full-Duplex Relaying
FDJ	-	Full-Duplex Jamming
HDC	-	Half-Duplex Constraint
i.i.d.	-	Independent and Identically Distributed
OHR	-	Opportunistic Half-Duplex Relaying
OSR	-	Opportunistic Two-Path Successive Relaying
PDF	-	Probability Density Function
SISO	-	Single-Input and Single-Output
SR	-	Successive Relaying
SNR	-	Signal-to-Noise Ratio
SINR	-	Signal-to-Interference-Plus-Noise Ratio
TDD	-	Time-Division-Duplex

LIST OF SYMBOLS

u	-	Lower case letter denote scalars
$\mathbf{u}$	-	Boldface lower case letters denote vectors
$\mathbf{U}$	-	Boldface upper case letters denote matrices
$\Pr(A)$	-	Probability of event A
$\binom{n}{k}$	-	Binomial coefficient indexed by n and k
$\mathbf{det}(.)$	-	Determinant
$\mathbf{exp}(.)$	-	Exponent
$\mathrm{Ei}(\cdot)$	-	Exponential integral function
$\log_2$	-	Logarithm with base 2
$\log$	-	Logarithm with base 10
$\ln x$	-	Natural logarithm
$[.]^T$	-	Transpose operation
$[.]^H$	-	Hermitian transpose operation
$\lvert . \rvert$	-	Absolute value
$[.]^+$	-	max (0, *x)*
$\in$	-	is an element of
$\bar{x}$	-	Statistical expected value
$\rightarrow$	-	Approaches
$\doteq$	-	Exponential equality
$\approx$	-	Approximately equal
$\triangleq$	-	Equal by definition
$\{ , \}$	-	the set of
$\sim$	-	is distributed as
$\mathcal{CN}(\mu, \sigma^2)$	-	Complex Gaussian distribution with mean μ and variance σ^2

CHAPTER 1

INTRODUCTION

This chapter begins with the introduction of this thesis in Section 1.1. Problem statements are presented in Section 1.2. Section 1.3 and 1.4 describe the objectives and scopes of this thesis respectively. Finally, the contributions and outlines of this thesis are highlighted in Section 1.5.

1.1 Introduction

The fifth generation (5G) wireless network will serve as a key enabler in meeting the ever increasing demand for data rates in future wireless applications. 5G is envisioned to deliver not only ultra-high data rate, but also ultra-wide radio coverage, ultra-large number of devices, and ultra-low latency [1]. 5G supports device-to-device and machine-to-machine communications, which contributes to the development of Internet of Things (IoT) [2]. In IoT, a large number of devices and machines with sensors and/or actuators are connected to the internet to form a highly dense network. In the dense network, a number of idle devices or machines with no message to transmit or receive can actively assist the network by assuming the role of relays. Relays offer additional paths for message transmission between the source and destination, subsequently improve the robustness of the transmission [3].

A transmission assisted by a relay, or more commonly known as cooperative communication, is introduced to improve the reliability of wireless transmission. In cooperative communication, relay assists the transmission by offering alternative independent transmission path between the source and the destination. The independent path delivers spatial diversity to help the communication system to overcome shadowing, deep fade and multipath. In cooperative communication, the requirement for a conventional relay to transmit and receive signals simultaneously in the same channel is traditionally assumed to be impractical. It is established that the power of the intended received signal of the relay is much lower than the power of the transmitted signal of the relay [4]. When operating simultaneously in the same channel, the self-transmitted signal saturates the receiver amplifier and analog-to-digital converter (ADC) and the relay is unable to isolate the intended received signal from the self-transmitted signal. In order to prevent this issue, the relay receives and transmits signals in two orthogonal frequency channels or time slots. The requirement to isolate the transmit and receive operations is generally known as the half-duplex constraint.

A source has to stop transmission of new message when the relay is transmitting message to the destination, due to the half-duplex constraint. Otherwise, the message transmitted by the source during the relay transmission phase will not be correctly received by the relay. This transmission scheme is also called half-duplex relaying (HDR). The HDR transmission requires double amount of channel resources compared to a direct transmission from source to destination without relay. As a result, the spectral efficiency of HDR is at most half of the spectral efficiency of direct transmission.

