LINK SELECTION SCHEMES FOR COOPERATIVE BUFFER-AIDED RELAY NETWORKS

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by

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LIST OF ABBREVIATIONS

3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AF	Amplify-and-Forward
AS	Antenna Switching
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPCU	Bits Per Channel Use
BSI	Buffer State Information
CELP	Code Excited Linear Prediction
CMOS	Complementary Metal-Oxide Semiconductor
C-MRC	Cooperative Maximal Ratio Combining
CSI	Channel State Information
DF	Decode-and-Forward
DSI	Delay State Information
DTS	Dynamic Transmission Schedule
EH	Energy Harvesting
FD	Full-Duplex
FS	Federal Standard

HD	Half-Duplex
ID	Information Decoding
i.i.d.	Independent and identically distributed
i.n.d.	Independent and non-identically distributed
IoT	Inter-of-Things
IRI	Inter-Relay Interference
LSB	Least Significant Bit
LTE	Long Term Evolution
MC	Markov Chains
MELP	Mixed Excitation Linear Prediction
MIMO	Multiple-Input-Multiple-Output
MSB	Most Significant Bit
NOMA	Non-Orthogonal Multiple Access
PS	Power Splitting
PTS	Predefined Transmission Schedule
QoS	Quality of Service
RD	The relay-to-destination link
RF	Radio Frequency
SNR	Signal-to-Noise Ratio
SR	The source-to-relay link
SS	Spatial Switching

SWIPT	Simultaneous Wireless Information and Power Transfer
TS	Time Switching
V2V	Vehicle-to-Vehicle
WWRF	Wireless World Research Forum

LIST OF SYMBOLS

α_i	The power splitting ratio in the i-th time slot
η	The efficiency of the energy conversion
$\gamma_{r,i}$	The instantaneous fading coefficient of the *RD* link in the i-th time slot, which has assumed to follow any fading distribution
$\gamma_{s,i}$	The instantaneous fading coefficient of the *SR* link in the i-th time slot, which has assumed to follow any fading distribution
$\mathscr{L}$	The Lagrangian
Ω_r	The average of $\gamma_{r,i}$
Ω_s	The average of $\gamma_{s,i}$
$O(\cdot)$	The big-O notation that represents the worst-case complexity order
π	The stationary distribution of the Markov chains
$\sigma_{i,j}$	The variance of the fading coefficient h_{ij} of the link l_{ij}
τ_{rd}	The average throughput of the *RD* link in SWIPT cooperative system
τ_{sr}	The average throughput of the *SR* link in SWIPT cooperative system
$\varphi(\cdot)$	Function that returns the number of filled elements in the buffer
$\boldsymbol{A}$	The state transition matrix of the Markov chains
a_f	The traffic activity factor of the system
a_j^k	Position of oldest packet in the relay R_k's mask $m_{j,k}$
a_j^s	Position of oldest packet in the source's mask m_j^s
B_m	The size of the masks

D_b	The delay bound of the network
$D_{j,\bullet}$	The j-th row of a matrix D
$D_{\bullet,j}$	The j-th column of a matrix D
$\text{diag}(\cdot)$	Function that returns the diagonal of the input matrix
$E\{\cdot\}$	The expectation
h_{ij}	The Rayleigh fading coefficient of the link l_{ij}
I	The identity matrix
K	Number of relays in the network
L	Size of the buffers
l_{i1}	The link that connects between the source and relay R_i
l_{i2}	The link that connects between the relay R_i and the destination
$m_{j,k}$	The mask of the relay R_k's buffer in state s_j
m_j^s	The mask of the source's buffer in state s_j
$O_{j\times k}$	All zeros matrix with dimension $j \times k$
Out_j	The set that contains all the updated relays' masks after an outage event in state s_j
P	Fixed transmission power used by all nodes in the i.i.d. fading case
P_{B_d}	The probability of selecting a balancing selection with distance d from the balanced state
P_{drop}	The probability of dropping a packet from its holding buffer in the entire system
P_{drop}^s	The probability of dropping a packet from the source's buffer

