Relaying strategies and protocol designs for buffer-aided cooperative relaying networks

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Relaying Strategies and Protocol Designs for Buffer-Aided Cooperative Relaying Networks

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Abstract

In this thesis, a new technique named buffer-aided relaying is studied to enhance the performance of wireless relaying networks. In particular, the transmission strategies that can improve diversity gain, maximize the system throughput and reduce the information delay are investigated.

First, we apply the buffer-aided relaying scheme into a space-shift-keying (SSK) based relaying system and propose a novel link adaptation method. The average symbol-error performance of the proposed link adaptation scheme is investigated and it is shown that the proposed scheme can achieve a diversity order of 2. In addition, the delay of the information packets at the relay node (RN) is investigated and two link adaptation schemes with reduced delay are proposed. It is shown that by jointly considering the buffer state, the proposed link adaptation schemes can achieve a relative small packet delay at the expense of a little performance loss.

Subsequently, a buffer-state based relay selection scheme is proposed for a buffer-aided multiple RNs system to reduce the average delay. Different from the existing relay selection schemes which select the RNs only based on the channel quality, our proposed relay selection scheme selects a RN based on both the channel quality and the buffer state of the RNs. The outage probability of the proposed relay selection scheme is obtained in a closed-form expression and it is shown that the proposed relay

selection scheme can outperform the existing relay selection schemes. In addition, analytical results also show that our proposed relay selection scheme has lower average packet delay as compared with the existing buffer-aided relay selection schemes.

Moreover, the application of the buffer-aided relaying scheme in a wireless-powered relaying system is also investigated. By assuming that the RNs of the system have no embedded power supply and are charged by the radio frequency (RF) signal transmitted by a power beacon (PB), a joint node-and-mode selection scheme is proposed. For the general system setup, some analytical results are obtained which provide useful insights in finding the optimal joint node-and-mode selection scheme. Following this, theoretical analysis is conducted for two specific systems, namely the single RN system and the multiple RNs system with a symmetric channel. For these system setups, the system throughput is obtained in closed-form expressions. Numerical results show that the system throughput can be improved by using the proposed transmission schemes.

Finally, we extend the buffer model into a wireless-powered cooperative communication network (WPCCN) and treat the battery of the SN as an energy queue. Based on this model, we investigate the long-term throughput of two proposed block-wise cooperative protocols, namely the block-wise harvest-and-transmit (BW-HaT) protocol and the block-wise mode adaptation (BW-MA) protocol. For the BW-HaT protocol, the throughput expression is obtained in closed form. For the BW-MA protocol, the optimal mode adaptation method that maximizes the throughput of the system is presented and the maximum throughput is given for different system setups. It is shown that the proposed transmission schemes can significantly increase the system throughput.

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List of Abbreviations

AF	Amplify-and-forward
AWGN	Additive white Gaussian noise
BER	Bit-error rate
BW-HaT	Block-wise harvest-and-transmit
BW-MA	Block-wise mode adaptation
BPSK	Binary phase-shift keying
BS	Base station
CDF	Cumulative distribution function
CSI	Channel state information
DF	Decode-and-forward
DN	Destination node
HAT	Harvest-and-transmit
HSAT	Harvest-store-and-transmit
LoS	Line-of-sight
MC	Markov chain
MIMO	Multiple-input multiple-output
MDP	Markov decision process method
PB	Power beacon

PDF	Probability density function
PEP	Pairwise error probability
QPSK	Quadrature phase-shift keying
RN	Relay node
RN-HAT	Relay node harvest-and-transmit
R-D	Relay-to-destination
RF	Radio frequency
RF-EH	Radio frequency energy harvesting
RS	Relay-station
SER	Symbol-error rate
SNR	Signal-to-noise ratio
S-R	Source-to-relay
SSK	Space-shift-keying
SN	Source node
SN-IT	Source node information transmission
SM	Spatial modulation
SWIPT	Simultaneous wireless information and power transfer
WPCN	Wireless-powered communication network
WPCCN	Wireless-powered cooperative communication network
UE	User equipment

List of Symbols

Throughout this thesis, bold letters denote vectors and matrices; lower case letters denote variables and parameters.

$ \cdot $	Absolute value
$(\cdot)^T$	Transpose operator
$(\cdot)^H$	Hermitian transpose operator
$(\cdot)^*$	Complex conjugate operator
$\Re\{\cdot\}$	Real part of a complex number
$\mathbb{E}(\cdot)$	Expectation of a random variable
$\Pr\{\cdot\}$	Probability of an event
τ	Throughput
N_0	Variance of additive Gaussian noise
L	Buffer size
$Q(\cdot)$	Q-function
$K_1(\cdot)$	First order modified Bessel function of the second kind
$K_0(\cdot)$	Modified Bessel function of the second kind with order zero
$I_0(\cdot)$	Modified Bessel function of the first kind with order zero

CONTENTS

$E_i(\cdot)$	Complete elliptic integral of the second kind
$Q(a, b)$	Marcum Q-function with parameters a and b

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Chapter 1

Introduction

The revolution of wireless telecommunication systems in the past decades has transformed existing wireless communication networks into an integrated network in which a broad class of services can be provided. Different from the fiber or coaxial cable based communication systems which are almost free of interference, signal propagating in a wireless communication system has to deal with more challenges such as multi-path fading, co-channel interference and adjacent channel interference [1]. Due to the dynamic nature of the wireless channel, it is a challenging task to design a reliable wireless system. Although the wireless channel has some drawbacks, it has the property of broadcasting which makes it possible to improve the system reliability by taking advantage of the environment diversity [2, 3]. On the other hand, the fast development of Internet of things and mobile Internet in recent years results in an exponential growth in high-speed data applications, such as social networking and high-quality wireless video streaming [4], which as a result, requires a significant throughput growth for modern wireless communication systems. It is required that the next generation wireless communication systems should achieve an energy and

spectral efficiency growth by a factor of at least 10, and a throughput growth by a factor of at least 25 [5].

Due to the fact of the fast expansion of high-rate high-fidelity wireless communication applications, a crucial task for the development of modern wireless communication system is to exploit new technologies that can achieve higher spectral efficiency and/or better communication quality. By allowing user terminals in a network to share their resources and help each other with data transmission, cooperative relaying technique can improve the overall network capacity and is robust to link failure caused by fading during electromagnetic radio transmission [6, 7]. In certain sense, a cooperative relaying system mimics a multiple-antenna system, but avoids the hardware difficulties in equipping multiple antennas in a single device [8, 9]. These merits of cooperative relaying make it a promising technique for future wireless communication systems. Since the cooperative relaying technique has so many advantages, it has recently been adopted in different new wireless systems such as 3GPP LTE-Advanced [10]. In addition, it has also been considered in WiMAX standards (IEEE 802.16j and IEEE 802.16m) [11] and WiFi standards (IEEE 802.11s and IEEE 802.11n) [12].

1.1 Background and Motivation

The idea of cooperative relaying communication network can be traced back to the early 1970s. In the seminal paper [13], Meulen introduced a three-terminal channel model and investigated ways of efficient communication between the three terminals assuming that all the terminals can cooperate. Later, Cover and Gamal [14] studied a special case of a three-terminal channel by asking one terminal (source) to simply

transmit new message, one terminal (destination) to simply receive, and the third terminal to receive messages from the source node (SN) and then forward them to the destination node (DN). They termed this channel as a relay channel and showed that with the help of a relay node (RN), the SN and DN can communicate at a higher rate as compared to the case with solely direct transmission from the SN to the DN. This finding confirms the benefits of cooperative relaying and sets the basis for the subsequent research interests in this area. Despite the early information-theoretical works in user cooperation, its application in wireless communication systems has drawn extensive attention only in recent years [6, 7, 15, 16]. A key motivation behind this is the increasing conflicts between the limited wireless spectral resources and the ever growing demand for higher transmission rates and better communication qualities. Due to the broadcast nature of wireless channel, the terminals in a network can hear each other without any extra cost. By combining these terminals to form a distributed multiple-input multiple-output (MIMO) system, the system throughput can be improved [17]. In addition, it has been shown in [10] and [18] that relaying can enhance the coverage and capacity of wireless networks. Furthermore, by using cooperative relaying, the energy consumption of system terminals can also be reduced [19, 20]. Generally, there are two kinds of strategies for relay deployment, namely the access-point relaying and the user cooperative relaying. For the access point relaying scheme, fixed RNs are deployed as access-points which help the communication between the SN and the DN [21]. In a user cooperative relaying scheme, one user terminal acts as RN for the other user terminals [6, 7]. As a result, these user terminals form a cooperative network. Currently, the fixed access-point relaying scheme has already been adopted in practical telecommunications systems, e.g.,

the LTE-Advanced systems use the fixed access-point relaying scheme to act as the back-haul network [22–24]. On the other hand, the application of user cooperative relaying scheme is still limited to literature and more works on cooperative relaying are still needed to make it applicable for practical wireless systems.

Recently, a buffer-aided relaying scheme has been proposed in [25] and [26]. Different from the conventional relaying systems, an information buffer is equipped at the RN and it can temporarily store the received packets before retransmitting them to the DN. With the help of a buffer, the RN can adaptively choose to transmit or to receive based on the channel quality of the source-to-relay (S-R) and the relay-to-destination (R-D) links in each time slot. Compared with the conventional relaying technique which always delivers a information packet from the SN to the DN in two successive time slots, the buffer-aided relaying system can benefit from the multi-hop diversity by using a proper link adaptation method [27]. It has also been shown that for the adaptive rate transmission system, in which the transmitter can adaptively change its information rate according to the channel response, a buffer-aided relaying scheme can significantly improve the system throughput [28]. As the buffer-aided relaying scheme has many benefits, it has attracted a lot of attention in recent years. Although buffer-aided relaying schemes can improve the reliability or the average achievable rate of the relaying systems, it also results in new problems for the cooperative relaying networks. For instance, the user scheduling approaches designed for the traditional relaying systems are no longer applicable for the buffer-aided relaying systems; the optimal RN selection strategy for the traditional relaying systems is no longer optimal when taking the buffer states into consideration; the delay of the cooperative relaying networks is increased if the buffering scheme is used at the

RNs; existing link adaptation approaches can not work well for relaying systems with asymmetric channels. To deal with these problems, in this thesis, we aim to design new relaying schemes for buffer-aided relaying systems.

1.2 Research Problems and Objectives

Research on applying buffer-aided relaying in cooperative relaying networks is new and more works are needed to address the problems that arise in this area. One key issue of applying the buffer-aided relaying scheme is to design effective link adaptation schemes for different cooperative relaying systems. This is important as for different cooperative relaying systems, the link adaptation schemes that can effectively take advantage of buffer-aided relaying are different. Furthermore, a wrongly designed link adaptation scheme may make the buffer of the RN unstable and thus make the system malfunction. In [26, 29–31], different link selection schemes were proposed for buffer-aided single RN or multiple RNs systems. The achievable diversity order and throughput were derived for the fixed-rate and adaptive-rate transmission systems, respectively. In addition, to apply buffer-aided relaying to practical systems, it needs to combine with the existing communication techniques, e.g., MIMO, beamforming and network coding, etc. To make a communication system work efficiently, it is of great importance to design effective communication strategies that can effectively take advantage of different communication techniques.

In most existing works on buffer-aided relaying, conventional linear modulation schemes, e.g., binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK), are adopted and the communication scheme is designed for these modulation schemes. In recent years, a promising technology named spatial modulation (SM)

method was proposed for the future MIMO systems [32, 33]. In SM, part of the information is mapped into the index of the active antenna and only one among the available transmit antennas is activated during signal transmission. Thus, SM can overcome some drawbacks of the conventional MIMO techniques [34], e.g., inter-antenna synchronization, inter-channel interference, high receiver complexity, size and cost of hardware due to the use of multiple transmitting radio frequency (RF) chains. These promising benefits of SM and buffer-aided relaying motivate us to combine these two techniques in one cooperative relaying system. Different from the conventional modulation schemes whose performance is determined by the channel fading gain the signal experienced, the performance of SM depends on the difference in channel gains of different transmitting antennas. Thus, the link adaptation method of the SM based buffer-aided relaying system should be redesigned to effectively make use of the multi-hop diversity. In Chapter 3, we consider a SSK-based (which is a special case of SM) buffer-aided relaying system and design effective communication strategies.

Although buffer-aided relaying can improve the diversity order or throughput of a cooperative relaying system, it may result in a large information delay at the RN [26, 28]. For systems with information delay constraint, it is important to design buffer-aided relaying schemes that can achieve a good tradeoff between different system performance metrics, e.g., the tradeoff between system reliability and information delay as well as the tradeoff between system throughput and information delay. Generally, it is a challenging task to find the tradeoff between delay and system reliability (throughput) as it is difficult to model the buffer state changes of the RN(s)

mathematically. Existing works on this area only provide some simple link adaptation schemes that can reduce the information delay at the RN(s) and it has been shown that the information delay can be reduced at the cost of some performance loss [28, 35, 36]. However, it is important to find the minimum achievable information delay if a certain performance is required. We investigate this problem in Chapter 4. Specifically, we propose a link adaptation scheme which takes the buffer state into account for a fixed-rate transmission system and derive the minimum buffer size required to achieve full diversity order.

Buffer-aided relaying improves the performance of a cooperative relaying network by opportunistically making use of the dynamic property of wireless channels [26, 28]. At each time slot, either the S-R link or the R-D link with a relatively better quality is selected to deliver information. Actually, this opportunistic transmission strategy can be applied not only in wireless cooperative relay networks but also in any other wireless networks. Recently, wireless-powered cooperative communication network (WPCCN) has been attracting a growing interest as it can prolong the life time of the energy-constrained wireless networks such as the wireless sensor networks by using the RF signal to transfer energy [37, 38]. For a WPCCN with RF signal powered RNs, a power beacon (PB) first transfers energy to the RNs by sending RF signals. The RNs then use the harvested energy to forward the information received from the SN to the DN. The WPCCN has the following properties: 1) The energy harvested through RF signal by the RNs is limited, and the information received from the SN in one time slot may need several time slots to be delivered to the DN by the RNs. Thus the RNs need a buffer to temporarily store the received information. 2) For the energy constraint RNs, the buffer-aided relaying scheme which increases the capacity

of the system can increase the energy efficiency of the RNs. Inspired by the benefits of buffer-aided relaying and considering the properties of WPCCN, we introduce the buffer-aided relaying scheme into WPCCN in Chapter 5 and propose an adaptive transmission scheme, in which each RN adaptively switches between two working modes.

In a WPCCN, the battery of the energy harvesting node works similarly to the information buffer of the RN of a buffer-aided relaying system with the information queue replaced by an energy queue. Thus, the opportunistic transmission strategy of buffer-aided relaying can also be applied in WPCCN to effectively make use of the harvested energy. By treating the battery as an energy queue, the WPCCN involves two types of coupled queues, namely the energy queue and the information queue. To make the WPCCN work efficiently by using this two-queue model, it is important to design effective transmission strategy. In Chapter 6, we investigate a WPCCN with a hybrid RN which works as both a relay and a PB and design an effective transmission strategy to maximize the system throughput.

1.3 Contributions

The main contributions of thesis can be summarized as follows:

- In Chapter 3, we investigate a buffer-aided dual-hop relaying system with SSK. We propose a novel adaptive transmission scheme for the considered SSK buffer-aided relaying system and show that by using the difference in channel gains between transmitting antennas as the quality measurement of the S-R link, the proposed scheme can effectively make use of the multi-hop diversity. The average symbol-error rate (SER) is used as the performance measurement of the

proposed scheme, and an exact closed-form expression of the average bit-error rate (BER) for the case that the SN has two transmit antennas is derived. For the system with arbitrary number of transmit antennas, an upper bound on the average SER is obtained. In addition, we investigate the delay of the information packets at the RN and propose two link adaptation schemes to reduce the average packet delay at the tradeoff of some performance loss. Numerical results validate the analytical expressions and confirm that the proposed transmission scheme can significantly improve the system performance as compared with the conventional relaying scheme.

- In Chapter 4, we propose a buffer-state based relay selection scheme for a buffer-aided relaying system with multiple RNs to reduce the average delay. Different from the existing relay selection schemes on buffer-aided relaying, the proposed relay selection scheme takes both the channel quality and the buffer state of the RNs into account to select the active link in each time slot. Thus, the proposed relay selection scheme involves a new design freedom. We use the Markov chain model to analyze the buffer state transition properties and the outage probability of the proposed relay selection scheme is obtained in a closed-form expression. Our analytical results show that the proposed buffer state based relay selection scheme can achieve full diversity order even if the buffer size of the RNs is only 3, while the existing existing relay selection schemes on buffer-aided relaying requires an infinite buffer size to achieve this full diversity order. In addition, the proposed relay selection scheme has much lower average packet delay compared with the existing relay selection schemes designed for the buffer-aided relaying systems. Furthermore, we show that the average information

delay of the proposed relay selection scheme does not increase as the buffer size increases.

- In Chapter 5, we investigate a WPCCN with multiple buffer-aided RNs. A joint node-and-mode selection scheme in which the RN and its transmission mode are jointly selected in each time slot is proposed. For the general system setup, the criterion to find the optimal joint node-and-mode selection scheme that maximize the system throughput is derived. Following this, the analysis is applied to two specific systems, i.e., the single RN system and the multiple RNs system with a symmetric channel. For these system setups, the system throughput and the corresponding optimal transmission scheme are obtained in closed-form expressions. Numerical results show that the throughput of the wireless-powered relaying system can be improved by using the proposed transmission schemes.
- Lastly, in Chapter 6, we extend the idea of opportunistic transmission strategy of buffer-aided relaying into a WPCCN which consists of a RF powered SN, a buffer-aided hybrid RN and a DN. The RN can be treated as an fixed access point with a constant power supply and it transfers power to the SN by using RF signals. We treat the battery of the SN as an energy queue, and as a result, the system involves two coupled queues, i.e., the energy queue and the information queue. Based on this model, we propose two block-wise cooperative protocols, namely, the block-wise harvest-and-transmit (BW-HaT) protocol and the block-wise mode adaptation (BW-MA) protocol, and investigate the maximum achievable throughput of these two protocols. For the BW-HaT protocol, the throughput expression is obtained in a closed-form expression. For the BW-MA protocol, the optimal mode adaptation method that maximizes the

throughput of the system is presented and the maximum throughput is given for different system setups. We show that by treating the battery of the SN as an energy queue and applying the opportunistic transmission strategy, the proposed BW-MA transmission schemes can significantly increase the system throughput.

1.4 Organization of Thesis

The structure of this thesis is organized as follows. First, in Chapter 2, we review the basics of buffer-aided relaying, including the principle of buffer-aided relaying and some design criteria that are usually applied in transmission strategy designs. A brief review on existing research works on buffer-aided relaying is also presented in this chapter. In Chapter 3, we combine buffer-aided relaying with the SSK modulation and provide a novel adaptive transmission scheme that can effectively make use of the multi-hop diversity. The information delay of buffer-aided relaying is considered in Chapter 4, where we take the buffer state of the RN into account and propose a buffer state based relay selection scheme that can effectively reduce the average information delay. In Chapter 5, a WPCCN with buffer-aided RNs is considered. By solving a non-convex binary optimization problem, the optimal joint node-and-mode selection scheme that maximizes the system throughput is derived. Chapter 6 extends the idea of the opportunistic transmission strategy of buffer-aided relaying to a WPCCN. By treating the battery of the SN as an energy queue, we provide a novel model adaptation scheme that can significantly increase the system throughput. In Chapter 7, we draw the conclusion and provide some potential future work. Lastly, the proofs for some analytical expressions are presented in Appendices.

Chapter 2

Literature Review

2.1 Overview

In conventional half-duplex relaying, the information is delivered from the SN to the DN in two successive time slots. As shown in Fig. 2.1, the SN transmits information to the RN in the i th time slot and the RN forwards the information to the DN in the $(i + 1)$ th time slot. As the transmissions of the SN and RN are pre-scheduled in this paradigm, the capacity of the relaying system is restricted by either the S-R or the R-D link with poor channel quality. Different from the traditional relaying scheme, by introducing data buffers at the RNs, there is no need for the RN to forward the received information in the next time slot. With the help of a buffer, the system can adaptively choose either the S-R link or the R-D link (with a relatively better

Figure 2.1: A three-node conventional relaying system.

Figure 2.2: A three-node buffer-aided relaying system.

channel quality) to transmit information in each time slot. As shown in Fig. 2.2, an information packet is delivered from the SN to the RN in the i th time slot as the S-R link has a relatively better channel quality. In the j th time slot, as the R-D link has a better channel quality, this information packet is forwarded from the RN to the DN. Recent research works on relaying systems have shown that buffer-aided relaying can significantly improve the performance of cooperative relaying systems.

The first buffer-aided relaying network was proposed in [39], in which a RN with an information buffer receives for a fixed number of time slots before forwarding the received information to the DN. Following this, in [26], the authors considered the buffer-aided multiple RNs system and proposed a max-max relay selection scheme. Although these works have shown that the ergodic capacity of the relaying system can be improved by introducing data buffers at the RNs, they failed to fully exploit the flexibility offered by RNs with buffers as the transmission of the SN and RN is still prefixed. To relax this limitation, Krikidis et al. proposed an max-link transmission scheme in [27], where each time slot is dynamically allocated to either the S-R link or R-D link based on the instantaneous channel quality of these two links and the status of the RNs' buffers. It was shown that the max-link transmission scheme can fully exploit the flexibility offered by the buffers at the RNs and achieve a diversity order two times of that of the conventional relaying schemes. Considering the great potential benefits of buffer-aided relaying, many research works on this topic have been carried out in recent years.

2.2 Buffer-Aided Single RN System

2.2.1 Fixed-Rate Transmission

For a communication system in which the transmitter can not obtain the channel state information (CSI), a fixed-rate transmission strategy is usually applied. In practical systems, this fixed-rate transmission strategy is also commonly adopted to reduce the complexity of user equipments (UEs). In [40], a three-node buffer-aided relaying system, including a SN, a RN and a DN, was considered. The SN and the RN transmit with fixed rates R_s and R_r , respectively. By assuming that the RN has a buffer with infinite size, the authors proved that a diversity order of 2 can be achieved by using buffer-aided relaying. Following this, a lot of work has been done to properly evaluate the performance of buffer-aided relaying schemes. In [35], the buffer-aided relaying scheme was combined with OFDM in a relaying system with a finite buffer RN. It was shown that significant power gain can be obtained for the finite size buffer-aided relaying systems. In [41], the throughput of a three-node buffer-aided relaying system was investigated and the link adaptation schemes that can reduce the packet delay at the RN was proposed. In all these works, a threshold based link adaptation method is applied, e.g., if the instantaneous channel gains $|h_{sr}|^2$ and $|h_{rd}|^2$ of the S-R and the R-D link satisfy $|h_{sr}|^2 > \rho|h_{rd}|^2$ ($|h_{sr}|^2 \leq \rho|h_{rd}|^2$), then the S-R (R-D) link is selected to transmit. It has been shown that by using the threshold based link adaptation method, the diversity order of 2 can only be achieved for the system with infinite buffer size. For the system with finite buffer size, only limited power gain can be obtained [35, 41].

The major limitation of the threshold based link adaptation method is that it

Figure 2.3: Outage probability of the fixed rate buffer-aided relaying scheme, with $R_s = R_r = 1\text{bps/Hz}$, $\Omega_s = \mathbb{E}\{|h_{sr}|^2\} = \Omega_r = \mathbb{E}\{|h_{rs}|^2\} = 1$.

requires an infinite buffer size to achieve the full diversity. To further improve the performance of a relaying system with finite buffer at the RN, in [42–44], the buffer state of the RN was taken into consideration in designing link adaptation schemes. The motivation of these works arises from the fact that if both links can successfully deliver a data packet, either link can be selected to transmit information. To reduce the probability of the event that the buffer becomes empty or full, in which only one link can be used to deliver information, the buffer state is taken into consideration in selecting the active link. Based on this argument, it has been shown in [43] and [44] that a buffer state threshold based method can achieve the maximum system throughput by using the Markov decision process method (MDP).

The buffer-aided bidirectional relaying system in which two UEs want to exchange

information through a RN was investigated in [36] and [45]. By defining different transmission modes, the optimal mode adaptation method that maximizes the system sum throughput was derived in [45]. To reduce the information packet delay at the RN, several mode selection schemes which take the buffer state into consideration were proposed in [36]. These works showed that both UEs of the bidirectional relaying system can benefit from information buffering at the RN. The buffer-aided full-duplex relaying system was investigated in [46] and [47]. By assuming that the SN and the RN can select their transmission rates from discrete sets of available transmission rates, a discrete-rate adaptive transmission scheme was proposed in [46] and it was shown that the throughput of a full-duplex relaying system can be improved by using the buffer-aided relaying scheme. In [47], the authors assumed that the system can switch between the half-duplex and the full-duplex mode and proposed a buffer-aided hybrid half-/full-duplex relaying scheme. It was shown that by properly switching between these two modes, the system throughput can be significantly improved. To make use of both the multi-user diversity and multi-hop diversity of the multi-UE relaying system, a joint UE and link selection problem was considered in [48, 49].

One major challenge of applying buffer-aided relaying is that it needs to know the CSI of the S-R and the R-D links before selecting the active link in each time slot. This results in extra overhead for the relaying systems. Moreover, for a system in which the channel response changes relatively fast, it is difficult to obtain the accurate CSI of the system in each time slot. Thus, the buffer-aided relaying system with outdated CSI was considered in [50] and [51]. It was shown that even with outdated CSI, the adaptive link selection scheme provides a significant coding gain over conventional relaying schemes. The buffer-aided relaying scheme improves the

performance of a cooperative relaying system by making use of the dynamic property of wireless channels, e.g., opportunistically choose the link with a relatively better quality in each time slot. If the channel responses in different time slots are correlated, it is generally believed that the performance improvement of buffer-aided relaying will be degraded. To analyze the performance of buffer-aided relaying in time-correlated fading channels, an analytical framework which is based on a super state Markov Mode was proposed in [52].

2.2.2 Adaptive-Rate Transmission

If the transmitter (the SN or the RN) knows the instantaneous channel response and has the ability to adaptively change its channel coding rate and modulation order, the system can adjust its transmitting rate to the achievable rate of the channel. In [28], a three-node relaying system with adaptive rate transmission was first investigated. The optimal link adaptation criterion that maximizes the system throughput was derived. This criterion is then widely adopted in the literature on buffer-aided relaying. It was shown that significant throughput gain can be obtained by using buffer-aided relaying. Following this, it has been pointed out in [53] that the buffer-aided half-duplex relaying can even achieve higher throughput than the ideal full-duplex relaying without information buffering at the RN if the channels of the S-R link and the R-D link are significantly unbalanced, e.g., the quality of the S-R link is much better than that of the R-D link. Inspired by these works, a buffer-aided relaying system with multiple UEs was investigated in [54–56], in which the optimal link adaptation method that maximizes the sum throughput was derived. Different from the works of [54–56], the UE fairness problem was considered in [57] and a link adaptation

2.2. BUFFER-AIDED SINGLE RN SYSTEM

Figure 2.4: Throughput ratios C_B/C_{conv} for different Ω_R/Ω_S values, where C_B and C_{conv} are the throughput of the buffer-aided relaying scheme and the conventional relaying scheme, respectively.

scheme that maximizes the minimum throughput of the UEs was proposed. In [58], the authors considered a buffer-aided multi-cast relay network and derived the link selection scheme that gives the maximal system throughput. In [59], a bidirectional buffer-aided relaying system was investigated and the long-term achievable rate region was derived.

Buffer-aided relaying scheme can also be applied in cognitive radio systems [60–62]. In [60], an overlay cognitive radio system in which the secondary SN acts as the RN of the primary UEs was considered and the optimal access strategy of the two pair of UEs was investigated to maximize the sum throughput of the system. Different from [60], an underlay cognitive buffer-aided relaying network in which the secondary SN and DN communicate through the help of a secondary RN was investigated in [61]. By

restricting the interference of the secondary UEs, an max-ratio based link adaptation scheme which has been proven to maximize the throughput of the secondary UEs was proposed. In [62], the authors took the feedback delay of buffer-aided relaying into consideration and investigated the impact of outdated CSI on the outage performance of buffer-aided underlay cognitive relaying networks.

As the buffer-aided relaying scheme enables a system to adaptively select an active link in each time slot, it was used to enhance the secure throughput of the relaying systems [63–66]. A two-hop half-duplex relay network with an external eavesdropper was considered in [63] and a novel link selection scheme was proposed to maximize the system secure throughput. In [64], this analysis was extended to the buffer-aided MIMO relaying system with multiple UEs. The security throughput of the buffer-aided full-duplex relaying system and buffer-aided cognitive radio system was investigated in [65] and [66], respectively. All these works showed that buffer-aided relaying schemes can significantly improve the system secure throughput.

2.2.3 Mixed-Rate Transmission

By taking the practical constraints into consideration, different transmission methods may be used by the two links of a relaying system. For instance, in a cellular system in which a UE transmits information to the base station (BS) through the help of a relay station (RS), the UE usually transmits with a fixed rate as it requires a low processing complexity. However, the RS may be able to obtain the CSI and communicate with the BS with adaptive rates as it is more powerful. For this relaying system, a mixed-rate transmission strategy can be adopted. In [67], a buffer-aided relaying with mixed-rate transmission was investigated. The optimal link adaptation

method that maximizes the system throughput was derived. It was shown that a throughput gain of up to 100% is possible as compared with the conventional relaying scheme if the channel qualities of the two links are significantly unbalanced. In [41], the tradeoff between the achievable rate and information delay was investigated. In the literature, the study on mixed-rate buffer-aided relaying is limited and mainly focuses on single RN systems. Thus, more works are needed to be carried out for a mixed-rate buffer-aided relaying system with multiple RNs.

2.3 Buffer-Aided Multiple RNs System

2.3.1 Relay Selection

For some relaying systems, multiple RNs are used to further improve the network performance. For a cooperative relaying system with multiple RNs, relay selection scheme has been proven to be an effective method to achieve the full diversity order while preserving the efficiency of the communication systems [68, 69]. The main advantage of the relay selection scheme is that it is easy to implement. As it only chooses the RN with the best end-to-end channel quality to forward the data packets, there is no need to perform any explicit synchronization process.

Max-Min Relay Selection

For the traditional decode-and-forward (DF) based relaying system without information buffering at the RN, the max-min relay selection scheme is considered as the optimal relay selection policy [68, 69]. The max-min relay selection scheme chooses the RN that provides the highest end-to-end signal-to-noise ratio (SNR) to forward

Figure 2.5: A relaying system with multiple relay nodes.

the signal (as illustrated in Fig. 2.5), i.e.,

$$R^* = \arg \max_{R_k} \min\{|h_{sr_k}|^2, |h_{r_k d}|^2\}. \quad (2.1)$$

It has been shown that the max-min relay selection approach provides a diversity order that is equal to the number of the RNs (e.g., K).

Max-Max Relay Selection

In [26], the max-max relay selection scheme was proposed for a relaying system in which the RNs are equipped with buffers. Specifically, the max-max relay selection scheme chooses the RN with the best S-R link to receive and the RN with the best R-D link to transmit. The relay selection policy of the max-max relay selection scheme can be expressed as follows:

$$R_r^* = \arg \max_{R_k} \{|h_{sr_k}|^2\}, R_t^* = \arg \max_{R_k} \{|h_{r_k d}|^2\}, \quad (2.2)$$

in which R_r^* and R_t^* denote the RNs selected for receiving and transmitting, respectively. As the max-max relay selection scheme still adapts the conventional two-slot cooperative transmission, the same diversity order as that of the max-min relay selection scheme is achieved. Compared with the max-min relay selection scheme, the max-max relay selection scheme achieves some coding gains.

Max-Link Relay Selection

In [27], the max-link relay selection scheme was proposed for a buffer-aided relaying system. Different from the conventional transmission schemes, it allows each time slot to be dynamically allocated to the SN or RN for transmission. By choosing the best link from all the available links (S-R and R-D links) in each time slot, the max-link relay selection scheme can achieve a diversity order equals to two times of that of the max-max relay selection scheme if the buffer size L is large enough. In the max-link relay selection scheme, the $S - R_k$ link is considered to be available if the corresponding buffer L_k of R_k satisfies $L_k < L$; the $R_k - D$ link link is considered to be available if the corresponding buffer L_k of R_k satisfies $L_k > 0$. Specifically, the max-link relay selection scheme can be expressed as follows:

$$R^* = \arg \max_{R_k} \left\{ \bigcup_{R_k: L_k < L} |h_{sr_k}|^2 \bigcup_{R_k: L_k > 0} |h_{r_kd}|^2 \right\}, \quad (2.3)$$

where R^* denotes the selected RN. If a S-R link is the strongest link, then the SN transmits and the selected RN receives. If a R-D link is the strongest link, then the selected RN transmits and the DN receives. In [29], the performance of the max-link selection scheme was investigated for the AF based buffer-aided relaying system. In [70], the authors showed that max-link relay selection scheme can significantly

improve the achievable rate of the adaptive-rate buffer-aided relaying system.

Following the work of [27], different relay selection schemes have been proposed for different kinds of buffer-aided relaying systems [71]. The relay selection scheme that maximizes the throughput of a buffer-aided cognitive relay network was investigated in [30]. Considering that the max-link selection scheme results in a large information delay at the RNs [27], in [72] and [73], a small size buffer was used at the RNs to restrict the information delay and the relay selection scheme minimizing the system outage probability was investigated. Different from [72] and [73], the information delay was reduced in [74] by simultaneously selecting multiple RNs to receive SN information in the S-R link. Thus, if one of these RNs in the R-D link, is not in outage, the information packet can be delivered to the DN. In addition, based on the fact that the max-max scheme can achieve a low information delay, a hybrid max-max, max-link relay selection scheme was proposed in [75] to achieve a tradeoff between delay and outage probability. Furthermore, to reduce the information delay, a relay selection scheme by taking the buffer state into consideration was proposed in [76]. However, the proposed scheme can only achieve a diversity order equals to the number of the RNs (e.g., K). In [31], [77] and [78], the buffer-aided relay selection scheme was investigated to improve the secrecy rate of the system.

2.3.2 Buffer-Aided Successive Relaying

In half-duplex relaying systems, as information is delivered from the SN to the DN by using two time slots, the system spectral efficiency is reduced. To reduce this throughput loss of using half-duplex relaying technique, a successive relaying scheme was proposed [79] and [80]. The main idea of successive relaying is to use two RNs

to alternately forward messages from the SN to the DN. It was shown that if the interference between these two RNs is weak or strong enough, significant portion of throughput loss due to half-duplex relaying can be recovered. To further improve the system reliability, the buffer-aided relaying method was applied in successive relaying systems in [81–86]. Specifically, in [81], different working modes were defined for a two RNs buffer-aided successive relaying system without considering the inter-relay interference. It was shown that a diversity order of 2 can be achieved by adaptively switching between different working modes. In [82], the inter-relay interference was taken into consideration and an interference cancellation method was provided. Following this, the analysis was extended to the RNs with multiple antennas in [83]. To deal with the case that successive relaying cannot be applied because of outage, an opportunistic buffer-aided successive relaying scheme was proposed in [84] and [86]. In [85], the buffer-aided successive relaying scheme was investigated in a relaying system equipped with energy harvesting RNs.

2.3.3 Buffer-Aided Multi-Hop Relaying

If the distance between the SN and DN is very long, more than one RN are needed to be deployed between the SN and DN to combat the path loss. A suitable scheme that can be employed to deal with such scenario is the multi-hop relaying technique, in which multiple RNs are connected in series between the SN and DN. In a conventional half-duplex multi-hop relaying network without spatial reuse, each hop is allocated with a time slot and the transmission of each node is pre-scheduled [87]. If the non-adjacent RNs are allowed to transmit simultaneously (with spatial reuse), the

throughput of multi-hop relaying networks can be increased [88]. Recently, the buffer-aided relaying scheme was applied to multi-hop relaying networks to further improve the system performance [89,90]. By relaxing the pre-schedule constraint of each hop, it was shown in [90] that the achievable diversity order of the multi-hop relaying system increases as the number of RNs increases. In [89], a novel link selection method which makes use of physical network coding was proposed. As the previous RNs know the information transmitted by the subsequent RNs, the interference from the subsequent RNs can be cancelled. Thus, multiple links can be activated simultaneously and hence the system throughput can be increased.

2.4 Summary

In this chapter, we have reviewed various buffer-aided relaying schemes. A comparison between the conventional relaying scheme and buffer-aided relaying scheme was first presented. Following this, a detailed review on the existing works on different buffer-aided relaying systems, including the single RN buffer-aided relaying system, multiple RNs buffer-aided relaying system, buffer-aided successive relaying system and multi-hop buffer-aided relaying system, was provided. All these existing works show the potential advantages of buffer-aided relaying.

Chapter 3

Buffer-Aided Amplify-and-Forward Relaying System with Space-Shift Keying

In this chapter, we investigate a SSK-based buffer-aided dual-hop relaying system. An adaptive transmission scheme in which the system adaptively chooses the S-R or the R-D links to transmit information in each time slot is proposed. The average symbol-error performance of the proposed adaptive transmission scheme is investigated. In addition, the delay of the information packets at the RN is investigated. To reduce the packet delay, two link adaptation schemes are proposed, which are shown to be able to reduce the average packet delay at the sacrifice of some performance loss. Numerical results are provided to validate our analytical derivations.

3.1 Introduction

In recent years, SM method has attracted a lot of interests as it is a promising technology for future MIMO systems [32, 33]. In SM, part of the information is mapped into the index of the active antenna and only one among the available transmit antennas is activated during signal transmission. Thus, SM can overcome some drawbacks of the conventional MIMO techniques [34], e.g., inter-antenna synchronization, inter-channel interference, high receiver complexity, size and cost of hardware due to the use of multiple transmit RF chains. SSK is a special case of SM [91], where the information is only conveyed by the index of the transmit antenna. For a system with N_t transmit antennas, $\log_2(N_t)$ bits of information can be delivered by each SSK symbol. It has been shown that with a moderate number of antennas, the SSK can outperform the corresponding conventional modulation scheme [92, 93]. Hence, SM has been widely investigated and confirmed to outperform many MIMO transmission schemes with practical implementation constraints [94].

Since SM has many advantages, it has also been applied to relay-aided and cooperative communication systems [95–103]. In [95] and [97], a DF-based relaying system using SM was investigated and the system performance was provided. In [96], the bit-error probability expressions of the amplify-and-forward (AF) and DF based relaying systems using SSK signal were derived. In [98] and [99], the authors extended the analysis to a multi-hop DF based relaying system. Different from the work of [95–99], in [100], the authors considered a SM relaying system with multiple RNs. A threshold-based best relay selection scheme was proposed and the BER of the proposed scheme was investigated. The results of these works have shown the potential benefits of using SM in relaying systems compared with conventional modulation

and MIMO schemes.

As SM can benefit the MIMO cooperative relaying networks, it is natural to combine SM method with buffer-aided relaying scheme. However, different from the conventional modulation schemes whose performance is determined by the channel fading gain experienced by the signal, the performance of SSK depends on the difference in channel gains of different transmitting antennas. Thus, the link adaptation method of the SSK based buffer-aided relaying system should be redesigned to effectively make use of the multi-hop diversity. In this chapter, we investigate the effective adaptive transmission scheme for the considered SSK relaying system. The main contributions and achievements of this chapter can be summarized as follows:

- A novel adaptive transmission scheme for the considered SSK relaying system is proposed. As SSK conveys information in the index of the transmit antenna, the link adaptation scheme of the SSK system is different from that of the traditional modulation scheme. By using the difference in channel gains between transmitting antenna as a quality measurement of the S-R link, the proposed scheme can effectively make use of the multi-hop diversity.
- The average symbol-error performance of the proposed scheme is investigated. Specifically, an exact closed-form expression of the average BER for the case that the SN has two transmit antennas is derived. For the system with arbitrary number of transmit antennas, an efficient algorithm is provided to find the optimal decision threshold and an upper bound on the average SER is obtained.
- The delay of the information packets at the RN is investigated and two link adaptation schemes are proposed, which are shown to be able to reduce the

Figure 3.1: A SSK-AF relaying system with information buffering at the relay node.

average packet delay at the tradeoff of some performance loss. The symbol-error performance of these two schemes is also investigated. Numerical results are provided to validate the analytical expressions and it is shown that the proposed transmission scheme can significantly improve the system performance as compared with the conventional relaying scheme.