Full-duplex relay has been proposed to improve the bandwidth efficiency. A typical full-duplex relay is equipped with two antennas and two radio frequency (RF) chains used to transmit and receive signals respectively. This allows the full-duplex relay to transmit and receives signals simultaneously in the same channel. However, this comes at a cost of self-interference at the relay. The transmitted signal at the transmit antenna interferes the received signal at the receive antenna. Recent literature shows that the self-interference can be minimised and the residual interference may be regarded as additive noise [5, 6]. Advanced signal isolation techniques in the analog, digital, and propagation domains are required by the full-duplex relay to suppress the self-interference. Such techniques require sophisticated hardware and/or advanced signal processing which significantly increases the cost and complexity of relay nodes [7]. This contradicts the original motivation of using relays to provide a low complexity and inexpensive solution to improve the wireless transmission [8].

Successive relaying protocols are introduced to improve the spectral efficiency using only conventional half-duplex relays [9–11]. In successive relaying protocols, multiple half duplex relays are scheduled to assist the source transmission continuously. One of the popular successive relaying protocols is known as two-path successive relaying (TPSR) [11]. In TPSR, two conventional relays, R_a and R_b are scheduled to assist the transmission from source S to destination D alternately. When one of the relays is transmitting message to the destination, the other relay goes into receiving mode to receive the message transmitted from the source. TPSR allows the source and destination to transmit and receive new messages continuously. As a result, TPSR can achieve the same spectral efficiency as full-duplex relaying. However, when operating in co-channel, the transmitted signal from the transmitting relay interfere the received signal of the receiving relay. This interference is known as inter-relay interference and it causes the performance bottleneck in TPSR.

On the other hand, owing to the broadcast nature of wireless transmission, the wireless security remains one of the main concerns in wireless communication. In wireless communication, a transmitted signal from the source can be readily overheard by an unauthorised node. The transmitted signal is not secured when the unauthorised node intercepts the signal. The unauthorised node with the purpose to intercept the transmission is known as eavesdropper. The presence of eavesdropper poses a serious challenge to the security of wireless transmission. Traditionally, information security is addressed at upper layers of the network protocol stack such as application layer, transport layer and networking layer, based on cryptography methods. The general idea of cryptography is to protect the message so that unauthorised nodes without a security key can gain no information of the encrypted message. However, an eavesdropper with extremely high computational capability is still able to intercept the encrypted message through an exhaustive key search. Recently, physical layer security is identified as a promising technique that secure the wireless transmission by exploiting the physical characteristics of the wireless channel. Relaying approach has also been proposed to enhance the secrecy of wireless transmission [12–14].

1.2 Problem Statements

This section presents the problem statements of this thesis. The problem statements are described in the following subsections.

1.2.1 The detrimental effect of inter-relay interference in TPSR

In TPSR scheme, two relays are scheduled to transmit and receive alternately to imitate the full-duplex relay to deliver continuous source transmission to the destination. As a result, TPSR can deliver the same spectral efficiency as the full-duplex relaying. This motivates the use of TPSR to address the cost and complexity of full-duplex relay. However, when operating in co-channel, the received signal of the receiving relay is interfered by the transmitted signal from the transmitting relay. This inter-relay interference degrades the performance of TPSR. In the early literature, the inter-relay interference is mitigated by operating the two relays in two orthogonal frequency channels [15]. However, the use of two orthogonal channels decreases the spectral efficiency of TPSR to half of the spectral efficiency of full-duplex relaying. This diverges from the original purpose of TPSR to achieve the spectral efficiency of full-duplex relaying. In [11], successive interference cancellation (IC) decoding strategy is proposed to minimise the inter-relay interference. In the IC decoding strategy, the relays decode the inter-relay interference and subtract it from the received signal, before proceed to decode the message transmitted from the source. However, the IC decoding strategy is only effective when the power of inter-relay interference is much stronger than the power of the intended signal from the source. Existing literature does not compare the ergodic capacity and outage probability of TPSR against HDR in various channel and interference conditions [11]. It is therefore a need to compare the performance of TPSR affected by inter-relay interference with the HDR in terms of ergodic capacity and outage probability in various channel and interference conditions. The performance investigation of TPSR is presented in Chapter 4.

1.2.2 The issues of relay selection in TPSR

In TPSR, two relays assist the transmission alternately to imitate the operation of a full-duplex relay. This enables TPSR to achieve the spectral efficiency of full-duplex relaying. However, when operating in co-channel, the alternate transmit and receive operations of the two relays generate interference to each other. The inter-relay interference is the main contributing factor to the performance bottleneck of TPSR in terms of ergodic capacity and outage probability. Existing literature employs relay pair selection techniques to improve the ergodic capacity, outage probability and the diversity-and-multiplexing tradeoff of TPSR [16, 17]. In [16] and [17], two relays are selected from N relays in initialisation phase using relay pair selection criteria. The relay pair selection criteria affect the performance of TPSR.