P_{ij}^{suc}	The probability of successful transmission in the link l_{ij}
P_{ij}^{t}	Transmission power used in the link l_{ij}
$P_{l_{k1}}^{j}$	The probability of selecting the link l_{k1} in state s_j
$P_{l_{k2}}^{j}$	The probability of selecting the link l_{k2} in state s_j
$P_{l_{ij}}^{o}$	The outage probability of the link l_{ij}
$P_{l_{ij}}^{W_d}$	The probability of selecting the balancing link l_{ij} that has distance d from the balanced state
$P_{l_{ij}}^{Z_d}$	The probability of selecting the unbalancing link l_{ij} that has distance d from the balanced state
P_{out}^{iid}	The system outage probability in i.i.d. fading case
P_{out}^{ind}	The system outage probability in i.n.d. fading case
$\Pr(\cdot)$	The probability of an event
P_s	The fixed transmission power of the source in SWIPT cooperative system
P_{B_d}	The probability of selecting an unbalancing selection with distance d from the balanced state
$\overline{P}_w$	The probability of w links are in outage
$\mathbb{P}_{l_{k2}}^{C_d}$	The probability of selecting the link l_{k2} for transmission, where $d = a_j^k$, in the i.n.d. fading case
$\mathbb{P}_{l_{k1}}^{E_d}$	The probability of selecting the link l_{k1} for transmission, where $d = \varphi(Q_k)$, in the i.n.d. fading case
Q_i	The buffer of the i-th relay

Q^s	The buffer of the source node
r_0	The targeted rate of the system
R_i	The i-th relay of the network
R_j^n	The set that contains all the updated relays' masks after selecting the relay R_n for reception in state s_j
S_j'	The updated of the source's mask after selecting one of the relays for transmission or an outage event in state s_j
S_j^r	The updated of the source's mask after selecting one of the relays for reception in state s_j
T_j^n	The set that contains all the updated relays' masks after selecting the relay R_n for transmission in state s_j
$\mathrm{W}(\cdot)$	The Lambert W function