3.2 System and Signal Models

3.2.1 System and Channel Models

As depicted in Fig. 3.1, the relaying system consists of a SN S equipped with N_t antennas, a single-antenna RN R and a single-antenna DN D . It is assumed that there is no direct link between S and D , e.g., due to physical obstacles. The information of S is delivered to D through the help of R . The SN transmits information by using the SSK signals and the half-duplex RN adopts the AF scheme. Time is divided into slots with equal duration and a block fading channel model is adopted, e.g., the channel gains between any two nodes are assumed to be constant over one time slot and change independently from one time slot to another. In the i th time slot, we denote the channel responses of the S-R and the R-D links as $\mathbf{h}_{sr}[i] = \{h_1[i], h_2[i], \dots, h_{N_t}[i]\}$

and $g[i]$, respectively, where $h_l[i]$, $l = 1, \dots, N_t$, is the channel response between the l th transmit antenna and the RN. In addition, we assume that the channels of the S-R and the R-D links experience independent flat Rayleigh fading. Thus $h_l[i]$ and $g[i]$ are complex-valued Gaussian random variables with zero mean and variance σ_{sr}^2 and σ_{rd}^2 , respectively. The RN R is assumed to have an information buffer and can temporarily store the received message before forwarding it to the destination. Thus, with the help of a buffer, the system can adaptively choose either the S-R or the R-D link to be active in each time slot based on the channel quality of these two links. Without loss of generality, we assume that the RN can obtain the channel responses of these two links at the beginning of each time slot by using the reference signals transmitted by S and D [29, 68, 69, 76, 104]. Based on the CSI, the RN decides which link to transmit and broadcasts its decision to S and D by using a one-bit feedback.

3.2.2 Signal Model

In a given time slot, either the S-R link or the R-D link is chosen to deliver an information packet. If the S-R link is selected in the i th time slot, the SN maps $\log_2(N_t)$ bits into a SSK symbol and transmits it to the RN. The SSK symbol alphabet for N_t transmit antennas, denoted by $\mathbb{S}_{N_t}$, is given by $\mathbb{S}_{N_t} \triangleq \{\mathbf{s}_l : l = 1, 2, \dots, N_t\}$ where $\mathbf{s}_l = [0, \dots, 0, 1, 0, \dots, 0]$ is a N_t dimensional column vector with the l th element to be 1 and the other elements to be zeros. The received signal at the RN can be written as

$$\begin{aligned} y_r[i] &= \sqrt{P_s} \mathbf{h}_{sr}^T[i] \mathbf{s}_l + n_r[i] \\ &= \sqrt{P_s} h_l[i] + n_r[i], \end{aligned} \tag{3.1}$$

where $l = 1, \dots, N_t$. $\mathbf{h}_{sr}^T[i]$ is the transposition of $\mathbf{h}_{sr}[i]$, P_s denotes the transmitting power of the SN and $n_r[i]$ is the additive white Gaussian noise (AWGN) at the RN with zero mean and variance N_0 . After receiving the information packet, the RN stores it in its buffer and the number of information packets stored in the buffer (denoted as $L[i]$) is increased by one. We assume that the buffer size of the RN is sufficiently large and can always store the message received from the SN. If the information buffer is nonempty ($L[i] > 0$) and the R-D link is selected to transmit in the i th time slot, the RN amplifies one of the information packets (received in a previous time slot j) stored in its buffer and forwards it to the destination and the number of information packet stored in the buffer is decreased by one. The received signal at the destination is given by

$$y_d[i] = A\sqrt{P_s}g[i]h_l[j] + Ag[i]n_r[j] + n_d[i], \quad (3.2)$$

where $A = \sqrt{\frac{P_r}{P_s\sigma_{sr}^2 + N_0}}$ is a fixed amplification factor, P_r is the transmit power of the RN and $n_d[i]$ is the AWGN at the RN with zero mean and variance N_0 . After noise normalization, we can rewrite (3.2) as

$$\hat{y}_d[i] = \sqrt{G[i]}g[i]h_l[i] + \hat{n}[i], \quad (3.3)$$

where $G[i] = \frac{A^2 P_s}{A^2 |g[i]|^2 + 1}$ and $\hat{n}[i]$ is a complex-valued Gaussian variable with zero mean and variance N_0 . The destination applies the maximum-likelihood detection to estimate the transmit antenna index (l) as follows:

$$\tilde{l} = \arg \min_{l=1, \dots, N_t} \left\{ \left| \hat{y}_d[i] - \sqrt{G[i]}g[i]h_l[i] \right|^2 \right\}. \quad (3.4)$$

3.3 Proposed Link Adaptation Scheme and Performance Analysis

3.3.1 Link Adaptation Scheme

In each time slot, the RN adaptively chooses the S-R link or the R-D link to transmit based on the quality of these two links. For the S-R link, we define the following metric:

$$\lambda_s[i] = \min_{l \neq k, l, k=1, \dots, N_t} \{\lambda_{lk}[i]\}, \quad (3.5)$$

where $\lambda_{lk}[i] = |h_{lk}[i]|^2 P_s / 2N_0$ and $h_{lk}[i] = h_l[i] - h_k[i]$. We use two binary decision variables $d_{sr}[i], d_{rd}[i] \in \{0, 1\}$ satisfying $d_{sr}[i] + d_{rd}[i] = 1$ to indicate which link is selected in the i th time slot. Specifically, we have $d_{sr}[i] = 1$ if the S-R link is selected and $d_{rd}[i] = 1$ if the R-D link is selected. Based on these definitions, the proposed link adaptation scheme can be expressed as follows:

$$\begin{cases} d_{sr}[i] = 1, \text{ if } \lambda_s[i] > \rho_0 \lambda_r[i] \text{ OR } L[i] = 0, \\ d_{rd}[i] = 1, \text{ if } \lambda_s[i] \leq \rho_0 \lambda_r[i], \end{cases} \quad (3.6)$$

where $\lambda_r[i] = \frac{P_r |g[i]|^2}{N_0}$. The parameter ρ_0 is the decision threshold which is chosen such that the two links have the same probability to be selected to transmit, e.g.,

$$\Pr \{\lambda_s > \rho_0 \lambda_r\} = \Pr \{\lambda_s \leq \rho_0 \lambda_r\} = 0.5, \quad (3.7)$$

where $\Pr\{\cdot\}$ denotes the probability of a certain event. By using the proposed link adaptation scheme, the S-R link and the R-D link have equal probability to transmit, thus the input rate of the buffer equals the output rate of the buffer. Hence, based on Theorem 2 of [28], we have that the event $L[i] = 0$ almost never happens and has no influence on the system performance when the buffer of the RN works in the steady state. Thus, in the following, we can assume that the RN always has data to forward.

Remark: For the case that a decision threshold $\rho < \rho_0$ is adopted, we have $\Pr\{\lambda_s > \rho\lambda_r\} > 0.5$. The input rate of the buffer is larger than the output rate and the buffer becomes unstable. For the case that a decision threshold $\rho > \rho_0$ is adopted, we have $\Pr\{\lambda_s > \rho\lambda_r\} < 0.5$. The input rate of the buffer is smaller than the achievable output rate and the number of the time slots in which $L[i] = 0$ can not be ignored.

3.3.2 Performance Analysis: $N_t = 2$

We first derive the error probability expression of the proposed transmission scheme for the special case of having $N_t = 2$ antennas. For notational simplicity, we omit the time index i of $G[i]$, $h_l[i]$, etc., in the following derivations. For a specific channel realization, the probability of detecting the wrong transmitting antenna by using the maximum-likelihood method can be expressed as

$$\begin{aligned} P_e &= \frac{1}{2} \Pr\{\tilde{l} = 2 | l = 1\} + \frac{1}{2} \Pr\{\tilde{l} = 1 | l = 2\} \\ &= \frac{1}{2} \Pr\left\{\left|\hat{y}_{d|l=1} - \sqrt{G}gh_1\right|^2 > \left|\hat{y}_{d|l=1} - \sqrt{G}gh_2\right|^2\right\} \\ &\quad + \frac{1}{2} \Pr\left\{\left|\hat{y}_{d|l=2} - \sqrt{G}gh_1\right|^2 < \left|\hat{y}_{d|l=2} - \sqrt{G}gh_2\right|^2\right\}, \end{aligned} \quad (3.8)$$

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where $\hat{y}_{d|l=1} = \sqrt{G}gh_1 + \hat{n}$ and $\hat{y}_{d|l=2} = \sqrt{G}gh_2 + \hat{n}$. After some algebraic manipulations, we can rewrite (3.8) as

$$P_e = \Pr \{G|g|^2|h_{12}|^2 < \tilde{n}\}, \quad (3.9)$$

where $h_{12} = h_1 - h_2$ and $\tilde{n} = \sqrt{G}\Re\{\hat{n}g^*h_{12}^*\}$. Here, $\Re\{\cdot\}$ denotes the real part of a complex number and $(\cdot)^*$ is the complex conjugate. Conditioning on the channel responses, h_1 , h_2 and g , $\tilde{n}$ is a Gaussian distributed random variable with zero mean and variance $2N_0G|g|^2|h_{12}|^2$. Thus, the error probability can be expressed as

$$P_e = Q\left(\sqrt{\frac{G|g|^2|h_{12}|^2}{2N_0}}\right), \quad (3.10)$$

where $Q(\cdot)$ denotes the Q-function. Substituting $A = \sqrt{\frac{P_r}{P_s\sigma_{sr}^2 + N_0}}$ and $G = \frac{A^2P_s}{A^2|g|^2 + 1}$ into (3.10), we have

$$\begin{aligned} P_e &= Q\left(\sqrt{\frac{P_rP_s|g|^2|h_{12}|^2}{2N_0(P_s\sigma_{sr}^2 + N_0 + P_r|g|^2)}}\right) \\ &= Q\left(\sqrt{\frac{\gamma_s\gamma_r}{C + \gamma_r}}\right), \end{aligned} \quad (3.11)$$

where $C = 1 + \frac{P_s\sigma_{sr}^2}{N_0}$, $\gamma_s = \frac{P_s|h_{12}|^2}{2N_0}$ and $\gamma_r = \frac{P_r|g|^2}{N_0}$. Here, we use the symbols γ_s and γ_r to show that $\gamma_s(\gamma_r)$ and $\lambda_s(\lambda_r)$ are two different random variables. Actually, according to (3.6), we have

$$\begin{cases} \gamma_s = \lambda_s, \text{ if } \lambda_s > \rho_0\lambda_r, \\ \gamma_r = \lambda_r, \text{ if } \lambda_s \leq \rho_0\lambda_r. \end{cases} \quad (3.12)$$

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As h_{12} and g are Gaussian random variables with zero mean and variance $2\sigma_{sr}^2$ and σ_{rd}^2 , respectively, we have that λ_s and λ_r are exponentially distributed random variables with parameters $\Omega_s = \frac{P_s\sigma_{sr}^2}{N_0}$ and $\Omega_r = \frac{P_r\sigma_{rd}^2}{N_0}$, respectively. To obtain the average bit error performance, the probability density function (PDF) expressions of γ_s and γ_r should be derived. Based on (3.12), we have

$$\begin{aligned}\Pr\{\gamma_s < x\} &= \Pr\{\lambda_s < x | \lambda_s > \rho_0\lambda_r\} \\ &= \frac{\Pr\{\rho_0\lambda_r < \lambda_s < x\}}{\Pr\{\lambda_s > \rho_0\lambda_r\}}.\end{aligned}\quad (3.13)$$

As we have $\Pr\{\lambda_s \leq \rho_0\lambda_r\} = \Pr\{\lambda_s > \rho_0\lambda_r\} = 0.5$, then, $\Pr\{\gamma_s < x\}$ can be rewritten as $\Pr\{\gamma_s < x\} = 2\Pr\{\rho_0\lambda_r < \lambda_s < x\}$, where $\Pr\{\rho_0\lambda_r < \lambda_s < x\}$ is given by

$$\begin{aligned}\Pr\{\rho_0\lambda_r < \lambda_s < x\} &= \int_0^{x/\rho_0} \int_{\rho\lambda_r}^x f(\lambda_s) f(\lambda_r) d\lambda_s d\lambda_r \\ &= \frac{\rho_0\Omega_r}{\Omega_s + \rho_0\Omega_r} \exp\left(-\frac{\Omega_s + \rho_0\Omega_r}{\rho_0\Omega_s\Omega_r}x\right) - \exp\left(-\frac{x}{\Omega_s}\right) + \frac{\Omega_s}{\Omega_s + \rho_0\Omega_r}.\end{aligned}\quad (3.14)$$

In addition, $\Pr\{\lambda_s > \rho_0\lambda_r\}$ can be obtained as

$$\begin{aligned}\Pr\{\lambda_s > \rho_0\lambda_r\} &= \int_0^\infty \int_{\rho_0\lambda_r}^\infty f(\lambda_s) f(\lambda_r) d\lambda_s d\lambda_r \\ &= \frac{\Omega_s}{\rho_0\Omega_r + \Omega_s}.\end{aligned}\quad (3.15)$$

Then we have $\Pr\{\lambda_s \leq \rho_0\lambda_r\} = 1 - \Pr\{\lambda_s > \rho_0\lambda_r\} = \frac{\rho_0\Omega_r}{\rho_0\Omega_r + \Omega_s}$. To make $\Pr\{\lambda_s \leq \rho_0\lambda_r\} = \Pr\{\lambda_s > \rho_0\lambda_r\}$, ρ_0 should be chosen as $\rho_0 = \frac{\Omega_s}{\Omega_r}$. Substituting (3.14) and (3.15)

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into (3.13), the cumulative distribution function (CDF) of γ_s is given by

$$F_s(\gamma_s) = 1 + \exp\left(-\frac{2\gamma_s}{\Omega_s}\right) - 2 \exp\left(-\frac{\gamma_s}{\Omega_s}\right). \quad (3.16)$$

By taking the first derivative of (3.16), the PDF of γ_s can be obtained as

$$f_s(\gamma_s) = \frac{2}{\Omega_s} \left[\exp\left(-\frac{\gamma_s}{\Omega_s}\right) - \exp\left(-\frac{2\gamma_s}{\Omega_s}\right) \right]. \quad (3.17)$$

Similarly, the PDF of γ_r can be derived as

$$f_r(\gamma_r) = \frac{2}{\Omega_r} \left[\exp\left(-\frac{\gamma_r}{\Omega_r}\right) - \exp\left(-\frac{2\gamma_r}{\Omega_r}\right) \right]. \quad (3.18)$$

Average Error Probability

We have already obtained the system BER for a specific channel realization as shown in (3.11). Usually, the average BER is used as the performance measurement of a communication system. To obtain the average BER $\bar{P}_e = \mathbb{E}\{P_e\}$ of the system, the CDF of the term $\frac{\gamma_s \gamma_r}{C + \gamma_r}$ should be obtained. Let $\gamma = \frac{\gamma_s \gamma_r}{C + \gamma_r}$, then we have

$$\begin{aligned} F_\gamma(x) &= \Pr \left\{ \frac{\gamma_s \gamma_r}{\gamma_r + C} < x \right\} \\ &= \int_0^\infty \Pr \left\{ \gamma_s < x + \frac{Cx}{\gamma_r} \right\} f_r(\gamma_r) d\gamma_r \\ &= \int_0^\infty \left[1 + \exp\left(-\frac{2x}{\Omega_s} - \frac{2Cx}{\Omega_s \gamma_r}\right) \right] f_r(\gamma_r) d\gamma_r \\ &\quad - \int_0^\infty 2 \exp\left(-\frac{x}{\Omega_s} - \frac{Cx}{\Omega_s \gamma_r}\right) f_r(\gamma_r) d\gamma_r. \end{aligned} \quad (3.19)$$

Based on the fact that $\int_0^\infty \exp(-\frac{\beta}{4x} - \eta x) = \sqrt{\frac{\beta}{\eta}} K_1(\sqrt{\beta\eta})$, we can obtain

$$\begin{aligned} F_\gamma(x) &= 4\sqrt{Z} \left[\sqrt{2} K_1(2\sqrt{2Z}) - K_1(4\sqrt{Z}) \right] \exp\left(-\frac{2x}{\Omega_s}\right) \\ &\quad + 4\sqrt{Z} \left[\sqrt{2} K_1(2\sqrt{2Z}) - 2K_1(2\sqrt{Z}) \right] \exp\left(-\frac{x}{\Omega_s}\right) + 1, \end{aligned} \quad (3.20)$$

where $Z = \frac{Cx}{\Omega_s \Omega_r}$ and $K_1(\cdot)$ is the first order modified Bessel function of the second kind. By substituting (3.17) and (3.18) into (3.19). The average error probability $\bar{P}_e$ is given by

$$\begin{aligned} \bar{P}_e &= \int_0^\infty Q(\sqrt{\gamma}) f_\gamma(\gamma) d\gamma \\ &= \int_0^\infty -Q'(\sqrt{\gamma}) F_\gamma(\gamma) d\gamma \\ &= \int_0^\infty \frac{F_\gamma(\gamma) \exp(-\gamma/2)}{2\sqrt{2\pi\gamma}} d\gamma, \end{aligned} \quad (3.21)$$

where $Q'(x) = (d/dx)Q(x)$ denotes the derivative of $Q(x)$. Substituting (3.20) into (3.21) and based on the fact that

$$\int_0^\infty \exp(-\beta x) K_1(\eta\sqrt{x}) = \frac{\eta}{8} \sqrt{\frac{\pi}{\beta^3}} \exp\left(\frac{\eta^2}{8\beta}\right) \left[K_1\left(\frac{\eta^2}{8\beta}\right) - K_0\left(\frac{\eta^2}{8\beta}\right) \right],$$

we can obtain

$$\begin{aligned} \bar{P}_e &= 0.5 + T_1 U_1 \{ \exp(T_1) [K_1(T_1) - K_0(T_1)] - \exp(2T_1) [K_1(2T_1) - K_0(2T_1)] \} \\ &\quad + 2T_2 U_2 \{ \exp(2T_2) [K_1(2T_2) - K_0(2T_2)] - \exp(T_2) [K_1(T_2) - K_0(T_2)] \}, \end{aligned} \quad (3.22)$$

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where $T_1 = \frac{2C}{\Omega_r(\Omega_s+4)}$, $T_2 = \frac{C}{\Omega_r(\Omega_s+2)}$, $U_1 = \sqrt{\frac{\Omega_s}{\Omega_s+4}}$, $U_2 = \sqrt{\frac{\Omega_s}{\Omega_s+2}}$, and $K_0(\cdot)$ is the 0th order modified Bessel function of the second kind.

Diversity Order

As the average error probability in (3.22) cannot offer any insight on the effect of different system parameters, we derive the achievable diversity order of the system in the following. For $x \rightarrow 0$, we have the following approximations [105]:

$$\sqrt{x}K_1(\sqrt{x}) \approx 1 + \frac{x}{2} \ln \frac{\sqrt{x}}{2} - \frac{5x^2}{64} + o(x^2) \quad (3.23)$$

and

$$\exp(-x) \approx 1 - x + \frac{x^2}{2} + o(x^2). \quad (3.24)$$

For $\Omega_s \rightarrow \infty$ and $\Omega_r \rightarrow \infty$, we have $\frac{Cx}{\Omega_s\Omega_r} \rightarrow 0$ and $\frac{x}{\Omega_s} \rightarrow 0$. Thus, by substituting (3.23) and (3.24) into (3.20), we can obtain

$$F(\gamma) \approx \frac{\gamma^2}{\Omega_s^2} + \frac{4\gamma^2}{\Omega_s\Omega_r} \ln 2 + \frac{10\gamma^2}{\Omega_r^2}. \quad (3.25)$$

Hence, the average error probability $\bar{P}_e$ can be approximated as

$$\bar{P}_e \approx \frac{1}{2\sqrt{2\pi}} \left(\frac{1}{\Omega_s^2} + \frac{4\ln 2}{\Omega_s\Omega_r} + \frac{10}{\Omega_r^2} \right) \int_0^\infty \gamma^{3/2} \exp(-\gamma/2) d\gamma. \quad (3.26)$$

From (3.26), we can observe that $\bar{P}_e$ decreases as $\frac{1}{\Omega_s^2} + \frac{4\ln 2}{\Omega_s\Omega_r} + \frac{10}{\Omega_r^2}$, thus, the achievable diversity order of the system is 2.

3.3.3 General Case of N_t Antennas

Previously, the BER of the system with $N_t = 2$ transmitting antennas is obtained in an exact closed-form expression. Following this, we generalize the framework to the system with $N_t > 2$ antennas. For this case, since it is mathematically intractable to get an exact closed-form expression for the error probability, we use the well-known union bounding technique to upper bound the average symbol-error probability. The average symbol-error probability of the proposed scheme is union bounded as

$$\overline{P}_e \leq \frac{1}{N_t} \sum_{l=1}^{N_t} \sum_{\tilde{l} \neq l}^{N_t} \text{PEP} \{ \mathbf{s}_l \rightarrow \mathbf{s}_{\tilde{l}} \}, \quad (3.27)$$

where $\text{PEP} \{ \mathbf{s}_l \rightarrow \mathbf{s}_{\tilde{l}} \}$ is the pairwise error probability (PEP) of deciding on $\mathbf{s}_{\tilde{l}}$ given that $\mathbf{s}_l$ is transmitted. The PEP for the arbitrary transmitting antenna can be expressed as

$$\text{PEP} \{ \mathbf{s}_l \rightarrow \mathbf{s}_{\tilde{l}} \} = \mathbb{E} \left[Q \left(\sqrt{\frac{\gamma_r \gamma_{l\tilde{l}}}{C + \gamma_r}} \right) \right], \quad (3.28)$$

where $\gamma_{l\tilde{l}} = \frac{P_s |h_{l\tilde{l}}|^2}{2N_0}$ and $\gamma_r = \frac{P_r |g|^2}{N_0}$. Similar to (3.12), we have

$$\begin{cases} \gamma_{l\tilde{l}} = \lambda_{l\tilde{l}}, & \text{if } \lambda_s > \rho_0 \lambda_r, \\ \gamma_r = \lambda_r, & \text{if } \lambda_s \leq \rho_0 \lambda_r. \end{cases} \quad (3.29)$$

Method to Obtain ρ_0

Different from the case of $N_t = 2$, for system with $N_t > 2$ antennas, as h_{lk_1} and h_{lk_2} ($k_1 \neq k_2$) are no longer independent Gaussian random variables, the random

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Algorithm 1 : To find ρ iteratively

Initialization:

Initialize $\overline{M}_{sr}[0] = 0$, $\overline{M}_{rd}[0] = 0$, $\rho[0] = 0$;

Iteration:

for $i = 1$ to N **do**

Generate random channel realizations (or measure in real time) for $h_l[i]$ and $g[i]$;

Find the values of

$$\lambda_s[i] = \min_{l \neq k} \left\{ \frac{P_s |h_{lk}[i]|^2}{N_0} \right\}, \quad \lambda_r[i] = \frac{P_r |g[i]|^2}{N_0};$$

if $\lambda_s[i] > \rho[i-1]\lambda_r[n]$ **then**

$$\overline{M}_{sr}[i] = \overline{M}_{sr}[i-1] + (1 - \overline{M}_{sr}[i-1])/i;$$

$$\overline{M}_{rd}[i] = (i-1)\overline{M}_{rd}[i-1]/i;$$

else

$$\overline{M}_{sr}[i] = (i-1)\overline{M}_{sr}[i-1]/i;$$

$$\overline{M}_{rd}[i] = \overline{M}_{rd}[i-1] + (1 - \overline{M}_{rd}[i-1])/i;$$

end if

$$\rho[i] = \rho[i-1] + \frac{\overline{M}_{rd}[i] - \overline{M}_{sr}[i]}{i};$$

end for

$$\rho_0 = \rho[N];$$

return ρ_0

variables λ_{lk_1} and λ_{lk_2} are correlated. Thus, it is difficult to find the distribution of $\lambda_s = \min_{l \neq k, l, k=1, \dots, N_t} \{\lambda_{lk}\}$. As a result, a closed-form expression for ρ_0 cannot be obtained by solving (3.7). Therefore, we propose an alternative approach to obtain ρ_0 , which is based on real-time channel measurements (or simulation). The complete steps of the proposed scheme are given in Algorithm 1, which can converge to a number within a small error tolerance value of the optimal ρ_0 satisfying (3.7) if a sufficient large number of iterations N is performed. It is noted here that the proposed Algorithm 1 belongs to the subgradient methods which are standard algorithms for convex optimization and are known to converge.

In Fig. 3.2, the recursively updated values of $\rho_0[i]$ using Algorithm 1 are shown. We generate $N = 5 \times 10^5$ channel realizations randomly. It can be observed that $\rho_0[i]$ converges as i increases. For the system with $N_t = 2$, $\sigma_{sr}^2 = \sigma_{rd}^2 = 1$, the

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Figure 3.2: Recursively updated values of ρ_0 using Algorithm 1.

theoretical value of ρ_0 should be 1, which is identical to the value when the proposed algorithm converges. Thus, the proposed algorithm can efficiently obtain the value of ρ_0 . In addition, for practical systems where the distributions of the channel impulse responses h_l and g are not perfectly known, Algorithm 1 can still serve as an efficient method to find ρ_0 .

Diversity order

In the following, we investigate the achievable diversity order of the system with $N_t > 2$ antennas. As it is difficult to obtain the distribution of γ_{ll} (because of the correlation between h_{ll}) for the system with $N_t > 2$ antennas, we first derive an upper bound for the average SER of the system.

Let $\gamma_s = \lambda_s$, if the condition $\lambda_s > \rho_0 \lambda_r$ is satisfied, then we have $\gamma_{ll} > \gamma_s$ as

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$\lambda_s = \min_{l \neq i} \{\lambda_{li}\}$. Thus we have

$$\begin{aligned} \text{PEP} \{ \mathbf{s}_l \rightarrow \mathbf{s}_{\bar{l}} \} &= \mathbb{E} \left[Q \left(\sqrt{\frac{\gamma_r \gamma_{l\bar{l}}}{C + \gamma_r}} \right) \right] \\ &\leq \mathbb{E} \left[Q \left(\sqrt{\frac{\gamma_r \gamma_s}{C + \gamma_r}} \right) \right], \end{aligned} \quad (3.30)$$

where

$$\begin{cases} \gamma_s = \lambda_s, \text{ if } \lambda_s > \rho_0 \lambda_r, \\ \gamma_r = \lambda_r, \text{ if } \lambda_s \leq \rho_0 \lambda_r. \end{cases} \quad (3.31)$$

Before deriving the achievable diversity order, we first give the following lemma.

Lemma 3.1: *The CDF of λ_s satisfies $F_{\lambda_s}(x) \leq 1 - \exp\left(-\frac{x}{\Omega_0}\right)$, where $\Omega_0 = \frac{2\Omega_s}{N_t(N_t-1)}$.*

Proof: We define $\mathbf{h} = \{|h_{12}|, \dots, |h_{1N_t}|, |h_{23}|, \dots, |h_{2N_t}|, \dots, |h_{(N_t-1)N_t}|\}$, which is a vector with dimension $\frac{N_t(N_t-1)}{2}$. Then, we investigate the cross-correlation between the elements of $\mathbf{h}$. According to equation (3) of [106], we have that for two zero-mean complex Gaussian random variables G_1 and G_2 with cross-correlation coefficient α , the cross-correlation coefficient between $|G_1|$ and $|G_2|$ is given by $\alpha_1 = \frac{(1+|\alpha|)E_i\left(\frac{2\sqrt{|\alpha|}}{1+|\alpha|}\right) - \frac{\pi}{2}}{2 - \frac{\pi}{2}}$, where $E_i(\cdot)$ denotes the complete elliptic integral of the second kind. As h_{li} is a zero-mean Gaussian random variable with variance $2\sigma_{sr}^2$, the cross-correlation coefficient between $h_{l_1l_2}$ and $h_{k_1k_2}$ is given by $\alpha = \mathbb{E}(h_{l_1l_2}h_{k_1k_2}^*)/2\sigma_{sr}^2$, where $h_{k_1k_2}^*$ is the conjugate of $h_{k_1k_2}$. It can be checked that $\alpha \in \{-1/2, 0, 1/2\}$ for the system under consideration. For $\alpha = 0$, we have $\alpha_1 = 0$. For the cases of $\alpha = -1/2$ and $\alpha = 1/2$, we have $\alpha_1 > 0$. For two random variables y_1 and y_2 with positive cross-correlation, the following result

always holds:

$$\begin{aligned}\Pr\{y_1 > x, y_2 > x\} &= \Pr\{y_1 > x\} \Pr\{y_2 > x | y_1 > x\} \\ &\geq \Pr\{y_1 > x\} \Pr\{y_2 > x\}.\end{aligned}\tag{3.32}$$

Based on this fact, we have

$$\begin{aligned}F_{\lambda_s}(x) &= 1 - \Pr\{\lambda_s > x\} \\ &= 1 - \Pr\left\{\min(\mathbf{h}) > \sqrt{\frac{2xN_0}{P_s}}\right\} \\ &= 1 - \Pr\left\{|h_{lk}| > \sqrt{\frac{2xN_0}{P_s}}, \forall l, k\right\} \\ &\leq 1 - \prod_{l=1}^{N_t-1} \prod_{k=l+1}^{N_t} \Pr\left\{|h_{lk}| > \sqrt{\frac{2xN_0}{P_s}}\right\} \\ &= 1 - \prod_{l=1}^{N_t-1} \prod_{k=l+1}^{N_t} \Pr\{\lambda_{lk} > x\},\end{aligned}\tag{3.33}$$

where $\min(\mathbf{h})$ denotes the smallest element of $\mathbf{h}$. As $\Pr\{\lambda_{lk} > x\} = \exp(-\frac{x}{\Omega_s})$, we can simplify (3.33) as $F_{\lambda_s}(x) \leq 1 - \exp(-\frac{x}{\Omega_0})$ with $\Omega_0 = \frac{2\Omega_s}{N_t(N_t-1)}$. ■

In Fig. 3.3, the simulation results on the CDF of λ_s are presented. For comparison reasons, the upper bound of $F_{\lambda_s}(x)$ given by **Lemma 3.1** is also plotted. It can be observed from Fig. 3.3 that the result $F_{\lambda_s}(x) \leq 1 - \exp(-x/\Omega_0)$ holds for the system with different number of transmitting antennas, which demonstrates the correctness of **Lemma 3.1**. Based on **Lemma 3.1**, we can obtain the following theorem:

Theorem 3.1: *The proposed link adaptation method can achieve a diversity order of 2 for the system with arbitrary number of antennas.*

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Figure 3.3: Comparisons of the CDF of λ_s with its upper bound given by **Lemma 3.1**, $\Omega_s = 1$.

Proof: Please refer to Appendix A.

3.3.4 Power allocation

To minimize the average symbol-error probability $\overline{P}_e$ of the system, the transmitting powers of the SN and RN should be properly allocated. Assuming that the total power of the system is P_t and the powers allocated to the SN and RN are $P_s = \mu P_t$ and $P_r = (1 - \mu)P_t$, respectively, we can form the following optimization problem to minimize $\overline{P}_e$:

$$\min_{\mu} \overline{P}_e, \quad s.t. \quad 0 < \mu < 1. \quad (3.34)$$

Algorithm 2 : To search for optimal μ

```

Initialize  $\mu[0] = 0, P_s = 0, P_r = 0$ ;
for  $i = 1$  to  $N$  do
     $\mu[i] = i/N, P_s = \mu[i]P_t, P_r = (1 - \mu[i])P_t$ ;
    Find the value of  $\rho_0[i]$  by using Algorithm 1;
    Find  $\bar{P}_e[i]$  through simulation;
end for
find  $i = \arg \min_i \{\bar{P}_e\}$ ;
return  $\mu[i]$ 

```

For the system with $N_t > 2$ transmitting antennas, as it is difficult to get a closed-form expression for ρ_0 , we cannot get a closed-form expression for $\bar{P}_e$. Thus, to find the optimal power allocation factor μ , a one-dimensional searching based method is proposed. The complete steps of the proposed scheme are given in Algorithm 2.

3.4 Link Adaptation Scheme with Reduced Delay

Although the decision threshold ρ_0 which satisfies (3.7) allows the system to achieve a diversity order of 2, it results in a large information packet delay at the RN [28]. To reduce the packet delay at the RN, we increase the value of the decision threshold to be ρ which is larger than ρ_0 and apply the following link adaptation method:

$$\begin{cases} d_{sr}[i] = 1, \text{ if } \lambda_s[i] > \rho\lambda_r[i] \text{ OR } L[i] = 0, \\ d_{rd}[i] = 1, \text{ if } \lambda_s[i] \leq \rho\lambda_r[i]. \end{cases} \quad (3.35)$$

By using this decision threshold (ρ), the probability for the S-R link to transmit which can be expressed as $\varepsilon = \Pr\{\lambda_s[i] > \rho\lambda_r[i]\}$ becomes smaller than 0.5 when the buffer of the RN is nonempty. Hence, the R-D link is assigned with a higher priority to

Figure 3.4: Markov chain model of the relay buffer. Note that in the n th state, the buffer stores n information packets.

forward the information packets stored in the buffer, which, as a result, reduces the packet delay at the RN. However, a larger decision threshold (ρ) will on the other hand increase the probability for the buffer to be empty and degrade the symbol-error performance of the system.

By using the states of the Markov chain (MC) to describe the number of data packets stored in the buffer, we can model the queuing dynamics of the buffer as a birth-death process as shown in Fig. 3.4. For the case that the buffer is empty, only the S-R link can be active as there is no packet in the buffer to be forwarded. Thus, the state transition probability from state 0 to state 1 is one. For the case that the buffer is nonempty, the link adaptation method of (3.35) is applied.

Denote π_n as the steady state probability of the buffer state n . Based on the local balance equations of the MC, we can obtain

$$\begin{aligned}\pi_0 &= (1 - \varepsilon) \pi_1, \\ \pi_1 &= \pi_0 + (1 - \varepsilon) \pi_2 \\ \pi_n &= \varepsilon \pi_{n-1} + (1 - \varepsilon) \pi_{n+1}, n = 2, 3, \dots \infty.\end{aligned}\tag{3.36}$$

Solving (3.36), we can obtain $\pi_n = \frac{\varepsilon^{n-1}}{(1-\varepsilon)^n} \pi_0$. Since $\sum_{n=0}^{\infty} \pi_n = 1$, we have $\pi_0 = \frac{1-2\varepsilon}{2(1-\varepsilon)}$. The average queuing length of the buffer can be expressed as $\bar{L} = \sum_{n=1}^{\infty} n \pi_n = \frac{1}{2(1-2\varepsilon)}$.

Based on the fact that the number of packets received by the RN must be equal

to the number of packets that leave the RN, we have that the probability for the R-D link to transmit is 0.5. Thus, according to Little's law, the average delay at the RN can be obtained as $D = \bar{L}/0.5 = 1/(1 - 2\varepsilon)$. It can be observed that as the value of ρ increases, the value of ε decreases, which, as a result, reduces the packet delay at the RN. The average symbol-error probability of the system is given as

$$\bar{P}_e = \pi_0 \bar{P}_{e|0} + \bar{\pi}_0 \bar{P}_{e|\bar{0}}, \quad (3.37)$$

where $\bar{\pi}_0 = 1 - \pi_0$, $\bar{P}_{e|0}$ and $\bar{P}_{e|\bar{0}}$ denote the symbol-error probabilities of the system when the buffer of the RN is empty and nonempty, respectively. For the system with $N_t = 2$ antennas, we have

$$\bar{P}_{e|0} = \mathbb{E} \left[Q \left(\sqrt{\frac{\gamma_r \lambda_s}{C + \gamma_r}} \right) \right], \quad \bar{P}_{e|\bar{0}} = \mathbb{E} \left[Q \left(\sqrt{\frac{\gamma_r \gamma_s}{C + \gamma_r}} \right) \right], \quad (3.38)$$

where in the expression of $\bar{P}_{e|0}$, the received SNR of the S-R link is λ_s which is an exponentially distributed random variable as no link adaptation is applied in this case. It can be shown that $\bar{P}_{e|0} > \bar{P}_{e|\bar{0}}$ and π_0 is an increasing function of ρ . Thus, the symbol-error probability of the system increases if a larger decision threshold (ρ) is adopted. For the link adaptation of (3.35), we can obtain $\pi_0 = \frac{2}{\bar{L}+2}$. It can be observed that for a small average delay $\bar{L}$, the probability of the information buffer to be empty becomes large and the symbol-error probability of the system is increased. To further decrease the symbol-error probability of the system when the average delay

$\bar{L}$ is small, we propose the following link adaptation scheme:

$$\begin{cases} d_{sr}[i] = 1, \text{ if } \lambda_s[i] > \rho[i]\lambda_r[i] \text{ OR } L[i] = 0, \\ d_{rd}[i] = 1, \text{ if } \lambda_s[i] \leq \rho[i]\lambda_r[i], \end{cases} \quad (3.39)$$

where $\rho[i] = \rho_0 + \delta[i](L[i] - Q_T)$ is the decision threshold, which is dynamically changed according to the buffer state. The parameters $\delta[i]$ and Q_T are used to control the changing rate of $\rho[i]$ and the average delay of the information packets, respectively. For the case that $\delta[i] > 0$, if the number of packets stored in the buffer is smaller than Q_T , then the value of $\rho[i]$ is decreased and the S-R link has a higher priority to transmit; if the number of packets stored in the buffer is larger than Q_T , then the value of $\rho[i]$ is increased and the R-D link has a higher priority to transmit. For fixed $\delta[i]$ and Q_T , the value of π_0 can be obtained by using a similar birth-death process as shown in Fig. 3.4 and the symbol-error probability can thus be expressed as (3.37).

3.5 Numerical Results and Discussion

To properly evaluate the performance of the proposed scheme, the performance of the conventional relaying scheme, in which the source information is always delivered to the destination in two successive time slots, is provided for comparisons.

In Fig. 3.5, the bit-error performance of the proposed scheme is provided for the system with $N_t = 2$ transmit antennas. It can be observed from Fig. 3.5 that the analytical results are in excellent agreement with the simulation results, which validates the correctness of the analytical expressions that we have derived. In addition, Fig. 3.5 also shows that the proposed scheme can achieve significant performance

Figure 3.5: Performance of the proposed adaptive transmission with $SNR = P_s/N_0 = P_r/N_0$.

improvement as compared with the conventional relaying scheme. To show that the proposed scheme can achieve a diversity order of 2, the asymptotic BER, which is given by equation (3.26), is also presented in Fig. 3.5. It can be observed that in high SNR region, the BER of the system can be well estimated by the asymptotic result.

In Fig. 3.6, the symbol-error performance of the proposed scheme with different values of power allocation factor α is presented. For the system with $N_t = 2$ antennas, the theoretical results are also presented. It can be observed that the theoretical results are in excellent agreement with the simulation results. Fig. 3.6 also shows that for systems with $N_t = 2$ and $N_t = 6$ antennas, more power should be allocated to the RN for the proposed transmission scheme. In addition, comparing the optimal power allocation factor for systems with different number of antennas, we can observe

3.5. NUMERICAL RESULTS AND DISCUSSION

Figure 3.6: Performance of the proposed adaptive transmission with different power allocation factors. $\sigma_{sr}^2 = \sigma_{rd}^2 = 1$, $P_s = \alpha P_t$, $P_r = (1 - \alpha)P_t$.

that as the number of transmitting antenna increases, more power should be allocated to the SN. This can be explained as follows: A larger number of transmitting antennas results in a smaller average value of λ_s , which dominates the system SER in high SNR region. Thus the average quality of the S-R link decreases as N_t increases.