In [16], two relays are selected individually with different criteria. First, the relay with the highest max-min capacity of source-to-relay channel and relay-to-destination channel is selected as the first relay, without considering the inter-relay interference. The second relay is selected from a decoding set of relays, $\mathcal{D}$ formed by the remaining relays which can decode the inter-relay interference and perform IC decoding of the source message. The qualified relays in $\mathcal{D}$ with the highest end-to-end capacity is then selected as the second relay. The individual selection of the relays reduces the pool of available relay pairs from $\binom{N}{2} = N(N-1)/2$ to $N-1$. Consequently, only $2/N$ of the available relay pairs are considered in the selection process. As a result, the best relay pair which achieves the highest capacity might not be considered in the selection process.

In [17], the inter-relay interference is utilised for superposition coding to provide additional diversity. A relay pair is qualified to perform superposition coding only when the source message and the inter-relay interference can be decoded by both relays. From the qualified relays, the relays with the largest and the second largest instantaneous capacity of the relay-to-destination channels are selected. Due to the strict requirement, the initialisation phase in [17] requires a total $1+N^2+2\log_2 N$ bits of overhead to acquire channel state information (CSI) of the relays and select the relay pair. In addition, the instantaneous end-to-end capacity is not considered in the relay selection. Therefore, the selected relay pair might not be the relay pair that achieves the highest capacity. On the other hand, the strict requirement of superposition coding may result in no relay pair being selected. As discussed in [17], when there is no qualified relay pair, the transmission mode falls back to the conventional HDR and a new relay needs to be selected. This further increases the overhead of the transmission. The use of capacity-wise suboptimal selection criteria in [16] and [17] motivates the proposal of new opportunistic TPSR schemes in Chapter 5.

In addition, based on the results in Chapter 4, TPSR does not always outperform HDR. Under certain channel conditions, HDR achieves higher ergodic capacity and lower outage probability than TPSR. Adaptive switching between TPSR and HDR modes has not been considered in the literature. This motivates the proposal of new adaptive TPSR schemes in Chapter 5.

1.2.3 TPSR in secrecy wireless communication

Relay provides substantial benefits not only in terms of reliability and spectral efficiency, but also beneficial in enhancing the secrecy of wireless transmission via physical layer security [12–14]. Physical layer security exploits the characteristics of the wireless channel such as channel fading and interference to improve transmission security. The existing literature on physical layer security mainly focuses on HDR [18–20]. In secrecy HDR, the relay cannot transmit and receive signal simultaneously in the same frequency channel due to the half-duplex constraint. This limits the performance of secrecy HDR. Recently, full-duplex relaying is proposed to improve transmission security [21]. The secrecy full-duplex relaying achieves higher secrecy capacity and lower secrecy outage probability than the secrecy HDR. This is because the full-duplex relay can transmit and receive signal simultaneously in the same frequency channel. However, this comes at a cost of self-interference because the reception of the full-duplex relay is interfered by its own transmission. Advanced signal isolation techniques in the analog, digital, and propagation domains are required to suppress the self-interference and this significantly increases the cost and complexity of full-duplex relay [7]. Alternatively, TPSR is proposed to imitate the full-duplex relaying by scheduling the operation of two conventional half duplex relays [11]. However, the use of TPSR for secrecy communication has not been considered in the literature and its secrecy performance remains unknown. This motivates the proposal of secrecy TPSR schemes in Chapter 6 to provide performance improvement in terms of secrecy ergodic capacity, secrecy outage probability and intercept probability.

1.3 Objectives

The objectives of this thesis are laid out as follows,

1. to investigate the effect of inter-relay interference to the ergodic capacity and outage probability of TPSR.
2. to propose opportunistic TPSR schemes with relay pair selection to improve the ergodic capacity and outage probability.
3. to propose secrecy TPSR schemes to improve the ergodic secrecy capacity, intercept probability and secrecy outage probability.