SKEMA-SKEMA PEMILIHAN PAUT BAGI PENIMBAL-DIBANTU RANGKAIAN KERJASAMA GEGANTI

ABSTRAK

Baru-baru ini, teknik kerjasama penyampaian pembantu penimbal telah muncul. Di kebolehlenturan yang ditawarkan oleh muatan penimbal telah dieksploitasi untuk meningkatkan prestasi dalam banyak segi seperti muatan, kenaikan kepelbagaian dan penggunaan tenaga. Walau bagaimanapun, peningkatan yang diberikan meningkatkan kelewatan penghantaran yang lebih tinggi. Objektif tesis ini adalah untuk membangunkan sistem kerjasama penyampaian dengan kekangan kelewatan dan tanpa kekangan kelewatan serta juga membangunkan skema untuk menentukan pemilihan paut yang optima bagi memaksimumkan celusan sistem kerjasama penyampaian berserta maklumat tanpa wayar dan pemindahan kuasa secara serentak (SWIPT). Pertamanya, untuk sistem kerjasama penyampaian yang tidak mempunyai kekangan kelewatan, satu skema pemilihan paut yang baharu telah dicadangkan. Skema ini telah mengeksploitasi keadaan maklumat saluran (CSI) dan keadaan maklumat penimbal (BSI) untuk mengekalkan keadaan bagi penimbal, dengan itu telah mengurangkan kebarangkalian gangguan. Prestasi kebarangkalian gangguan diselidik untuk taburan tak bersandar dan sama (i.i.d.) dan taburan tak bersandar dan tidak sama (i.n.d.) pelunturan Rayleigh disiasat. Berbanding dengan skema berasaskan-keadaan-penimbal (BSB) yang menawarkan kebarangkalian gangguan yang minima diantara skema-skema sebelumnya, skema yang dicadangkan dapat mencapai prestasi yang sama dengan menggunakan kuasa penghantaran yang lebih rendah. Dalam rangkaian tiga nod, pengurangan kuasa yang ditawarkan telah mencapai 2.5 dBW pada beberapa nilai kuasa (sebagai contoh menggunakan 17 dBW selain 19.5 dBW). Satu skema pemilihan paut baharu telah dicadangkan untuk sistem kerjasama penyampai masa nyata dengan kadar maklumat khusus dan kekangan kelewatan. Skema yang dicadangkan memanfaatkan CSI, BSI dan maklumat keadaan kelewatan (DSI) untuk meminimumkan gangguan dan kebarangkalian bingkisan turun dan mencapai celusan yang lebih tinggi. Untuk mencapai maksud ini, ia menggunakan maklumat tersebut untuk bertolak ansur di antara pemilihan penyampai penerimaan dan penghantaran. Skema yang dicadangkan dianalisa dalam i.i.d. dan i.n.d. saluran pelunturan Rayleigh. Bagi sistem yang mempunyai kekangan kelewatan yang tinggi, keputusan simulasi menunjukkan bahawa skema yang dicadangkan menawarkan kebarangkalian penurunan bingkisan yang lebih rendah dan celusan yang lebih tinggi berbanding dengan skema pemilihan penyampai yang terkenal. Skema yang dicadangkan menawarkan pengurangan kuasa yang melebihi 1 dBW dalam beberapa simulasi. Akhir sekali, SWIPT dalam sistem penyampai pembantu penimbal telah dibincangkan. Teknik pemisahan kuasa (PS) telah dipertimbangkan untuk pelaksanaan SWIPT. Skema pemilihan paut optima yang memaksimumkan celusan telah dicadangkan. Dalam setiap lubang alur masa, nisbah PS yang optima digunakan jika sekiranya sumber dipilih untuk penghantaran, manakala penyampai akan menghantar dengan kuasa optima jika dipilih. Berbanding dengan skema lazim yang menggunakan jadual penghantaran yang telah ditetapkan, keputusan simulasi menunjukkan bahawa skema yang dicadangkan menawarkan celusan yang lebih tinggi dan gandaan nisbah isyarat-kepada-hingar (SNR) melebihi 10 dB di beberapa kawasan SNR.

LINK SELECTION SCHEMES FOR COOPERATIVE BUFFER-AIDED RELAY NETWORKS

ABSTRACT

Recently, cooperative buffer-aided relaying technique has emerged. In which, the flexibility offered by the buffering capability is exploited to improve the performance in many aspects such as capacity, diversity gain and power consumption. However, the improvement comes at the price of higher transmission delay. In this thesis, the objectives are to develop the cooperative relaying systems with and without delay constraints as well as to determine an optimal link selection scheme that maximizes the throughput of cooperative relaying systems with simultaneous wireless information and power transfer (SWIPT). First, for cooperative relaying systems without delay constraints, a new link selection scheme that minimizes the outage probability is proposed. It exploits the channel state information (CSI) and buffer state information (BSI) to maintain the states of the buffers, thereby minimizing the outage probability. The outage probability performances in independent and identically distributed (i.i.d.) and independent and non-identically distributed (i.n.d.) Rayleigh fading channels are investigated. As compared to the buffer-state-based (BSB) scheme that offers the minimum outage probability among previous schemes, simulation results show that the proposed scheme offers lower outage probability and can achieve the BSB scheme's performance using less transmission power. In the three-node network, the offered reduction in power has reached 2.5 dBW at some power values (e.g., using 17 dBW instead of 19.5 dBW). For real-time cooperative relaying systems with specific information rates and delay constraints, a new link selection scheme is proposed. The proposed scheme exploits the CSI, BSI and delay state information (DSI) to minimize the outage and packet dropping probabilities and achieve higher throughput. In order to achieve that, it uses these information to compromise between the selections of relays for reception and transmission. The proposed scheme is analysed in the i.i.d. and i.n.d. Rayleigh fading channels. For systems with high delay constraints, simulation results show that the proposed scheme offers lower packet dropping probability and higher throughput as compared to the renowned relay selection schemes. The proposed scheme offers reduction in power that exceeds 1 dBW in some simulations. Lastly, SWIPT in cooperative buffer-aided relaying systems is investigated. Power splitting (PS) technique is considered for SWIPT implementation. An optimal link selection scheme that maximizes the system throughput is proposed. In each time slot, an optimal PS ratio is employed if the source is chosen for transmission, while the relay transmits with optimal power if selected. As compared to the conventional schemes that use predefined transmission schedule, simulation results show that the proposed scheme offers higher throughput and signal-to-ratio (SNR) gain that exceeds 10 dB at some SNR regions.