In Fig. 3.7, we present the symbol-error performance of the proposed scheme for the system with $N_t = 4$ antennas. For comparisons, the symbol-error performance of the buffer-aided SSK relaying system using the following link adaptation scheme is also provided:

$$\begin{cases} d_{sr}[i] = 1, \text{ if } \lambda_{sr}[i] > \rho_0 \lambda_r[i] \text{ OR } L[i] = 0, \\ d_{rd}[i] = 1, \text{ if } \lambda_{sr}[i] \leq \rho_0 \lambda_r[i], \end{cases} \quad (3.40)$$

Figure 3.7: Performance comparisons of different link adaptation schemes with $SNR = P_s/N_0 = P_r/N_0$, $N_t = 4$, $\sigma_{sr}^2 = \sigma_{rd}^2 = 1$.

where $\lambda_{sr}[i] = \sum_{l=1}^{N_t-1} \sum_{k=l+1}^{N_t} \omega_{lk} \lambda_{lk}[i]$ is the weighted sum of $\lambda_{lk}[i]$ and is used as the metric to determine the quality of the S-R link. The weights ω_{lk} of $\lambda_{lk}[i]$ satisfy $\sum_{l=1}^{N_t-1} \sum_{k=l+1}^{N_t} \omega_{lk} = 1$. In addition, for the element $\lambda_s[i] = \min_{l \neq k} \{\lambda_{lk}[i]\}$, we rewrite its weight as $\omega_{\min}$, e.g., if $\lambda_s[i] = \min_{l \neq k} \{\lambda_{lk}[i]\} = \lambda_{12}[i]$, we have $\omega_{\min} = \omega_{12}$. To show the significance of $\lambda_s[i]$ in determining the system performance, different values of $\omega_{\min}$ are assigned to $\lambda_s[i]$ in our simulation. For a fixed value of $\omega_{\min}$, the remaining elements λ_{lk} are assigned with an identical weight $\omega_{lk} = \frac{1-\omega_{\min}}{N_t(N_t-1)/2-1}$. To obtain the symbol-error performance of the link adaptation method of (3.40), we first determine the decision threshold ρ_0 , which satisfies $\Pr\{\lambda_{sr}[i] > \rho_0 \lambda_r[i]\} = \Pr\{\lambda_{sr}[i] \leq \rho_0 \lambda_r[i]\}$, by using Algorithm 1. Based on the decision threshold ρ_0 , the link adaptation scheme of

Figure 3.8: Performance of the link adaptation scheme of equation (3.35) with different decision thresholds. $SNR = P_s/N_0 = P_r/N_0$, $N_t = 4$, $\sigma_{sr}^2 = 2$, $\sigma_{rd}^2 = 1$.

(3.40) is then performed and the symbol-error probabilities are obtained. It can be observed from Fig. 3.7 that as the value of $\omega_{\min}$ increases, the symbol-error probability of the system decreases. For the case that $\omega_{\min} = 1$, the weights ω_{lk} of all the remaining elements λ_{lk} become zero. Thus, we have $\lambda_{sr}[i] = \sum_{l=1}^{N_t-1} \sum_{k=l+1}^{N_t} \omega_{lk} \lambda_{lk}[i] = \min_{l \neq k} \{\lambda_{lk}[i]\}$ and the link adaptation scheme of (3.40) becomes identical to the link adaptation scheme given by (3.6). It can be observed from Fig. 3.7 that the scheme with $\omega_{\min} = 1$ achieves the best symbol-error performance, which shows the superiority of our proposed link adaptation scheme. The reason that the symbol-error probability decreases with respect to $\omega_{\min}$ in relatively high SNR region can be explained as follows: In the relatively high SNR region, the quality of the S-R link is determined by $\lambda_s[i]$. If a small value is assigned to $\omega_{\min}$, the link adaptation method of (3.40), which measures

the “averaged” SNR of the S-R link, may still select the S-R link to transmit even if the value of $\lambda_s[i]$ is very small. Thus the link adaptation method of (3.40) cannot effectively make use of the multi-hop diversity if a small value is assigned to $\omega_{\min}$.

In Fig. 3.8, the symbol-error probabilities of the link adaptation scheme given by equation (3.35) with different decision thresholds are presented, where the value of ρ_0 satisfies the condition $\Pr\{\lambda_{sr}[i] > \rho_0 \lambda_r[i]\} = \Pr\{\lambda_{sr}[i] \leq \rho_0 \lambda_r[i]\}$ and is determined by using Algorithm 1. It can be observed from Fig. 3.8 that as the value of the decision threshold ρ increases, the symbol-error probability of the system becomes worse. This observation can be explained as follows: As the value of ρ becomes larger, the probability for the buffer of the relay node to be empty (π_0) increases. Since no link adaptation is applied when the buffer of the relay node is empty, we have $\bar{P}_{e|0} > \bar{P}_{e|\bar{0}}$. As the symbol-error probability of the system is given by $\bar{P}_e = \pi_0 \bar{P}_{e|0} + \bar{\pi}_0 \bar{P}_{e|\bar{0}}$, we can conclude that a larger ρ results in a higher symbol-error probability.

In Fig. 3.9, we show the performance of the link adaptation scheme given by (3.39). The values of $\delta[i]$ are set as ρ_0 and $5\rho_0$ for the cases of $L[i] < Q_T$ and $L[i] \geq Q_T$, respectively. Q_T is set to be $Q_T = \{3, 4, 20\}$ and the corresponding average packet delay at the RN is given by $D = \{2.17, 2.52, 10.18\}$ (obtained through simulation). It can be observed from Fig. 3.9 that as the value of Q_T increases, the symbol-error probability of the system decreases. In addition, when $Q_T = 20$ which results in an average packet delay of 10.18 time slots, the performance loss becomes very small.

In Fig. 3.10, we show the tradeoff between the symbol-error probability and the average packet delay (at the RN) for the link adaptation schemes of (3.35) and (3.39). For the link adaptation scheme of (3.35), the tradeoff curve is obtained by assigning different values to the decision threshold ρ . For each value of ρ , we can get a point

Figure 3.9: Performance of the link adaptation scheme of equation (3.39) with $SNR = P_s/N_0 = P_r/N_0$, $N_t = 4$, $\sigma_{sr}^2 = \sigma_{rd}^2 = 1$, $\delta[i] = \rho_0$ if $L[i] < Q_T$; $\delta[i] = 5\rho_0$ if $L[i] \geq Q_T$.

$(D(\rho), \bar{P}_e(\rho))$. Thus, by changing the value of ρ , we can obtain the tradeoff curve. For the link adaptation scheme of (3.39), the tradeoff curve is obtained by changing the value of Q_T . The value of δ is determined by using two different strategies: 1) $\delta[i] = \rho_0/Q_T$, 2) $\delta[i] = \rho_0$ if $L[i] < Q_T$ and $\delta[i] = 5\rho_0$ if $L[i] \geq Q_T$. It can be observed from Fig. 3.10 that as the average packet delay increases, the symbol-error probability decreases for both schemes. In addition, Fig. 3.10 also shows that in a low delay region, the link adaptation scheme of (3.39) achieves lower symbol-error probability as compared to the scheme of (3.35). This performance improvement of the link adaptation scheme of (3.39) is obtained at the tradeoff of adjusting the decision threshold dynamically by considering the buffer state. Thus for the relaying system with a tight delay constraint, the link adaptation scheme of (3.39) is preferred.

Figure 3.10: Delay performance tradeoff of different link adaptation schemes with $SNR = P_s/N_0 = P_r/N_0 = 20\text{dB}$, $N_t = 4$.

3.6 Summary

We have considered a buffer-aided relaying system with SSK signal. By equipping an information buffer at the RN, we have proposed an adaptive transmission scheme. The average symbol-error performance of the proposed adaptive transmission scheme has been investigated. In addition, by using asymptotic analysis, we have shown that the proposed scheme can achieve a diversity order of 2. Furthermore, the packet delay of the proposed scheme has also been investigated and two link adaptation schemes that can reduce the packet delay at the RN have been provided. Numerical results have shown that the proposed transmission scheme can significantly improve the system performance as compared with that of the conventional relaying scheme.

Chapter 4

Buffer-State Based Link Adaptation Scheme with Reduced Packet Delay

In this chapter, we propose a buffer-state based relay selection scheme for a finite buffer-aided cooperative relaying system. Different from the existing relay selection schemes which select the RNs only based on the channel quality, our proposed relay selection scheme selects a RN based on both the channel quality and the buffer state of the RNs. It is shown that the proposed buffer-state based relay selection scheme can outperform the existing relay selection schemes. Our analytical results also show that if the buffer size of each RN is greater than 2, the proposed relay selection scheme can achieve full diversity. In addition, we show that the proposed relay selection scheme has lower average packet delay as compared with the max-link relay selection scheme. Furthermore, the average packet delay of the proposed relay selection scheme does not increase as the buffer size increases.

4.1 Introduction

Relay selection scheme has been proven to be an effective method to achieve the full diversity order while preserving the efficiency of communication systems [68]. The main advantage of the relay selection scheme is its implementation simplicity. As it only chooses the RN with the best end-to-end channel quality to forward the data packets, there is no need to perform any explicit synchronization process.

In a traditional DF-based cooperative relaying system, the max-min relay selection scheme is often considered as the optimal relay selection method [68,69,107]. By using the max-min relay selection scheme, the RN with the highest gain among all of the minima of the S-R and R-D channel gain pairs is chosen to retransmit the messages. It has been shown that the max-min relay selection scheme can achieve a diversity order equal to the number of RNs. To further improve the performance of the cooperative relaying system, the max-max relay selection scheme was proposed in [26]. In the max-max relay selection scheme, each RN is required to be equipped with a buffer to temporarily store the received packets. With the help of a buffer, the system can choose different RNs for reception and transmission. Specifically, the max-max relay selection scheme chooses the RN with the strongest S-R channel to receive, and it chooses the RN with the strongest R-D channel to transmit. Compared with the max-min relay selection scheme, the max-max relay selection scheme achieves the same diversity order while providing a significant coding gain. In all these relay selection schemes, the relaying process is performed in a predefined schedule, in which the selected RN receives the packets from the SN during certain predefined time slot and forwards the packets to the DN during another pre-allocated time slot.

Recently, in [28] and [108], the constraint of delivering the messages in a predefined

time schedule is relaxed for the buffer-aided relaying system and a relay selection scheme which always chooses the best link among all the available S-R and R-D links in each time slot was proposed. It has been shown that by adaptively selecting the optimal link in each time slot, the average achievable rate of the relaying system can be significantly improved. In [27], a fixed-rate relaying system with multiple RNs equipped with a finite size buffer was investigated and the max-link relay selection method was proposed. In each time slot, the available link with the strongest channel gain is chosen to receive or to transmit the message. The authors proved that as the buffer size of the RNs increases, the max-link relay selection scheme can achieve a diversity order equal to two times the number of RNs. However, this diversity gain can only be achieved when the buffer size is large enough. In addition, the max-link relay selection scheme results in a large average delay for the transmitted packets especially when the buffer size is large.

As information delay is an important issue of wireless communications, especially for systems with a tight delay constraint, it is of great significance to enhance the existing relay selection schemes on buffer-aided relaying to reduce the information delay. Thus, in this chapter, we propose a buffer-state based relay selection scheme for the buffer-aided relaying systems with multiple RNs. In the proposed relay selection scheme, the best RN is selected based on both the channel quality and the buffer states. The main contributions of this chapter can be summarized as follows:

- A novel buffer-state based relay selection scheme for the buffer-aided relaying system is proposed. It aims to improve the reliability while reducing the average packet delay of the buffer-aided relaying system. A two-step method is also provided to implement the proposed relay selection scheme.

- The outage probability of the proposed relay selection scheme is analyzed by using the MC model and a closed-form expression is obtained. Analytical and simulation results show that the proposed relay selection scheme can outperform the existing relay selection schemes.
- The average packet delays for both the max-link relay selection scheme and the proposed buffer-state based relay selection scheme are analyzed. It is proved that for the case that the buffer size (L) of each RN satisfies $L \geq 3$, the proposed relay selection scheme can achieve full diversity order and has a smaller average packet delay than that of the max-link relay selection scheme. Furthermore, it is proved that for a relative high SNR regime, the average delay of the proposed relay selection scheme will not increase as the buffer size increases.

4.2 System Model and Assumptions

As shown in Fig. 4.1, the considered system consists of one SN S , one DN D and K RNs R_k , for $1 \leq k \leq K$. It is assumed that all the nodes have one antenna each and they are working in a half-duplex mode. Thus, they can not transmit and receive simultaneously. We also assume that there is no direct link between the SN and the DN and the communication can only be completed with the help of the RNs [27]. Each RN has a data buffer of size L . The buffer is used to temporarily store the packets coming from the SN that have been successfully decoded at the RN.

We use L_k ($0 \leq L_k \leq L$) to denote the number of packets stored in the buffer of R_k . For different values of L_k , the RN R_k has different number of available links:

- $L_k = 0$: Only the S-R link is available as there is no packet to be transmitted.

Figure 4.1: System model: Source S communicates with the destination D with the help of K RNs.

- $0 < L_k < L$: Both the S-R link and the R-D link are available.
- $L_k = L$: Only the R-D link is available as there is no buffer for storing a new packet.

For notational simplicity, we use l_{ij} ($i \in \{s, r_1, \dots, r_K\}$, $j \in \{r_1, \dots, r_K, d\}$) to denote the link between node i and node j . When a source packet is successfully received by the k th RN R_k , the corresponding buffer L_k is increased by one. When a packet is successfully transmitted by R_k , L_k is then decreased by one. Time is assumed to be divided into slots with equal duration and in each time slot, a selected transmitter transmits a packet with a fixed power P . We assume that a packet can be released from the buffer (either the buffer of the SN or the buffer of the RN) only when it is successfully received. This can be achieved by adopting the widely used retransmission process based on the Acknowledgement/Negative-Acknowledgement mechanism. It is also assumed that S always has packets to transmit.

We adapt a non-selective Rayleigh block fading channel model in which the channel coefficients are constant during one time slot and change independently from one

time slot to another. The channel coefficient h_{ij} between the link l_{ij} is assumed to be a circularly symmetric complex Gaussian distributed random variable with zero mean and variance Ω_{ij} [109, 110]. Without loss of generality, we also assume that the received signals at the receivers are corrupted by AWGN with zero mean and unit variance. Thus the received SNR between the link l_{ij} can be expressed as $\gamma_{ij} = P|h_{ij}|^2$. We assume that the system aims to deliver information at a fixed target rate r_0 . Thus each link l_{ij} is characterised by the outage probability which can be expressed as

$$\begin{aligned} P_{ij} &= \Pr\{(1/2)\log_2(1 + \gamma_{ij}) < r_0\} \\ &= 1 - e^{-\frac{2^{2r_0}-1}{\Omega_{ij}P}}, \end{aligned} \quad (4.1)$$

where the factor $1/2$ results from the fact that each packet is delivered from S to D by using two time slots.

4.3 Buffer-State Based Relay Selection Scheme

The proposed relay selection scheme aims to reduce the average delay and further improve the reliability of the buffer-aided relaying system. To achieve this goal, the following two-stage method is adopted to implement it.

Stage one: At the beginning of each time slot, the SN and DN broadcast a short reference signals to all the RNs, respectively. Based on these reference signals, each RN can obtain the associated channel gains $|h_{sr_k}|^2$ and $|h_{r_kd}|^2$. By jointly considering its buffer state L_k and the channel coefficients $|h_{sr_k}|^2$, $|h_{r_kd}|^2$, each RN decides to receive or to transmit in each time slot by using the method presented in Table 4.1.

In Table 4.1, we assume that $L \geq 2$. This assumption is based on the following

Table 4.1: Link adaptation method in the first stage.

Cases	l_{sr_k}	l_{r_kd}	L_k	Decision
Case 1	out	out		S
Case 2		out	$L_k = L$	S
Case 3	out		$L_k = 0$	S
Case 4	suc	out	$L_k < L$	R
Case 5	out	suc	$L_k > 0$	T
Case 6	suc	suc	$L_k \geq 2$	T
Case 7	suc	suc	$L_k \leq 1$	R

facts: 1) When $L = 1$, Case 6 of Table 4.1 is no longer applicable. 2) For the system with $L = 1$, by removing Case 6 of Table 4.1, the proposed relay selection scheme actually becomes the max-link relay selection scheme. Thus, to distinguish the proposed relay selection scheme from the max-link relay selection scheme, it is assumed that $L \geq 2$. The term “out” used in Table 4.1 denotes that the corresponding link is in outage; “suc” means that the link is not in outage; “S” denotes that the RN keeps in silence (neither transmits nor receives); “R” means that the RN chooses to receive; “T” denotes that the RN chooses to transmit a packet.

Remark: Case 6 gives the RN higher priority to transmit when both the S-R and the R-D links are available, which aims to reduce the packet delay. Case 7 is designed to reduce the probability that the buffer of the RN becomes empty, which aims to increase the number of available links of the system (as a result, increase the reliability of the system). The decisions made for Case 1 to Case 5 are easy to follow.

After each RN makes its own decision, the system enters the second stage.

Stage two: In this stage, a central controlling node is used to collect the decisions made in stage one of all the RNs. Any RN that can communicate with the others can be selected as the central controlling node. Without loss of generality, we assume that R_1 is the central controlling node. Thus, in this stage, all the other RNs send their

buffer-state information and decisions to R_1 . Based on this information, R_1 selects the best RN and decides whether it is to transmit or to receive. Denote $\mathcal{Q}_t$ and $\mathcal{Q}_r$ as the set of RNs that decide to transmit and receive in the first stage, respectively. For different scenarios, the best RN is selected as follows:

- $\mathcal{Q}_r = \emptyset$, $\mathcal{Q}_t \neq \emptyset$ ($\emptyset$ denotes the empty set): In this scenario, no RN chooses to receive a packet and the system can only choose a RN from $\mathcal{Q}_t$ to transmit a packet. Denote $L_{max}^t = \max\{L_k | R_k \in \mathcal{Q}_t\}$. R_1 first finds out the set of RNs

$$\mathcal{Q}_{max}^t = \arg \max_{R_k \in \mathcal{Q}_t} \{L_k = L_{max}^t\} \quad (4.2)$$

whose buffer has L_{max}^t packets. Then R_1 uniformly chooses one RN from $\mathcal{Q}_{max}^t$ to transmit a packet.

- $\mathcal{Q}_r \neq \emptyset$, $\mathcal{Q}_t = \emptyset$: In this scenario, no RN chooses to transmit and the system can only choose a RN from $\mathcal{Q}_r$ to receive a packet. Denote $L_{min}^r = \min\{L_k | R_k \in \mathcal{Q}_r\}$. R_1 first finds out the set of RNs

$$\mathcal{Q}_{min}^r = \arg \min_{R_k \in \mathcal{Q}_r} \{L_k = L_{min}^r\} \quad (4.3)$$

whose buffer has L_{min}^r packets. Then R_1 uniformly chooses one RN from $\mathcal{Q}_{min}^r$ to receive a packet.

- $\mathcal{Q}_r \neq \emptyset$, $\mathcal{Q}_t \neq \emptyset$: In this scenario, the system first finds out the values of L_{max}^t ($L_{max}^t = \max\{L_k | R_k \in \mathcal{Q}_t\}$) and L_{min}^r ($L_{min}^r = \min\{L_k | R_k \in \mathcal{Q}_r\}$). Based on the values of L_{max}^t and L_{min}^r , R_1 finds the best RN and its working mode (to receive or to transmit) by using the policies presented in Table 4.2. If it

4.3. BUFFER-STATE BASED RELAY SELECTION SCHEME

chooses to transmit, then R_1 uniformly chooses one RN from $\mathcal{Q}_{max}^t$ to transmit, otherwise, R_1 uniformly chooses one RN from $\mathcal{Q}_{min}^r$ to receive.

- $\mathcal{Q}_r = \emptyset, \mathcal{Q}_t = \emptyset$: In this scenario, all the available links are in outage according to Table 4.1. Thus there is no need for R_1 to select a best RN.

Table 4.2: Relay selection method in the second stage.

Cases	L_{max}^t	L_{min}^r	Decision
Case 1	$L_{max}^t = L$		T
Case 2	$L_{max}^t < L$	$L_{min}^r = 0$	R
Case 3	$2 \leq L_{max}^t < L$	$L_{min}^r > 0$	T
Case 4	$L_{max}^t = 1$	$L_{min}^r > 0$	R

Remark: It can be observed that the relay selection method used in stage two always chooses the RN that has the maximum (minimum) number of packets to transmit (receive). These selection strategies are designed based on the following reasons: 1) The probability that the buffer of the RNs to be empty or full is decreased which in turn, increases the number of average available links. 2) The number of packets in the buffers of the RNs can be balanced through these methods, which as a result, reduces the maximum delay of the packets.

Remark: In the scenario $\mathcal{Q}_r \neq \emptyset$ and $\mathcal{Q}_t \neq \emptyset$, we design Case 1, Case 2 and Case 4 in Table 4.2 to increase the number of available links of the system in the following time slot, which aims to improve the system reliability. From Case 1 and Case 3, it can be observed that the system has a higher priority to transmit, which aims to reduce the average delay of the packets.

4.4 Outage Probability Analysis

The outage probability of the proposed buffer-state based relay selection scheme is investigated by using the MC model [27]. To show the advantages of our proposed scheme, the max-link relay selection scheme is used as a benchmark and some comparisons are carried out between these two schemes.

4.4.1 State Transition Matrix of the Markov Chain

We use the states of the MC to describe the number of data packets (L_k) stored in each buffer. For the k th ($k = 1, \dots, K$) RN, L_k has $L + 1$ different values, thus, there are $(L + 1)^K$ states in total. The n th state is expressed as

$$s_n \triangleq (L_1, L_2, \dots, L_K), \quad 1 \leq n \leq (L + 1)^K. \quad (4.4)$$

Let $\mathbf{A}$ denote the $(L + 1)^K \times (L + 1)^K$ state transition matrix of the MC, in which the entry $\mathbf{A}_{mn} = \Pr(X_{t+1} = s_m | X_t = s_n)$ stands for the transition probability of moving from state s_n at time slot t to state s_m at time slot $t + 1$. According to the proposed buffer-state based relay selection scheme, the transition probability $\mathbf{A}_{mn}$ depends on the status of the relay buffers and the set of available links that can successfully transmit one packet. In the following, we denote the set of available links that can successfully transmit one packet as successful links for short. Denote Ψ_n and Ψ_n^s as the set of available links and the set of successful links for state s_n , respectively. Note that it satisfies $\Psi_n^s \subset \Psi_n$.

To construct the state transition matrix $\mathbf{A}$, the connectivity between the different states of the buffers should be identified. In each time slot, the buffer state can be

modified according to the following rules: i) One of the RNs is selected to transmit a packet and the number of packets in its buffer is decreased by one; ii) One of the RNs is selected to receive a packet and the number of packets in its buffer is increased by one. iii) The buffer status remains unchanged if all the available links are in outage.

Based on these state transition rules, the set of states that connects with state s_n (can be arrived from state s_n through one step transition) which is denoted as U_n can be obtained. Based on the fact that for different Ψ_n^s , the probabilities of transiting from state s_n to state s_m have different values, thus, we have

$$\mathbf{A}_{mn} = \sum_{\Psi_n^s \subset \Psi_n} \Pr(\Psi_n^s) \Pr(s_n \rightarrow s_m | \Psi_n^s), \quad (4.5)$$

in which $s_m \in U_n$ is a state that connects with the state s_n . $\Pr(\Psi_n^s)$ is the probability of the event that a subset Ψ_n^s of the available links Ψ_n can successfully deliver a packet, which can be expressed as

$$\Pr(\Psi_n^s) = \prod_{l_{ij} \in \Psi_n^s} (1 - P_{ij}) \prod_{\substack{l_{ij} \in \Psi_n \\ l_{ij} \notin \Psi_n^s}} P_{ij}. \quad (4.6)$$

The value of $\Pr(s_n \rightarrow s_m | \Psi_n^s)$ depends on the specific relay selection scheme used. According to the proposed relay selection approach, $\Pr(s_n \rightarrow s_m | \Psi_n^s)$ can be easily calculated. When all the available links are unable to deliver a packet, the buffer status remains unchanged. Thus we have

$$\mathbf{A}_{nn} = \prod_{l_{ij} \in \Psi_n} P_{ij}. \quad (4.7)$$

For the case of $s_m \notin U_n$, as the system cannot transit from state s_n to state s_m in one

step, we have $\mathbf{A}_{mn} = 0$. In the following, a simple example is provided to visualize the approach for calculating the matrix $\mathbf{A}$.

4.4.2 A Simple Example with $K = 2$ and $L = 2$

For the buffer-aided relaying system with $K = 2$ and $L = 2$, there are 9 buffer states in total, which are shown in Table 4.3.

Table 4.3: States of the relaying system with $K = 2$ and $L = 2$.

States	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9
$L_1 L_2$	00	01	02	10	11	12	20	21	22

For simplicity, we assume that the channel responses between any two nodes are independent and identically distributed (i.i.d.) with zero mean and unit variance in this example. Thus, the outage probabilities of all the links are identical and can be expressed as $P_0 = 1 - e^{-\frac{2^{2r_0}-1}{P}}$. The corresponding state transition matrix $\mathbf{A}$ can be expressed as

$$\mathbf{A} = \begin{pmatrix} P_0^2 & P_0^2 \bar{P}_0 & 0 & P_0^2 \bar{P}_0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1-P_0^2}{2} & P_0^3 & \bar{P}_0 & 0 & \frac{P_0^2(1-P_0^2)}{2} & 0 & 0 & 0 & 0 \\ 0 & P_0 \bar{P}_0 & P_0^2 & 0 & 0 & P_0^2 \bar{P}_0 & 0 & 0 & 0 \\ \frac{1-P_0^2}{2} & 0 & 0 & P_0^3 & \frac{P_0^2(1-P_0^2)}{2} & 0 & \bar{P}_0 & 0 & 0 \\ 0 & \bar{P}_0 & 0 & \bar{P}_0 & P_0^4 & \bar{P}_0 & 0 & \bar{P}_0 & 0 \\ 0 & 0 & P_0 \bar{P}_0 & 0 & \frac{1-P_0^2}{2} & P_0^3 & 0 & 0 & \frac{1-P_0^2}{2} \\ 0 & 0 & 0 & P_0 \bar{P}_0 & 0 & 0 & P_0^2 & P_0^2 \bar{P}_0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-P_0^2}{2} & 0 & P_0 \bar{P}_0 & P_0^3 & \frac{1-P_0^2}{2} \\ 0 & 0 & 0 & 0 & 0 & P_0 \bar{P}_0 & 0 & P_0 \bar{P}_0 & P_0^2 \end{pmatrix},$$

where $\bar{P}_0 = 1 - P_0$ is the probability that a packet can be successfully delivered.

As an illustrative example, here we show the process of calculating $\mathbf{A}_{25}$ by using (4.5), (4.6) and the proposed relay selection method. For the current buffer state s_5 , as there is only one packet stored in the buffer of each RN, all the links are available.

Thus we have $\Psi_5 = \{l_{sr1}, l_{sr2}, l_{r1d}, l_{r2d}\}$. To transit from s_5 to s_2 , R_1 should transmit a packet to the DN, thus the link l_{r1d} must be successful. Therefore, for the cases that $l_{r1d} \notin \Psi_5^s$, we have $\Pr(s_5 \rightarrow s_2 | \Psi_5^s) = 0$. According to the proposed relay selection scheme, the two links l_{sr1}, l_{sr2} should be in outage, otherwise R_1 and R_2 will choose to receive a packet and it is impossible to transit from s_5 to s_2 . Based on these facts, we can conclude that for the cases of $l_{sr1} \in \Psi_5^s$ or $l_{sr2} \in \Psi_5^s$, the result $\Pr(s_5 \rightarrow s_2 | \Psi_5^s) = 0$ always holds. As a result, there are only two cases in which the buffer state can transit from s_5 to s_2 : 1) $\Psi_5^s = \{l_{r1d}\}$; 2) $\Psi_5^s = \{l_{r1d}, l_{r2d}\}$.

- For the case of $\Psi_5^s = \{l_{r1d}\}$, according to (4.6), we have $\Pr(\Psi_5^s) = P_0^3(1 - P_0)$ and $\Pr(s_5 \rightarrow s_2 | \Psi_5^s) = 1$.
- For the case of $\Psi_5^s = \{l_{r1d}, l_{r2d}\}$, we have $\Pr(\Psi_5^s) = P_o^2(1 - P_o)^2$ and $\Pr(s_5 \rightarrow s_2 | \Psi_5^s) = \frac{1}{2}$.

Thus $\mathbf{A}_{25}$ can be calculated as

$$\begin{aligned} \mathbf{A}_{25} &= P_0^3(1 - P_0) + \frac{1}{2}P_o^2(1 - P_o)^2 \\ &= \frac{P_0^2(1 - P_o^2)}{2}. \end{aligned}$$

4.4.3 Steady State Distribution of the Markov Chain

As the stationary distribution of the buffer states which is denoted by a column vector $\boldsymbol{\pi}$ of the MC reflects the long-term system performance, we will calculate the value of $\boldsymbol{\pi}$ in this section. The one-step state transition matrix $\mathbf{A}$ of the proposed relay selection scheme has the following property:

Lemma 4.1: *The one-step state transition matrix $\mathbf{A}$ of the proposed relay selection scheme is irreducible and aperiodic.*

Proof: Due to the structure of the problem and the fact that $P_{ij} > 0$, it can be observed that it is possible for the system to transit from any state to all other states. That is to say, the state space of the considered MC is a single communicating class. Thus, the considered MC is irreducible. Based on the facts that the outage probability of the system is greater than zero and the state of the buffer remains unchanged when the system is in outage, it can be concluded that the probability of staying at any state after N and $N + 1$ transitions is greater than zero. Thus, the considered MC is aperiodic. ■

As $\mathbf{A}$ is irreducible and aperiodic, according to [27], the stationary distribution vector can be obtained as

$$\boldsymbol{\pi} = (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1}\mathbf{b}, \quad (4.8)$$

where $\boldsymbol{\pi} = [\pi_1, \dots, \pi_{(L+1)^K}]$, $\mathbf{b} = [1, \dots, 1]^T$, $\mathbf{I}$ is the identity matrix and $\mathbf{B}$ is a $(L+1)^K \times (L+1)^K$ matrix in which all elements have a value of one.

The total $(L+1)^K$ buffer states can be divided into two categories. The first category contains the $(L-1)^K$ states in which all the relay buffers are neither full nor empty. Thus, the states in the first category always provide $2K$ available links. The second category contains the $(L+1)^K - (L-1)^K$ states in which at least one of the relay buffers is either full or empty. Thus, the system in these states has a number of available links less than $2K$. In the following, we use $\mathcal{F}_1$ and $\mathcal{F}_2$ to denote the set of states in the first category and the second category, respectively. Note that this state categorization can be applied to both the max-link relay selection scheme and the

proposed relay selection scheme. By grouping the states of $\mathcal{F}_1$ and $\mathcal{F}_2$ as two “super-states” $s_{\mathcal{F}_1}$ and $s_{\mathcal{F}_2}$, respectively. We can form a new MC with transition probabilities $\mathbf{A}_{\mathcal{F}_1\mathcal{F}_2} = \Pr(X_{t+1} = s_{\mathcal{F}_1} | X_t = s_{\mathcal{F}_2})$ and $\mathbf{A}_{\mathcal{F}_2\mathcal{F}_1} = \Pr(X_{t+1} = s_{\mathcal{F}_2} | X_t = s_{\mathcal{F}_1})$. The values of $\mathbf{A}_{\mathcal{F}_2\mathcal{F}_1}$ and $\mathbf{A}_{\mathcal{F}_1\mathcal{F}_2}$ which denote transition probabilities from $\mathcal{F}_1$ to $\mathcal{F}_2$ and from $\mathcal{F}_2$ to $\mathcal{F}_1$, respectively, are given by

$$A_{\mathcal{F}_1\mathcal{F}_2} = \Pr(X_{t+1} = s_{\mathcal{F}_1} | X_t = s_{\mathcal{F}_2}) = \sum_{s_m \in \mathcal{F}_2} \sum_{s_n \in \mathcal{F}_1} \Pr(X_{t+1} = s_n | X_t = s_m), \quad (4.9)$$

$$A_{\mathcal{F}_2\mathcal{F}_1} = \Pr(X_{t+1} = s_{\mathcal{F}_2} | X_t = s_{\mathcal{F}_1}) = \sum_{s_m \in \mathcal{F}_1} \sum_{s_n \in \mathcal{F}_2} \Pr(X_{t+1} = s_n | X_t = s_m). \quad (4.10)$$

Similar definition can be applied to the max-link relay selection scheme to obtain $\overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_2}$ and $\overline{\mathbf{A}}_{\mathcal{F}_2\mathcal{F}_1}$. Based on these definitions, we can obtain the following results:

Lemma 4.2: *The transition probabilities $\mathbf{A}_{\mathcal{F}_1\mathcal{F}_2}$ and $\mathbf{A}_{\mathcal{F}_2\mathcal{F}_1}$ as well as the transition probabilities $\overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_2}$ and $\overline{\mathbf{A}}_{\mathcal{F}_2\mathcal{F}_1}$ satisfy $\mathbf{A}_{\mathcal{F}_1\mathcal{F}_2} > \overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_2}$, $\mathbf{A}_{\mathcal{F}_2\mathcal{F}_1} < \overline{\mathbf{A}}_{\mathcal{F}_2\mathcal{F}_1}$.*

Proof: Suppose that $s_n \in \mathcal{F}_2$ is a state that can transit from $\mathcal{F}_2$ to $\mathcal{F}_1$ in one step. Then there must be only one empty buffer or only one full buffer in state s_n . For the max-link relay selection scheme, as it always chooses the link with the best channel coefficient, it is possible for the system to choose another link even if the link associated with a empty or full relay buffer can successfully deliver a packet. However, for the buffer-state based relay selection scheme, once the link associated with a empty or full relay buffer is able to deliver a packet, the highest priority is assigned to it and it must be chosen to transmit, which as a result, makes the system transit from $\mathcal{F}_2$ to $\mathcal{F}_1$. Thus, the result $\mathbf{A}_{\mathcal{F}_1\mathcal{F}_2} > \overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_2}$ always holds. As the proposed buffer-state based relay selection scheme gives the RNs with $L = 1$ a higher priority to receive and the RNs with $L \geq 2$ a higher priority to transmit while the max-link

relay selection scheme gives each link equal priority, thus we have $\mathbf{A}_{\mathcal{F}_2\mathcal{F}_1} < \overline{\mathbf{A}}_{\mathcal{F}_2\mathcal{F}_1}$. ■

For the buffer-state based relay selection scheme, we define $\pi_{s_{\mathcal{F}_1}}$ and $\pi_{s_{\mathcal{F}_2}}$ as the stationary probabilities of the states $s_{\mathcal{F}_1}$ and $s_{\mathcal{F}_2}$, respectively. Based on the properties of MC, we have

$$\pi_{s_{\mathcal{F}_1}} = \sum_{s_n \in \mathcal{F}_1} \pi_n, \quad (4.11)$$

$$\pi_{s_{\mathcal{F}_2}} = \sum_{s_n \in \mathcal{F}_2} \pi_n. \quad (4.12)$$

Similar definition can be applied to the max-link selection scheme to obtain $\overline{\pi}_{s_{\mathcal{F}_1}}$ and $\overline{\pi}_{s_{\mathcal{F}_2}}$. Based on these definitions, we can obtain the following results:

Lemma 4.3: *The stationary probabilities $\pi_{s_{\mathcal{F}_1}}$ and $\pi_{s_{\mathcal{F}_2}}$ as well as the stationary probabilities $\overline{\pi}_{s_{\mathcal{F}_1}}$ and $\overline{\pi}_{s_{\mathcal{F}_2}}$ satisfy $\pi_{s_{\mathcal{F}_1}} > \overline{\pi}_{s_{\mathcal{F}_1}}$, $\pi_{s_{\mathcal{F}_2}} < \overline{\pi}_{s_{\mathcal{F}_2}}$.*

Proof: We can form two MCs with the following state transition matrices for the max-link relay selection scheme and the buffer-state based relay selection scheme, respectively:

$$\mathbf{T} = \begin{pmatrix} \mathbf{A}_{\mathcal{F}_1\mathcal{F}_1} & \mathbf{A}_{\mathcal{F}_1\mathcal{F}_2} \\ \mathbf{A}_{\mathcal{F}_2\mathcal{F}_1} & \mathbf{A}_{\mathcal{F}_2\mathcal{F}_2} \end{pmatrix}, \quad (4.13)$$

$$\overline{\mathbf{T}} = \begin{pmatrix} \overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_1} & \overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_2} \\ \overline{\mathbf{A}}_{\mathcal{F}_2\mathcal{F}_1} & \overline{\mathbf{A}}_{\mathcal{F}_2\mathcal{F}_2} \end{pmatrix}. \quad (4.14)$$

Denote $\boldsymbol{\pi}_{\mathcal{F}} = [\pi_{s_{\mathcal{F}_1}}, \pi_{s_{\mathcal{F}_2}}]^T$ and $\overline{\boldsymbol{\pi}}_{\mathcal{F}} = [\overline{\pi}_{s_{\mathcal{F}_1}}, \overline{\pi}_{s_{\mathcal{F}_2}}]^T$ such that they satisfy

$$\mathbf{T}\boldsymbol{\pi}_{\mathcal{F}} = \boldsymbol{\pi}_{\mathcal{F}}, \quad (4.15)$$

$$\overline{\mathbf{T}}\overline{\boldsymbol{\pi}}_{\mathcal{F}} = \overline{\boldsymbol{\pi}}_{\mathcal{F}}. \quad (4.16)$$

Based on the fact that for any MC, the sum of the elements that lie in the same column of the state transition matrix equals to one, equation (4.15) can be rewritten as

$$\mathbf{A}_{\mathcal{F}_1\mathcal{F}_1}\pi_{s_{\mathcal{F}_1}} + \mathbf{A}_{\mathcal{F}_1\mathcal{F}_2}\pi_{s_{\mathcal{F}_2}} = \pi_{s_{\mathcal{F}_2}}, \quad (4.17)$$

$$\overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_1}\overline{\pi}_{s_{\mathcal{F}_1}} + \overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_2}\overline{\pi}_{s_{\mathcal{F}_2}} = \overline{\pi}_{s_{\mathcal{F}_2}}. \quad (4.18)$$

As it satisfies $\pi_{s_{\mathcal{F}_1}} + \pi_{s_{\mathcal{F}_2}} = 1$ and $\overline{\pi}_{s_{\mathcal{F}_1}} + \overline{\pi}_{s_{\mathcal{F}_2}} = 1$, then we can obtain

$$\pi_{s_{\mathcal{F}_1}} = \frac{\mathbf{A}_{\mathcal{F}_1\mathcal{F}_2}}{\mathbf{A}_{\mathcal{F}_2\mathcal{F}_1} + \mathbf{A}_{\mathcal{F}_1\mathcal{F}_2}}, \quad (4.19)$$

$$\overline{\pi}_{s_{\mathcal{F}_2}} = \frac{\overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_2}}{\overline{\mathbf{A}}_{\mathcal{F}_2\mathcal{F}_1} + \overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_2}}. \quad (4.20)$$

As it satisfies $\mathbf{A}_{\mathcal{F}_1\mathcal{F}_2} > \overline{\mathbf{A}}_{\mathcal{F}_1\mathcal{F}_2}$, $\mathbf{A}_{\mathcal{F}_2\mathcal{F}_1} < \overline{\mathbf{A}}_{\mathcal{F}_2\mathcal{F}_1}$, we have $\pi_{s_{\mathcal{F}_1}} > \overline{\pi}_{s_{\mathcal{F}_1}}$, $\pi_{s_{\mathcal{F}_2}} < \overline{\pi}_{s_{\mathcal{F}_2}}$. ■

Lemma 4.4: *As the buffer size approaches infinity, the probability for the system to stay in the states of $\mathcal{F}_2$ approaches zero. That is $\lim_{L \rightarrow \infty} \pi_{s_{\mathcal{F}_2}} = 0$.*

Proof: It has been proved in [27] that the max-link relay selection scheme satisfies $\lim_{L \rightarrow \infty} \overline{\pi}_{s_{\mathcal{F}_2}} = 0$. As it satisfies $\pi_{s_{\mathcal{F}_2}} < \overline{\pi}_{s_{\mathcal{F}_2}}$, then we have $\lim_{L \rightarrow \infty} \pi_{s_{\mathcal{F}_2}} = 0$. ■

4.4.4 Outage Probability

Similar to the definition adapted in [27] for the max-link relay selection scheme, the outage probability for the proposed relay selection scheme is defined as the probability that all the available links are in outage. This definition is based on the fact that as long as there is at least one available link not in outage, the system can deliver a

packet. Thus, the outage probability of the system can be obtained as

$$P_{\text{out}} = \sum_{n=1}^{(L+1)^K} \pi_n \mathbf{A}_{nn}. \quad (4.21)$$

4.4.5 Diversity Order

In order to show the diversity order of the proposed relay selection scheme, we assume that all the channel responses are i.i.d. with $\Omega_{ij} = 1$ in this subsection. Thus, the outage probabilities of all the links are identical and can be expressed as $P_0 = 1 - e^{-(\frac{2^{2r_0-1}}{P})}$. The diversity order can be defined as [111]

$$d = - \lim_{\gamma \rightarrow \infty} \frac{\log(P_{\text{out}})}{\log \gamma}, \quad (4.22)$$

where γ is the average SNR for each link. As it is assumed that the AWGN has unit variance, we have $\gamma = P$.