1.4 Scopes

This thesis considers the single-input and single-output (SISO) communication scenarios with a source and a destination assisted by two half-duplex relays. This thesis only considers a single-hop relaying scenario because a multi-hop relaying scenario provides a very limited gain in the achievable data rate compared to the single-hop relaying scenario [22]. The half-duplex relays cannot transmit and receive signal simultaneously in the same frequency channel due to half duplex constraint. The relays apply decode-and-forward (DF) strategy to assist the transmission. By using DF strategy, the relays decode the messages from the source, re-encode and then transmits to destination. The DF strategy avoids amplified noise in the relayed signal. The transmit power of the source and relays are fixed to unity. All the nodes are equipped with single antenna. The receivers of the relays and destination are corrupted by complex circularly symmetric additive white Gaussian noise in real and imaginary components with distribution $\mathcal{CN}\left(0, \sigma^2\right)$. All channels are reciprocal and follow quasi-static, frequency flat Rayleigh fading distribution. The channels are independent and identically distributed (i.i.d.), unless stated otherwise. In the secrecy transmission scenario, an eavesdropper equipped with a single antenna without jamming capability is considered. Without loss of generality, it is assumed that the direct channel between source and destination does not exist due to severe shadowing and/or extreme path loss, as in the existing literature [16, 17, 21].

The performance of the proposed schemes are simulated in MATLAB software using Monte Carlo technique. Each of the Monte Carlo simulations take 100,000 trials to ensure the accuracy of the simulation results. The average signal-to-noise ratio (SNR) is defined as $1/\sigma^2$ in the simulations. The performance metrics measured by the simulations in Chapter 4 and 5 are ergodic capacity and outage probability. In Chapter 5, tradeoff between target rate and outage probability is evaluated to validate the diversity-and-multiplexing tradeoff. Meanwhile, the ergodic secrecy capacity, intercept probability and secrecy outage probability are considered in Chapter 6. The performance of the proposed schemes also are evaluated analytically using information theory and statistical tools. During the derivation of the analytical results, the table of integrals in [23] serves as a reference in solving complex integration problems and the order statistics in [24] is used to quantify the distribution of the maximum and minimum values. In Chapter 5, the closed form equations for ergodic capacity, outage probability and diversity-and-multiplexing tradeoff of the proposed schemes are derived. Whereas, the analytical equations for intercept probability and secrecy outage probability of proposed schemes in Chapter 6 are derived.

In this thesis, multiple-input and multiple-output (MIMO) communication and power allocation are not considered. This thesis evaluates the performance of the proposed schemes in worst case scenario using Rayleigh fading model, without considering the effect of path loss.The transmission for channels with fast fading is not included in this thesis. The various channel conditions in Chapter 4 and 5 refer to the various levels of inter-relay interference. For the proposed secrecy transmission schemes in Chapter 6, the design of wiretap coding is not considered in this thesis.

1.5 Contributions of the Thesis

The original contributions of this thesis can be summarised as follow,

- The ergodic capacity and outage probability of the existing TPSR schemes affected by inter-relay interference are investigated in various channel and interference conditions characterised by different interference levels and compared to HDR in Chapter 4. The results reveal that TPSR does not always perform better than conventional HDR.
- New relay pair selection criteria based on the instantaneous end-to-end capacity are proposed in Chapter 5.
- New opportunistic TPSR schemes with relay pair selection are proposed in Chapter 5. The proposed opportunistic TPSR schemes are compared to existing opportunistic HDR, opportunistic TPSR schemes and full-duplex relaying schemes numerically in terms of ergodic capacity and outage probability. Information-theoretic analytical results on ergodic capacity, outage probability and diversity-and-multiplexing tradeoff of the proposed opportunistic TPSR schemes are derived.
- New adaptive opportunistic TPSR schemes are proposed in Chapter 5 to further improve the ergodic capacity and outage probability in various channel conditions characterised by different interference levels.
- New secrecy TPSR schemes are proposed in Chapter 6. The proposed secrecy TPSR schemes are compared to existing secrecy HDR and secrecy full-duplex relaying schemes numerically in terms of ergodic secrecy capacity, intercept probability and secrecy outage probability. Information-theoretic analytical results on intercept probability and secrecy outage probability of the proposed secrecy TPSR schemes are derived.

1.6 Outlines of the Thesis

The rest of this thesis is organised as follows. Chapter 2 gives an overview on the background and covers the literature review of the research topics in this thesis. Chapter 3 describes the research methodology of this research. Chapter 4 investigates the performance of TPSR in the presence of inter-relay interference. Chapter 5 presents the proposed opportunistic TPSR schemes. Chapter 6 describes the proposed secrecy TPSR schemes. Chapter 7 concludes the thesis and recommends several future work.

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