CHAPTER ONE

INTRODUCTION

Cooperative communication has received considerable interest as a promising technique for future wireless networks. The offered diversity in cooperative communication is exploited to mitigate fading. Accordingly, communication reliability, coverage and throughput of wireless networks can be enhanced. The fundamental concept is that relay nodes can act as a virtual antenna array to assist in communication from a source node to a destination node. In Multiple-input-multiple-output (MIMO) systems, the transmitted signal from each antenna undergoes independent fading conditions. The multiple antennas of MIMO systems offer space diversity. In cooperative relay networks, relay nodes are located in different geographical locations, and thus each relay encounters independent fading conditions. Similar to MIMO systems, the relay nodes together offer space diversity. Therefore, cooperative relay network is referred to as "virtual MIMO" or "virtual antenna array" frequently in the literature (Laneman et al., 2004).

Based on the relay selection policy, a relay or multiple relay nodes are selected to assist in the communication. Compared to multiple relay nodes selection schemes, single relay selection schemes have received more attention by virtue of their greater efficiency in exploiting resources without affecting performance (Krikidis et al., 2012). In single relay selection schemes, a selected relay receives a packet from the source node in a given time slot and retransmits it to the destination in the next time slot. However, because it is not necessary for the selected relay to offer the best source-to-relay (*SR*) and relay-to-destination (*RD*) links simultaneously, these schemes may not exploit the best available links (Ikhlef et al., 2012a).

In order to overcome this limitation, relays with buffers are used recently (Nomikos et al., 2016). The flexibility offered by the buffering capability is exploited. The basic idea is that more than one relay can be selected for reception and transmission. The max-max relay selection (MMRS) scheme that uses predefined transmission schedule (PTS) is proposed in (Ikhlef et al., 2012a). The MMRS scheme allocates the odd time slots for the reception from the source and the even time slots for the relaying of the received packets to the destination. A relay that is selected for reception can store the received packet in its buffer and is not required to retransmit the packet in the next time slot. Hence, in any odd time slot, the relay with the strongest link to the source can be selected for reception, while the relay with the strongest link to the destination can be selected for transmission in the following even time slot. As compared to conventional schemes (i.e., with buffer-less relays) such as (Bletsas et al., 2006; Michalopoulos & Karagiannidis, 2008), the MMRS scheme achieves the same diversity order, but it offers signal-to-noise ratio (SNR) coding gain. However, the flexibility offered by the buffering capability is not fully exploited to select the best available links due to the use of PTS. More specifically, during odd time slots, some *RD* links with better channel qualities than all *SR* links may exist. Also, during even time slots, some *SR* links may have better channel qualities than all *RD* links.