For the case that each RN has infinite buffer size, i.e., $L \rightarrow \infty$, the outage probability of the system can be rewritten as

$$P_{\text{out}}^{\infty} = \lim_{L \rightarrow \infty} \sum_{s_n \in \mathcal{F}_1} \pi_n \mathbf{A}_{nn} + \lim_{L \rightarrow \infty} \sum_{s_n \in \mathcal{F}_2} \pi_n \mathbf{A}_{nn}. \quad (4.23)$$

As we have proved in **Lemma 4.4** that $\lim_{L \rightarrow \infty} \pi_{s_{\mathcal{F}_2}} = 0$ and based on the facts that $\pi_n \leq \pi_{s_{\mathcal{F}_2}}$, $\mathbf{A}_{nn} < 1$, (4.23) can be simplified as

$$P_{\text{out}}^{\infty} = \lim_{L \rightarrow \infty} \sum_{s_n \in \mathcal{F}_1} \pi_n \mathbf{A}_{nn}. \quad (4.24)$$

For a state $s_n \in \mathcal{F}_1$, there are always $2K$ available links, thus we have $\mathbf{A}_{nn} = P_o^{2K}$.

Then (4.24) can be further simplified as

$$P_{\text{out}}^{\infty} = P_0^{2K} = \left[1 - e^{-\left(\frac{2^{2r_0-1}}{P}\right)} \right]^{2K}. \quad (4.25)$$

Thus for $L \rightarrow \infty$, the achievable diversity order of the system is

$$d_{\infty} = - \lim_{\gamma \rightarrow \infty} \frac{\log(P_{\text{out}})}{\log \gamma} = 2K, \quad (4.26)$$

which is the same as that of the max-link relay selection scheme. However, we show in the following that different from the max-link relay selection scheme, our proposed scheme achieves this diversity order even when the buffer size is only $L = 3$.

Lemma 4.5: *For the proposed relay selection scheme with $L \geq 3$, the stationary probability π_n of a state s_n which has $2K - m$ ($m \geq 1$) available links satisfies $\pi_n < C_m \left(\frac{P_0}{1-P_0} \right)^m$, where C_m is a constant value.*

Proof: Please refer to Appendix B. ■

Based on this lemma, we have

Theorem 4.1: *The proposed relay selection scheme with $L \geq 3$ can achieve a diversity order of $d = 2K$.*

Proof: It has been proven in **Lemma 4.5** that for any state s_n with $2K - m$ ($m \geq 1$) available links, the result $\pi_n < C_m \left(\frac{P_0}{1-P_0} \right)^m$ always holds. Thus, we have

$$\begin{aligned} P_{\text{out}} &= \sum_{n=1}^{(L+1)^K} \pi_n \mathbf{A}_{nn} \\ &\leq \sum_{s_n \in \mathcal{G}_0} \pi_n \mathbf{A}_{nn} + \sum_{m=1}^K \sum_{s_n \in \mathcal{G}_m} C_m \left(\frac{P_0}{1-P_0} \right)^m \mathbf{A}_{nn}. \end{aligned} \quad (4.27)$$

Based on the fact that for a state s_n with $2K - m$ available links, $\mathbf{A}_{nn} = P_0^{2K-m}$. We can rewrite (4.27) as

$$P_{\text{out}} \leq \sum_{s_n \in \mathcal{G}_0} \pi_n P_0^{2K} + \sum_{m=1}^K \sum_{s_n \in \mathcal{G}_m} \frac{C_m P_0^{2K}}{(1 - P_0)^m}. \quad (4.28)$$

Based on the definition of diversity order, we can conclude that the proposed relay selection scheme can achieve a diversity order of $2K$ for the system with $L \geq 3$. ■

4.5 Average Packet Delay Analysis

In the following, we analyze and compare the average packet delays of the max-link relay selection scheme and the proposed relay selection scheme. In general, the delay of a packet includes two parts, i.e., the delay at the SN and the delay at the RNs which are denoted as D_s and D_r , respectively.

4.5.1 Average Packet Delay at the Source Node

According to Little's law, the average delay at the SN is given by $D_s = \frac{E[q_s]}{\eta_s}$, where $E[q_s]$ is the average queuing length at the SN and η_s is the throughput of the SN.

We assume that the SN always has packets to transmit, thus the queuing length at the SN depends on how often it is chosen to transmit, which again depends on the probability that a S-R link is selected. Similar to [29], the queuing length at the SN can be obtained as

$$E[q_s] = 1 - P_{S \rightarrow R}, \quad (4.29)$$

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where $P_{S \rightarrow R}$ is the probability that a S-R link is chosen to deliver a packet. Based on the fact that the number of packets received by the RNs must be equal to the number of packets that leave these RNs, we have

$$P_{S \rightarrow R} = P_{R \rightarrow D}, \quad (4.30)$$

where $P_{R \rightarrow D}$ is the probability that a R-D link is selected to transmit a packet. As the system always stays in the following three states: (i) to stay in outage, (ii) to use a S-R link to send a packet, (iii) to choose a R-D link to transmit a packet, thus, we can obtain

$$P_{\text{out}} + P_{S \rightarrow R} + P_{R \rightarrow D} = 1. \quad (4.31)$$

Combining (4.30) and (4.31), we have

$$E[q_s] = \frac{1 + P_{\text{out}}}{2}. \quad (4.32)$$

The throughput of the SN can be expressed as

$$\eta_s = P_{S \rightarrow R} = \frac{1 - P_{\text{out}}}{2}. \quad (4.33)$$

Combining (4.32), (4.33) and by using Little's law, we can obtain the average delay of the SN as

$$D_s = \frac{1 + P_{\text{out}}}{1 - P_{\text{out}}}. \quad (4.34)$$

4.5.2 Average Delay at the Relay Nodes

Based on the fact that only one packet can be delivered in each time slot, we can conclude that it takes $\sum_{k=1}^K L_k$ time slots for the RNs to transmit the packets stored in their buffers. Thus, in this subsection, we treat the buffers of all the RNs as one equivalent buffer to derive the average delay of R-D link. Denote $L_k^{s_n}$ as the queuing length of R_k at the buffer state s_n . Then the queuing length of the equivalent buffer at state s_n can be obtained as $L_{EQ}^{s_n} = \sum_{k=1}^K L_k^{s_n}$. The average queuing length of the equivalent buffer can thus be expressed as

$$E[q_{EQ}] = \sum_{n=1}^{(L+1)^K} \pi_n L_{EQ}^{s_n} = \sum_{n=1}^{(L+1)^K} \sum_{k=1}^K \pi_n L_k^{s_n}. \quad (4.35)$$

The throughput of the R-D link can be obtained as

$$\eta_r = P_{R \rightarrow D} = \frac{1 - P_{\text{out}}}{2}. \quad (4.36)$$

Combining (4.35) and (4.36), we can express the average delay of the R-D link as

$$D_r = \frac{2}{1 - P_{\text{out}}} \sum_{n=1}^{(L+1)^K} \sum_{k=1}^K \pi_n L_k^{s_n}. \quad (4.37)$$

The overall average packet delay of the system can thus be obtained as

$$\begin{aligned} E[D] &= E[D_s] + E[D_r] \\ &= \frac{1 + P_{\text{out}}}{1 - P_{\text{out}}} + \frac{2}{1 - P_{\text{out}}} \sum_{n=1}^{(L+1)^K} \sum_{k=1}^K \pi_n L_k^{s_n}. \end{aligned} \quad (4.38)$$

To get some insights on the average delay of the proposed relay selection scheme, the following two lemmas are provided.

Lemma 4.6: *As the SNR approaches infinity, the buffer-aided relaying system with $L \geq 2$ and using the proposed relay selection scheme almost always stays in $K + 1$ specific buffer states and it satisfies $\lim_{SNR \rightarrow \infty} \sum_{n=1}^{(L+1)^K} \sum_{k=1}^K \pi_n L_k^{s_n} = K + \frac{1}{2}$.*

Proof: Please refer to Appendix C. ■

Lemma 4.7: *For the system with $L \geq 2$, the average delay of the max-link relay selection scheme satisfies $\lim_{SNR \rightarrow \infty} E[D_{ml}] = KL + 1$, while the average delay of the proposed relay selection scheme satisfies $\lim_{SNR \rightarrow \infty} E[D_{sb}] = 2K + 2$.*

Proof: As the SNR approaches infinity, the outage probability of every link approaches zero. For the max-link relay selection scheme, the probability for a RN to receive a packet equals to the probability for it to transmit a packet, as a result, the average queuing length for the equivalent buffer is $KL/2$ [29]. Based on (4.38), it can be obtained that $\lim_{SNR \rightarrow \infty} E[D_{ml}] = KL + 1$, in which D_{ml} is the delay of the max-link relay selection scheme. For the proposed relay selection scheme, it has been shown in **Lemma 4.6** that the average queuing length for the equivalent buffer is $K + 1/2$. Thus the average overall delay of the proposed scheme can be obtained as $\lim_{SNR \rightarrow \infty} E[D_{sb}] = 2K + 2$, where D_{sb} is the delay of the proposed relay selection scheme. ■

Lemma 4.7 indicates that, for the proposed buffer-state based relay selection scheme, as the SNR increases, the average delay of the packets only increases linearly with the number of RNs K , while for the max-link relay selection scheme, it increases linearly with both the number of RNs K and the buffer size L .

Figure 4.2: Outage probabilities of different relay selection schemes for a system setting with $K = 2$, $L = 2$, $r_0 = 1$ BPCU and $\Omega_{ij} = 1$.

4.6 Numerical Results and Discussion

To evaluate the performance of the proposed buffer-state based relay selection scheme, some numerical results are presented. To make a comparison, the corresponding results of the max-min relay selection scheme, the max-max relay selection scheme and the max-link relay selection scheme are also provided. The selection bound which refers to the ideal relay selection scheme where all the links are always available is also presented as a reference.

In Fig. 4.2, the outage probabilities of the four relay selection schemes are provided, where we have $K = 2$, $L = 2$ and system target rate is set as $r_0 = 1$ bit per channel use (BPCU). For the max-max relay selection scheme, we provide a lower

bound of the outage probability which is obtained by assuming that the buffer of each RN can neither be full nor be empty. It can be observed from Fig. 4.2 that for a buffer size of $L = 2$, the max-min relay selection scheme, the max-max relay selection scheme and the max-link relay selection scheme all achieve a diversity equal to the number of RNs, which is in line with the results shown in [27]. Compared with the other three schemes, the proposed buffer-state based relay selection scheme achieves better performance. As it has been proved in [27] that the max-link relay selection scheme outperforms the max-max relay selection scheme and the max-min relay selection scheme, here we just provide the reason why the proposed scheme outperforms the max-link relay selection scheme. According to **Lemma 4.6**, the proposed scheme is more likely to stay in the buffer state set $\mathcal{F}_1$ which always provides $2K$ available links. Thus, as compared with the max-link relay selection scheme, the proposed scheme has more average available links which results in better outage performance. Based on the fact that the selection bound achieves a diversity order of 4, we can conclude that for $L = 2$, the proposed scheme achieves a diversity order between 2 and 4.

In Fig. 4.3, we compare the outage probabilities of the proposed relay selection scheme and the max-link relay selection scheme with different buffer sizes. For the buffer sizes of $L = 2$ and $L = 3$, the corresponding analytical results are also presented. It can be observed that the analytical results are in good agreement with the simulation results. We observe from Fig. 4.3 that as the buffer size increases, the outage probabilities of both the proposed relay selection scheme and the max-link relay selection scheme approach the selection bound and the proposed scheme achieves full

Figure 4.3: Outage probabilities of the max-link relay selection scheme and the proposed relay selection scheme for different buffer sizes with $K = 2$, $r_0 = 1\text{BPCU}$ and $\Omega_{ij} = 1$.

diversity. Meanwhile, for systems with the same buffer size, the proposed relay selection scheme always outperforms the max-link relay selection scheme. Furthermore, it also can be observed from Fig. 4.3 that the proposed relay selection scheme converges much faster to the selection bound as the buffer size increases as compared with the max-link relay selection scheme. The max-link relay selection scheme approaches the selection bound and achieves full diversity order which is equal to 4 when the buffer size satisfies $L \geq 50$, while the proposed scheme approaches the selection bound and achieves full diversity order when the buffer size is $L = 3$, which is consistent with the result of **Theorem 4.1**. These results reveal the potential of the proposed scheme in relaying systems with a delay constraint.

4.6. NUMERICAL RESULTS AND DISCUSSION

Figure 4.4: Outage probability of different schemes with $K = 4$, $L = 2$ and 3 , and $r_0 = 1\text{BPCU}$.

In Fig. 4.4, we plot the outage probability results for the system with $K = 4$ RNs. For comparisons, the performances of the system with both i.i.d. and n.i.i.d. channels are also presented. For the system with an i.i.d. channel, the average path gain of each link is set as $\Omega_{ij} = 1$. For the system with a n.i.i.d. channel, the average path gains of link l_{sr_1} and link l_{r_4d} are increased to be $\Omega_{sr_1} = \Omega_{r_4d} = 3$ while the average path gains of the remaining links are still set to be one ($\Omega_{sj} = \Omega_{id} = 1, j \neq r_1, i \neq r_4$). It can be observed that the proposed relay selection scheme outperforms all the existing relay selection schemes for both i.i.d. and n.i.i.d. channels. In addition, for the max-link relay selection scheme, we can observe that even though the channel qualities of the l_{sr_1} and l_{r_4d} links of the n.i.i.d. channel are better than that of the i.i.d. channel, the performance of the system actually degrades. This performance loss can be explained

Figure 4.5: Comparisons of the average delay for the max-link relay selection scheme and the proposed relay selection scheme for different number of relay nodes and buffer sizes.

as follows. The max-link relay selection scheme always chooses the link with the best channel quality. Thus, it is more likely for the system to choose link l_{sr_1} to receive and link l_{r_4d} to transmit, respectively. As a result, the buffers of R_1 and R_4 are more likely to be full and empty, respectively. Hence, the average number of available links is actually reduced as compared with the i.i.d. channel setup. On the other hand, it can be observed from Fig. 4.4 that the proposed relay selection scheme can effectively overcome this problem for the n.i.i.d. channel setup as it takes the buffer state of each RN into consideration.

In Fig. 4.5, the average delay, which is measured in number of time slots used to deliver a packet, of the proposed relay selection scheme and the max-link relay

Figure 4.6: Comparisons of the average delay for the max-link relay selection scheme and the proposed relay selection scheme as the buffer size increases with SNR=20dB and $r_0 = 1$ BPCU.

selection scheme is compared. It can be observed that as SNR increases, the average delays of both schemes decrease. This results from the fact that as SNR increases, the outage probability of the system decreases and fewer time slots are needed to successfully deliver a packet. It is also shown in Fig. 4.5 that when $L = 2$, the proposed relay selection scheme has a higher delay as compared with the max-link relay selection scheme, while it has a lower average delay when $L \geq 3$. These results can be explained as follows. The larger delay of the proposed relay selection scheme with $L = 2$ results from “Case 4” of stage two of the proposed relay selection scheme presented in Section III. Case 4 of stage two indicates that if it satisfies $L_{max}^t = 1$, the system should choose to receive a new packet (note that $\mathcal{Q}_r$ is not empty in

Case 4 of stage two). Meanwhile, Case 4 with $L = 2$ and $L_{max}^t = 1$ implies that $L_{min}^r = 1$. Thus, in Case 4, each RN has one packet in the buffer and the proposed relay selection method gives the RNs a higher priority to receive while the max-link relay selection scheme always chooses the link with best channel quality. Hence, the average delay of the proposed relay selection scheme is increased. Actually, Case 4 of stage two is designed to give systems with $L \geq 3$ the ability to achieve full diversity at the tradeoff of increasing the average system delay. In fact, the average delay of the proposed scheme can be further decreased if the reliability of the proposed scheme can be sacrificed. For the cases with $L \geq 3$, the proposed relay selection scheme gives the RNs higher priority to transmit if the condition $L_{max}^t \geq 2$ is satisfied, which results in a lower average delay as compared with the max-link relay selection scheme. From Fig. 4.5, we can also observe that for a system with $K = 2$, the proposed scheme achieves almost the same average delay for $L = 2$ and $L = 4$ if SNR is larger than 14dB. In fact, in **Lemma 4.7**, we have shown that the average delay of the proposed relay selection scheme does not increase as L increases in high SNR regime.

In Fig. 4.6, we compare the average delays of the proposed relay selection scheme with the max-link relay selection scheme for different buffer sizes. The SNR is set as 20dB. It can be seen from Fig. 4.6 that the average delay of the max-link relay selection scheme increases linearly with the buffer size L , while the average delay of the proposed relay selection scheme does not increase as the buffer size L increases, which is consistent with the results presented in **Lemma 4.7**.

4.7 Summary

We have proposed a buffer-state based relay selection scheme for the cooperative relaying system with finite buffers at the RNs. It has been shown that the proposed relay selection scheme has a lower outage probability as compared with the existing relay selection schemes. Furthermore, we have shown that the proposed relay selection scheme can achieve full diversity for a system with a small buffer size of $L = 3$, while the existing max-link relay selection schemes need a buffer size of $L \rightarrow \infty$ to achieve this diversity order. The average packet delays of both the max-link relay selection scheme and the proposed relay selection scheme have also been investigated. It has been shown that as compared with the max-link relay selection scheme, the proposed relay selection scheme has a larger average delay when $L = 2$. For $L \geq 3$, the proposed relay selection scheme has a lower average delay than that of the max-link relay selection scheme.

Chapter 5

Throughput Maximization for Wireless-Powered Buffer-Aided Cooperative Relaying Systems

In this chapter, we apply the buffer-aided relaying scheme to a WPCCN in which the RNs without embedded power supply are charged by the RF signal transmitted by a PB. To maximize the system throughput, a joint node-and-mode selection scheme in which the RN and its transmission mode are jointly selected in each time slot is investigated. For the general system setup, some analytical results are obtained which provide useful insights in finding the optimal joint node-and-mode selection scheme. Following this, the analysis is applied to two specific systems, namely, the single RN system and the multiple RNs system with a symmetric channel. For these system setups, the system throughput is obtained in closed-form expressions. Numerical results show that the proposed transmission schemes can improve the throughput of the WPCCN.

5.1 Introduction

As an effective method to prolong the life time of energy-constrained wireless networks, radio frequency energy harvesting (RF-EH) technology has recently attracted a lot of attentions [112, 113]. Since RF signal can transfer both information and energy, a research area on simultaneous wireless information and power transfer (SWIPT) has emerged. In [114–117], the SWIPT scheme was investigated and the fundamental tradeoff between information transfer and energy transfer for different systems was derived. Besides SWIPT, another promising research topic on RF-EH is the wireless-powered communication network (WPCN). A typical WPCN usually contains a hybrid access point and one or more UEs. The hybrid access point charges power to UEs by sending RF signals in the downlink, while the UEs harvest energy and use the harvested energy to transfer information to the hybrid access point in the uplink. To make a WPCN work efficiently, one important issue is to design effective communication protocols [37, 118]. The RF-EH technology has also been applied in cooperative relaying networks recently [119–124]. In [120] and [121], the AF and DF based WPCNs were investigated, respectively. In [122], a block-wise EH scheme was proposed for both AF and DF based WPCNs. Different from the works of [37, 118–123], in which the UEs or RNs use the harvest-and-transmit (HAT) scheme [37], a harvest-store-and-transmit scheme was adopted in [125–128].

In this chapter, we apply the buffer-aided relaying scheme to a WPCN with multiple RNs. The RNs have no embedded power supply, thus they need to harvest energy before forwarding the information to the DN. Similar to [129] and [130], we assume that there exists a PB which is responsible for sending wireless energy to the RNs. The motivation of this combination results from the following considerations:

Figure 5.1: Wireless-powered relaying system with buffer-aided relays.

1) The energy harvested by the RNs through RF signal is limited, and the information received from the SN in one time slot may need several time slots to be delivered to the DN by the RNs. Thus, the RNs need a buffer to temporarily store the received information. 2) Buffer-aided relaying scheme achieves higher system capacity and reliability as compared with the conventional relaying methods [55, 131]. 3) For the energy constraint RNs, the buffer-aided relaying scheme which increases the capacity of the system can increase the energy efficiency of the RNs. Inspired by these benefits, we introduce the buffer-aided relaying scheme to a WPCCN and propose an adaptive transmission scheme, in which each RN adaptively switches between two working modes. To maximize the system throughput, a joint node-and-mode selection scheme in which the RN and its transmission mode are jointly selected in each time slot is investigated. The main contributions of this chapter are summarized as follows:

- We introduce the buffer-aided relaying scheme to a WPCCN and propose an adaptive transmission scheme to improve system throughput. In the proposed scheme, each RN adaptively switches between two transmission modes, namely

the SN information transmission (SN-IT) mode and the RN harvest-and-transmit (RN-HAT) mode.

- To maximize the system throughput, we propose a joint node-and-mode selection scheme. Specifically, we consider that only one of the RNs will be selected to receive or forward information in each time slot. For the general system setup, some analytical results are provided which can give some insights in finding the optimal joint node-and-mode selection scheme that maximizes the system throughput. For some special cases, e.g., the single RN system and the system with a symmetric channel, the maximum throughput is obtained in closed-form expressions and the optimal transmission schemes are given.
- Numerical results are provided to validate the analytical expressions that we have derived. For comparisons, the throughput of a WPCCN without information buffering at the RNs is used as benchmark. Numerical results show that the proposed adaptive transmission schemes can improve the system throughput.

5.2 System Model and Communication Scheme

5.2.1 System and Channel Model

As shown in Fig. 5.1, the considered cooperative relaying system consists of a SN S , a DN D and K ($K \geq 1$) RNs R_k , $k = 1, 2, \dots, K$. Due to the long distance or physical obstacles between the SN and DN, there is no direct link between them. We assume that the SN has a constant power supply, while the RNs have tight energy constraints as they have no embedded power supply. Thus, the RNs need to be first

charged up before forwarding the information to the DN. Similar to [130], we assume that there exists a PB which is responsible for transferring energy to the RN through RF signals. All nodes are assumed to be equipped with single antenna and work in a half-duplex mode. Furthermore, each RN is assumed to be equipped with an information buffer and can temporarily store the messages received from the SN.

Similar to [119], time is divided into slots with equal duration T and a block fading channel is assumed in which the channels between any two nodes are constant during a time slot T and change independently from one time slot to the next. We assume that the channels of the $S - R_k$, $R_k - D$ and PB-to- R_k ($PB - R_k$) links experience independent flat Rayleigh fading. Thus the channel gains $h_k[i]$, $g_k[i]$ and $f_k[i]$ of the $S - R_k$, $R_k - D$ and $PB - R_k$ links during the i th time slot are exponentially distributed random variables with mean values Ω_{sr_k} , Ω_{r_kd} and Ω_{pr_k} , respectively. In addition, the received signals at the receivers are corrupted by the AWGN with zero mean and unit variance.

5.2.2 Communication Scheme

In each time slot, one of the RNs will be selected to either receive source information or forward information to the DN. As each RN possesses a buffer, it can adaptively choose to receive or to transmit information in each time slot. Based on this result, we define two transmission modes:

- *SN-IT mode*: The SN transmits information to R_k if the k th RN is selected. As the SN has a constant power supply, it transmits with a fixed power P_s .
- *RN-HAT mode*: If the k th RN is selected in the i th time slot, the PB first uses a fraction of time $\alpha_{k,i}T$ to transfer energy to R_k . The transmitting power of

the PB is denoted as P_{pb} . In the remaining time of $(1 - \alpha_{k,i})T$, the RN R_k uses all the harvested energy to forward the information stored in its buffer.

For a buffer-aided cooperative relaying system with multiple RNs, the joint RN-and-link selection scheme has been proven to be an effective method to improve system reliability [70, 131]. Inspired by this result, we propose a joint node-and-mode selection scheme which can be implemented through the following two-step method for the considered WPCCN:

1. The SN, PB and DN broadcast reference signals to all the RNs sequentially, and each RN uses these reference signals to estimate the associated channel gains $h_k[i]$, $g_k[i]$ and $f_k[i]$. Based on this information, each RN determines its working mode individually. Then each RN feeds its decision back to the SN. In addition, the fraction of time $\alpha_{k,i}T$ used for energy harvesting is also fed back if the RN-HAT mode is selected.
2. After receiving the feedbacks of the RNs, the SN jointly selects the RN and its transmission mode. This selection result is then broadcasted to all other nodes.

Similar to [123] and [131], we assume that the RNs can obtain perfect CSI by using the reference signals for simplicity. In addition, it is assumed that the feedbacks of the RNs and the selection result of the SN can always be correctly received.

5.2.3 Indicator Variables

To indicate which RN is selected and which working mode the selected RN adopts in the i th time slot, two binary variables $d_{k,i}^{sr} \in \{0, 1\}$ and $d_{k,i}^{rd} \in \{0, 1\}$ are introduced.

More precisely, the values of $d_{k,i}^{sr}$ and $d_{k,i}^{rd}$ are determined by

$$d_{k,i}^{sr} = \begin{cases} 1, & \text{if } R_k \text{ works in SN-IT mode,} \\ 0, & \text{otherwise,} \end{cases} \quad (5.1)$$

and

$$d_{k,i}^{rd} = \begin{cases} 1, & \text{if } R_k \text{ works in RN-HAT mode,} \\ 0, & \text{otherwise,} \end{cases} \quad (5.2)$$

respectively. As only one RN is selected in each time slot, we have $\sum_{k=1}^K (d_{k,i}^{sr} + d_{k,i}^{rd}) = 1$, for $\forall i$. We assume that the SN and RN transmit with fixed rates R_{sr} and R_{rd} , respectively. For fixed-rate transmission, if the achievable rate of the $R_k - D$ link ($S - R_k$ link) is smaller than R_{rd} (R_{sr}), e.g., $\log_2(1 + g_k[i]P_{r_k}[i]) < R_{rd}$ ($\log_2(1 + h_k[i]P_s) < R_{sr}$), where $P_{r_k}[i]$ is the transmitting power of R_k in the i th time slot, then the $R_k - D$ link ($S - R_k$ link) is in outage. Two binary variables $\mathcal{O}_{k,i}^{sr}$ and $\mathcal{O}_{k,i}^{rd}$ are used to indicate whether or not the $S - R_k$ and $R_k - D$ links are in outage in the i th time slot, e.g.,

$$\mathcal{O}_{k,i}^{sr} = \begin{cases} 1, & \text{if the } S - R_k \text{ link is successful,} \\ 0, & \text{otherwise,} \end{cases} \quad (5.3)$$

$$\mathcal{O}_{k,i}^{rd} = \begin{cases} 1, & \text{if the } R_k - D \text{ link is successful,} \\ 0, & \text{otherwise.} \end{cases} \quad (5.4)$$

As we assume a Rayleigh fading channel, the outage probability of the $S - R_k$ link is given by $p_{sk} = 1 - \exp\left(-\frac{2^{R_{sr}} - 1}{\Omega_{sr_k} P_s}\right)$. For the $R_k - D$ link, the value of $\mathcal{O}_{k,i}^{rd}$ depends on $f_k[i]$, $g_k[i]$ and $\alpha_{k,i}$ as the transmitting power $P_{r_k}[i]$ is coupled with $f_k[i]$ and $\alpha_{k,i}$.

5.2.4 Buffer Dynamics

SN-IT mode: If R_k is selected and it works in SN-IT mode ($d_{k,i}^{sr} = 1$), the SN transmits with a fixed rate R_{sr} to R_k . The information stored in the buffer of R_k at the end of the i th time slot is given by

$$L_k[i] = L_k[i - 1] + \mathcal{R}_{sr_k}[i], \quad (5.5)$$

where $\mathcal{R}_{sr_k}[i] = \mathcal{O}_{k,i}^{sr} R_{sr}$. In this chapter, we assume that the buffer size of the RN is sufficiently large and the RN can always store the message received from the SN.

RN-HAT mode: If R_k is selected and it works in RN-HAT mode ($d_{k,i}^{rd} = 1$), R_k first uses a fraction of time $\alpha_{k,i}T$ to harvest energy. By assuming that the noise power can not be harvested, the amount of energy harvested by R_k in the i th time slot can be expressed as

$$E_k[i] = \alpha_{k,i} \eta P_{pb} f_k[i] T, \quad (5.6)$$

where the constant $\eta \in (0, 1)$ is the energy conversion efficiency at the RNs. For notational convenience, the per-slot time duration T is normalized to be one in the sequel. With this normalization, the energy and power are equivalently used throughout this chapter. In the remaining time of duration $(1 - \alpha_{k,i})T$, R_k uses all the harvested energy to forward the information stored in its buffer. The number of bits transmitted

by R_k can be expressed as

$$\mathcal{R}_{r_k d}[i] = \min\{L_k[i-1], R_{r_k d}[i]\}, \quad (5.7)$$

where $R_{r_k d}[i] = (1 - \alpha_{k,i})\mathcal{O}_{k,i}^{rd}R_{rd}$. The $\min\{\cdot\}$ operation results from the fact that the maximum number of bits that can be sent by R_k is limited by the number of bits stored in its buffer. Different from the SN-IT mode, the equivalent rate $R_{r_k d}[i]$ of the RN-HAT mode depends on $f_k[i]$, $g_k[i]$ and the parameter $\alpha_{k,i}$. The information stored in the buffer of R_k at the end of the i th time slot is given by

$$L_k[i] = L_k[i-1] - \mathcal{R}_{r_k d}[i]. \quad (5.8)$$

5.2.5 Throughput of the System

By assuming that the SN always has data to transmit, the average received and transmitted rates of R_k , denoted by τ_{sk} and τ_{kd} , respectively, can be expressed as

$$\begin{aligned} \tau_{sk} &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N d_{k,i}^{sr} \mathcal{R}_{sr_k}[i] \\ &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N d_{k,i}^{sr} \mathcal{O}_{k,i}^{sr} R_{sr} \end{aligned}$$

and

$$\begin{aligned} \tau_{kd} &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N d_{k,i}^{rd} \mathcal{R}_{r_k d}[i] \\ &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N d_{k,i}^{rd} \min\{L_k[i-1], (1 - \alpha_{k,i})\mathcal{O}_{k,i}^{rd}R_{rd}\}, \end{aligned}$$

where N is the number of time slots used by the system. The throughput of the system, which is defined as the average rate received at the DN is given by

$$\begin{aligned}\tau &= \sum_{k=1}^K \tau_{kd} \\ &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{k=1}^K \sum_{i=1}^N d_{k,i}^{rd} \min\{L_k[i-1], \bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd}\},\end{aligned}\quad (5.9)$$

where $\bar{\alpha}_{k,i} = 1 - \alpha_{k,i}$. To maximize the system throughput τ , the values of the variables $d_{k,i}^{sr}$ and $d_{k,i}^{rd}$ should be properly chosen in each time slot.

5.3 Joint Node-and-Mode Selection Scheme

5.3.1 Problem Formulation

To maximize the system throughput, the RN and its working mode should be carefully selected in each time slot. Based on the definition of system throughput, we can form the following optimization problem for $N \rightarrow \infty$ to maximize the system throughput:

$$\begin{aligned}\underset{d_{k,i}^{sr}, d_{k,i}^{rd}, \alpha_{k,i}, \forall i, k}{\text{maximize}} \quad &: \tau = \frac{1}{N} \sum_{k=1}^K \sum_{i=1}^N d_{k,i}^{rd} \mathcal{R}_{rd}[i] \\ \text{s.t.} \quad &\sum_{k=1}^K (d_{k,i}^{sr} + d_{k,i}^{rd}) = 1, \forall i \\ &d_{k,i}^{sr} \in \{0, 1\}, d_{k,i}^{rd} \in \{0, 1\}, \forall k, i \\ &0 \leq \alpha_{k,i} \leq 1, \forall k, i.\end{aligned}\quad (5.10)$$

where $\mathcal{R}_{rd}[i] = \min\{L_k[i-1], R_{rd}[i]\}$ is the transmitting rate of R_k in the i th time slot with $R_{rd}[i] = (1 - \alpha_{k,i}) \mathcal{O}_{k,i}^{rd} R_{rd}$. This problem is difficult to be solved as the

value of $\mathcal{R}_{r_k d}[i]$ depends on the buffer state of R_k . However, it has been shown in [28] and [41] that for systems with a block fading channel, the optimal joint node-and-mode selection scheme that maximizes τ should always make $d_{k,i}^{sr}$ and $d_{k,i}^{rd}$ ergodic stationary processes satisfying $\tau_{sk} = \tau_{kd}$ for $\forall k$. Thus, the optimal values of $d_{k,i}^{sr}$ and $d_{k,i}^{rd}$ should always satisfy the following equation for $N \rightarrow \infty$:

$$\frac{1}{N} \sum_{i=1}^N d_{k,i}^{rd} \mathcal{R}_{r_k d}[i] = \frac{1}{N} \sum_{i=1}^N d_{k,i}^{sr} \mathcal{R}_{sr_k}[i], \forall k. \quad (5.11)$$

In addition, it has been proved in [28] and [41] that by using the optimal joint node-and-mode selection scheme, the event that $Q_k[i-1] < R_{r_k d}[i]$ for $\forall k$ is almost impossible to happen. Thus, it has negligible influence on the system throughput. Hence, the optimal joint node-and-mode selection scheme always satisfies the following equation for $N \rightarrow \infty$:

$$\frac{1}{N} \sum_{i=1}^N d_{k,i}^{rd} \min\{L_k[i-1], R_{r_k d}[i]\} = \frac{1}{N} \sum_{i=1}^N d_{k,i}^{rd} R_{r_k d}[i]. \quad (5.12)$$

Based on (5.11) and (5.12), problem (5.10) can be rewritten as the following equivalent problem:

$$\begin{aligned} \underset{d_{k,i}^{sr}, d_{k,i}^{rd}, \alpha_{k,i}, \forall i, k}{\text{maximize}} & : \frac{1}{N} \sum_{k=1}^K \sum_{i=1}^N d_{k,i}^{rd} \bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd} \\ \text{s.t. C1} & : \frac{1}{N} \sum_{i=1}^N d_{k,i}^{rd} \bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd} = \frac{1}{N} \sum_{i=1}^N d_{k,i}^{sr} \mathcal{O}_{k,i}^{sr} R_{sr}, \forall k \\ \text{C2} & : \sum_{k=1}^K (d_{k,i}^{sr} + d_{k,i}^{rd}) = 1, 0 \leq \alpha_{k,i} \leq 1, \forall k, i \\ \text{C3} & : d_{k,i}^{sr} \in \{0, 1\}, d_{k,i}^{rd} \in \{0, 1\}, \forall k, i. \end{aligned} \quad (5.13)$$

5.3.2 Throughput Maximization

By solving problem (5.13), we obtain the following results:

Lemma 5.1: *The joint node-and-mode selection method that maximizes the throughput of the system is given by*

$$\begin{cases} d_{k,i}^{rd} = 1, & \text{if } (1 - \lambda_k) R_{rd}^{k,m}[i] = \max \mathcal{A}[i], \\ d_{k,i}^{sr} = 1, & \text{if } \lambda_k \mathcal{O}_{k,i}^{sr} R_{sr} = \max \mathcal{A}[i] \text{ AND } R_k \text{ is selected,} \\ d_{k,i}^{rd} = d_{k,i}^{sr} = 0, & \text{otherwise,} \end{cases}$$

for $\forall k$, where $R_{rd}^{k,m}[i] = \max_{\alpha_{k,i}} \{\bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd}\}$ and $\mathcal{A}[i]$ is a set given by

$$\begin{aligned} \mathcal{A}[i] = & \{\lambda_1 \mathcal{O}_{1,i}^{sr} R_{sr}, \lambda_2 \mathcal{O}_{2,i}^{sr} R_{sr}, \dots, \lambda_K \mathcal{O}_{K,i}^{sr} R_{sr}, \\ & (1 - \lambda_1) R_{rd}^{1,m}[i], (1 - \lambda_2) R_{rd}^{2,m}[i], \dots, (1 - \lambda_K) R_{rd}^{K,m}[i]\}. \end{aligned}$$

The parameter λ_k is a decision threshold whose value should be chosen such that the constraint C1 of problem (5.13) is satisfied for $\forall k$.

Proof: Please refer to Appendix D. ■

The following operations can be performed in each time slot at the RNs and SN, respectively, to jointly select the RN and its working mode:

1. After obtaining the associated channel gains $h_k[i]$, $g_k[i]$ and $f_k[i]$, each RN decides whether or not the $S - R_k$ link is in outage and finds out the value of $R_{rd}^{k,m}[i] = \max_{\alpha_{k,i}} \{\bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd}\}$. By comparing the values of $\bar{\lambda}_k R_{rd}^{k,m}[i]$ and $\lambda_k \mathcal{O}_{k,i}^{sr} R_{sr}$, each RN decides which mode to adopt individually. Following this, the decision and the value of $R_{rd}^{k,m}[i]$ is fed back to the SN.

2. Based on the feedbacks from the RNs, the SN selects one RN and determines its transmission mode by using the method of **Lemma 5.1**. The selection result is then broadcasted to all other nodes.

It can be observed that if R_k works in the RN-HAT mode, it always transmits with the maximum equivalent achievable rate $R_{rd}^{k,m}[i]$. As the value of $R_{rd}^{k,m}[i]$ depends on the random variables $f_k[i]$ and $g_k[i]$, $R_{rd}^{k,m}[i]$ is also a random variable, whose expression and distribution are given by the following corollary.

Corollary 5.1: *The maximum equivalent rate $R_{rd}^{k,m}[i]$ of R_k is given by*

$$R_{rd}^{k,m}[i] = \frac{\eta P_{pb} f_k[i] g_k[i] R_{rd}}{\eta P_{pb} f_k[i] g_k[i] + 2^{R_{rd}} - 1}, \quad (5.14)$$

which has a CDF given by

$$F_{R_{rd}^{k,m}}(x) = 1 - \sqrt{\frac{\mu x}{R_{rd} - x}} K_1 \left(\sqrt{\frac{\mu x}{R_{rd} - x}} \right), \quad (5.15)$$

where $\mu = \frac{4(2^{R_{rd}} - 1)}{\eta P_{pb} \Omega_{pr_k} \Omega_{r_k d}}$, $K_1(\cdot)$ is the modified first order Bessel function of second kind.

Proof: To support a fixed transmission rate R_{rd} , the transmitting power of R_k should be no less than $\frac{2^{R_{rd}} - 1}{g_k[i]}$. Otherwise, the R-D link is in outage and the achievable rate of the RN which works in the RN-HAT mode becomes zero. As the transmitting power of R_k is given by $P_{r_k}[i] = \frac{\alpha_{k,i} \eta P_{pb} f_k[i]}{1 - \alpha_{k,i}}$, then we have

$$R_{r_k d}[i] = \begin{cases} 0, & \text{if } \alpha_{k,i} < \frac{2^{R_{rd}} - 1}{\eta P_{pb} f_k[i] g_k[i] + 2^{R_{rd}} - 1}, \\ (1 - \alpha_{k,i}) R_{rd}, & \text{if } \alpha_{k,i} \geq \frac{2^{R_{rd}} - 1}{\eta P_{pb} f_k[i] g_k[i] + 2^{R_{rd}} - 1}. \end{cases}$$

5.3. JOINT NODE-AND-MODE SELECTION SCHEME

It can be observed that the maximal value of $R_{r_k d}[i]$ is achieved when $\alpha_{k,i} = \frac{2^{R_{rd}} - 1}{\eta P_{pb} f_k[i] g_k[i] + 2^{R_{rd}} - 1}$.