Using dynamic transmission schedule (DTS), many adaptive link selection schemes are proposed such as the schemes in (Krikidis et al., 2012), (Luo & Teh, 2015) and (Oiwa & Sugiura, 2016a). In these schemes, the flexibility offered by the buffering ability is fully exploited. In each time slot, among all the available SR and RD links, a link is selected based on the selection policy. A relay has an available link to the source (destination) if its buffer is not full (empty). An outage event occurs only if all links that are available for selection are in outage. A relay selection scheme that uses DTS is called adaptive, where the adaptivity in the selection may depend on many parameters (e.g., channel states and buffer states) and differ from one scheme to another. Adaptive link selection schemes achieve a diversity up to twice the number of relays and SNR coding gain as compared to the MMRS scheme (Ikhlef et al., 2012a) and conventional schemes such as (Bletsas et al., 2006; Michalopoulos & Karagiannidis, 2008). However, the diversity and the SNR coding gains are achieved at the price of more average transmission delay. In this thesis, cooperative buffer-aided relaying systems with and without delay constraints are considered.

Recently, both industry and academia have endeavoured a lot of effort to improve the energy efficiency for future wireless networks (Hossain et al., 2012). Considerable stake of these efforts has been paid on simultaneous wireless information and power transfer (SWIPT) as a promising method to extend the lifetime of the energy constrained wireless networks (Krikidis et al., 2014; Xiao et al., 2016). Motivated by the achieved results in SWIPT and future wireless networks' trends, SWIPT in cooperative buffer-aided relaying systems is investigated.

1.1 Problem Statement

A relay with non-empty and non-full buffer concurrently can be selected for either reception or transmission, while a relay with empty (full) buffer can be selected for reception (transmission) only. Maintaining buffers states (i.e., keep the buffers states away from empty and full states) increases the number of available links for selections and the offered spatial diversity. An outage occurs if all the available links are in outage. Thus, maintaining the states of the buffers minimizes the outage probability.

The buffer-state-based (BSB) scheme proposed in (Luo & Teh, 2015) considers the states of the buffers as well as transmission delay in its selection policy. However, the concentration and priority given to minimize the average transmission delay in the BSB selection policy resulted in imperfect preservation of the buffers' states. The impact of that on the outage probability performance is more obvious in independent and non-identically distributed (i.n.d.) fading case, where maintaining the states of the buffers is more difficult. Therefore, the desire to set a relay selection policy that preserves the states of the buffers from being empty or full to the great possible extent served as the main motivation for the first contribution of the present thesis. In which, cooperative relaying systems without delay constraints are targeted.

Although delay is considered in many buffer-aided relay selection schemes such as the hybrid scheme in (Oiwa et al., 2016b), the BSB (Luo & Teh, 2015), BAFDAs (Nomikos et al., 2016), G-MMRS and G-ML (Oiwa & Sugiura, 2016a) schemes, their performances have not been assessed under certain delay constraints (i.e., there is no specific time constraint that must be met). More importantly, in all these schemes, the average delay is reduced by minimizing the average buffering delay of the relays, while delay at the source node is neglected.

In delay-sensitive applications, packets are formed according to certain rates and must be received by the destination within the maximum permitted delay (Akyildiz & Vuran, 2010; Goodman & Wei, 1991; Mellouk, 2013), where the delay at the source is counted. A delayed packet beyond the delay bound is considered useless and is dropped from its holding buffer (Goodman & Wei, 1991; Wong, 1993; Yan-Zhang et al., 2006). For instance, in real-time speech communications, speech coders are usually used. In which, the interval of the frame is selected in such a way that the statistics of the speech within the frame interval remain constant (Chu, 2004). The length of the frame interval is between 20 to 30 ms (Chu, 2004), while transmission rate of the source depends on many factors such as speech coder type (e.g., the bit-rates of FS 1016 CELP and FS MELP speech coders equal to 4.8 and 2.4 kbps, respectively (Chu, 2004)) and channel coding.

The considered cooperative buffer-aided relaying systems with certain delay constraints and specific source information rates have not been studied in any of the previous buffer-aided link selection schemes in the literature. The source node has specific information rate means that the source is not saturated with data and the system has certain traffic activity factor. For instance, the traffic activity factors, denoted by a_f henceforth, of the voice and video telephony systems equal 60% and 100%, respectively (Chevallier et al., 2006). The desire to fill this gap by proposing a relay selection policy for these systems is the main motivation for the second contribution of the thesis.

Two practical techniques of SWIPT have been investigated intensively in the literature, in particular, power splitting (PS) and time switching (TS) techniques (Krikidis et al., 2014; Yuan-Liu, 2016). In PS technique, a portion of the received signal energy is exploited for information decoding (ID), while using the remaining for energy harvesting (EH). By contrast, in TS technique, the receiver splits the time between EH and ID. As the received signal in PS technique is used for both EH and ID simultaneously, PS protocols are more efficient than TS protocols (Krikidis et al., 2014). It has been shown in (Nasir et al., 2013) and (Yuan-Liu, 2016) that PS protocols offer higher throughput except for low SNR region.

Recently, SWIPT has been studied in buffer-aided relay networks such as the works in (Alsharoa et al., 2017; El Shafie & Al-Dhahir, 2016; Fei-Wang et al., 2017; Kuang-Liu & Kung, 2017; Luo & Teh, 2016). Among all the existing schemes in the literature, the use of DTS is only considered in the TS-based scheme in (Luo & Teh, 2016). In all other schemes, communication is organised in two or three phases with PTS (i.e., fixed sequence). The source node transmits its information to the relay (or relays, where some schemes select more than one relay) in a certain phase even if the relay (or relays) to the destination link has better channel quality. Similarly, the selected relay (or relays) uses the harvested energy to retransmit the source information to the destination in a phase with predetermined sequence (i.e., PTS) even if the channel quality of the link is worse than the source to relay (or relays) link.

As compared to TS-based link selection schemes, PS-based schemes are more efficient (Krikidis et al., 2014; Yuan-Liu, 2016). Based on intensive search on the literature, there has been no scheme considering both the use of DTS and PS technique for SWIPT implementation. Motivated by the achieved benefits of both using adaptive link selection schemes (more efficient than schemes with PTS) and PS technique (more efficient than TS technique (Krikidis et al., 2014)), an adaptive link selection with SWIPT is investigated, where PS technique is considered.

1.2 Thesis Objectives

This thesis aims to provide flawless link selection schemes for cooperative relaying systems with/without delay and energy constraints. The main objectives of the thesis are:

1. Develop a link selection scheme that minimizes the outage probability to the great possible extent for cooperative relaying systems without delay constraints.
2. Develop a link selection for real-time cooperative relaying systems with delay constraints, which maximizes the system throughput.
3. Determine an optimal link selection scheme that maximizes the throughput of cooperative relaying systems with SWIPT.

1.3 Summary of Contributions

The major contributions of the thesis include:

1. Adaptive link selection scheme for cooperative relaying systems without delay constraints:
    - a new link selection scheme that exploits the channel state information (CSI) and buffer state information (BSI) to minimize the system outage is introduced. This scheme offers minimal outage probability as compared to the existing schemes in the literature.

- The outage probability analysis of the proposed scheme in independent and identically distributed (i.i.d.) and i.n.d. fading models has been derived.

2. Adaptive link selection scheme for real-time cooperative relaying systems with specific information rates and certain delay bounds:

   - A novel link selection scheme that exploits the CSI, BSI and delay state information (DSI) to minimize the outage and packet dropping probabilities and maximize the throughput of the system is presented.
   - Network modelling of the considered systems with specific information rates and delay bounds, which have not been considered in previous buffer-aided schemes, is provided. The modelling is independent of the proposed selection policy and can be used for the analysis of any buffer-aided schemes (e.g., (Krikidis et al., 2012; Luo & Teh, 2015)) in the considered systems.
   - The analysis in terms of outage probability, packet dropping probability of the source node, packet dropping probability of the system and the system throughput in i.i.d. and i.n.d. fading models is presented.