Thus, we have $R_{rd}^{k,m}[i] = \frac{\eta P_{pb} f_k[i] g_k[i] R_{rd}}{\eta P_{pb} f_k[i] g_k[i] + 2^{R_{rd}} - 1}$ whose CDF is given by

$$\begin{aligned} F_{R_{rd}^{k,m}}(x) &= \Pr \left(R_{rd}^{k,m}[i] < x \right) \\ &= \Pr \left(f_k[i] g_k[i] < \frac{(2^{R_{rd}} - 1)x}{\eta P_{pb}(R_{rd} - x)} \right). \end{aligned} \quad (5.16)$$

Let $v = \frac{(2^{R_{rd}} - 1)x}{\eta P_{pb}(R_{rd} - x)}$, then we have

$$\begin{aligned} \Pr(f_k[i] g_k[i] < v) &= \int_0^\infty \Pr \left(f_k[i] < \frac{v}{g_k[i]} \right) f_{g_k[i]}(g) dg \\ &= 1 - \frac{1}{\Omega_{r_k d}} \int_0^\infty \exp \left(\frac{-v}{\Omega_{pr_k} g} - \frac{g}{\Omega_{r_k d}} \right) dg \\ &= 1 - \sqrt{\frac{4v}{\Omega_{pr_k} \Omega_{r_k d}}} K_1 \left(\sqrt{\frac{4v}{\Omega_{pr_k} \Omega_{r_k d}}} \right). \end{aligned} \quad (5.17)$$

Substituting $v = \frac{(2^{R_{rd}} - 1)x}{\eta P_{pb}(R_{rd} - x)}$ into (5.17), we can obtain (5.15). ■

By using the transmission scheme of **Lemma 5.1**, we can obtain the maximum long-term achievable throughput of the system as an average over $N \rightarrow \infty$ time slots. However, to obtain the system throughput τ , the value of λ_k for $\forall k$ needs to be determined. In the following, we investigate the condition that the optimal value of λ_k needs to satisfy.

Lemma 5.2: *The optimal values of λ_k , $\forall k$ can only be 1) Case one: all ones, e.g., $\lambda_1 = \lambda_2 = \dots = \lambda_K = 1$; 2) Case two: all smaller than one, e.g., $0 < \lambda_1 < 1, \dots, 0 < \lambda_K < 1$.*

Proof: It can be observed from the selection criterion given in **Lemma 5.1** that for the case of $\lambda_k > 1$, only the SN-IT mode will be selected for R_k and for the case

of $\lambda_k \leq 0$, only the RN-HAT mode will be selected for the k th RN. As a result, constraint C1 of (5.13) can not be satisfied for R_k in these two cases. Thus we can conclude that the value of λ_k must satisfy $0 < \lambda_k \leq 1$ for $\forall k$.

Without loss of generality, we assume that $\lambda_1 = 1$ while the others satisfy $0 < \lambda_k < 1$ ($k \geq 2$). For this assumption, as we have $R_{rd}^{k,m}[i] > 0$, it can be observed that R_1 will never be chosen to forward information to the DN according to **Lemma 5.1**. On the other hand, as we have $\lambda_1 > \lambda_k$, the probability of choosing R_1 to receive information from the SN is a positive value. As a result, it is impossible to make R_1 satisfy constraint C1 of (5.13). Thus this assumption can not hold. For the other cases which do not satisfy **Lemma 5.2**, we can show that constraint C1 of (5.13) can not be satisfied by using a similar method. Thus we conclude that the optimal λ_k can either be all ones or all smaller than one. ■

5.3.3 Optimal Condition and Selection Method for Case One

Optimal condition

To determine whether the optimal values of λ_k for $\forall k$ are all ones, we need to figure out the existence of a joint node-and-mode selection method satisfying **Lemma 5.1** as well as the KKT condition when $\lambda_k = 1$ for $\forall k$. By assuming that *Case one* holds, we have

$$\mathcal{A}[i] = \{\mathcal{O}_{1,i}^{sr} R_{sr}, \dots, \mathcal{O}_{K,i}^{sr} R_{sr}, 0R_{rd}^{1,m}[i], \dots, 0R_{rd}^{K,m}[i]\}.$$

According to **Lemma 5.1**, the system should work in the SN-IT mode if there exists a RN that is not in outage. For the case that there are more than one RN that can

successfully receive source information, any one of them can be selected to receive information. To satisfy the requirement that $d_{k,i}^{sr}$ is an ergodic stationary process, we give each RN a probability to be chosen to receive in this case. For a system with K RNs, there are $2^K - 1$ non-empty decoding sets Ψ_n , $n = 1, 2, \dots, 2^K - 1$. Here, a decoding set is defined as a set of RNs that can successfully decode the source message, e.g., $\Psi_n = \{R_1, R_2\}$ if R_1 and R_2 are not in outage. The probability for the decoding set to be Ψ_n can be expressed as

$$\Pr\{\Psi_n\} = \prod_{R_k \in \Psi_n} \bar{p}_{sk} \prod_{R_k \notin \Psi_n} p_{sk}, \quad (5.18)$$

where p_{sk} is the outage probability of the $S - R_k$ link and $\bar{p}_{sk} = 1 - p_{sk}$. For the n th decoding set, we denote the probability of selecting R_k to receive information as $p_{n,k}$. Note that: 1) $p_{n,k} = 0$ if $R_k \notin \Psi_n$, 2) $p_{n,k} = 1$ if $\Psi_n = \{R_k\}$, 3) $\sum_{k=1}^K p_{n,k} = 1$ and $0 \leq p_{n,k}$.

Remark: As a block fading channel mode is assumed, we have that $\mathcal{O}_{k,i}^{sr}$ for $\forall k$ is an ergodic stationary process. Thus, by giving each RN of a decoding set Ψ_n a probability $p_{n,k}$ to be selected to receive information, $d_{k,i}^{sr}$ of **Lemma 5.1** also becomes an ergodic stationary process. Thus the optimal conditions given in [28] are satisfied.

Based on this method, the long-term average received rate of R_k is given by

$$\tau_{sk} = R_{sr} \sum_{n=1}^{2^K-1} \Pr\{\Psi_n\} p_{n,k}, \quad (5.19)$$

for *Case one*. We denote the sequence of probabilities as a tuple given by

$$\mathcal{P} = (p_{1,1}, p_{1,2}, \dots, p_{1,K}, p_{2,1}, p_{2,2}, \dots, p_{2,K}, \dots, p_{2^K-1,1}, p_{2^K-1,2}, \dots, p_{2^K-1,K}). \quad (5.20)$$

For a specific $\mathcal{P}$, the achievable rates of the S-R link can be expressed as $\mathcal{R}_{sr}(\mathcal{P}) = (\tau_{s1}, \tau_{s2}, \dots, \tau_{sK})$. Then the achievable rate region of S-R link is given by $\mathcal{C}_{sr} \triangleq \bigcup_{\mathcal{P}} \mathcal{R}_{sr}(\mathcal{P})$, which is the union over all the achievable rate tuples $\mathcal{R}_{sr}(\mathcal{P})$.

When all the S-R links are in outage, according to **Lemma 5.1**, we can set any one of $d_{k,i}^{sr}$ and $d_{k,i}^{rd}$ to be 1 in this case ($\lambda_k = 1$). Similarly, we denote the rates of R-D links as $\mathcal{R}_{rd}(\mathcal{S}) = (\tau_{1d}, \tau_{2d}, \dots, \tau_{Kd})$, where $\mathcal{S}$ denotes the possible strategy used to select a specific RN and its working mode when all the S-R links are in outage. The achievable rate region of the R-D link is given by $\mathcal{C}_{rd} \triangleq \bigcup_{\mathcal{S}} \mathcal{R}_{rd}(\mathcal{S})$.

Different from the S-R link in which a selection strategy can be represented by a probability sequence $\mathcal{P}$, it is difficult to give an expression for $\mathcal{S}$. To determine the region of $\mathcal{C}_{rd}$, we first characterize the boundary of $\mathcal{C}_{rd}$. A commonly used method to find the boundary of $\mathcal{C}_{rd}$ is to solve a sequence of weighted sum rate maximization problems, each for a different weight vector. Let $\boldsymbol{\omega} = [\omega_1, \omega_2, \dots, \omega_K]$ denote the weight vector, where ω_k is the “rate reward” for τ_{kd} . The components of the weight vector need to satisfy $0 \leq \omega_k \leq 1$ and $\sum_{k=1}^K \omega_k = 1$. The weighted sum rate maximization problem which determines the boundary of $\mathcal{C}_{rd}$ can thus be expressed as

$$\begin{aligned}
 & \max_{d_{k,i}^{rd}, \forall k,i} \sum_{k=1}^K \omega_k \tau_{kd} \\
 & s.t. \quad \sum_{k=1}^K d_{k,i}^{rd} \leq 1 \\
 & \quad d_{k,i}^{rd} \in \{0, 1\}, \forall k, i.
 \end{aligned} \tag{5.21}$$

When *Case one* holds, the average transmitted rate of the k th RN can be expressed

as

$$\tau_{kd} = \left(\prod_{k=1}^K p_{sk} \right) \frac{1}{N} \sum_{i=1}^N d_{k,i}^{rd} R_{rd}^{k,m}[i]. \quad (5.22)$$

Substituting (5.22) into (5.21), the optimal strategy that maximizes problem (5.21) can be obtained as

$$\mathcal{S}^*(\boldsymbol{\omega}) = \begin{cases} d_{k,i}^{rd} = 1, & \text{if } \omega_k R_{rd}^{k,m}[i] = \max \mathcal{B}[i], \\ d_{k,i}^{rd} = 0, & \text{otherwise,} \end{cases} \quad (5.23)$$

where $\mathcal{B}[i] = \{\omega_1 R_{rd}^{1,m}[i], \omega_2 R_{rd}^{2,m}[i], \dots, \omega_K R_{rd}^{K,m}[i]\}$. For a specific weight vector $\boldsymbol{\omega}$, by using the method given by (5.23), we can get a point $\mathcal{R}_{rd}(\boldsymbol{\omega}) = (\tau_{1d}, \tau_{2d}, \dots, \tau_{Kd})$ which lies on the boundary of $\mathcal{C}_{rd}$. All the boundary points form the boundary curve $l = \bigcup_{\boldsymbol{\omega}} \mathcal{R}_{rd}(\boldsymbol{\omega})$.

Corollary 5.2: *Given a strategy $\mathcal{S}^*(\boldsymbol{\omega})$ and the corresponding boundary point $\mathcal{R}_{rd}(\boldsymbol{\omega})$, any rate point $\mathcal{R}_{rd} = (p\tau_{1d}, p\tau_{2d}, \dots, p\tau_{Kd})$ with $0 \leq p \leq 1$, which lies in the line segment formed by the origin point $(0, \dots, 0)$ and $\mathcal{R}_{rd}(\boldsymbol{\omega})$ can be achieved by using the following strategy $\mathcal{S}$:*

$$\begin{cases} d_{k,i}^{rd} = 1, & \text{if } \omega_k R_{rd}^{k,m}[i] = \max \mathcal{B}[i] \text{ AND } \mathcal{C} = 1, \\ d_{k,i}^{rd} = 0, & \text{otherwise,} \end{cases} \quad (5.24)$$

where $\mathcal{C}$ is a random variable with $\Pr\{\mathcal{C} = 1\} = p$.

Based on **Corollary 5.2**, the achievable rate region $\mathcal{C}_{rd}$ can be obtained as the convex hull formed by the point $\mathcal{R}_{rd} = (0, \dots, 0)$ and all the boundary points, that

Figure 5.2: The regions of $\mathcal{C}_{sr}$ and $\mathcal{C}_{rd}$ for the two RNs system: (a) $\mathcal{C}_{sr} \cap \mathcal{C}_{rd} \neq \emptyset$; (b) $\mathcal{C}_{sr} \cap \mathcal{C}_{rd} = \emptyset$.

is $\mathcal{C}_{rd} = \bigcup_{\omega} \text{Conv}((0, \dots, 0), \mathcal{R}_{rd}(\omega))$.

Illustrative example: We consider a system with two RNs R_1 and R_2 . For this system setup, assuming that the optimal values of λ_1 and λ_2 are one, we have $\mathcal{A}[i] = \{\mathcal{O}_{1,i}^{sr} R_{sr}, \mathcal{O}_{2,i}^{sr} R_{sr}, 0R_{rd}^{1,m}[i], 0R_{rd}^{2,m}[i]\}$. The possible non-empty decoding sets are given by $\Psi_1 = \{R_1\}$; $\Psi_2 = \{R_2\}$; $\Psi_3 = \{R_1, R_2\}$. If the decoding set is Ψ_1 , R_1 should be selected to receive. If the decoding set is Ψ_2 , R_2 should be selected to receive. If Ψ_3 is the decoding set, we denote the probability of choosing R_1 and R_2 to receive information as $p_{3,1}$ and $p_{3,2}$ ($p_{3,1} + p_{3,2} = 1$), respectively. According to (5.18) and (5.19), the received rates of R_1 and R_2 are given by

$$\tau_{s1} = p_{s2} \bar{p}_{s1} R_{sr} + \bar{p}_{s1} \bar{p}_{s2} p_{3,1} R_{sr}$$

and

$$\tau_{s2} = p_{s1} \bar{p}_{s2} R_{sr} + \bar{p}_{s1} \bar{p}_{s2} p_{3,2} R_{sr},$$

respectively. Thus, as illustrated by Fig. 5.2, the region of $\mathcal{C}_{sr} = (\tau_{s1}, \tau_{s2})$ is the line

segment formed by $\tau_{s1} + \tau_{s2} = (1 - p_{s1}p_{s2})R_{sr}$, $\tau_{s1} \geq p_{s2}\bar{p}_{s1}R_{sr}$ and $\tau_{s2} \geq p_{s1}\bar{p}_{s2}R_{sr}$.

When both the $S - R_1$ and $S - R_2$ links are in outage, by solving problem (5.21) for the scenario of $K = 2$, we can obtain the following strategy

$$\begin{cases} d_{1,i}^{rd} = 1, d_{2,i}^{rd} = 0, & \text{If } \omega_1 R_{rd}^{1,m}[i] \geq \omega_2 R_{rd}^{2,m}[i], \\ d_{1,i}^{rd} = 0, d_{2,i}^{rd} = 1, & \text{If } \omega_1 R_{rd}^{1,m}[i] < \omega_2 R_{rd}^{2,m}[i], \end{cases} \quad (5.25)$$

which gives the values of the boundary points $\tau_{1d}(\boldsymbol{\omega})$ and $\tau_{2d}(\boldsymbol{\omega})$ as

$$\tau_{1d}(\boldsymbol{\omega}) = p_{s1}p_{s2}\mathbb{E} \left(R_{rd}^{1,m}[i] | \omega_1 R_{rd}^{1,m}[i] \geq \omega_2 R_{rd}^{2,m}[i] \right),$$

and

$$\tau_{2d}(\boldsymbol{\omega}) = p_{s1}p_{s2}\mathbb{E} \left(R_{rd}^{2,m}[i] | \omega_1 R_{rd}^{1,m}[i] < \omega_2 R_{rd}^{2,m}[i] \right),$$

respectively, where $\mathbb{E} \left(R_{rd}^{1,m}[i] | \omega_1 R_{rd}^{1,m}[i] \geq \omega_2 R_{rd}^{2,m}[i] \right)$ denotes the conditional expectation of $R_{rd}^{1,m}[i]$ given the condition of $\omega_1 R_{rd}^{1,m}[i] \geq \omega_2 R_{rd}^{2,m}[i]$. Then, as illustrated by Fig. 5.2, the region of $\mathcal{C}_{rd}$ can be found as $\mathcal{C}_{rd} = \bigcup_{\boldsymbol{\omega}} \text{Conv}((0, 0), (\tau_{1d}(\boldsymbol{\omega}), \tau_{2d}(\boldsymbol{\omega})))$. After getting $\mathcal{C}_{sr}$ and $\mathcal{C}_{rd}$, we have the following result:

Theorem 5.1: *If the condition $\mathcal{C}_{sr} \cap \mathcal{C}_{rd} \neq \emptyset$ is satisfied, the optimal values of λ_k , for $\forall k$, are all ones and the throughput of the system is given by $\tau = \left(1 - \prod_{k=1}^K p_{sk}\right) R_{sr}$. Otherwise the optimal value of λ_k should satisfy $0 < \lambda_k < 1$ for $\forall k$.*

Proof: If the condition $\mathcal{C}_{sr} \cap \mathcal{C}_{rd} \neq \emptyset$ holds, we can always find a point $\mathcal{R}_{sr}(\mathcal{P}) = \mathcal{R}_{rd}(\mathcal{S}) \in \mathcal{C}_{sr} \cap \mathcal{C}_{rd}$, i.e., a pair of strategy $(\mathcal{P}, \mathcal{S})$ satisfying constraint C1 of (5.13). As the strategy pair $(\mathcal{P}, \mathcal{S})$ is obtained based on **Lemma 5.1** under the assumption of $\lambda_k = 1$ for $\forall k$, it maximizes the system throughput and the optimal value of λ_k

should be one. Based on the fact that when *Case one* holds, the system should work in SN-IT mode if there exists a S-R link that is not in outage, the throughput of the system can thus be obtained as $\tau = \left(1 - \prod_{k=1}^K p_{sk}\right) R_{sr}$. If $\mathcal{C}_{sr} \cap \mathcal{C}_{rd} = \emptyset$, then it is impossible to find a pair of strategy $(\mathcal{P}, \mathcal{S})$ satisfying constraint C1 of (5.13) for *Case one*. Thus, according to **Lemma 5.2**, λ_k should satisfy $0 < \lambda_k < 1$ in this case. ■

Optimal transmission scheme for case one

If *Case one* holds, we can always find a point $\mathcal{R}_{sr}(\mathcal{P}) = \mathcal{R}_{rd}(\mathcal{S}) = (\tau_{1d}^0, \tau_{2d}^0, \dots, \tau_{Kd}^0) \in \mathcal{C}_{sr} \cap \mathcal{C}_{rd}$. The corresponding optimal joint node-and-mode selection method achieving this rate point can be found through the following process:

- If the decoding set Ψ_n is non-empty, give the k th RN a probability $p_{n,k}$ to receive source information, where the value of $p_{n,k}$ is the one given in $\mathcal{P}$.
- If all S-R links are in outage, the optimal policy can be found by using the following two steps: 1) Find the intersection point between the line, which is formed by the origin $(0, \dots, 0)$ and $\mathcal{R}_{sr}(\mathcal{P}) = (\tau_{1d}^0, \tau_{2d}^0, \dots, \tau_{Kd}^0)$, and the boundary curve $l = \bigcup_{\omega} \mathcal{R}_{rd}(\omega)$ through solving the following equation:

$$\begin{cases} \frac{\tau_{1d}^0}{\tau_{1d}^0} = \frac{\tau_{2d}^0}{\tau_{2d}^0} \dots = \frac{\tau_{Kd}^0}{\tau_{Kd}^0}, \\ l = \bigcup_{\omega} \mathcal{R}_{rd}(\omega). \end{cases}$$

- 2) Denote the intersection point as $\mathcal{R}_{rd}^I = (\tau_{1d}^I, \tau_{2d}^I, \dots, \tau_{Kd}^I)$, then the following strategy

$$\begin{cases} d_{k,i}^{rd} = 1, & \text{if } \omega_k R_{rd}^{k,m}[i] = \max \mathcal{B}[i] \text{ AND } \mathcal{C} = 1, \\ d_{k,i}^{rd} = 0, & \text{otherwise,} \end{cases}$$

achieves the rate point $\mathcal{R}_{rd} = (\tau_{1d}^0, \tau_{2d}^0, \dots, \tau_{Kd}^0)$, where $\mathcal{C}$ is a random variable with $\Pr\{\mathcal{C} = 1\} = \tau_{1d}^0/\tau_{1d}^I$ and ω_k is the k th component of the weight vector $\boldsymbol{\omega}$.

As illustrated by case (a) of Fig. 5.2, there may exist more than one rate point lying in the region $\mathcal{C}_{sr} \cap \mathcal{C}_{rd}$ and each corresponds to a joint node-and-mode selection method. As all these methods achieve the same system throughput $(1 - p_{s1}p_{s2})R_{sr}$, they are all optimal schemes.

5.3.4 Optimal Condition and Selection Method for Case Two

Optimal condition

As have been proved in **Theorem 5.1**, *Case two* holds when $\mathcal{C}_{sr} \cap \mathcal{C}_{rd} = \emptyset$. To find out the optimal selection scheme for *Case two*, the value of λ_k should be obtained. Based on **Lemma 5.1**, the average received and transmitted rates of R_k are given by

$$\tau_{sk} = \Pr\{d_{k,i}^{sr} = 1\} R_{sr}$$

and

$$\tau_{kd} = \Pr\{d_{k,i}^{rd} = 1\} \mathbb{E}\left(R_{rd}^{k,m}[i] | d_{k,i}^{rd} = 1\right),$$

respectively, for *Case two*, where

$$\Pr\{d_{k,i}^{sr} = 1\} = \Pr\{\lambda_k R_{sr} = \max \mathcal{A}[i]\}$$

and

$$\Pr \{d_{k,i}^{rd} = 1\} = \Pr \left\{ (1 - \lambda_k) R_{rd}^{k,m}[i] = \max \mathcal{A}[i] \right\}.$$

As the optimal value of λ_k should make $\tau_{sk} = \tau_{kd}$, $\forall k$, we can get the optimal value of λ_k by jointly solving the K equations.

Illustrative example: Similarly, we consider a system with two RNs, then we have $\mathcal{A}[i] = \{\lambda_1 \mathcal{O}_{1,i}^{sr} R_{sr}, \lambda_2 \mathcal{O}_{2,i}^{sr} R_{sr}, \bar{\lambda}_1 R_{rd}^{1,m}[i], \bar{\lambda}_2 R_{rd}^{2,m}[i]\}$, where $\bar{\lambda}_1 = 1 - \lambda_1$ and $\bar{\lambda}_2 = 1 - \lambda_2$ for *Case two*. As the expressions of $\Pr\{d_{k,i}^{sr} = 1\}$ and $\Pr\{d_{k,i}^{rd} = 1\}$ depend on the relative values of λ_k , they need to be calculated separately for the following three cases: 1) $\lambda_1 > \lambda_2$, 2) $\lambda_1 < \lambda_2$, 3) $\lambda_1 = \lambda_2$.

For the case of $\lambda_1 > \lambda_2$, according to **Lemma 5.1**, we have

$$\tau_{s1} = \bar{p}_{s1} \prod_{k=1}^2 F_{R_{rd}^{k,m}}(\lambda_1 R_{sr} / \bar{\lambda}_k) R_{sr} \quad (5.26)$$

and

$$\tau_{s2} = p_{s1} \bar{p}_{s2} \prod_{k=1}^2 F_{R_{rd}^{k,m}}(\lambda_1 R_{sr} / \bar{\lambda}_k) R_{sr}, \quad (5.27)$$

where $F_{R_{rd}^{k,m}}(x)$ is the CDF of $R_{rd}^{k,m}[i]$. The values of τ_{1d} and τ_{2d} can be obtained as

$$\begin{aligned} \tau_{1d} = & \bar{p}_{s1} \mathbb{E} \left(R_{rd}^{1,m}[i] | \bar{\lambda}_1 R_{rd}^{1,m}[i] \geq \max\{\bar{\lambda}_2 R_{rd}^{2,m}[i], \lambda_1 R_{sr}\} \right) \\ & + \bar{p}_{s2} p_{s1} \mathbb{E} \left(R_{rd}^{1,m}[i] | \bar{\lambda}_1 R_{rd}^{1,m}[i] \geq \max\{\bar{\lambda}_2 R_{rd}^{2,m}[i], \lambda_2 R_{sr}\} \right), \\ & + p_{s1} p_{s2} \mathbb{E} \left(R_{rd}^{1,m}[i] | \bar{\lambda}_1 R_{rd}^{1,m}[i] \geq \bar{\lambda}_2 R_{rd}^{2,m}[i] \right) \end{aligned} \quad (5.28)$$

and

$$\begin{aligned}
 \tau_{2d} = & \bar{p}_{s1} \mathbb{E} \left(R_{rd}^{2,m}[i] | \bar{\lambda}_2 R_{rd}^{2,m}[i] \geq \max\{\bar{\lambda}_1 R_{rd}^{1,m}[i], \lambda_1 R_{sr}\} \right) \\
 & + \bar{p}_{s2} p_{s1} \mathbb{E} \left(R_{rd}^{2,m}[i] | \bar{\lambda}_2 R_{rd}^{2,m}[i] \geq \max\{\bar{\lambda}_1 R_{rd}^{1,m}[i], \lambda_2 R_{sr}\} \right) \\
 & + p_{s1} p_{s2} \mathbb{E} \left(R_{rd}^{2,m}[i] | \bar{\lambda}_2 R_{rd}^{2,m}[i] \geq \bar{\lambda}_1 R_{rd}^{1,m}[i] \right), \tag{5.29}
 \end{aligned}$$

respectively. Similarly, we can get the values of τ_{sk} and τ_{kd} ($\forall k$) for the case of $\lambda_1 < \lambda_2$. By using a two dimensional searching method, we can find a pair of λ_1 and λ_2 satisfying $\tau_{s1} = \tau_{1d}$ and $\tau_{s2} = \tau_{2d}$.

For the case of $\lambda_1 = \lambda_2 = \lambda$, the values of τ_{1d} and τ_{2d} are given by

$$\begin{aligned}
 \tau_{1d} = & \overline{p_{s1} p_{s2}} \mathbb{E} \left(R_{rd}^{1,m}[i] | \bar{\lambda} R_{rd}^{1,m}[i] \geq \max\{\bar{\lambda} R_{rd}^{2,m}[i], \lambda R_{sr}\} \right) \\
 & + p_{s1} p_{s2} \mathbb{E} \left(R_{rd}^{1,m}[i] | R_{rd}^{1,m}[i] \geq R_{rd}^{2,m}[i] \right) \tag{5.30}
 \end{aligned}$$

and

$$\begin{aligned}
 \tau_{2d} = & \overline{p_{s1} p_{s2}} \mathbb{E} \left(R_{rd}^{2,m}[i] | \bar{\lambda} R_{rd}^{2,m}[i] \geq \max\{\bar{\lambda} R_{rd}^{1,m}[i], \lambda R_{sr}\} \right) \\
 & + p_{s1} p_{s2} \mathbb{E} \left(R_{rd}^{2,m}[i] | R_{rd}^{2,m}[i] \geq R_{rd}^{1,m}[i] \right), \tag{5.31}
 \end{aligned}$$

respectively, where $\bar{\lambda} = 1 - \lambda$ and $\overline{p_{s1} p_{s2}} = 1 - p_{s1} p_{s2}$. If both RNs can successfully decode source information and the condition $\lambda R_{sr} > \max\{\bar{\lambda} R_{rd}^{1,m}[i], \bar{\lambda} R_{rd}^{2,m}[i]\}$ is satisfied, according to **Lemma 5.1**, we can choose any one of the RNs to receive information. In this case, we give R_1 and R_2 the probabilities p_c ($0 \leq p_c \leq 1$) and $\bar{p}_c = 1 - p_c$, respectively, to receive information. Thus, the values of τ_{s1} and τ_{s2} are

given by

$$\tau_{s1} = \bar{p}_{s1}(p_{s2} + \bar{p}_{s2}p_c) \prod_{k=1}^2 F_{R_{rd}^{k,m}}(\lambda R_{sr}/\bar{\lambda}_k) R_{sr} \quad (5.32)$$

and

$$\tau_{s2} = \bar{p}_{s2}(p_{s1} + \bar{p}_{s1}\bar{p}_c) \prod_{k=1}^2 F_{R_{rd}^{k,m}}(\lambda R_{sr}/\bar{\lambda}_k) R_{sr}, \quad (5.33)$$

respectively. To satisfy $\tau_{s1} = \tau_{1d}$ and $\tau_{s2} = \tau_{2d}$ simultaneously, the value of p_c should satisfy $\frac{\tau_{1d}}{\tau_{2d}} = \frac{\bar{p}_{s1}(p_{s2} + \bar{p}_{s2}p_c)}{\bar{p}_{s2}(p_{s1} + \bar{p}_{s1}\bar{p}_c)}$. Based on these results, we can use a one dimensional searching method to find the optimal value of λ which makes $\tau_{sk} = \tau_{kd}$ ($k = 1, 2$). After finding out the optimal values of λ_1 and λ_2 , we can obtain the optimal joint node-and-mode selection method.

Optimal transmission scheme for case two

Here we also take a two-RN system as an example.

- If the optimal values of λ_1 and λ_2 satisfy $\lambda_1 > \lambda_2$ ($\lambda_1 < \lambda_2$), the optimal joint node-and-mode selection method is given by **Lemma 5.1**.
- If the optimal values of λ_1 and λ_2 satisfy $\lambda_1 = \lambda_2 = \lambda$, the optimal joint node-and-mode selection method is given as follows: Let the k th RN forward information if it satisfies $(1 - \lambda)R_{rd}^{k,m}[i] = \max \mathcal{A}[i]$. Otherwise, let R_1 (R_2) to receive source information if we have $\mathcal{O}_{1,i}^{sr} = 1$ and $\mathcal{O}_{2,i}^{sr} = 0$ ($\mathcal{O}_{1,i}^{sr} = 0$ and $\mathcal{O}_{2,i}^{sr} = 1$). Assign R_1 and R_2 with probabilities p_c and $\bar{p}_c$, respectively, to receive source information if we have $\mathcal{O}_{1,i}^{sr} = 1$ and $\mathcal{O}_{2,i}^{sr} = 1$, where the value of p_c should satisfy $\frac{\tau_{1d}}{\tau_{2d}} = \frac{\bar{p}_{s1}(p_{s2} + \bar{p}_{s2}p_c)}{\bar{p}_{s2}(p_{s1} + \bar{p}_{s1}\bar{p}_c)}$.

Similarly, for arbitrary number of RNs, the optimal value of λ_k can be obtained by using the searching method. However, this method has a high complexity and it is difficult to obtain a closed-form expression for the system throughput τ as well. Thus, to provide some insights, in the following, we investigate two special systems, namely, the single RN system and the multiple RNs system with a symmetric channel.

5.3.5 Special Cases

Single RN system

For notational simplicity, we omit the subscript k of $d_{k,i}^{sr}$, $\alpha_{k,i}$, etc., for the single RN system in the following. As there is just one RN, only the working mode of the RN needs to be determined and **Lemma 5.1** can be rewritten as:

$$\begin{cases} d_i^{sr} = 1, \text{ if } (1 - \lambda)R_{rd}^m[i] \leq \lambda \mathcal{O}_i^{sr} R_{sr}, \\ d_i^{rd} = 1, \text{ if } (1 - \lambda)R_{rd}^m[i] \geq \lambda \mathcal{O}_i^{sr} R_{sr}. \end{cases} \quad (5.34)$$

Let $\bar{R}_{rd}^m = \mathbb{E}(R_{rd}^m[i])$ denote the average value of $R_{rd}^m[i]$, then we can get the following results.

Theorem 5.2: *If the condition $p_{sr}\bar{R}_{rd}^m \geq (1 - p_{sr})R_{sr}$ is satisfied, the optimal mode adaptation method is given by*

$$\begin{cases} d_i^{rd} = 1, \text{ if } \mathcal{O}_i^{sr} = 0 \text{ AND } \mathcal{C} = 1, \\ d_i^{sr} = 1, \text{ otherwise,} \end{cases} \quad (5.35)$$

where p_{sr} is the outage probability of the S-R link and $\mathcal{C}$ is a random variable with $\Pr(\mathcal{C} = 1) = \frac{(1-p_{sr})R_{sr}}{p_{sr}\bar{R}_{rd}^m}$. The throughput of the system is given by $\tau = (1 - p_{sr})R_{sr}$.

Proof: By assuming that the optimal value of λ is 1, according to (5.34), we have $d_i^{sr} = 1$ if $O_i^{sr} = 1$. Thus, the achievable rate of the S-R link is given by $\mathcal{C}_{sr} = (1 - p_{sr})R_{sr}$. When $O_i^{sr} = 0$, the equation $(1 - \lambda)R_{rd}^m[i] = \lambda O_i^{sr} R_{sr}$ always holds and either d_i^{sr} or d_i^{rd} could be set as 1. By solving problem (5.21) for a single RN case, we have $0 \leq \mathcal{C}_{rd} \leq p_{sr}\overline{R}_{rd}^m$. To make the assumption $\lambda = 1$ hold, we have $\mathcal{C}_{sr} \cap \mathcal{C}_{rd} \neq \emptyset$, which results in $p_{sr}\overline{R}_{rd}^m \geq (1 - p_{sr})R_{sr}$. To satisfy the constraint C1 of (5.13), we set the probability of $d_i^{rd} = 1$ to be p_c when $O_i^{sr} = 0$. Then we can get

$$\frac{1}{N} \sum_{i=1}^N d_i^{rd} R_{rd}^m[i] = p_c p_{sr} \overline{R}_{rd}^m \quad (5.36)$$

and

$$\frac{1}{N} \sum_{i=1}^N d_i^{sr} O_i^{sr} R_{sr} = (1 - p_{sr})R_{sr}. \quad (5.37)$$

To satisfy the KKT condition, we have $p_c p_{sr} \overline{R}_{rd}^m = (1 - p_{sr})R_{sr}$, which results in $p_c = \frac{(1-p_{sr})R_{sr}}{p_{sr}\overline{R}_{rd}^m}$. The throughput of the system is thus given by $\tau = (1 - p_{sr})R_{sr}$ in this case. ■

Remark: The mode adaptation method given in **Theorem 5.2** is applicable to a system in which the outage probability of the S-R link is high. For this system, the maximum achievable rate $(1 - p_{sr})R_{sr}$ of S-R link is a small value. As a result, the S-R link becomes system bottleneck and the system chooses SN-IT mode once the S-R link is successful. When the S-R link is in outage, the RN forwards information to the DN in a fraction $p_c = \frac{(1-p_{sr})R_{sr}}{p_{sr}\overline{R}_{rd}^m}$ of the time slot. In the rest fraction $(1 - p_c)$ of time slot, the RN keep silence (neither transmit nor receive information) to save energy. In practical systems in which information delay is an important issue, the

RN can also choose to always transmit when the S-R link is in outage to reduce the information delay at the RN.

Theorem 5.3: *If the condition $p_{sr}\bar{R}_{rd}^m < (1 - p_{sr})R_{sr}$ is satisfied, the optimal mode adaptation method is given by*

$$\begin{cases} d_i^{sr} = 1, \text{ if } \mathcal{O}_i^{sr} = 1 \text{ AND } R_{rd}^m[i] < \mu R_{sr}, \\ d_i^{rd} = 1, \text{ otherwise,} \end{cases} \quad (5.38)$$

where the value of μ satisfies the following equation:

$$\frac{p_{sr}\bar{R}_{rd}^m}{\bar{p}_{sr}} + \int_{\mu R_{sr}}^{\infty} x f_{R_{rd}^m}(x) dx = F_{R_{rd}^m}(\mu R_{sr}) R_{sr}, \quad (5.39)$$

in which $\bar{p}_{sr} = 1 - p_{sr}$ and $f_{R_{rd}^m}(x) = dF_{R_{rd}^m}(x)/dx$ is the PDF of $R_{rd}^m[i]$. The system throughput is given by $\tau = \bar{p}_{sr}F_{R_{rd}^m}(\mu R_{sr}) R_{sr}$.

Proof: If the condition $p_{sr}\bar{R}_{rd}^m < (1 - p_{sr})R_{sr}$ is satisfied, according to **Theorem 5.1**, the optimal value of λ should satisfy $0 < \lambda < 1$. Let $\mu = \lambda/(1 - \lambda)$, then equation (5.34) can be rewritten as (5.38). By using the method of (5.38), we have

$$\frac{1}{N} \sum_{i=1}^N d_i^{rd} R_{rd}^m[i] = p_{sr}\bar{R}_{rd}^m + \bar{p}_{sr} \int_{\mu R_{sr}}^{\infty} x f_{R_{rd}^m}(x) dx \quad (5.40)$$

and

$$\frac{1}{N} \sum_{i=1}^N d_i^{sr} \mathcal{O}_i^{sr} R_{sr} = \bar{p}_{sr} F_{R_{rd}^m}(\mu R_{sr}) R_{sr}. \quad (5.41)$$

To satisfy the KKT condition, we can obtain (5.39). The system throughput is $\tau = \bar{p}_{sr}F_{R_{rd}^m}(\mu R_{sr}) R_{sr}$ in this case. ■

Remark: The mode adaptation method given in **Theorem 5.3** is applicable to a system whose outage probability p_{sr} of S-R link is relatively low. To maximize the efficiency of each time slot (maximize the system throughput), the method of (5.38) allows the S-R link to transmit when $\mathcal{O}_i^{sr} = 1$ and the value of $R_{rd}^m[i]$ is small ($R_{rd}^m[i] < \mu R_{sr}$). While if the value of $R_{rd}^m[i]$ is relatively large or the S-R link is in outage, it is more efficient to let the R-D link to deliver information.

Multiple RNs system with a symmetric channel

Before investigating the throughput of the system which has a symmetric channel quality, we first give the following lemma:

Lemma 5.3: *For any two RNs R_{k_1} and R_{k_2} ($k_1 \neq k_2$), if the conditions $\Omega_{sr_{k_1}} = \Omega_{sr_{k_2}}$, $\Omega_{pr_{k_1}} = \Omega_{pr_{k_2}}$ and $\Omega_{r_{k_1}d} = \Omega_{r_{k_2}d}$ are satisfied, then we have $\lambda_{k_1} = \lambda_{k_2}$.*

Proof: If the conditions $\Omega_{sr_{k_1}} = \Omega_{sr_{k_2}}$, $\Omega_{pr_{k_1}} = \Omega_{pr_{k_2}}$ and $\Omega_{r_{k_1}d} = \Omega_{r_{k_2}d}$ are satisfied, we have 1) the outage probabilities of the $S - R_{k_1}$ and $S - R_{k_2}$ links are identical; 2) $R_{rd}^{k_1,m}[i]$ and $R_{rd}^{k_2,m}[i]$ have the same distribution. Based on these results and assuming that $\lambda_{k_1} > \lambda_{k_2}$, according to the optimal selection method of **Lemma 5.1**, we have that the probability of selecting the $S - R_{k_1}$ link to deliver information is larger than that of selecting the $S - R_{k_2}$ link, e.g., $\Pr\{d_{k_1,i}^{sr} = 1\} > \Pr\{d_{k_2,i}^{sr} = 1\}$. On the other hand, as $R_{rd}^{k_1,m}[i]$ and $R_{rd}^{k_2,m}[i]$ have the same distribution, the $R_{k_2} - D$ link is more likely to be selected to deliver information than the $R_{k_1} - D$ link. Thus we have $\tau_{sr_{k_1}} > \tau_{sr_{k_2}}$ and $\tau_{r_{k_1}d} < \tau_{r_{k_2}d}$. Based on these results, if the condition $\tau_{sr_{k_1}} = \tau_{r_{k_1}d}$ is satisfied, we always have $\tau_{sr_{k_2}} < \tau_{r_{k_2}d}$, which means that it is impossible for R_{k_2} to satisfy constraint C1. Thus, $\lambda_{k_1} > \lambda_{k_2}$ can not hold for the optimal joint node-and-mode selection method. Similarly, it can be shown that $\lambda_{k_1} < \lambda_{k_2}$ can not make

$\tau_{sr_{k_1}} = \tau_{r_{k_1}d}$ and $\tau_{sr_{k_2}} = \tau_{r_{k_2}d}$ hold simultaneously. Hence we have $\lambda_{k_1} = \lambda_{k_2}$. $\blacksquare$

For the system with a symmetric channel, we have $p_{sr} = p_{sk}$ and $f_{R_{rd}^{k,m}}(x) = f_{R_{rd}^m}(x)$ for $\forall k$, with $f_{R_{rd}^{k,m}}(x)$ being the PDF of $R_{rd}^{k,m}[i]$. According to **Lemma 5.3**, we have $\lambda_1 = \lambda_2 \cdots = \lambda_K = \lambda$ in this case. Define $p_{sr}^o = (p_{sr})^K$, $R_{rd}^m[i] = \max\{R_{rd}^{1,m}[i], R_{rd}^{2,m}[i], \dots, R_{rd}^{K,m}[i]\}$ and $\bar{R}_{rd}^m = \mathbb{E}(R_{rd}^m[i])$, then we have the following result:

Theorem 5.4: *For the system with a symmetric channel, if the condition $\bar{p}_{sr}^o R_{sr} > p_{sr}^o \bar{R}_{rd}^m$ is satisfied, then the system throughput is given by $\tau = \bar{p}_{sr}^o F_{R_{rd}^m}(\mu R_{sr}) R_{sr}$, where $\bar{p}_{sr}^o = 1 - p_{sr}^o$ and $F_{R_{rd}^m}(x) = \left(F_{R_{rd}^{k,m}}(x)\right)^K$ is the CDF of R_{rd}^m . The value of μ satisfies the following equation:*

$$\int_{\mu R_{sr}}^{\infty} x f_{R_{rd}^m}(x) dx + \frac{p_{sr}^o \bar{R}_{rd}^m}{\bar{p}_{sr}^o} = F_{R_{rd}^m}(\mu R_{sr}) R_{sr}, \quad (5.42)$$

where $f_{R_{rd}^m}(x) = dF_{R_{rd}^m}(x)/dx$ is the PDF of $R_{rd}^m[i]$.

Proof: We assume that $0 < \lambda < 1$. For a symmetric channel system, according to **Lemma 5.1**, there are two kinds of events in which the k th ($\forall k$) RN will be chosen to forward information: 1) All S-R links are in outage and $R_{rd}^{k,m}[i] = R_{rd}^m[i]$; 2) There exists at least one S-R link that is successful and the conditions $R_{rd}^{k,m}[i] = R_{rd}^m[i]$ and $(1 - \lambda)R_{rd}^{k,m}[i] > \lambda R_{sr}$ are satisfied.

Based on these observations and the fact that $\Pr\{R_{rd}^{k,m}[i] = R_{rd}^m[i]\} = \frac{1}{K}$ for a symmetric channel system, we have

$$\Pr\{d_{k,i}^d = 1\} = \frac{p_{sr}^o}{K} + \frac{\bar{p}_{sr}^o}{K} \bar{F}_{R_{rd}^m}(\mu R_{sr}), \forall k, \quad (5.43)$$

where $\mu = \lambda/(1 - \lambda)$ and $\bar{F}_{R_{rd}^m}(x) = 1 - F_{R_{rd}^m}(x)$. Thus, all RNs have an identical

output throughput which is given by

$$\tau_{kd} = \frac{\bar{p}_{sr}^o}{K} \int_{\mu R_{sr}}^{\infty} x f_{R_{rd}^m}(x) dx + \frac{p_{sr}^o \bar{R}_{rd}^m}{K}. \quad (5.44)$$

Since all RNs have the same output throughput, to satisfy constrain C1 of (5.13), we give each RN in a non-empty decoding set the same probability to receive source information if the condition $(1 - \lambda)R_{rd}^m[i] < \lambda R_{sr}$ is satisfied. Thus, the probability of choosing the k th RN to receive information is given by

$$\begin{aligned} \Pr\{d_{k,i}^{sr} = 1\} &= F_{R_{rd}^m}(\mu R_{sr}) \sum_{k=0}^{K-1} \binom{K-1}{k} \frac{(\bar{p}_{sr})^{k+1} (p_{sr})^K}{(k+1)(p_{sr})^{k+1}} \\ &= \frac{\bar{p}_{sr}^o}{K} F_{R_{rd}^m}(\mu R_{sr}). \end{aligned} \quad (5.45)$$

As a result, the input throughput of each RN is given by

$$\tau_{sk} = \frac{\bar{p}_{sr}^o}{K} F_{R_{rd}^m}(\mu R_{sr}) R_{sr}. \quad (5.46)$$

To satisfy $\tau_{sk} = \tau_{kd}$ for $\forall k$, equation (5.42) must hold. In addition, it can be observed that τ_{sk} is a monotonic increasing function of λ (as $\mu = \lambda/(1 - \lambda)$) while τ_{kd} is a monotonic decreasing function of λ . Moreover, we have $\lim_{\lambda \rightarrow 1} \tau_{sk} = \frac{\bar{p}_{sr}^o R_{sr}}{K}$, $\lim_{\lambda \rightarrow 1} \tau_{kd} = \frac{p_{sr}^o \bar{R}_{rd}^m}{K}$ for $\forall k$. Thus, to find a $\lambda \in (0, 1)$ making $\tau_{sk} = \tau_{kd}$ for $\forall k$, the condition $\bar{p}_{sr}^o R_{sr} > p_{sr}^o \bar{R}_{rd}^m$ must be satisfied. ■

Remark: For a multiple RNs system with a symmetric channel, each RN achieves identical input and output throughput by using the optimal transmission scheme. Thus, (5.42) ensure that the KKT condition is satisfied for all RNs. Based on this observation, we can treat the multiple RNs system with a symmetric channel as K

equivalent single RN systems, in which the input and output throughputs of each RN are given by $\frac{\bar{p}_{sr}^o}{K} F_{R_{rd}^m}(\mu R_{sr}) R_{sr}$ and $\frac{\bar{p}_{sr}^o}{K} \int_{\mu R_{sr}}^{\infty} x f_{R_{rd}^m}(x) dx + \frac{p_{sr}^o \bar{R}_{rd}^m}{K}$, respectively. This explains the similarity between the forms of **Theorem 5.4** and **Theorem 5.3**.

Corollary 5.3: *For a symmetric channel system with $\bar{p}_{sr}^o R_{sr} > p_{sr}^o \bar{R}_{rd}^m$, the following joint node-and-mode selection scheme achieves the maximum system throughput, where the value of λ makes $\mu = \lambda/(1 - \lambda)$ satisfy (5.42):*

- *If the condition $(1 - \lambda) R_{rd}^m[i] = \max \mathcal{A}[i]$ is satisfied, choose the k th RN with $R_{rd}^{k,m}[i] = R_{rd}^m[i]$ to forward information. Otherwise, randomly select a RN in the decoding set in a uniform manner to receive SN information.*

Proof: If the condition $\bar{p}_{sr}^o R_{sr} > p_{sr}^o \bar{R}_{rd}^m$ holds, we have $\lambda \in (0, 1)$ according to the proof of **Theorem 5.4**. Based on this result, it can be shown that the average input and output rates of each RN are given by (5.46) and (5.44), respectively. As the value of λ makes $\mu = \lambda/(1 - \lambda)$ satisfy (5.42), the method of **Corollary 5.3** satisfies $\tau_{sk} = \tau_{kd}$ for $\forall k$ and achieves a system throughput $\tau = \bar{p}_{sr}^o F_{R_{rd}^m}(\mu R_{sr}) R_{sr}$. ■

Remark: Similar to the single RN scenario, the scheme of **Corollary 5.3** allows the S-R link to transmit when $\mathcal{O}_i^{sr} = 1$ and the maximum equivalent transmission rate of the R-D link is small ($R_{rd}^m[i] < \mu R_{sr}$) to maximize system throughput. In addition, **Corollary 5.3** always selects the RN R_k with maximal equivalent transmission rate ($R_{rd}^{k,m}[i] = R_{rd}^m[i]$) to transmit, which further increases the efficiency of each time slot.

Theorem 5.5: *For the system with a symmetric channel, if the condition $\bar{p}_{sr}^o R_{sr} \leq p_{sr}^o \bar{R}_{rd}^m$ is satisfied, then the throughput of the system is given by $\tau = \bar{p}_{sr}^o R_{sr}$.*

Proof: For a symmetric channel system with $\bar{p}_{sr}^o R_{sr} \leq p_{sr}^o \bar{R}_{rd}^m$, it is impossible to find a $\lambda \in (0, 1)$ that satisfies $\tau_{sk} = \tau_{kd}$ for $\forall k$ according to **Theorem 5.4**. Thus the value of λ can only be 1 based on the results of **Lemma 5.2**. In this case, the system

always works in SN-IT mode if there exists a RN that is not in outage. Thus, the system throughput is given by $\tau = \bar{p}_{sr}^o R_{sr}$. ■

Corollary 5.4: *For a symmetric channel system with $\bar{p}_{sr}^o R_{sr} \leq p_{sr}^o \bar{R}_{rd}^m$, the following joint node-and-mode selection scheme achieves the maximum system throughput:*

- *If the decoding set is non-empty $\Psi_n \neq \emptyset$, the system should randomly select a RN in the decoding set in a uniform manner to receive SN information. Otherwise, it should choose the k th RN to forward information if the conditions $R_{rd}^{k,m}[i] = R_{rd}^m[i]$ and $\mathcal{C} = 1$ are satisfied, where $\mathcal{C}$ is a random variable with $\Pr\{\mathcal{C} = 1\} = \bar{p}_{sr}^o R_{sr} / p_{sr}^o \bar{R}_{rd}^m$.*

Proof: For a symmetric channel system with $\bar{p}_{sr}^o R_{sr} \leq p_{sr}^o \bar{R}_{rd}^m$, we have $\lambda = 1$. Thus, the system works in SN-IT mode if there exists a RN that is not in outage. For each non-empty decoding set $\Psi_n \neq \emptyset$, if we randomly select a RN of Ψ_n in a uniform manner to receive SN information, we have

$$\tau_{sk} = \bar{p}_{sr} \sum_{k=0}^{K-1} \binom{K-1}{k} \frac{R_{sr} (\bar{p}_{sr})^k (p_{sr})^K}{(k+1) (p_{sr})^{k+1}} = \frac{\bar{p}_{sr}^0 R_{sr}}{K}, \forall k. \quad (5.47)$$

On the other hand, as we have $\Pr\{R_{rd}^{k,m}[i] = R_{rd}^m[i]\} = \frac{1}{K}$, by using the method of **Corollary 5.4**, the output throughput of the RNs is given by $\tau_{kd} = \frac{p_{sr}^0 \bar{R}_{rd}^m}{K} \Pr\{\mathcal{C} = 1\} = \frac{\bar{p}_{sr}^0 R_{sr}}{K}$. Thus, the method of **Corollary 5.4** satisfies $\tau_{sk} = \tau_{kd}$ for $\forall k$ and achieves a system throughput $\tau = \sum_{k=1}^K \tau_{kd} = \bar{p}_{sr}^0 R_{sr}$. ■

Remark: Similar to **Theorem 5.2**, the method given in **Corollary 5.4** is applicable to systems in which the outage probability p_{sr} of the S-R links is high, which makes the S-R link the bottleneck of the system and the system chooses SN-IT mode once any one the S-R link is successful.

5.4 Numerical Results and Discussion

In the following, we present some numerical results to evaluate the performance of the proposed transmission scheme. We set the noise power at both the RNs and DN as $\sigma^2 = -80\text{dBm}$. Similar to [130], the path loss levels of all the S-R and R-D links are set as $L_{sr} = L_{rd} = -70\text{dB}$, which corresponds to a distance of around 100 meters for a typical micro-cellular network. The path loss of the PB-R links is set as $L_{pbr} = -40\text{dB}$. The energy harvesting efficiency is set as $\eta = 0.5$.

We first investigate the single RN system and evaluate the performance of the proposed adaptive transmission scheme. In Fig. 5.3, the average throughput τ of the proposed transmission scheme in a single RN system is provided. For comparisons, the performance of the conventional DF-based wireless-powered relaying scheme used in [132] is also presented. For the conventional DF-based relaying scheme, there is no buffer at the RN and the information is forwarded to the DN once it is successfully decoded. Specifically, in the scheme of [132], a fraction of time $\alpha_i T$ is first used for transferring energy from the PB to the RN. The remaining time $(1 - \alpha_i)T$ is used for information transmission, such that the SN delivers information to the RN in the first block time $(1 - \alpha_i)T/2$ and the RN forwards information to DN by using all the harvested energy in the remaining time $(1 - \alpha_i)T/2$. The maximum achievable rate of this scheme in the i th time slot can be expressed as $\tau_i^m = \max_{\alpha_i} \min \left\{ \frac{1 - \alpha_i}{2} \mathcal{O}_i^{sr} R_{sr}, \frac{1 - \alpha_i}{2} \mathcal{O}_i^{rd} R_{rd} \right\}$. Based on this result, the long-term average throughput of the conventional scheme is thus given by $\tau_c = \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N \tau_i^m$.

For the analytical results of the proposed scheme presented in Fig. 5.3, we first find out the optimal mode adaptation method by verifying whether or not the condition $p_{sr} \bar{R}_{rd}^m \geq (1 - p_{sr}) R_{sr}$ holds. If the optimal mode adaptation method is the one given

Figure 5.3: Performance comparisons for the wireless-powered relaying system with and without a buffer-aided relay, $R_{sr} = R_{rd} = 1\text{bps/Hz}$, $P_{pb} = 40\text{dBm}$ and $K = 1$.

in equation (5.35), then we have $\tau = (1 - p_{sr})R_{sr}$. If the optimal mode adaptation method is the one given in equation (5.38), we then find the optimal value of λ numerically by using a bisection searching method and the throughput of the system is given by $\tau = \bar{p}_{sr} F_{R_{rd}^m} \left(\frac{\lambda R_{sr}}{1-\lambda} \right) R_{sr}$. The simulation results provided in Fig. 5.3 for the proposed scheme are obtained by using the optimal mode selection scheme given in **Theorem 5.2** and **Theorem 5.3** in which the values of λ are set as those obtained by using the numerical searching method. It can be observed that the analytical results coincide with the simulation results. In addition, compared with the conventional scheme used in [132], the proposed adaptive mode selection scheme achieves a higher average throughput.

In Fig. 5.4, we present the throughput of the proposed scheme for a single RN

Figure 5.4: Performance of the wireless-powered buffer-aided relaying system with different transmission rates, $P_{pb} = 40\text{dBm}$, $K = 1$.

system with different system parameters. For the system with $\Omega_{sr} = \Omega_{rd} = \Omega_{pr} = 1$, it can be verified that the optimal mode adaptation method is the one given in equation (5.35) when $P_s \leq -10\text{dBm}$ for the rate pairs $(R_{sr} = 1, R_{rd} = 1)$ and $(R_{sr} = 1, R_{rd} = 2)$. Thus, the systems with these rate pairs achieve the same throughput if $P_s \leq -10\text{dBm}$. When it satisfies $P_s > -10\text{dBm}$, the optimal mode adaptation method is the one given in equation (5.38) and the system with $(R_{sr} = 1, R_{rd} = 2)$ achieves a higher throughput as the throughput of the R-D link is improved by increasing R_{rd} from 1 to 2. Comparing the throughput of the systems with rate pairs $(R_{sr} = 2, R_{rd} = 1)$ and $(R_{sr} = 1, R_{rd} = 1)$, it can be observed that for $P_s \leq -10\text{dBm}$, the system with $(R_{sr} = 1, R_{sr} = 1)$ has a higher throughput. This can be explained as follows: (i) For $P_s \leq -10\text{dBm}$, the optimal mode adaptation

Figure 5.5: Throughput of the wireless-powered buffer-aided relaying system with different number of relay nodes, $\Omega_{sr_k} = \Omega_{r_kd} = \Omega_{pr_k} = 1$, $R_{sr} = R_{rd} = 1\text{bps/Hz}$.

method is the one given in equation (5.35) and the throughput is determined by the S-R link. (ii) The system with $R_{sr} = 2$ has a higher outage probability in the S-R link as compared with the system with $R_{sr} = 1$. For $P_s \geq -6\text{dBm}$, the outage probability of the S-R link is small and the optimal mode adaptation method is the one given in equation (5.38), the system with $(R_{sr} = 2, R_{sr} = 1)$ can achieve a higher throughput. For the system with $\Omega_{sr} = 2$ and $\Omega_{rd} = \Omega_{pr} = 1$, the optimal mode adaptation method is the one given in equation (5.35) when $P_s \leq -14\text{dBm}$ for the rate pairs $(R_{sr} = 1, R_{rd} = 1)$ and $(R_{sr} = 1, R_{rd} = 2)$. Thus, the systems with these parameters achieve the same throughput for $P_s \leq -14\text{dBm}$. In addition, the system with $\Omega_{sr} = 2$ and $\Omega_{rd} = \Omega_{pr} = 1$ achieves a higher throughput than that of the system with $\Omega_{sr} = \Omega_{rd} = \Omega_{pr} = 1$ as the channel quality of the S-R link is improved.

5.4. NUMERICAL RESULTS AND DISCUSSION

Figure 5.6: Performance of the wireless-powered buffer-aided relaying system with asymmetric channel qualities, $K = 2$, $[\Omega_{sr1}, \Omega_{r1d}, \Omega_{pr1}] = [0.8, 1, 1.2]$, $[\Omega_{sr2}, \Omega_{r2d}, \Omega_{pr2}] = [1.2, 0.8, 1.5]$ and $R_{sr} = R_{rd} = 1\text{bps/Hz}$.

In Fig. 5.5, we present the performance of the proposed scheme for a multiple RNs system with a symmetric channel. It can be observed that when $P_s \leq -14\text{dBm}$, the systems with $P_{pb} = 40\text{dBm}$ and $P_{pb} = 30\text{dBm}$ achieve the same throughput as the S-R link is the bottleneck of these two systems for P_s in this region. In addition, as the number of RNs increases, the throughput of the system is improved. Fig. 5.5 also shows that the throughput improvement decreases as the number of RNs increases. For system with $P_{pb} = 40\text{dBm}$, the throughput improvement becomes negligible when $K \geq 3$ and $P_s \geq -10\text{dBm}$.

In Fig. 5.6, a system with an asymmetric channel is investigated. The number of RNs is set as $K = 2$. By assuming that $\lambda_k = 1$ for $\forall k$, Fig. 5.6 (a) and (b) present

Figure 5.7: Throughput of the wireless-powered buffer-aided relaying system with finite buffer size, $\Omega_{sr_k} = \Omega_{r_kd} = \Omega_{pr_k} = 1$, $R_{sr} = R_{rd} = 1\text{bps/Hz}$.

$\mathcal{C}_{sr}$ which is a line segment and the boundary $l = \bigcup_{\omega} \mathcal{R}_{rd}(\omega)$ of $\mathcal{C}_{rd}$. From Fig. 5.6 (a), it can be observed that for $P_{pb} = 30\text{dBm}$, $\mathcal{C}_{sr} \cap \mathcal{C}_{rd} \neq \emptyset$ if $P_s \leq -13\text{dBm}$, thus the system throughput is given by $\tau = (1 - p_{s1}p_{s2})R_{sr}$ when $P_s \leq -13\text{dBm}$. Fig. 5.6 (b) shows that for $P_{pb} = 40\text{dBm}$, $\mathcal{C}_{sr} \cap \mathcal{C}_{rd} \neq \emptyset$ holds if $P_s \leq -12\text{dBm}$, thus the S-R link is the bottleneck of the system ($\tau = (1 - p_{s1}p_{s2})R_{sr}$) when $P_s \leq -12\text{dBm}$. Fig. 5.6 (c) gives the system throughput for different P_s . It can be observed that when $P_s \leq -13\text{dBm}$, the two systems have the same throughput as the S-R link is the bottleneck of the both systems. For the system with $P_{pb} = 30\text{dBm}$ ($P_{pb} = 40\text{dBm}$), when $P_s > -13\text{dBm}$ ($P_s > -12\text{dBm}$), the optimal values of λ_1 and λ_2 are found by using a two dimensional searching method. Based on these optimal values of λ_1 and λ_2 , the simulation results are obtained by using the joint mode-and-node selection

method given by **Lemma 5.1**.

In Fig. 5.7, we investigate the influence of the buffer size on the system throughput. The joint node-and-mode selection method used here is identical to the one adopted in the system with infinite buffer size except for the case that the buffer of the RN is full. If the buffer is full, the SN stops receiving information in the following time slot(s). The buffer size of each RN shown in Fig. 5.7 is normalized by the transmission rate of the S-R link and is measured as $Q_{\max} = LR_{sr}$. It can be observed from Fig. 5.7 that as the buffer size increases, the throughput of the system with finite buffer size approaches that of the system with infinite buffer size. When $Q_{\max} \geq 30R_{sr}$, similar throughput can be achieved for the systems with finite and infinite buffer sizes.

5.5 Conclusion

In this chapter, we have studied a WPCCN which consists of a SN, multiple RNs and a DN. The RNs have no embedded power supply and are powered by a PB. By assuming that each RN possesses a buffer, we proposed a joint node-and-mode selection scheme in which a single RN and its transmission mode are jointly selected in each time slot. The optimal joint node-and-mode selection scheme that maximizes system throughput was investigated. In addition, for the single RN system and the multiple RNs systems with symmetric channels, the system throughput was obtained in closed-form expressions and the corresponding optimal joint node-and-mode selection scheme was provided. By comparing with the conventional WPCCNs without buffer at the RNs, we have shown that the throughput of a WPCCN can be improved by using the proposed adaptive transmission schemes.

Chapter 6

Wireless-Powered Relaying System with Buffer-Aided Hybrid Relay

In this chapter, we extend the idea of opportunistic transmission of buffer-aided relaying to a WPCCN which consists of a RF-powered SN, a buffer-aided hybrid RN and a DN. We assume that the hybrid RN has an information buffer and treat the battery of the SN as an energy queue. As a result, the system involves two coupled queues, namely, the energy queue and the information queue. Based on this model, we propose two block-wise cooperative protocols, i.e., the BW-HaT protocol and the BW-MA protocol, and investigate the maximum achievable throughput of these two protocols. For the BW-HaT protocol, the system throughput is obtained in a closed-form expression. For the BW-MA protocol, the optimal mode adaptation method that maximizes system throughput is presented. It is shown that by simultaneously transmitting information and energy to the DN and SN, respectively, the proposed transmission schemes can significantly increase the system throughput.

6.1 Introduction

In existing works on WPCN, two transmitting schemes, namely the HAT scheme and the harvest-store-and-transmit (HSAT) scheme, are generally adopted by the RF-powered nodes. In the HAT scheme which was adopted in [37, 122, 123], the RF-powered nodes use the harvested energy to transmit information once the energy harvesting process is terminated. Thus, the HAT scheme can be treated as a charging-discharging process which can be realized by simple electrical circuits. Different from the HAT scheme, the HSAT scheme, which is adopted in [125, 127, 128], allows the nodes to accumulate the energy they have harvested, e.g., the harvested energy can be stored for future use. As a result, the HSAT scheme requires the nodes to be equipped with an energy accumulating and storage block (battery) [127]. Compared with the HAT scheme, the HSAT scheme uses the harvested energy more efficiently at the expense of increasing the complexity of the energy harvesting nodes. Although existing works [125, 127, 128] on HSAT treated the battery of the RF-powered node as an energy queue, they failed to fully make use of the dynamic property of the wireless channel. Inspired by the buffer-aided relaying scheme, we extend the idea of opportunistic transmission to a WPCCN which consists of a SN, a hybrid RN and a DN. The SN has no embedded power supply and is powered by the RF signal transmitted by the hybrid RN. As RF signal can simultaneously carry information and energy, the RN, which also has an information buffer, transmits information to the DN and delivers energy to the SN at the same time. It is also assumed that the SN is equipped with an energy storage block (battery) and the HSAT scheme is applied. By treating the battery of the SN and the information buffer of the RN as two coupled queues, we

Figure 6.1: A wireless-powered cooperative communication system with a hybrid relay node.

investigate the long-term throughput of two different block-wise cooperative protocols, i.e., the BW-HaT and BW-MA protocols. For the BW-HaT protocol, in which the SN starts to transmit information once enough energy is harvested, the system throughput is obtained in a closed-form expression. For the BW-MA protocol, we assume that the RN knows the CSI of the S-R and R-D links and can adaptively choose which node (the SN or RN) to transmit in each time slot. Based on these assumptions, the optimal mode adaptation method that maximizes the system throughput is presented and the maximum throughput is obtained for different system setups. Theoretical and numerical results show that by simultaneously transmitting information and energy to the DN and SN, respectively, the proposed transmission scheme can significantly increase the system throughput.

6.2 System Model and Assumptions

6.2.1 System Model

As illustrated in Fig. 6.1, we consider a cooperative relaying system in which a SN S communicates with the DN D through the help of an intermediate RN R . It is

assumed that there is no direct link between the SN and DN due to the long distance or physical obstacles between them. All nodes are equipped with single antenna and work in a half-duplex mode. We also assume that the SN has no embedded power supply, e.g., a sensor node, and the hybrid RN has a constant power supply. In this system setup, the RN is not only responsible for forwarding information of the SN to DN, it also acts as the power supply of the SN by charging it via microwave radiation. The SN first harvests energy from the RF signal transmitted by the RN and then it uses the harvested energy to transmit information to the RN. The hybrid RN uses the DF method to forward the message to the DN. As RF signal can simultaneously carry information and power, the RN also transmits power to the SN while it forwards information to the DN.

Remark: The proposed system can be viewed as a sensor network in which the sensor nodes are powered by a dedicated PB (R). As the sensor nodes are energy constraint and cannot transmit with a relatively high power level, they deliver the collected data to the PB which is close to them. The PB collects sensor nodes' data and acts as a RN to forward it to a data center (i.e., the DN).

In this chapter, the following assumptions are adopted:

- Compared to the power used for signal transmission, the processing power of the transmit and receive circuitry at the SN and RN is negligible [117].
- The SN and RN transmit with fixed powers P_s and P_r , respectively. Thus, the SN needs to harvest sufficient energy before it sends message to the RN.
- The SN and RN transmit with fixed rates R_{sr} and R_{rd} , respectively, which is suitable for the system that requires a low processing complexity, e.g., a system using a fixed coding and modulation scheme.

- It is also assumed that the information buffer of the RN and the battery storage capacity of the SN are sufficiently large. With this assumption, the asymptotic throughput of the system is obtained.

6.2.2 Channel Model

Similar to [119], we adopt the block-fading channel model, i.e., the channel coefficient between any two nodes is assumed to be a constant within a time slot duration T and changes independently from one time slot to the next. The channel responses of the S-R and R-D links are characterized by large-scale path loss and independent small-scale fading. By denoting the distances between the S-R and R-D links as d_{sr} and d_{rd} , respectively, the fading channel gains of the S-R and R-D links in the i th time slot can be expressed as $h_{sr}(i) = \varphi G_{sr}(i)(d_{sr}/d_0)^{-\alpha}$ and $h_{rd}(i) = \varphi G_{rd}(i)(d_{rd}/d_0)^{-\alpha}$, respectively, where α is the path-loss factor, φ is the propagation loss measured at the reference distance d_0 , $G_{sr}(i)$ and $G_{rd}(i)$ model the small-scale fading effect. The instantaneous SNRs of the S-R and R-D links can be expressed as $\gamma_{sr}(i) = P_s h_{sr}(i)/\sigma^2$ and $\gamma_{rd}(i) = P_r h_{rd}(i)/\sigma^2$, respectively, where σ^2 is the variance of the AWGN received at the receivers. The average SNRs of the S-R and R-D links are denoted by $\Omega_{sr} = \mathbb{E}[\gamma_{sr}(i)]$ and $\Omega_{rd} = \mathbb{E}[\gamma_{rd}(i)]$, respectively, where $\mathbb{E}[x]$ denotes the expectation of a random variable x .

Due to the relatively short power-transfer distance between the SN and RN, a line-of-sight (LoS) path is likely to exist between them, thus, we use Rician fading to model the channel response of the S-R link. Denote the ratio between the power in direct path and the power in the other scattered paths as K , then the PDF of $\gamma_{sr}(i)$

is given by

$$f(\gamma_{sr}) = \frac{K+1}{\Omega_{sr}} \exp\left(-K - \frac{K+1}{\Omega_{sr}}\gamma_{sr}\right) \times I_0\left(2\sqrt{\frac{K(K+1)\gamma_{sr}}{\Omega_{sr}}}\right), \quad (6.1)$$

where $I_0(\cdot)$ is the modified Bessel function of the first kind with order zero. Different from the S-R link, we assume that channel of the R-D link experiences Rayleigh fading. Thus, $\gamma_{rd}(i)$ is exponentially distributed with the following PDF:

$$f(\gamma_{rd}) = \frac{1}{\Omega_{rd}} \exp\left(-\frac{\gamma_{rd}}{\Omega_{rd}}\right). \quad (6.2)$$

6.2.3 Outage Indicator Variables

To facilitate the analysis, we define outage indicators $\mathcal{O}_{sr}(i)$ and $\mathcal{O}_{rd}(i)$ to indicate whether or not the S-R and R-D links are in outage. If the S-R link (R-D link) is successful, then we have $\mathcal{O}_{sr}(i) = 1$ ($\mathcal{O}_{rd}(i) = 1$). Otherwise, we have $\mathcal{O}_{sr}(i) = 0$ ($\mathcal{O}_{rd}(i) = 0$). The probabilities that the S-R and R-D links can successfully transmit an information packet are given by

$$\begin{aligned} p_{sr} &= \int_{2^{R_{sr}}-1}^{\infty} f(\gamma_{sr}) d\gamma_{sr} \\ &= Q_1\left(\sqrt{2K}, \sqrt{\frac{(2^{R_{sr}+1}-2)(K+1)}{\Omega_{sr}}}\right) \end{aligned} \quad (6.3)$$

and

$$p_{rd} = \int_{2^{R_{rd}}-1}^{\infty} f(\gamma_{rd}) d\gamma_{rd} = \exp\left(-\frac{2^{R_{rd}}-1}{\Omega_{rd}}\right), \quad (6.4)$$

respectively, where $Q_1(a, b)$ is the Marcum Q-function with parameters a and b .

6.2.4 Transmission Modes

In each time slot, either the SN or RN transmits. If the SN transmits, an information packet is transmitted from the SN to RN. Otherwise, the RN delivers an information packet to the DN and transfers energy to the SN simultaneously.

RN Transmission

By assuming that the noise power at the SN can not be harvested [119], the amount of energy harvested by the SN in the i th time slot can be expressed as

$$E(i) = \eta P_r h_{sr}(i) T, \quad (6.5)$$

where the constant $\eta \in (0, 1)$ is the energy conversion efficiency at the SN. For notational convenience, the per-slot time duration T is normalized to be one. With this normalization, the values of energy and power become identical and therefore they are used equivalently throughout this chapter. At the end of the i th time slot, the total energy stored in the battery of the SN, denoted by $L_s(i)$, is given by

$$L_s(i) = L_s(i-1) + E(i). \quad (6.6)$$

At the same time, the RN delivers information to the DN. The amount of information transmitted by the RN in the i th time slot is given by

$$R_{rd}(i) = \min\{L_r(i-1), R_{rd}\}, \quad (6.7)$$

where the function $\min\{\cdot\}$ arises from the fact that the information transmitted should be no larger than the amount of information stored in the buffer of the RN. The amount of information stored in the buffer of the RN at the end of the i th time slot is given by

$$L_r(i) = L_r(i-1) - \mathcal{O}_{rd}(i)R_{rd}(i). \quad (6.8)$$

Remark: At the end of the i th time slot, if the DN successfully decodes the message, it sends an acknowledgement to the RN. After receiving the acknowledgement, the RN releases the corresponding part of its buffer. Otherwise, it keeps the information packet in the buffer and the amount of information stored in the RN's buffer remains unchanged, i.e., $L_r(i) = L_r(i-1)$ if the R-D link is in outage.

SN Transmission

We assume that the SN always has information to send, thus, if the energy stored in the SN's battery in the i th time slot satisfies $L_s(i-1) \geq P_s$, the SN can transmit information to the RD. The amount of energy stored in the battery of the SN at the end of the i th time slot is given by

$$L_s(i) = L_s(i-1) - P_s. \quad (6.9)$$

The total information stored in the RN's buffer at the end of the i th time slot is given by

$$L_r(i) = L_r(i-1) + \mathcal{O}_{sr}(i)R_{sr}. \quad (6.10)$$

Transmission Indicator Variable

We introduce a binary variables $d(i) \in \{0, 1\}$ to indicate which node transmits in each time slot. Specifically, $d(i) = 0$ indicates that the SN transmits in the i th time slot and $d(i) = 1$ indicates that the RN transmits.

6.2.5 Performance Metric

We adopt the long-term average throughput as the performance metric. By exploiting $d(i)$ and $\mathcal{O}_{rd}(i)$, the long-term average number of bits that arrive at the DN per time slot is given by

$$\begin{aligned}\tau &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N d(i) \mathcal{O}_{rd}(i) R_{rd}(i) \\ &= \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N d(i) \mathcal{O}_{rd}(i) \min\{L_r(i-1), R_{rd}\},\end{aligned}\tag{6.11}$$

where N is the number of time slots used. In this chapter, we use τ to denote the system throughput. For notational simplicity, we also define

$$\tau_{sr} = \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr}\tag{6.12}$$

and

$$\tau_{rd} = \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N d(i) \mathcal{O}_{rd}(i) R_{rd}.\tag{6.13}$$

In the following sections, we investigate the long-term average throughput of the BW-HaT and BW-MA schemes. The BW-HaT scheme was first proposed in [119], where

the authors investigated the long-term average throughput of a WPCCN with energy constraint RN.

6.3 Throughput Analysis of the BW-HaT Scheme

In this section, the average throughput of the BW-HaT scheme is investigated. In the following, we first present the communication protocol of the BW-HaT scheme.

6.3.1 BW-HaT Protocol

In the BW-HaT protocol, the SN transmits information to the RN once the condition $L_s(i) \geq P_s$ is satisfied. Otherwise, the RN transmits and the SN harvests energy, e.g.,

$$d(i) = \begin{cases} 0 & \text{if } L_s(i) \geq P_s, \\ 1 & \text{if } L_s(i) < P_s. \end{cases} \quad (6.14)$$

To realize this transmission strategy, the SN checks its available energy at the beginning of each time slot. Once there is sufficient energy, it sends 1 bit to the RN to indicate SN transmission. The BW-HaT protocol has the following advantages: 1) It is suitable for the device with a small energy storage capability, e.g., the device with a super capacitor. 2) It does not require the SN to dynamically change the time duration used for information transmission. The SN transmits in a time slot based manner. 3) It requires no CSI at the transmitter side.

6.3.2 Throughput Analysis

Before analyzing the throughput of the BW-HaT scheme, we first characterize the probabilities of SN and RN transmission. For notational simplicity, we use $P_h = \eta P_r \mathbb{E}[h_{sr}(i)]$ to denote the average per time slot harvested energy at the SN. Based on this notation, we can obtain the following lemma.

Lemma 6.1: *The probabilities of SN and RN transmissions are given by $\Pr\{d(i) = 0\} = \frac{P_h}{P_s + P_h}$ and $\Pr\{d(i) = 1\} = \frac{P_s}{P_s + P_h}$, respectively.*

Proof: Please refer to Appendix E. ■

Remark: It can be observed from Lemma 1 that for the BW-HaT scheme, the probabilities for SN and RN transmissions are determined by the parameter $\theta = P_h/P_s$. Increasing the value of θ (decreasing P_s) allocates more time slots for SN transmission while decreasing the value of θ (increasing P_s) allocates more time slots for RN transmission.

Based on **Lemma 6.1**, we can rewrite (6.12) as $\tau_{sr} = \frac{P_h}{P_s + P_h} p_{sr} R_{sr}$ and $\tau_{rd} = \frac{P_s}{P_s + P_h} p_{rd} R_{rd}$, respectively. Then the throughput of the BW-HaT scheme is given by the following theorem:

Theorem 6.1: *The long-term average throughput of the BW-HaT scheme is given by $\tau = \min\{\tau_{sr}, \tau_{rd}\}$.*

Proof: For the case of $\tau_{rd} < \tau_{sr}$, the information buffer of the RN is absorbing. For an absorbing queue, the condition $R_{rd} < L_r(i)$ almost always holds and we have $R_{rd}(i) = \min\{L_r(i-1), R_{rd}\} = R_{rd}$. Thus, we have $\tau = \tau_{rd}$. For the case of $\tau_{rd} \geq \tau_{sr}$, the S-R link becomes the bottleneck of the system. Based on the flow conservation law which reveals that the information departures from the buffer can not exceed the information input to the buffer, we have $\tau = \tau_{sr}$. ■

For the case of $\tau_{rd} < \tau_{sr}$, the information buffer of the RN becomes absorbing and a fraction of the information sent by the SN will be trapped and can never be delivered to the DN. For this case, the following lemma provides a useful indication for system designs.

Lemma 6.2: *For the case of $\tau_{rd} < \tau_{sr}$, we can always increase the transmit power of the SN (P_s) to a certain value P_s^* which makes $\tau_{sr}(P_s^*) = \tau_{rd}(P_s^*)$. The maximum achievable throughput of the system is given by $\tau = \tau_{rd}(P_s^*) = \frac{P_s^*}{P_s^* + P_h} p_{rd} R_{rd}$.*

Proof: It can be observed that τ_{rd} is a monotonic increasing function of P_s and it satisfies $\lim_{P_s \rightarrow \infty} \tau_{rd} = p_{rd} R_{rd}$. In addition, we have $\lim_{P_s \rightarrow \infty} \tau_{sr} = 0 < \lim_{P_s \rightarrow \infty} \tau_{rd}$. For the case of $\tau_{sr}(P_s) > \tau_{rd}(P_s)$, since τ_{sr} and τ_{rd} are continuous functions of P_s , there must be a $P_s^* > P_s$ satisfying the condition $\tau_{sr}(P_s^*) = \tau_{rd}(P_s^*)$. Based on the result that $\tau = \min\{\tau_{sr}, \tau_{rd}\}$, it is easy to check that the maximum achievable rate of the system is given as $\tau = \frac{P_s^*}{P_s^* + P_h} p_{rd} R_{rd}$. ■

Lemma 6.3: *For the case of $P_r \rightarrow \infty$, the optimal value of P_s which maximizes the throughput of the system should satisfy $\frac{P_h}{P_s} = \frac{R_{rd}}{R_{sr}}$.*

Proof: For a fixed $\theta = P_h/P_s$, as $P_r \rightarrow \infty$, we have $p_{sr} = 1$ and $p_{rd} = 1$. As we have $\tau = \min\{\frac{P_h}{P_s + P_h} R_{sr}, \frac{P_s}{P_s + P_h} R_{rd}\}$, the maximum value of τ is achieved when $\frac{P_h}{P_s + P_h} R_{sr} = \frac{P_s}{P_s + P_h} R_{rd}$, which results in $\frac{P_h}{P_s} = \frac{R_{rd}}{R_{sr}}$ after some manipulations. ■

6.4 Throughput Analysis of the BW-MA Scheme

In the BW-HaT scheme, the SN transmits once enough energy is harvested without considering the CSI of the S-R link. If the S-R link is in outage, this part of energy is wasted. In this section, we assume that the RN can obtain the CSI of the two links at the beginning of each time slot. Based on the CSI, the RN decides which link to

transmit in each time slot. Specifically, the following processes are performed:

- The SN checks its available energy at the start of each time slot. If the available energy is not enough, i.e., $L_s(i) < P_s$, the RN keeps on transmitting and the SN keeps on harvesting energy. Once the condition $L_s(i) \geq P_s$ is satisfied, the SN sends a short reference signal to the RN.
- The RN uses this reference signal to estimate the CSI of the S-R link. If the S-R link is in outage, the RN sends 1 bit to indicate RN transmission and the SN keeps on harvesting energy. Otherwise, it sends 1 bit to the DN to request that the DN sends a reference signal.
- After receiving the reference signal sent by the DN, the RN estimates the CSI of the R-D link. Based on the CSI of the two links, the RN decides which node to transmit and broadcasts its decision to the SN and DN.

Note that the SN may keep on harvesting energy for a sequence of successive time slots in BW-MA scheme even if the condition $L_s(i) \geq P_s$ is satisfied.

6.4.1 Problem Formulation

To maximize the system throughput, the RN should properly choose which node to transmit in each time slot. For the special case that both the S-R and R-D links are in outage, no information can be successfully delivered by both links. Thus, the system should always let the RN transfer energy to the SN in this case, which helps to improve the system throughput. This result is confirmed in the mode adaptation methods derived in the following sections. To find the optimal mode adaptation

scheme that maximize the long-term throughput τ , we formulate the following optimization problem for $N \rightarrow \infty$:

$$\begin{aligned}
 & \max_{d(i), \forall i} \quad \tau \\
 & s.t. \text{ C1 : } \tau \leq \tau_{sr} \\
 & \quad \text{C2 : } d(i) = 1, \text{ if } L_s(i) < P_s \\
 & \quad \text{C3 : } d(i)(1 - d(i)) = 0.
 \end{aligned} \tag{6.15}$$

Constraint C1 of (6.15) results from the flow conservation law. Constraint C2 ensures that the SN transmits only if the condition $L_s(i) \geq P_s$ is satisfied. Constraint C3 ensures $d(i) \in \{0, 1\}$.

6.4.2 Maximum Throughput of the S-R Link

Problem (6.15) is difficult to be solved as it is coupled with the battery state of the SN ($L_s(i)$). In the following, we first find out the maximum achievable throughput of the S-R link and obtain the following optimization problem:

$$\begin{aligned}
 & \max_{d(i), \forall i} \quad \tau_{sr} \\
 & s.t. \text{ C1 : } d(i) = 1, \text{ if } L_s(i) < P_s \\
 & \quad \text{C2 : } d(i)(1 - d(i)) = 0.
 \end{aligned} \tag{6.16}$$

Then we have the following lemma.

Lemma 6.4: *If the condition $p_{sr}P_s < \eta P_r \bar{p}_{sr} \mathbb{E}[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0]$ is satisfied,*

the mode adaptation method that maximizes τ_{sr} is given by

$$d(i) = \begin{cases} 0, & h_{sr}(i) \geq \Gamma_0, \\ 1, & h_{sr}(i) < \Gamma_0, \end{cases}$$

where p_{sr} is given by (6.3) and $\bar{p}_{sr} = 1 - p_{sr}$, $\Gamma_0 = \frac{2^{R_{sr}} - 1}{P_s/\sigma^2}$. The maximum achievable throughput of the S-R link is given by $\tau_{sr}^{\max} = p_{sr}R_{sr}$.

Proof: Without considering the power constraint of the SN, the maximum achievable throughput of the S-R link is $p_{sr}R_{sr}$, which can be achieved by using the method that the SN transmits when the S-R link is not in outage. With this transmission scheme, the SN harvests energy only when the S-R link is in outage and the average harvest energy of the SN is given by $P_{\text{in}} = \eta P_r \bar{p}_{sr} \mathbb{E}[h_{sr}(i) \mid h_{sr}(i) < \Gamma_0]$, where $\Gamma_0 = \frac{2^{R_{sr}} - 1}{P_s/\sigma^2}$ is a threshold (if $h_{sr}(i) < \Gamma_0$, the S-R link is in outage). The average power used by the SN to transmit information is given by $P_{\text{out}} = p_{sr}P_s$. If it satisfies $P_{\text{in}} > P_{\text{out}}$, the battery of the SN is absorbing and the condition $L_s(i) > P_s$ always holds. Thus, the maximum throughput $p_{sr}R_{sr}$ of the S-R link is achieved. ■

For the case of $p_{sr}P_s \geq \eta P_r \bar{p}_{sr} \mathbb{E}[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0]$, some time slots during which the S-R link is not in outage should be used to harvest energy from the RN. Denote the set of indices with $d(i) = 1$ as I and the set of indices with $d(i) = 0$ as $\bar{I}$ for the scenario of $L_s(i) \geq P_s$. Then, for $N \rightarrow \infty$, the average input and output powers of the SN are given by $P_{\text{in}} = \frac{1}{N} \sum_{L_s(i) < P_s} E(i) + \frac{1}{N} \sum_I d(i)E(i)$ and $P_{\text{out}} = \frac{1}{N} \sum_{\bar{I}} (1 - d(i))P_s$, respectively, where $E(i) = \eta P_r h_{sr}(i)$. Based on these observations, we can obtain the following result.

Lemma 6.5: *If the condition $p_{sr}P_s \geq \eta P_r \bar{p}_{sr} \mathbb{E}[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0]$ is satisfied, the optimal mode adaptation method that maximizes the long-term average throughput*

of the S-R link should always make the battery of the SN work at the edge of non-absorbing ($P_{in} = P_{out}$) and the following equation holds for $N \rightarrow \infty$:

$$\frac{1}{N} \sum_{L_s(i) < P_s} E(i) + \frac{1}{N} \sum_I d(i)E(i) = \frac{1}{N} \sum_{\bar{I}} d(i)E(i).$$

Proof: Please refer to Appendix F. ■

Remark: **Lemma 6.5** indicates that the mode adaptation policy that maximizes the throughput of the S-R link almost always makes the battery of the SN be charged up to such a level that the energy stored in the battery exceeds the energy needed for transmitting information. The number of time slots in which the event $L_s(i) < P_s$ occurs is negligible and the event $L_s(i) < P_s$ has a negligible influence on the throughput of the S-R link. Similar results have been obtained in [133].

According to **Lemma 6.5**, the optimal mode adaptation method that maximizes the throughput of the S-R link should be chosen from the set of methods which satisfy $P_{in} = P_{out}$ and make the influence of the event $L_s(i) < P_s$ negligible. Thus, when $N \rightarrow \infty$, problem (6.16) is equivalent to

$$\begin{aligned} & \max_{d(i), \forall i} \quad \frac{1}{N} \sum_{i=1}^N (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr} \\ & s.t. \quad \frac{1}{N} \sum_{i=1}^N d(i)E(i) = \frac{1}{N} \sum_{i=1}^N (1 - d(i))P_s, \\ & \quad \quad d(i)(1 - d(i)) = 0. \end{aligned} \tag{6.17}$$

By solving problem (6.17), we have the following lemma.

Lemma 6.6: *If the condition $p_{sr}P_s \geq \eta P_r \bar{p}_{sr} \mathbb{E}[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0]$ is satisfied,*

Figure 6.2: Mode adaptation region maximizing the throughput of the S-R link.

the mode adaptation method that maximizes τ_{sr} is given by

$$d(i) = \begin{cases} 0, & \Gamma_0 \leq h_{sr}(i) \leq \Gamma_1, \\ 1, & \text{otherwise,} \end{cases}$$

where $\Gamma_0 = \frac{2^{R_{sr}} - 1}{P_s / \sigma^2}$ and the parameter Γ_1 is the solution of the following equation:

$$\int_0^{\Gamma_0} h_{sr} f(h_{sr}) dh_{sr} + \int_{\Gamma_1}^{\infty} h_{sr} f(h_{sr}) dh_{sr} = \frac{P_s}{\eta P_r} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}, \quad (6.18)$$

where $f(h_{sr})$ is the PDF of h_{sr} , which is given as equation (6.1) with γ_{sr} replaced by h_{sr} . The maximum throughput of the S-R link is given by $\tau_{sr}^{\max} = R_{sr} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}$.

Proof: Please refer to Appendix G ■

Remark: It can be observed that $\int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}$ is a monotonic increasing function of Γ_1 . As it is difficult to get a closed-form expression for Γ_1 , we can use a bisection searching method to find Γ_1 numerically.

6.4.3 System throughput with the S-R Link as Bottleneck

In this subsection, the system throughput is investigated for the case that the S-R link is the bottleneck of the system. Based on **Lemma 6.4**, we can obtain the following theorem.

Theorem 6.2: *If the conditions $p_{sr}P_s < \eta P_r \bar{p}_{sr} \mathbb{E}[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0]$ and $p_{sr}R_{sr} \leq p_{rd}\bar{p}_{rd}R_{rd}$ are satisfied, the throughput of the system is given by $\tau = p_{sr}R_{sr}$. The optimal mode adaptation method that achieves this throughput is given by **Lemma 6.4**.*

Proof: If the condition $p_{sr}P_s < \eta P_r \bar{p}_{sr} \mathbb{E}[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0]$ holds, the throughput of the S-R link is maximized by using the mode adaptation method of **Lemma 6.4**. The corresponding average throughput of the R-D link is given as $\tau_{rd} = p_{rd}R_{rd}\bar{p}_{sr}$. If the condition $p_{sr}R_{sr} \leq p_{rd}R_{rd}\bar{p}_{sr}$ is satisfied, we have $\tau_{sr} \leq \tau_{rd}$. Based on the flow conservation law, the average system throughput is thus given by $\tau = \tau_{sr}$ and the optimal mode adaptation method that maximizes the throughput of the system is the one presented in **Lemma 6.4**. This completes the proof. $\blacksquare$

Based on **Lemma 6.6**, we can obtain the following theorem.

Theorem 6.3: *If the conditions*

$$p_{sr}P_s \geq \eta P_r \bar{p}_{sr} \mathbb{E}[h_{sr}(i) \mid h_{sr}(i) \leq \Gamma_0] \quad (6.19)$$

and

$$\frac{R_{sr}}{p_{rd}R_{rd}} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr} \leq 1 - \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}, \quad (6.20)$$

are satisfied, the system throughput is given by $\tau = R_{sr} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}$. The optimal mode adaptation method achieving this throughput is given by **Lemma 6.6**.

Proof: If equation (6.19) is satisfied, then the throughput of the S-R link is maximized by using the mode adaptation method of **Lemma 6.6**. The average throughput of the R-D and S-R links are given by

$$\tau_{rd} = p_{rd} R_{rd} \left(1 - \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr} \right) \quad (6.21)$$

and

$$\tau_{sr} = R_{sr} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}, \quad (6.22)$$

respectively. If equation (6.20) is satisfied, we have $\tau_{sr} \leq \tau_{rd}$. Based on the flow conservation law, the average system throughput is $\tau = \tau_{sr}$ and the optimal mode adaptation method that maximizes the throughput of the system is the one presented in **Lemma 6.6**. ■

6.4.4 System Throughput with the R-D link as Bottleneck

In this subsection, the system throughput is investigated for the case that the R-D link is the bottleneck of the system. We first assume that the RN transmits when $\mathcal{O}_{rd}(i) = 1$. Under this assumption, the maximum achievable rate of the S-R link is given by the following lemma.

Lemma 6.7: *With the constraint that $d(i) = 1$ when $\mathcal{O}_{rd}(i) = 1$, the mode adaptation method that maximizes the throughput of the S-R link is given by*

$$\text{Case one : } d(i) = \begin{cases} 0, & \Gamma_0 \leq h_{sr}(i) \text{ AND } h_{rd}(i) \leq \Gamma'_0, \\ 1, & \text{otherwise,} \end{cases}$$

if the condition $\bar{p}_{rd}p_{sr}P_s < P_r\bar{p}_{sr}\bar{p}_{rd}\mathbb{E}[h_{sr}|h_{sr} < \Gamma_0] + p_{rd}P_h$ is satisfied, where $\Gamma'_0 = \frac{2R_{rd}-1}{P_r/\sigma^2}$ and $\bar{p}_{rd} = 1 - p_{rd}$. The conditional maximum throughput of the S-R link is given by $\tau_{sr}^{\text{cm}} = \bar{p}_{rd}p_{sr}R_{sr}$.

$$\text{Case two : } d(i) = \begin{cases} 0, & \Gamma_0 < h_{sr}(i) < \Gamma_1 \text{ AND } h_{rd}(i) \leq \Gamma'_0, \\ 1, & \text{otherwise,} \end{cases}$$

if the condition $\bar{p}_{rd}p_{sr}P_s \geq P_r\bar{p}_{sr}\bar{p}_{rd}\mathbb{E}[h_{sr}|h_{sr} < \Gamma_0] + p_{rd}P_h$ is satisfied, where the parameter Γ_1 satisfies the following equation:

$$\bar{p}_{rd}\mathbb{E}[h_{sr}|h_{sr} < \Gamma_0] + \bar{p}_{rd}\mathbb{E}[h_{sr}|h_{sr} > \Gamma_1] = \frac{\bar{p}_{rd}P_s}{\eta P_r} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr} - p_{rd}\mathbb{E}[h_{sr}].$$

The conditional maximum throughput of the S-R link is $\tau_{sr}^{\text{cm}} = \bar{p}_{rd}R_{sr} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr})dh_{sr}$.

Proof: Under the constraint that $d(i) = 1$ when $\mathcal{O}_{rd} = 1$, the maximum achievable throughput of the S-R link is $\bar{p}_{rd}p_{sr}R_{sr}$, which can be achieved by using the method that the SN transmits when the S-R link is not in outage (and the R-D link is in outage). With this transmission scheme (as illustrated in case one of Fig. 6.3), the average harvested power of the SN is given by $P_{\text{in}} = P_r\bar{p}_{sr}\bar{p}_{rd}\mathbb{E}[h_{sr}|h_{sr} < \Gamma_0] + p_{rd}P_h$. The average power used by the SN to transmit information is given by $P_{\text{out}} = \bar{p}_{rd}p_{sr}P_s$. If it satisfies $P_{\text{in}} > P_{\text{out}}$, the battery of the SN is absorbing and the condition $L_s(i) > P_s$ is always satisfied. Thus the maximum throughput $\bar{p}_{rd}p_{sr}R_{sr}$ of the S-R link is achieved in this case. If the condition $P_{\text{in}} \leq P_{\text{out}}$ is satisfied, then some time slots during which the S-R link is not in outage should be used to harvest energy from the RN. Based on **Lemma 6.5**, the optimal mode adaptation method should make the battery work at the boundary of non-absorbing. Thus we can form the following

Figure 6.3: Mode adaptation region maximizing the throughput of the S-R link with the constraint $d(i) = 1$ when $\mathcal{O}_{rd} = 1$.

optimization problem for $N \rightarrow \infty$ to maximize the throughput of the S-R link:

$$\begin{aligned}
 & \max_{d(i), \forall i} \frac{\bar{p}_{rd}}{N} \sum_{i=1}^N (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr} \\
 & s.t. \quad \frac{\bar{p}_{rd}}{N} \sum_{i=1}^N d(i) E(i) + p_{rd} P_h = \frac{\bar{p}_{rd}}{N} \sum_{i=1}^N (1 - d(i)) P_s, \\
 & \quad d(i) (1 - d(i)) = 0,
 \end{aligned} \tag{6.23}$$

where $\bar{p}_{rd}$ results from the constraint that $d(i) = 1$ when $\mathcal{O}_{rd} = 1$. Solving problem (6.23) by using the Lagrange dual method, we can obtain the results of case two. ■

Based on **Lemma 6.7**, we can get the following theorem.

Theorem 6.4: *If the condition $\tau_{sr}^{cm} > p_{rd} R_{rd}$ is satisfied, then the achievable system throughput is given by $\tau = p_{rd} R_{rd}$. The mode adaptation method that achieves this throughput is given by*

$$d(i) = \begin{cases} 0, & \Gamma_0 < h_{sr}(i) < \Gamma_1^* \text{ AND } h_{rd}(i) \leq \Gamma'_0, \\ 1, & \text{otherwise,} \end{cases} \tag{6.24}$$

where Γ_1^* satisfies $p_{rd}R_{rd} = \bar{p}_{rd}R_{sr} \int_{\Gamma_0^*}^{\Gamma_1^*} f(h_{sr})dh_{sr}$.

Proof: When the condition $\tau_{sr}^{\text{cm}} > p_{rd}R_{rd}$ is satisfied, the information buffer of the RN is absorbing if the mode adaptation method of case one or case two of **Lemma 6.7** is adopted and a fraction of the information sent by the SN will be trapped in the buffer of the RN. To avoid this information trapping problem, we can reduce the number of time slots used by the SN to transmit information. By using the method of (6.24), we have $\tau_{sr} = \bar{p}_{rd}R_{sr} \int_{\Gamma_0^*}^{\Gamma_1^*} f(h_{sr})dh_{sr}$ and $\tau_{rd} = p_{rd}R_{rd}$. As it satisfies $p_{rd}R_{rd} = \bar{p}_{rd}R_{sr} \int_{\Gamma_0^*}^{\Gamma_1^*} f(h_{sr})dh_{sr}$, we have $\tau_{sr} = \tau_{rd}$. Thus, the achievable throughput of the system is $\tau = \tau_{rd} = p_{rd}R_{rd}$. Note that by using the mode adaptation method of **Theorem 6.4**, the battery of the SN is absorbing and the condition $L_s(i) > P_s$ is always satisfied. ■

6.4.5 System Throughput for General Cases

In this subsection, the system throughput is investigated for the cases that neither the S-R link nor the R-D link is the bottleneck of the system. For this system setup, the following results always hold: 1) The information buffer of the RN is absorbing ($\tau_{sr}^{\text{max}} > \tau_{rd}$) for the mode adaptation method of **Lemma 6.4** or **Lemma 6.6**. 2) $\tau_{sr}^{\text{cm}} < \tau_{rd}$ is satisfied for the mode adaptation methods of **Lemma 6.7**. Before investigating the system throughput, we first give the following two lemmas:

Lemma 6.8: *If neither the S-R link nor the R-D link is the bottleneck of the system, the optimal mode adaptation method should make the buffer of the RN work at the edge of non-absorbing.*

Proof: Note that the condition $\tau \leq \tau_{sr}$ always holds because of the flow conservation law. As we have $\tau_{sr}^{\text{max}} > \tau_{rd} = \tau$ for the mode adaptation methods of **Lemma**

6.4 and **Lemma 6.6**, we can always find a mode adaptation method which makes the buffer of the RN absorbing, e.g.,

$$\tau_{sr} = \frac{1}{N} \sum_I \mathcal{O}_{sr}(i) R_{sr} > \frac{1}{N} \sum_{\bar{I}} \mathcal{O}_{rd}(i) R_{rd} = \tau, \quad (6.25)$$

where I and $\bar{I}$ denote the sets in which $d(i) = 0$ and $d(i) = 1$ hold, respectively. As we have $\tau_{rd} > \tau_{sr}^{\text{cm}}$ for the mode adaptation method of **Lemma 6.7** which let RN transmit ($d(i) = 1$) if $\mathcal{O}_{rd}(i) = 1$, we can conclude that set I must contain the case that: $d(i) = 0$ when $\mathcal{O}_{rd}(i) = 1$. Based on this observation, we have that the method of (6.25) is not optimal as we can increase the value of τ by moving some indices which satisfy the condition $\mathcal{O}_{rd}(i) = 1$ from I to $\bar{I}$. Note that this operation increases the input power of the SN and reduces the output power of the SN. Thus it always satisfies the condition $P_{\text{in}} \geq P_{\text{out}}$. However, once the condition $\tau_{sr} = \tau$ is satisfied, moving more indices which satisfy $\mathcal{O}_{rd}(i) = 1$ from I to $\bar{I}$ will result in a decrease in both τ and τ_{sr} . Thus, the optimal mode adaptation method should always make the buffer of the RN work at the boundary of non-absorbing. ■

Lemma 6.9: *If neither the S-R link nor the R-D link is the bottleneck of the system, then for the optimal mode adaptation method, the battery of the SN is either absorbing or at the edge of non-absorbing.*

Proof: For an optimal mode adaptation method, we denote ε^* as the sets of indices in which the conditions $d(i) = 1$ and $\mathcal{O}_{rd}(i) = 1$ hold simultaneously. Thus the throughput of the system can be expressed as $\tau^* = \frac{1}{N} \sum_{\varepsilon^*} R_{rd}$. Denote $\bar{\varepsilon}^*$ as all the remaining time slots except the ones in ε^* . As we have $\tau_{rd} > \tau_{sr}^{\text{cm}}$ by using the method of **Lemma 6.7**, and based on the result of **Lemma 6.8**, we can conclude

that $\bar{\varepsilon}^*$ must contain some time slots during which the condition $\mathcal{O}_{rd}(i) = 1$ holds. Then we maximize the throughput of the S-R link in the set of time slots $\bar{\varepsilon}^*$ and denote the conditional maximum throughput of the S-R link as $\tau_{sr}^c = \max_{d(i) \in \bar{\varepsilon}^*} \tau_{sr}$. In the following, we show that τ_{sr}^c cannot be larger than τ^* by contradiction. Suppose that we can find a mode adaptation method which makes $\tau_{sr}^c > \tau^*$, then the system throughput can be improved by moving some time slots of $\bar{\varepsilon}^*$ which satisfy $\mathcal{O}_{rd}(i) = 1$ into ε^* . Thus, we can conclude that the optimal mode adaptation method should always maximize τ_{sr}^c . Similar to the proof of **Lemma 6.7**, it can be shown that the mode adaptation method that maximizes τ_{sr}^c should always make the battery absorbing or stay at the edge of non-absorbing. Thus, the SN's battery is either absorbing or at the edge of non-absorbing for an optimal transmission method. ■

Based on **Lemma 6.8** and **Lemma 6.9**, we can obtain the following theorem.

Theorem 6.5: *For a system in which neither the S-R link nor the R-D link is the bottleneck, the mode adaptation method that maximizes the system throughput is given by*

$$\text{Case one: } d(i) = \begin{cases} 0, \text{ if } \mathcal{O}_{rd}(i) = 0 \text{ AND } \mathcal{O}_{sr}(i) = 1, \\ 0, \text{ if } \mathcal{O}_{rd}(i) = 1 \text{ AND } \Gamma_0 \leq h_{sr}(i) \leq \Gamma^*, \\ 1, \text{ otherwise,} \end{cases}$$

if $\mathbb{E}[h_{sr}|h_{sr} < \Gamma_0] + p_{rd}\mathbb{E}[h_{sr}|h_{sr} > \Gamma^*] > \frac{P_s}{\eta P_r} \left(\int_{\Gamma_0}^{\Gamma^*} f(h_{sr})dh_{sr} + \bar{p}_{rd} \int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr} \right)$ is satisfied, where the value of Γ^* satisfies

$$\int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr} = \frac{p_{sr}R_{sr} - p_{rd}R_{rd} + p_{sr}p_{rd}R_{rd}}{p_{rd}(R_{sr} + R_{rd})}.$$

The throughput of the system is given as $\tau = R_{sr} \left(\int_{\Gamma_0}^{\Gamma^*} f(h_{sr}) dh_{sr} + p_{rd} \int_{\Gamma^*}^{\infty} f(h_{sr}) dh_{sr} \right)$.

$$\text{Case two : } d(i) = \begin{cases} 0, \text{ if } \mathcal{O}_{rd}(i) = 1 \text{ AND } \Gamma_0 \leq h_{sr}(i) \leq \Gamma_2, \\ 0, \text{ if } \mathcal{O}_{rd}(i) = 0 \text{ AND } \Gamma_0 \leq h_{sr}(i) \leq \Gamma_1, \\ 1, \text{ otherwise,} \end{cases}$$

if $\mathbb{E}[h_{sr}|h_{sr} < \Gamma_0] + p_{rd}\mathbb{E}[h_{sr}|h_{sr} > \Gamma^*] \leq \frac{P_s}{\eta P_r} \left(\int_{\Gamma_0}^{\Gamma^*} f(h_{sr}) dh_{sr} + \bar{p}_{rd} \int_{\Gamma^*}^{\infty} f(h_{sr}) dh_{sr} \right)$ is satisfied, where the parameters Γ_1 and Γ_2 satisfy

$$p_{rd}R_{sr} \int_{\Gamma_0}^{\Gamma_2} f(h_{sr}) dh_{sr} + \bar{p}_{rd}R_{sr} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr} = \bar{p}_{sr}p_{rd}R_{rd} + R_{rd}p_{rd} \int_{\Gamma_2}^{\infty} f(h_{sr}) dh_{sr},$$

$$p_{rd}P_s \int_{\Gamma_0}^{\Gamma_2} f(h_{sr}) dh_{sr} + \bar{p}_{rd}P_s \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr} = \eta \bar{p}_{sr}P_r \bar{h}_{sr}^0 + \eta p_{rd}P_r \bar{h}_{sr}^1 + \eta \bar{p}_{rd}P_r \bar{h}_{sr}^2,$$

in which $\bar{h}_{sr}^0 = \mathbb{E}[h_{sr}|h_{sr} < \Gamma_0]$, $\bar{h}_{sr}^1 = \mathbb{E}[h_{sr}|h_{sr} > \Gamma_1]$ and $\bar{h}_{sr}^2 = \mathbb{E}[h_{sr}|h_{sr} > \Gamma_2]$. The throughput of the system is given as $\tau = p_{sr}p_{rd}R_{rd} + R_{rd}p_{rd} \int_{\Gamma_2}^{\infty} f(h_{sr}) dh_{sr}$.

Proof: Please refer to Appendix H. ■

6.5 Numerical Results and Discussion

In this section, the performance of the BW-HaT and BW-MA schemes is evaluated. Similar to the simulation setups used in [37], the channel gains are modelled as $h_{sr}(i) = 10^{-3}d_{sr}^{-\alpha}G_{sr}(i)$ and $h_{rd}(i) = 10^{-3}d_{rd}^{-\alpha}G_{rd}(i)$, where $G_{sr}(i)$ and $G_{rd}(i)$ denote the short-term channel fading gains which have mean values of one. The factor 10^{-3} used in $h_{sr}(i)$ results from that a 30dB average signal power attenuation is assumed

Figure 6.4: Average throughput of the BW-HaT scheme with $P_r = 25\text{dBm}$, $R_{sr} = 1\text{bps/Hz}$, $R_{rd} = 1\text{bps/Hz}$, $d_{sr} = 5\text{m}$ and $d_{rd} = 500\text{m}$.

at a reference distance of 1m. The notations α , d_{sr} and d_{rd} denote the pathloss exponent, the distance between the SN and RN and the distance between the RN and DN, respectively. We set $\alpha = 3$ and the variance of the received AWGN at the RN and DN is assumed to be $\sigma^2 = -100\text{dBm}$ [122]. As the channels of the S-R and R-D links experience Rician fading and Rayleigh fading, respectively, the PDF expressions of the received SNRs of the S-R and R-D links are given by equations (6.1) and (6.2), respectively. The energy harvesting efficiency of the UE is set as $\eta = 0.5$. In the simulation, the throughput is obtained by averaging over 10^6 time slots, while generating independent fading channel gains, $h_{sr}(i)$ and $h_{rd}(i)$, for each time slot.

In Fig. 6.4, the average throughput of the BW-HaT scheme is investigated. To verify the correctness of the theoretical expressions, both the theoretical results and

Figure 6.5: Achievable throughput of the BW-MA scheme with $P_r = 25$ dBm, $K = 5$, $R_{sr} = 1$ bps/Hz, $R_{rd} = 1$ bps/Hz, $d_{sr} = 5$ m and $d_{rd} = 500$ m.

the simulation results of τ_{sr} and τ_{rd} are presented. It can be observed that the analytical results match well with the simulation results. In addition, it can also be observed that when the transmitting power of the SN is low ($P_s < -28$ dBm), according to **Lemma 6.1**, most of the time slots are allocated for SN transmission, the R-D link becomes the bottleneck of the system and the information buffer of the RN is absorbing in this region. Furthermore, as the outage probability of the S-R link with $K = 10$ is smaller than that of the S-R link with $K = 0$, the value of τ_{sr} for the S-R link with $K = 10$ is larger than that of the S-R link with $K = 0$. However, as the value of P_s increases, this gap becomes 0 as the outage probability of the S-R link approaches 0 for this system setup. According to **Lemma 6.1**, for the systems with $K = 10$ and $K = 0$, the probability for RN to transmit is the same. Thus the

values of τ_{rd} are identical for these two system setups. When $P_s > -28\text{dBm}$, more time slots are used for RN transmission to transfer power to the SN, thus the S-R link becomes the bottleneck of the system.

In Fig. 6.5, we show the achievable throughput of the BW-MA scheme. To verify the optimal mode adaptation method used for different SN transmitting power levels, the theoretical results of τ_{sr} and τ_{rd} are also presented. For the simulation results of τ , we first obtain the optimal mode adaptation method that maximizes the throughput of the system. Then, we find out the values of the related parameters, e.g., Γ_0 , Γ_1 , Γ_2 and Γ^* , numerically. Following this, we use these parameters to perform the mode adaptation process to obtain the simulation results. It can be observed from Fig. 6.5 that the theoretical results match very well with the simulation results, which confirm the correctness of the theoretical expressions. Furthermore, it can be observed from Fig. 6.5 that if the transmitting power of the SN satisfies the condition $P_s < a$, the S-R link becomes the bottleneck of the system and the optimal mode adaptation method is the one given in **Lemma 6.6**. This results from the fact that if the transmitting power of the SN is small, the value of Γ_0 is relatively large (the outage probability of the S-R link is large). As a result, the conditions of **Theorem 6.2** are satisfied. For the region $a < P_s < b$, neither the S-R link nor the R-D link is the bottleneck of the system and the mode adaptation method of **Theorem 6.5** is used. Specifically, we first find out the value of Γ^* and then check whether the condition $P_{\text{in}} > P_{\text{out}}$ is satisfied. If it holds, the mode adaptation method of case one of **Theorem 6.5** will be adopted. Otherwise, the mode adaptation method of case two of **Theorem 6.5** is used. When $P_s > b$, more time slots are needed for RN transmission to transmit energy to the SN as the transmitting power of the SN is relatively high. As a result,

Figure 6.6: Achievable throughput comparisons for different transmission schemes with different relay node transmitting power levels, $K = 5$, $R_{sr} = 1\text{bps/Hz}$, $R_{rd} = 1\text{bps/Hz}$, $d_{sr} = 5\text{m}$ and $d_{rd} = 500\text{m}$.

the S-R link becomes the bottleneck and the mode adaptation method of **Lemma 6.6** is adopted.

In Fig. 6.6, the achievable throughput of the considered WPCCN with different transmission schemes are provided. For comparisons, the results of two benchmark schemes, namely, the fixed time (FT) transmission and conventional relaying (CR) schemes, are also presented. In the FT transmission scheme, each time slot is divided into two sub time slots with equal duration. In the first sub time slot, the SN uses all the energy it has harvested in the previous time slot to transmit information to the RN. The RN receives the information and stores it in the buffer if the information

is successfully decoded. In the second sub time slot, if the buffer of the RN is non-empty, the RN extracts information from its buffer and delivers it to the DN and the SN harvests energy at the same time. For the case that the buffer of the RN is empty, the RN still transmits to transfer energy to the SN. For the CR scheme, similar to the BW-HaT scheme, the SN uses the block-wise harvest-and-transmission method. The differences between the CR scheme and the BW-HaT scheme are as follows: Once enough energy is harvested by the SN ($L_s(i) \geq P_s$), one information packet is delivered from the SN to DN in two successive time slots if it is successfully decoded by the RN as no buffer is used at the RN [119, 123].

The throughput of the BW-MA scheme, BW-HaT scheme and CR scheme given in Fig. 6.6 is the maximum achievable throughput obtained by optimizing the transmitting power of the SN. We can observe from Fig. 6.6 that the BW-MA scheme achieves a higher throughput than that of the BW-HaT scheme as the time slots are more properly used. However, the BW-MA scheme needs more resources to obtain the CSI of the two links as compared with the BW-HaT scheme. We also observe from Fig. 6.6 that by adding a data buffer at the RN, the BW-HaT scheme achieves a higher throughput than that of the CR scheme. The throughput gain of the BW-HaT scheme over the FT scheme arises from the fact that the SN of the FT scheme uses all the energy it has harvested in the previous time slot to transmit information, which is not an efficient way to use the harvested energy as compared with the BW-HaT scheme with a fixed optimized transmitting power.

In Fig. 6.7, the effect of the information buffer size of the RN on the system throughput is investigated. The mode adaption process (BW-MA scheme) is performed in the same way as the system which has an infinite buffer size except for the

Figure 6.7: Effect of the size of information buffer on the throughput of the system with $P_r = 25\text{dBm}$, $R_{sr} = 1\text{bps/Hz}$, $R_{rd} = 1\text{bps/Hz}$, $d_{sr} = 5\text{m}$ and $d_{rd} = 500\text{m}$.

case that the buffer is full. If the buffer is full, the RN is forced to transmit in the next time slot. The buffer size shown in Fig. 6.7 is normalized by the transmission rate of the SN and is measured by the number of information packets that can be stored by the RN. For instance, if the maximum number of packets that can be stored in the buffer of the RN is K , the buffer size is then denoted by $L_r^{\max} = KR_{sr}$. It can be observed from Fig. 6.7 that as the buffer size increases, the achievable rate of the finite buffer size system approaches the achievable rate of the system with infinite buffer.

In Fig. 6.8, the effect of the battery capacity of the SN on the system throughput is investigated. The mode adaption process is performed in the same way as the system which has an infinite battery capacity except for the case that the battery

Figure 6.8: Effect of the battery capacity of the SN on the throughput of the system with $P_r = 25\text{dBm}$, $R_{sr} = 1\text{bps/Hz}$, $R_{rd} = 1\text{bps/Hz}$, $d_{sr} = 5\text{m}$ and $d_{rd} = 500\text{m}$.

is full. If the battery is full, the SN stops harvesting energy in the following time slot(s). The battery capacity shown in Fig. 6.8 is normalized by the average received power P_h of the SN and is measured as $L_s^{\max} = KP_h$. It can be observed from Fig. 6.8 that as the battery capacity increases, the achievable rate of the system with a finite battery capacity approaches the achievable rate of the system with an infinite battery capacity.

6.6 Summary

In this chapter, we have studied a WPCCN which consists of a SN, a hybrid RN and a DN. By assuming that the RN has an information buffer and can temporary store the

information it receives, we have investigated the long-term throughput of two different block-wise cooperative protocols, namely, the BW-HaT protocol and the BW-MA protocol. For the BW-HaT protocol, the system expression was obtained in closed-form expression. For the BW-MA protocol, the optimal mode adaptation method that maximizes the system throughput was obtained and the maximum achievable throughput was derived for different system setups. It has been shown that through simultaneously transmitting information and energy to the DN and SN, the proposed BW-MA scheme can significantly increase the system throughput.

Chapter 7

Conclusions and Future Work

7.1 Conclusion

In this thesis, we focused on designing effective communication strategies for buffer-aided relaying systems to improve the performance of wireless relaying networks.

We started with a SSK-based buffer-aided relaying system. The aim of this work is to improve the performance of SSK-based relaying systems. As the information of a SSK signal is conveyed by the index of the transmit antenna, we have proposed an novel link adaptation scheme based on the difference in channel gains of different antennas to effectively make use of the multi-hop diversity. An exact closed-form expression of the average BER has been obtained for the system in which the SN has two transmit antennas. For the system with arbitrary number of transmit antennas, an upper bound has been provided. In addition, to reduce the packet delay, two link adaptation schemes have also been proposed, which can reduce the average packet delay at the sacrifice of some performance loss.

Following that, the delay of a buffer-aided relaying system has been investigated

and a buffer-state based relaying scheme has been proposed. The proposed relay selection scheme takes both the channel quality and the buffer state of the RNs into account to select one optimal RN in each time slot. The outage probability of the proposed relay selection scheme has been obtained and it has been shown that the proposed scheme can achieve a lower outage probability than the existing relay selection schemes. In addition, we have also shown that the proposed relay selection scheme has a lower average packet delay as compared with the existing relay selection schemes designed for buffer-aided relaying systems.

Considering that data buffering is an important technique in WPCCN, we then applied the buffer-aided relaying scheme to WPCCN. A joint node-and-mode selection scheme has been proposed and the maximum achievable system throughput has been investigated. We have derived the optimal joint node-and-mode selection criterion for the general system setup. Following this, the criterion was applied to two specific systems, i.e., the single RN system and the multiple RNs system with a symmetric channel. For these system setups, the optimal transmission schemes have been obtained in closed-form expressions. It has been shown that the throughput of the WPCCN can be improved by using a buffer-aided relaying scheme.

Lastly, we have extended the opportunistic transmission strategy of buffer-aided relaying to a WPCCN and treated the battery of the SN as an energy queue. Based on this model, we have investigated the long-term throughput of two proposed block-wise cooperative protocols, namely, the BW-HaT protocol and the BW-MA protocol. We have shown that the proposed transmission schemes can significantly increase the system throughput.

In summary, in this thesis, we have shown the potential benefits of applying buffer-aided relaying in different wireless communication systems. It has been shown that as compared with conventional relaying schemes, buffer-aided relaying can significantly improve the system performance.

7.2 Future Works

There are several directions in which the research presented in this thesis could be extended. Firstly, the single RN SSK-based system investigated in Chapter 3 could be extended to the multiple RNs case. The link selection scheme of multiple RNs buffer-aided SSK system is an interesting problem to be investigated. In addition, we only considered the average information delay constraint at the RN in Chapter 4. In practice, there are other delay constraints, e.g., the statistical delay constraint [134–136], which are also important to be considered. Thus, the transmission schemes with these delay constraints should also be investigated.

A buffer-aided relaying scheme needs to know the CSI at the RN to adaptively select the active link. However, in some practical communication systems, it is difficult to obtain perfect CSI at the RN. Thus, the transmission scheme for a buffer-aided relaying system with CSI errors [71], outdated CSI [50,51,62] and statistical CSI [52] still needs further investigation. In addition, the existing link selection schemes on buffer-aided relaying assume that there is a central control node responsible for collecting CSI information and selecting a optimal link in each time slot [74–76]. However, this assumption results in extra overhead for a relaying system. To reduce the overhead of performing link selection, it is of great interest to consider a distributed link selection scheme for buffer-aided relaying systems. Furthermore, the performance gain

of buffer-aided relaying schemes over conventional relaying methods depends on the changing rate of channel coefficients [52]. On one hand, a slow-changing channel degrades the performance of buffer-aided relaying. On the other hand, a fast-changing channel requires a more frequent feedback. Thus, it is of great significance to properly evaluate the performance of buffer-aided relaying by taking practical constraints into account. As energy efficiency is becoming an important issue in the 5th generation wireless communication systems, the application of buffer-aided relaying to improve the energy efficiency of relaying systems [137–139] should be investigated in future studies.

Appendix A

Proof of Theorem 3.1

Based on **Lemma 3.1**, the CDFs of γ_s and γ_r are upper bounded as

$$\begin{aligned}\Pr\{\gamma_s < x\} &= \Pr\{\lambda_s < x | \lambda_s > \rho_0 \lambda_r\} \\ &= \frac{\Pr\{\rho_0 \lambda_r < \lambda_s < x\}}{\Pr\{\lambda_s > \rho_0 \lambda_r\}} \\ &< 2 \Pr\{\lambda_s < x\} \Pr\left\{\lambda_r < \frac{x}{\rho_0}\right\} \\ &\leq 2 \left(1 - e^{-\frac{x}{\Omega_0}}\right) \left(1 - e^{-\frac{x}{\rho_0 \Omega_r}}\right) = \hat{F}_s(x),\end{aligned}\tag{A.1}$$

and

$$\begin{aligned}\Pr\{\gamma_r < x\} &= \Pr\{\lambda_r < x | \lambda_s < \rho_0 \lambda_r\} \\ &= \frac{\Pr\{\lambda_s / \rho_0 < \lambda_r < x\}}{\Pr\{\lambda_s < \rho_0 \lambda_r\}} \\ &< 2 \Pr\{\lambda_r < x\} \Pr\left\{\lambda_s < \frac{x}{\rho_0}\right\} \\ &\leq 2 \left(1 - e^{-\frac{x}{\Omega_r}}\right) \left(1 - e^{-\frac{\rho_0 x}{\Omega_0}}\right) = \hat{F}_r(x),\end{aligned}\tag{A.2}$$

respectively. Then we have

$$\begin{aligned}
\Pr \left\{ \frac{\gamma_r \gamma_s}{\gamma_r + C} < x \right\} &= \int_0^\infty \Pr \left\{ \gamma_s < x + \frac{Cx}{\gamma_r} \right\} f_r(\gamma_r) d\gamma_r \\
&< \int_0^\infty \hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right) f_r(\gamma_r) d\gamma_r \\
&= \int_0^\infty \frac{d \left[\hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right) F_r(\gamma_r) \right]}{d\gamma_r} d\gamma_r - \int_0^\infty \frac{d\hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right)}{d\gamma_r} F_r(\gamma_r) d\gamma_r.
\end{aligned}$$

Since $\hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right)$ is a decreasing function of γ_r , we have $\frac{d\hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right)}{d\gamma_r} < 0$. Thus we have

$$\begin{aligned}
\int_0^\infty \frac{d\hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right)}{d\gamma_r} F_r(\gamma_r) d\gamma_r &> \int_0^\infty \frac{d\hat{F}_s \left(\frac{C+\gamma_r}{\gamma_r} x \right)}{d\gamma_r} \hat{F}_r(\gamma_r) d\gamma_r \\
&= \int_0^\infty \frac{d \left[\hat{F} \left(\frac{C+\gamma_r}{\gamma_r} x \right) \hat{F}_r(\gamma_r) \right]}{d\gamma_r} d\gamma_r - \frac{d\hat{F}_r(\gamma_r)}{d\gamma_r} \hat{F}_s \left(\frac{C+\gamma_r}{\gamma_r} x \right) d\gamma_r.
\end{aligned}$$

As we have

$$\int_0^\infty \frac{d \left[\hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right) F_r(\gamma_r) \right]}{d\gamma_r} d\gamma_r = \hat{F}_s(x) \tag{A.3}$$

and

$$\int_0^\infty \frac{d \left[\hat{F} \left(x + \frac{Cx}{\gamma_r} \right) \hat{F}_r(\gamma_r) \right]}{d\gamma_r} d\gamma_r = 2\hat{F}_s(x), \tag{A.4}$$

then we can obtain

$$\begin{aligned} \Pr \left\{ \frac{\gamma_r \gamma_s}{\gamma_r + C} < x \right\} &< \int_0^\infty \frac{d\hat{F}_r(\gamma_r)}{d\gamma_r} \hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right) d\gamma_r - 2 \left(1 - e^{-\frac{x}{\Omega_0}} \right) \left(1 - e^{-\frac{x}{\rho_0 \Omega_r}} \right) \\ &< \int_0^\infty \frac{d\hat{F}_r(\gamma_r)}{d\gamma_r} \hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right) d\gamma_r. \end{aligned} \quad (\text{A.5})$$

Substituting (A.1) and (A.2) into (A.5), we can obtain equation (A.9) (at the bottom of next page) where $A = \frac{\rho_0 \Omega_r + \Omega_0}{\Omega_r \Omega_0}$. Substituting (3.23) into (A.9), we can obtain

$$\begin{aligned} \int_0^\infty \frac{d\hat{F}_r(\gamma_r)}{d\gamma_r} \hat{F}_s \left(x + \frac{Cx}{\gamma_r} \right) d\gamma_r &\approx \frac{4x^2 N_t (N_t - 1)}{\rho_0 \Omega_r} \left[\frac{1}{\Omega_r} \ln \left(1 + \frac{\rho_0 \Omega_r}{\Omega_0} \right) + \frac{\rho_0}{\Omega_0} \ln \left(1 + \frac{\Omega_0}{\rho_0 \Omega_r} \right) \right] \\ &+ \frac{4x^2}{\rho_0^2 \Omega_r \Omega_0}. \end{aligned} \quad (\text{A.6})$$

According to (A.5), we can obtain

$$F_\gamma(x) = \Pr \left\{ \frac{\gamma_r \gamma_s}{\gamma_r + C} < x \right\} < \frac{M_1(x)}{\Omega_r \Omega_0} + \frac{M_2(x)}{\Omega_r^2}, \quad (\text{A.7})$$

where we have $M_1(x) = \frac{4x^2}{\rho_0^2} + N_t(N_t - 1) \ln \left(1 + \frac{\Omega_0}{\rho_0 \Omega_r} \right)$ and $M_2(x) = \frac{4x^2 N_t(N_t - 1)}{\rho_0} \ln \left(1 + \frac{\rho_0 \Omega_r}{\Omega_0} \right)$.

Substituting (A.7) into (3.30), we can obtain

$$\begin{aligned} \text{PEP} \{ \mathbf{s}_l \rightarrow \mathbf{s}_{\bar{l}} \} &\leq \mathbb{E} [Q(\gamma)] = \int_0^\infty \frac{F_\gamma(\gamma) \exp(-\gamma/2)}{2\sqrt{2\pi}\sqrt{\gamma}} d\gamma \\ &< \int_0^\infty \frac{M_1(\gamma) \exp(-\gamma/2)}{2\Omega_r \Omega_0 \sqrt{2\pi}\gamma} d\gamma + \int_0^\infty \frac{M_2(\gamma) \exp(-\gamma/2)}{2\Omega_r^2 \sqrt{2\pi}\gamma} d\gamma. \end{aligned} \quad (\text{A.8})$$

It can be observed from (A.8) that the system can achieve a diversity order of 2.

$$\begin{aligned}
\int_0^\infty \frac{d\hat{F}_r(\gamma_r)}{d\gamma_r} \hat{F}_s\left(x + \frac{Cx}{\gamma_r}\right) d\gamma_r &= 1 - e^{-\frac{x}{\Omega_0}} \sqrt{\frac{4Cx}{\Omega_r\Omega_0}} K_1\left(\sqrt{\frac{4Cx}{\Omega_r\Omega_0}}\right) \\
&+ e^{-\frac{Ax}{\rho_0}} \sqrt{\frac{4CAx}{\rho_0\Omega_r}} K_1\left(\sqrt{\frac{4CAx}{\rho_0\Omega_r}}\right) - e^{-\frac{x}{\Omega_0}} \sqrt{\frac{4C\rho_0x}{\Omega_0^2}} K_1\left(\sqrt{\frac{4C\rho_0x}{\Omega_0^2}}\right) \\
&- e^{-\frac{x}{\rho_0\Omega_r}} \sqrt{\frac{4Cx}{\Omega_r\Omega_0}} K_1\left(\sqrt{\frac{4Cx}{\Omega_r\Omega_0}}\right) + e^{-\frac{Ax}{\rho_0}} \sqrt{\frac{4CAx}{\Omega_0}} K_1\left(\sqrt{\frac{4CAx}{\Omega_0}}\right) \\
&+ e^{-\frac{x}{\Omega_0}} \sqrt{\frac{4CAx}{\Omega_0}} K_1\left(\sqrt{\frac{4CAx}{\Omega_0}}\right) + e^{-\frac{x}{\rho_0\Omega_r}} \sqrt{\frac{4CAx}{\rho_0\Omega_r}} K_1\left(\sqrt{\frac{4CAx}{\rho_0\Omega_r}}\right) \\
&- e^{-\frac{Ax}{\rho_0}} \sqrt{\frac{4CA^2x}{\rho_0}} K_1\left(\sqrt{\frac{4CA^2x}{\rho_0}}\right) - e^{-\frac{x}{\rho_0\Omega_r}} \sqrt{\frac{4Cx}{\rho\Omega_r^2}} K_1\left(\sqrt{\frac{4Cx}{\rho\Omega_r^2}}\right), \quad (\text{A.9})
\end{aligned}$$

Appendix B

Proof of Lemma 4.5

As the system has at least K available links for any buffer state, we partition the total buffer states into $K + 1$ subsets: $\mathcal{G}_0, \mathcal{G}_1, \dots, \mathcal{G}_K$, in which $\mathcal{G}_m$, for $0 \leq m \leq K$, is the set of states that have $2K - m$ available links (m of these RNs have either full buffer or empty buffer).

As only a best RN is chosen to receive or transmit in each time slot, we can conclude that a state $s_n \in \mathcal{G}_m$ can only transit into the state(s) that lies in $\mathcal{G}_{m+1}$, $\mathcal{G}_{m-1}$ or $\mathcal{G}_m$ in one time slot. By grouping the states s_n in $\mathcal{G}_m$ as a “super-state” $s_{\mathcal{G}_m}$, we can form a MC as shown in Fig. B.1, in which $s_{\mathcal{G}_m}$ denotes the state that the system has $2K - m$ available links.

Figure B.1: State diagram of the Markove chain representing the buffer state subsets and the transitions between them.

We used λ_m and μ_{m+1} to denote the transition probabilities from state $s_{\mathcal{G}_m}$ to $s_{\mathcal{G}_{m+1}}$ and from state $s_{\mathcal{G}_{m+1}}$ to $s_{\mathcal{G}_m}$, respectively. Based on the global balance equation of MC, we can obtain the following equations:

$$\begin{aligned}\pi_{s_{\mathcal{G}_0}} \lambda_0 &= \pi_{s_{\mathcal{G}_1}} \mu_1, \\ \pi_{s_{\mathcal{G}_{K-1}}} \lambda_{K-1} &= \pi_{s_{\mathcal{G}_K}} \mu_K, \\ \pi_{s_{\mathcal{G}_{m-1}}} \lambda_{m-1} + \pi_{s_{\mathcal{G}_{m+1}}} \mu_{m+1} &= \pi_{s_{\mathcal{G}_m}} \mu_m + \pi_{s_{\mathcal{G}_m}} \lambda_m, m = 1, \dots, K-1,\end{aligned}\tag{B.1}$$

in which $\pi_{s_{\mathcal{G}_m}}$ is the stationary probability of state $s_{\mathcal{G}_m}$. By jointly solving the equations of (B.1), we have

$$\pi_{s_{\mathcal{G}_m}} = \pi_{s_{\mathcal{G}_0}} \prod_{j=0}^{m-1} \frac{\lambda_j}{\mu_{j+1}}, m = 1, 2, \dots, K.\tag{B.2}$$

As it satisfies $\sum_{m=0}^K \pi_{s_{\mathcal{G}_m}} = 1$, we can obtain

$$\pi_{s_{\mathcal{G}_0}} = \left[1 + \sum_{m=1}^K \prod_{j=0}^{m-1} \frac{\lambda_j}{\mu_{j+1}} \right]^{-1}.\tag{B.3}$$

In the following, we show that the conditions $\lambda_m \leq |\mathcal{G}_m| |\mathcal{G}_{m+1}| P_0$ and $\mu_m \geq 1 - P_0$ always hold, where $|\mathcal{G}_m|$ and $|\mathcal{G}_{m+1}|$ denote the number of states included in the subsets $\mathcal{G}_m$ and $\mathcal{G}_{m+1}$, respectively.

For the proposed relay selection scheme, the transition from a state $s_n \in \mathcal{G}_m$ to another state $s_{\bar{n}} \in \mathcal{G}_{m+1}$ which decreases the number of available links of the system can only occur through the following two cases:

- *Case one:* The system chooses a RN which has one packet in the buffer to transmit.

-
- *Case two*: The system chooses a RN which has $L - 1$ packets in the buffer to receive.

As the proposed relay selection scheme gives the RN with one packet ($L - 1 \geq 2$ packets) in the buffer higher priority to receive (transmit), for *Case one* (*Case two*) to happen, the S-R (R-D) link of the RN should be in outage and the R-D (S-R) link should be successful. This event happens with a probability $(1 - P_0)P_0$ which is smaller than P_0 . Thus we have

$$\Pr(X_{t+1} = s_{\bar{n}} | X_t = s_n) < P_0. \quad (\text{B.4})$$

The transition probability λ_m is given by

$$\begin{aligned} \lambda_m &= \Pr(X_{t+1} = s_{\mathcal{G}_{m+1}} | X_t = s_{\mathcal{G}_m}) \\ &= \sum_{s_n \in \mathcal{G}_m} \sum_{s_{\bar{n}} \in \mathcal{G}_{m+1}} \Pr(X_{t+1} = s_{\bar{n}} | X_t = s_n). \end{aligned} \quad (\text{B.5})$$

Based on the fact that the number of possible state transitions between $\mathcal{G}_m$ and $\mathcal{G}_{m+1}$ is upper bounded by $|\mathcal{G}_m||\mathcal{G}_{m+1}|$, thus we have

$$\lambda_m \leq |\mathcal{G}_m||\mathcal{G}_{m+1}|P_0. \quad (\text{B.6})$$

For the proposed relay selection scheme, the transition of a state $s_{\bar{n}} \in \mathcal{G}_{m+1}$ into a state $s_n \in \mathcal{G}_m$ can only occur through the following case:

- The system chooses one from the $m + 1$ RNs which have either empty or full buffer to receive or transmit, respectively.

As the proposed relay selection scheme gives the RNs with full buffer and empty

buffer the highest priority to transmit and receive, respectively, to transit a state $s_{\bar{n}} \in \mathcal{G}_{m+1}$ into a state $s_n \in \mathcal{G}_m$, at least one available link of these $m+1$ RNs should not be in outage. Hence, we have

$$\Pr(X_{t+1} = s_n | X_t = s_{\bar{n}}) = 1 - P_0^{m+1}. \quad (\text{B.7})$$

As $m \geq 0$, we have

$$\Pr(X_{t+1} = s_n | X_t = s_{\bar{n}}) \geq 1 - P_0. \quad (\text{B.8})$$

Since $\mu_m = \sum_{s_{\bar{n}} \in \mathcal{G}_{m+1}} \sum_{s_n \in \mathcal{G}_m} \Pr(X_{t+1} = s_{\bar{n}} | X_t = s_n)$, we can obtain that

$$\mu_m \geq 1 - P_0. \quad (\text{B.9})$$

Combining (B.2), (B.6) and (B.9), we can obtain that

$$\pi_{s_{\mathcal{G}_m}} = \pi_{s_{\mathcal{G}_0}} \prod_{j=0}^{m-1} \frac{\lambda_j}{\mu_{j+1}} \leq \pi_{s_{\mathcal{G}_0}} C_m \left(\frac{P_0}{1 - P_0} \right)^m, \quad (\text{B.10})$$

where $C_m = \prod_{j=0}^{m-1} |\mathcal{G}_j| |\mathcal{G}_{j+1}|$. Based on the fact that $\pi_{s_{\mathcal{G}_0}} < 1$, we have

$$\pi_{s_{\mathcal{G}_m}} < C_m \left(\frac{P_0}{1 - P_0} \right)^m. \quad (\text{B.11})$$

As $\pi_{s_{\mathcal{G}_m}} = \sum_{s_n \in \mathcal{G}_m} \pi_n$, we conclude that for any state $s_n \in \mathcal{G}_m$ ($1 \leq m \leq K$), its stationary probability satisfies $\pi_n < C_m \left(\frac{P_0}{1 - P_0} \right)^m$.

Appendix C

Proof of Lemma 4.6

We partition the total buffer states into two subsets: $\mathcal{N}_1$ and $\mathcal{N}_2$. The subset $\mathcal{N}_1$ contains the following $K + 1$ states: 1) The state in which the buffer of every RN has one packet; 2) The K states in which one of the RNs has two packets in its buffer while the others have one packet in their buffers. The subset $\mathcal{N}_2$ contains all the remaining states. By grouping the states of $\mathcal{N}_1$ and $\mathcal{N}_2$ as two “super-states” $s_{\mathcal{N}_1}$ and $s_{\mathcal{N}_2}$, we can form a two-state MC. Denote λ and μ as the transition probability from state $s_{\mathcal{N}_1}$ to $s_{\mathcal{N}_2}$ and the transition probability from $s_{\mathcal{N}_2}$ to $s_{\mathcal{N}_1}$, respectively. By using the global balance equation of MC, we have:

$$\pi_{s_{\mathcal{N}_1}} \lambda = \pi_{s_{\mathcal{N}_2}} \mu, \quad (\text{C.1})$$

in which $\pi_{s_{\mathcal{N}_1}}$ and $\pi_{s_{\mathcal{N}_2}}$ are the stationary probabilities of the states $s_{\mathcal{N}_1}$ and $s_{\mathcal{N}_2}$, respectively. As it satisfies $\pi_{s_{\mathcal{N}_1}} + \pi_{s_{\mathcal{N}_2}} = 1$, we have

$$\pi_{s_{\mathcal{N}_1}} = \frac{\mu}{\lambda + \mu}, \quad \pi_{s_{\mathcal{N}_2}} = \frac{\lambda}{\lambda + \mu}. \quad (\text{C.2})$$

By using a similar method of proving **Lemma 4.5**, it can be shown that the transition probabilities λ and μ satisfy $\lambda < |\mathcal{N}_1|P_0$ and $\mu > 1 - P_0$, respectively. Based on this result and the fact that $\lim_{SNR \rightarrow \infty} P_0 = 0$, we can obtain: $\lim_{SNR \rightarrow \infty} \pi_{s_{\mathcal{N}_1}} = 1$ and $\lim_{SNR \rightarrow \infty} \pi_{s_{\mathcal{N}_2}} = 0$. Thus, the system stays in these $K+1$ specific states with probability one when SNR approaches infinity. In the following, we assume that the system always stays in these $K+1$ specific states in high SNR regime.

Suppose that the system stays in the state that all RNs have one packet in the buffer. In the next time slot, the system will choose one RN randomly to receive a packet (based on Case 7 of stage one and Case 4 of stage two). As a result, the selected RN has two packets in its buffer and all the other RNs have one packet in their buffers. Following this, the RN with two packets in its buffer will be chosen to transmit a packet in the following time slot (according to Case 6 of stage one and Case 3 of stage two). As a result, all the relay buffers again store only one packet. This process repeats as the number of time slots increases. Thus, we can conclude that when SNR approaches infinity, the system stays in the state that all RNs have one packet in the buffer with a probability approaching $1/2$. The probability for the system to stay in the other K states also approaches $1/2$ when SNR approaches infinity. Based on this result, the average number of packets stored in the buffers is given by $\frac{K}{2} + \frac{K+1}{2} = K + \frac{1}{2}$, which results in $\lim_{SNR \rightarrow \infty} \sum_{j=1}^{(L+1)^K} \sum_{k=1}^K \pi_j L_k^{s_j} = K + \frac{1}{2}$.

Appendix D

Proof of Lemma 5.1

Problem (5.13) is non-convex as the variables $d_{k,i}^{sr}$ and $d_{k,i}^{rd}$ are binary. To handle this problem, we relax $d_{k,i}^{sr}$, $d_{k,i}^{rd}$ to be $0 \leq d_{k,i}^{sr} \leq 1$, $0 \leq d_{k,i}^{rd} \leq 1$ and form the following problem:

$$\begin{aligned}
 & \underset{d_{k,i}^{sr}, d_{k,i}^{rd}, \alpha_{k,i}, \forall i, k}{\text{maximize}} : \frac{1}{N} \sum_{k=1}^K \sum_{i=1}^N d_{k,i}^{rd} \bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd} \\
 & \text{s.t. C1 : } \frac{1}{N} \sum_{i=1}^N d_{k,i}^{rd} \bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd} = \frac{1}{N} \sum_{i=1}^N d_{k,i}^{sr} \mathcal{O}_{k,i}^{sr} R_{sr}, \forall k \\
 & \text{C2 : } \sum_{k=1}^K (d_{k,i}^{sr} + d_{k,i}^{rd}) = 1, 0 \leq \alpha_{k,i} \leq 1, \forall k, i \\
 & \text{C3 : } 0 \leq d_{k,i}^{sr} \leq 1, 0 \leq d_{k,i}^{rd} \leq 1, \forall k, i.
 \end{aligned} \tag{D.1}$$

As problem (D.1) is a linear problem of $d_{k,i}^{sr}$ and $d_{k,i}^{rd}$, the maximum value should always be achieved at the vertices. Thus, the optimal solution of $d_{k,i}^{sr}$ and $d_{k,i}^{rd}$ should always be binary and there is no performance loss between the original problem and the relaxed one. In the following, it will be shown that the optimal solution $d_{k,i}^{sr}$ and

$d_{k,i}^{rd}$ of problem (D.1) is always binary, which proves the equivalence between problem (5.13) and problem (D.1). We use the Lagrange dual method to obtain the optimal solution. The Lagrangian of the relaxed problem is given by

$$\begin{aligned}\mathcal{L} &= \frac{1}{N} \sum_{k=1}^K \sum_{i=1}^N d_{k,i}^{rd} \bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd} - \frac{\lambda_k}{N} \sum_{k=1}^K \sum_{i=1}^N (d_{k,i}^{rd} \bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd} - d_{k,i}^{sr} \mathcal{O}_{k,i}^{sr} R_{sr}) \\ &= \frac{1}{N} \sum_{i=1}^N \sum_{k=1}^K [d_{k,i}^{rd} \bar{\lambda}_k \bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd} + d_{k,i}^{sr} \lambda_k \mathcal{O}_{k,i}^{sr} R_{sr}],\end{aligned}$$

where λ_k is the Lagrangian multiplier and $\bar{\lambda}_k = 1 - \lambda_k$. As $\alpha_{k,i}$ is independent with $d_{k,i}^{sr}$ and $d_{k,i}^{rd}$, we can first maximize the value of $\mathcal{L}$ with respect to $\alpha_{k,i}$ and get the following result:

$$\bar{\mathcal{L}} = \frac{1}{N} \sum_{i=1}^N \sum_{k=1}^K \left[d_{k,i}^{rd} \bar{\lambda}_k R_{rd}^{k,m}[i] + d_{k,i}^{sr} \lambda_k \mathcal{O}_{k,i}^{sr} R_{sr} \right],$$

where $R_{rd}^{k,m}[i] = \max_{\alpha_{k,i}} \{\bar{\alpha}_{k,i} \mathcal{O}_{k,i}^{rd} R_{rd}\}$ is a continuous-valued random variable which denotes the maximum equivalent achievable rate of the $R_k - D$ link if R_k is chosen to work in the RN-HAT mode. As $\bar{\mathcal{L}}$ is a linear function of $d_{k,i}^{rd}$, $d_{k,i}^{sr}$ and the constraint $\sum_{k=1}^K (d_{k,i}^{sr} + d_{k,i}^{rd}) = 1$ should be satisfied, to maximize $\bar{\mathcal{L}}_i$, we should make $d_{k,i}^{rd} = 1$ if the condition $(1 - \lambda_k) R_{rd}^{k,m}[i] = \max \mathcal{A}[i]$ is satisfied. For the case of $\lambda_k \mathcal{O}_{k,i}^{sr} R_{sr} = \max \mathcal{A}[i]$, we can let $d_{k,i}^{rd} = 1$ to maximize $\bar{\mathcal{L}}$. Considering that the following scenario¹ may happen for certain system setup:

$$\lambda_{k_1} \mathcal{O}_{k_1,i}^{sr} R_{sr} = \dots = \lambda_{k_l} \mathcal{O}_{k_l,i}^{sr} R_{sr} = \max \mathcal{A}[i], \quad (\text{D.2})$$

¹For continuous-valued random variables $R_{rd}^{k_1,m}[i]$ and $R_{rd}^{k_2,m}[i]$, the probability of $\bar{\lambda}_{k_1} R_{rd}^{k_1,m}[i] = \bar{\lambda}_{k_2} R_{rd}^{k_2,m}[i] = \lambda_{k_3} \mathcal{O}_{k_3,i}^{sr} R_{sr}$ is zero.

where k_1 and k_l denote the k_1 th RN and k_l th RN, respectively. We select one from these RNs to receive information in this case. Based on these results, we can thus get the method given in **Lemma 5.1**. In addition, to satisfy the KKT condition, the values of λ_k should be chosen to make the method of **Lemma 5.1** satisfy constraint C1 of problem (5.13).

Appendix E

Proof of Lemma 6.1

Let us consider the time slots that are used for transferring energy from the RN to SN. Denote the energy harvested in the i th energy harvesting time slot as P_i . Then we have that P_i , for $i = 1, 2, \dots$, are independent and identically distributed with the mean value P_h . Let $S_n = \sum_{i=1}^n P_i$ and $m(K) = \max \{n : S_n \leq KP_s\}$. According to [140], $m(K)$ is then a renewal process. Based on Theorem 3.1 of [140], we have

$$\lim_{K \rightarrow \infty} m(K) = \frac{KP_s}{P_h}, \quad (\text{E.1})$$

which indicates that for the SN to transmit K blocks of information (an amount of energy KP_s needs to be harvested), an average number of $\frac{KP_s}{P_h} + 1$ time slots are needed to harvest energy from the RN. Thus the probabilities of SN transmission and RN transmission are given by $\Pr\{d(i) = 0\} = \lim_{K \rightarrow \infty} \frac{K}{K + KP_s/P_h + 1} = \frac{P_h}{P_s + P_h}$ and $\Pr\{d(i) = 1\} = \lim_{K \rightarrow \infty} \frac{KP_s/P_h + 1}{K + KP_s/P_h + 1} = \frac{P_s}{P_s + P_h}$, respectively.

Appendix F

Proof of Lemma 6.5

First, we should note that the condition $P_{\text{in}} \geq P_{\text{out}}$ always holds because of the flow conservation law. The equality holds only if the battery is not absorbing. We first assume that there exists a method (a pair of I and $\bar{I}$) which makes the battery of the SN absorbing, e.g., for $N \rightarrow \infty$, we have

$$\begin{aligned} P_{\text{in}} &= \frac{1}{N} \sum_{L_s(i) < P_s} E(i) + \frac{1}{N} \sum_I E(i) \\ &> \frac{1}{N} \sum_{\bar{I}} P_s = P_{\text{out}}. \end{aligned}$$

As we have $P_{\text{out}} \geq P_{\text{in}}$ for the mode adaptation method of **Lemma 6.4** which lets SN transmit ($d(i) = 0$) if the condition $\mathcal{O}_{sr}(i) = 1$ holds, we can conclude that the set I must contain the case: $d(i) = 1$ when $\mathcal{O}_{sr}(i) = 1$. Based on this result, we can observe that this method is not optimal as the throughput of the S-R link can be improved by moving some of the indices with $\mathcal{O}_{sr}(i) = 1$ from I to $\bar{I}$, which leads to an increase of τ_{sr} at the expense of a decrease in P_{in} . However, once the condition

$P_{\text{in}} = P_{\text{out}}$ is satisfied, moving more indices in I to $\bar{I}$ will decrease both P_{in} and τ_{sr} because less energy can be used by the SN to transmit information. Thus, the optimal mode adaptation method that maximizes τ_{sr} always makes the battery of the SN works at the boundary of non-absorbing [28]. In the following, we will prove that when the battery works at the boundary of non-absorbing, the following equation holds for $N \rightarrow \infty$:

$$\frac{1}{N} \sum_{L_s(i) < P_s} E(i) + \frac{1}{N} \sum_I E(i) = \frac{1}{N} \sum_I E(i). \quad (\text{F.1})$$

When the battery works at the boundary of non-absorbing, we have $P_{\text{in}} = P_{\text{out}}$ which results in

$$\begin{aligned} \frac{1}{N} \sum_I E(i) &\leq \underbrace{\frac{1}{N} \sum_{L_s(i) < P_s} E(i) + \frac{1}{N} \sum_I E(i)}_{P_{\text{in}}} \\ &= \underbrace{\frac{1}{N} \sum_{\bar{I}} P_s}_{P_{\text{out}}}. \end{aligned} \quad (\text{F.2})$$

Then we move a small fraction set of indices ω , where $|\omega|/N \rightarrow 0$ for $N \rightarrow \infty$ (e.g., $|\omega| = \sqrt{N}$) and $|\omega|$ denotes the cardinality of ω , from $\bar{I}$ to I . As a result, the battery of the SN becomes absorbing and we have

$$\begin{aligned} \frac{1}{N} \sum_{I \cup \omega} E(i) &= \frac{1}{N} \sum_{L_s(i) < P_s} E(i) + \frac{1}{N} \sum_{I \cup \omega} E(i) \\ &> \frac{1}{N} \sum_{\bar{I} \setminus \omega} P_s, \end{aligned} \quad (\text{F.3})$$

where the equality of the first two terms arises from the fact that if the battery of the SN is absorbing, $L_s(i) > P_s$ almost always holds. Combining (F.2) and (F.3), we have

$$\frac{1}{N} \sum_I E(i) \leq \frac{1}{N} \sum_{\bar{I}} P_s \quad (\text{F.4})$$

and

$$\frac{1}{N} \sum_{I \cup \omega} E(i) > \frac{1}{N} \sum_{\bar{I} \setminus \omega} P_s. \quad (\text{F.5})$$

If the first term of (F.4) holds with inequality, then moving the subset of indices ω from from $\bar{I}$ to I causes a discontinuity in $\lim_{N \rightarrow \infty} \frac{1}{N} \sum_I E(i)$ and/or a discontinuity in $\lim_{N \rightarrow \infty} \frac{1}{N} \sum_{\bar{I}} P_s$. As it is assumed $|\omega|/N \rightarrow 0$ for $N \rightarrow \infty$, we have

$$\frac{1}{N} \sum_{\omega} E(i) = 0 \quad (\text{F.6})$$

and

$$\frac{1}{N} \sum_{\omega} P_s = 0. \quad (\text{F.7})$$

Thus, such a discontinuity of $\lim_{N \rightarrow \infty} \frac{1}{N} \sum_I E(i)$ and/or a discontinuity in $\lim_{N \rightarrow \infty} \frac{1}{N} \sum_{\bar{I}} P_s$ is impossible. Hence, (F.4) must hold with equality. By jointly considering (F.2), we have

$$\frac{1}{N} \sum_I E(i) = \frac{1}{N} \sum_{L_s(i) < P_s} E(i) + \frac{1}{N} \sum_I E(i). \quad (\text{F.8})$$

Appendix G

Proof of Lemma 6.6

Problem (6.17) is non-convex as the variables $d(i)$ are binary. To handle this problem, we relax $d(i)$ to be $0 \leq d(i) \leq 1$ and form the following problem:

$$\begin{aligned} \max_{d(i), \forall i} \quad & \frac{1}{N} \sum_{i=1}^N (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr} \\ \text{s.t.} \quad & \frac{1}{N} \sum_{i=1}^N d(i) E(i) = \frac{1}{N} \sum_{i=1}^N (1 - d(i)) P_s, \\ & 0 \leq d(i) \leq 1. \end{aligned} \tag{G.1}$$

In the following, it will be shown that the optimal solution $d(i)$ of problem (G.1) is always binary ($d(i) = 0$ or $d(i) = 1$), which proves the equivalence between problem (6.17) and problem (G.1). Problem (G.1) is a linear problem and we use the Lagrange dual method to obtain the optimal solution. The Lagrangian of problem (G.1) can be formed as

$$\mathcal{L}(d(i)) = \frac{1}{N} \sum_{i=1}^N (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr} - \frac{\lambda}{N} \left(\sum_{i=1}^N (1 - d(i)) P_s - \sum_{i=1}^N d(i) \eta P_r h_{sr}(i) \right),$$

where $\lambda \geq 0$ is the Lagrangian multiplier. After some manipulations, we have

$$\mathcal{L}(d(i)) = \frac{1}{N} \sum_{i=1}^N (\lambda \eta P_r h_{sr}(i) + \lambda P_s - \mathcal{O}_{sr}(i) R_{sr}) d(i) + C, \quad (\text{G.2})$$

where $C = \frac{1}{N} \sum_{i=1}^N \mathcal{O}_{sr}(i) R_{sr} - \lambda P_s$ is a constant independent of $d(i)$. According to (G.2), the mode adaptation method that maximizes $\mathcal{L}(d(i))$ is given by

$$d(i) = \begin{cases} 0, & \text{if } \lambda \eta P_r h_{sr}(i) + \lambda P_s < \mathcal{O}_{sr}(i) R_{sr}, \\ 1, & \text{if } \lambda \eta P_r h_{sr}(i) + \lambda P_s \geq \mathcal{O}_{sr}(i) R_{sr}, \end{cases} \quad (\text{G.3})$$

and the optimal value of λ should satisfy

$$\sum_{i=1}^N (1 - d(i)) P_s - \sum_{i=1}^N d(i) \eta P_r h_{sr}(i) = 0. \quad (\text{G.4})$$

It can be observed from (G.3) that the value of λ should be larger than 0, otherwise it is impossible for equation (G.4) to be held. According to (G.3), if the S-R link is in outage ($\mathcal{O}_{sr}(i) = 0$), $d(i)$ should be chosen as $d(i) = 1$. For the case that the S-R link is not in outage ($\mathcal{O}_{sr}(i) = 1$), $d(i)$ is set as 0 only if it satisfies $\Gamma_0 < h_{sr}(i) < \Gamma_1$, where $\Gamma_1 = (R_{sr} - \lambda P_s) / \lambda \eta P_r$. Thus, we can rewrite (G.3) as

$$d(i) = \begin{cases} 0, & \text{if } \Gamma_0 < h_{sr}(i) < \Gamma_1, \\ 1, & \text{otherwise.} \end{cases} \quad (\text{G.5})$$

According to (G.4), the optimal λ should satisfy $\sum_{i=1}^N (1 - d(i)) P_s - \sum_{i=1}^N d(i) \eta P_r h_{sr}(i) = 0$, which could be rewritten as the following equation as $d(i)$ and $h_{sr}(i)$ are ergodic

and stationary processes:

$$\int_0^{\Gamma_0} h_{sr} f(h_{sr}) dh_{sr} + \int_{\Gamma_1}^{\infty} h_{sr} f(h_{sr}) dh_{sr} = \frac{P_s}{\eta P_r} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}. \quad (\text{G.6})$$

The maximum throughput of the S-R link is given by $\tau_{sr} = R_{sr} \int_{\Gamma_0}^{\Gamma_1} f(h_{sr}) dh_{sr}$.

Appendix H

Proof of Theorem 6.5

Based on **Lemma 6.8** and **Lemma 6.9**, the optimal mode adaptation method should make the buffer of the RN work at the edge of non-absorbing which makes $\tau = \tau_{rd}$ hold and the battery of the SN is either absorbing or at the edge of non-absorbing which makes the influence of $L_s(i) < P_s$ negligible. Thus, we form the following optimization problem:

$$\begin{aligned} \max_{d(i), \forall i} \quad & \frac{1}{N} \sum_{i=1}^N d(i) \mathcal{O}_{rd}(i) R_{rd} \\ \text{s.t.} \quad & \frac{1}{N} \sum_{i=1}^N (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr} = \frac{1}{N} \sum_{i=1}^N d(i) \mathcal{O}_{rd}(i) R_{rd}, \\ & \frac{1}{N} \sum_{i=1}^N (1 - d(i)) P_s \leq \frac{1}{N} \sum_{i=1}^N d(i) E(i), \\ & d(i) (1 - d(i)) = 0. \end{aligned} \tag{H.1}$$

Similar to the method used in Appendix G, we relax $d(i)$ to be $0 \leq d(i) \leq 1$ and then use the Lagrange dual method to obtain the optimal solution. After some

manipulations, the Lagrangian of the relaxed problem is given by

$$\begin{aligned}\mathcal{L}(d(i)) = & \frac{1}{N} \sum_{i=1}^N ((1 - \lambda) \mathcal{O}_{rd}(i) R_{rd} + \mu \eta P_r h_{sr}(i)) d(i) \\ & + \frac{1}{N} \sum_{i=1}^N (\mathcal{O}_{sr}(i) R_{sr} - \mu P_s) (1 - d(i)),\end{aligned}\tag{H.2}$$

where λ and $\mu \geq 0$ are the dual variables. Based on the KKT condition, the optimal values of λ , $d(i)$ and μ should satisfy

$$\begin{aligned}\mu \left(\sum_{i=1}^N (1 - d(i)) P_s - \sum_{i=1}^N d(i) \eta P_r h_{sr}(i) \right) &= 0, \\ \sum_{i=1}^N d(i) \mathcal{O}_{rd}(i) R_{rd} - \sum_{i=1}^N (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr} &= 0.\end{aligned}$$

Case one: If we have $\mu = 0$, then $\mathcal{L}(d(i))$ can be written as

$$\mathcal{L}(d(i)) = \frac{1}{N} \sum_{i=1}^N d(i) \mathcal{O}_{rd}(i) R_{rd} - \frac{\lambda}{N} \left(\sum_{i=1}^N d(i) \mathcal{O}_{rd}(i) R_{rd} - \sum_{i=1}^N (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr} \right).$$

Solving this problem by using the method in Appendix B of [41], we can obtain

$$d(i) = \begin{cases} 0, & \text{if } \mathcal{O}_{rd}(i) = 0 \text{ AND } \mathcal{O}_{sr}(i) = 1, \\ 1, & \text{if } \mathcal{O}_{rd}(i) = 1 \text{ AND } \mathcal{O}_{sr}(i) = 0, \\ 0, & \text{if } \mathcal{O}_{rd}(i) = 1, \mathcal{O}_{sr}(i) = 1 \text{ AND } \mathcal{C} = 0, \\ 1, & \text{if } \mathcal{O}_{rd}(i) = 1, \mathcal{O}_{sr}(i) = 1 \text{ AND } \mathcal{C} = 1, \\ 1, & \text{if } \mathcal{O}_{rd}(i) = 0 \text{ AND } \mathcal{O}_{sr}(i) = 0, \end{cases}$$

where $\mathcal{C}$ is a random variable with $\Pr\{\mathcal{C} = 1\} = \frac{p_{sr}R_{sr}-p_{rd}R_{rd}+p_{sr}p_{rd}R_{rd}}{p_{sr}p_{rd}(R_{sr}+R_{rd})}$. Note that case 2 and case 3 in theorem 2 of [41] do not hold when neither the S-R link nor the R-D link is the bottleneck of the system. This mode adaptation method indicates that when both the S-R and R-D links are successful, the system gives a probability $\Pr\{\mathcal{C} = 1\}$ for RN to transmit. Under this constraint, the maximum power that can be harvested by the SN can be found by solving the following optimization problem:

$$\begin{aligned} \max_{\mathcal{A}} \quad & \eta P_r \int_{\mathcal{A}} h_{sr} f(h_{sr}) f(h_{rd}) dh_{sr} dh_{rd} \\ \text{s.t.} \quad & \int_{\mathcal{A}} f(h_{sr}) f(h_{rd}) dh_{sr} dh_{rd} = P_c, \end{aligned} \quad (\text{H.3})$$

where $P_c = p_{sr}p_{rd} \Pr\{\mathcal{C} = 1\}$ and $\mathcal{A}$ is the region used for RN transmission when both the S-R and R-D links are successful (as illustrated in case one of Fig. H.1). The Lagrange dual of problem (H.3) can be expressed as

$$\mathcal{L}(\mathcal{A}, \lambda) = \eta P_r \int_{\mathcal{A}} \left(h_{sr} - \frac{\lambda}{\eta P_r} \right) f(h_{sr}) f(h_{rd}) dh_{sr} dh_{rd} + \lambda P_c, \quad (\text{H.4})$$

where λ is the Lagrange dual variable. To maximize $\mathcal{L}(\mathcal{A}, \lambda)$, the region $\mathcal{A}$ should be chosen as the area with $h_{sr} > \frac{\lambda}{\eta P_r}$. Define $\Gamma^* = \frac{\lambda}{\eta P_r}$, then the maximum harvested energy harvested by the SN can be expressed as

$$P_{\text{in}} = \eta P_r \mathbb{E}[h_{sr} | h_{sr} < \Gamma_0] + \eta P_r p_{rd} \mathbb{E}[h_{sr} | h_{sr} > \Gamma^*],$$

Figure H.1: Mode adaptation method of the general case.

where the value of Γ^* satisfies $\int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr} = p_{sr} \Pr\{C = 1\}$, which results from the constraint of (H.3). By using this method, the output power of the SN is given by

$$P_{\text{out}} = P_s \left(\int_{\Gamma_0}^{\Gamma^*} f(h_{sr})dh_{sr} + \bar{p}_{rd} \int_{\Gamma^*}^{\infty} f(h_{sr})dh_{sr} \right).$$

If the condition $P_{\text{in}} > P_{\text{out}}$ is satisfied, then the battery of the SN is absorbing and $L_s(i) > P_s$ almost always holds. This proves case one of **Theorem 6.5**.

Case two: If we have $\mu > 0$, according to (H.2), the mode adaptation method that maximizes $\mathcal{L}(d(i))$ is

$$d(i) = \begin{cases} 1, & \text{if } \bar{\lambda}\mathcal{R}_{rd}(i) + \mu\eta P_r h_{sr}(i) \geq \lambda\mathcal{R}_{sr}(i) - \mu P_s, \\ 0, & \text{if } \bar{\lambda}\mathcal{R}_{rd}(i) + \mu\eta P_r h_{sr}(i) < \lambda\mathcal{R}_{sr}(i) - \mu P_s, \end{cases} \quad (\text{H.5})$$

where $\bar{\lambda} = 1 - \lambda$, $\mathcal{R}_{sr}(i) = \mathcal{O}_{sr}(i)R_{sr}$ and $\mathcal{R}_{rd}(i) = \mathcal{O}_{rd}(i)R_{rd}$. The parameters λ and μ should satisfy

$$\sum_{i=1}^N (1 - d(i))P_s - \sum_{i=1}^N d(i)\eta P_r h_{sr}(i) = 0 \quad (\text{H.6})$$

and

$$\sum_{i=1}^N d(i) \mathcal{O}_{rd}(i) R_{rd} - \sum_{i=1}^N (1 - d(i)) \mathcal{O}_{sr}(i) R_{sr} = 0. \quad (\text{H.7})$$

Simplifying (H.5), we can get the mode adaptation method of case two.

List of Author's Publications

Journal papers:

- [1] S. Luo and K. C. Teh, "Performance of space-shift keying with buffer-aided amplify-and-forward relaying," accepted for publication in the *IEEE Trans. Veh. Technol.*
- [2] S. Luo and K. C. Teh, "Adaptive transmission for cooperative NOMA system with buffer-aided relaying," accepted for publication in the *IEEE Commun. Lett.*
- [3] S. Luo and K. C. Teh, "Throughput maximization for wireless-powered buffer-aided cooperative relaying systems," *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2299-2310, Apr. 2016.
- [4] S. Luo, G. Yang, and K. C. Teh, "Throughput of wireless-powered relaying system with buffer-aided hybrid relay," *IEEE Trans. Wireless Commun.*, vol. 15, no. 7, pp. 4790-4801, Jul. 2016.
- [5] S. Luo and K. C. Teh, "Buffer state based relay selection for buffer-aided cooperative relaying systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5430-5439, Jun. 2015.

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- [6] S. Luo and K. C. Teh, "Amplify-and-forward buffer-aided two-way relay ARQ system with relay combination," *IEEE Commun. Lett.*, vol. 19, no.2, pp. 299-302, Feb. 2015.
 - [7] S. Luo and K. C. Teh, "Diversity-multiplexing tradeoff of opportunistic relay system with multiple-antenna destination," *IET Commun.*, 2014, 8, (14), pp. 2563-2573.

Conference papers:

- [1] S. Luo and K. C. Teh, and W. Wang, "Wireless-powered cooperative communication with buffer-aided relay," in *Proc. IEEE ICC*, May 2016, pp. 1-6.
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