3. An optimal adaptive buffer-aided link selection scheme that applies power splitting technique for SWIPT is introduced. Based on the CSI, the proposed scheme optimally selects one of the links to maximize the system throughput. The optimal power splitting and the optimal transmission power of the relay are computed. The system is modelled and analysed such that any fading distribution can be followed (e.g., Rayleigh, Nakagami, Rician).

1.4 Scope of Work

This thesis focuses on improving the performance of the cooperative buffer-aided relaying systems with and without delay constraints. Also, it considers the use of SWIPT as a promising technique for future wireless networks. In order to accomplish the objectives, three link selection schemes are proposed. Each scheme is analysed as stated in Section 1.3. In addition, MATLAB simulations are made to verify the validity of the analysis as well as to assess the performance of the proposed schemes by comparing their simulation results with those of the state-of-art link selection schemes. There is no hardware realization throughout the thesis.

1.5 Thesis Outlines

The thesis consists of seven chapters, where the remaining six chapters are outlined as follows; Chapter 2 introduces a background for cooperative communications and reviews the related works in the literature. Chapter 3 introduces the used methodology to accomplish the objectives of the thesis. The methodology consists of three sections each of which is indicating to one of the three considered systems, in particular, cooperative buffer-aided relaying systems with/without delay constraints and cooperative systems that use SWIPT for communication. For each of the three systems, the system model, the theoretical method that has been followed to analyse the performance and the followed method to assess the performance are provided. Chapter 4 presents the proposed link selection scheme for cooperative relaying systems without delay constraints, the outage probability analysis and numerical results to assess the performance of the proposed scheme. Chapter 5 provides the network modelling of the real-time cooperative relaying systems with specific information rates and delay bounds, the proposed scheme, the analysis of the system and numerical results to evaluate the system performance. Chapter 6 presents the proposed communication strategy for the considered cooperative relaying systems with SWIPT, the optimal link selection scheme and numerical results to assess the system performance. Chapter 7 concludes the main contributions of the thesis and discusses challenges and opportunities for future researches.

CHAPTER TWO

BACKGROUND AND RELATED WORKS

Due to the direct impact of wireless communications on every aspects of our lives, it has received a lot of interest from both academia and industry. For instance, in 2010, the profit of mobile communications sector alone was 174 billion euros, which is higher than the profits of aerospace and pharmaceutical (Xiang-Wang et al., 2014). As a result, wireless communication sector has one of the fastest growth rates in both academia and industry. Nevertheless, with the explosive growth rate of the wireless devices and services, fulfilling and improving the quality of service (QoS) are always challenging tasks. Based on a study made by the wireless world research forum (WWRF), by 2017, seven trillion devices are predicted to be in service of seven billion people (Xiang-Wang et al., 2014). Hence, wireless communication has been attractive in the last two decades and will continue to do so at least in the near future.

In wireless communications, transmitted signal may arrive at the receiver with multiple copies from different paths due to reflection or diffraction. The addition of these multipath copies can be constructive or destructive that may cause severe signal attenuation. The impact of fading can be mitigated by using one of the diversity methods, where multiple copies of the signal are transmitted over channels that experience independent fading. The main diversity methods are switching in frequency, time or space. In frequency diversity, different copies of the signal are transmitted over different frequencies. The bandwidth used for the transmission of each signal must exceed the coherence bandwidth, and thus channel responses are uncorrelated. The coherence bandwidth is the maximum range of frequencies over which fading channels are correlated. In time diversity, different copies of the signal are transmitted on different time intervals such that channel responses are uncorrelated. Each time interval must exceeds the coherence time. In space diversity or so-called spatial diversity, signal copies are transmitted from different location such that channel responses are uncorrelated. In this thesis, spatial diversity is targeted. Henceforth, diversity is referring to spatial diversity unless mentioned.

Multiple-input-multiple-output (MIMO) system is the most common used system exploiting the spatial diversity. Accordingly, fading can be mitigated and higher throughput can be achieved. In MIMO systems, nodes possess multiple antennas. The spacing between antennas has to be greater than half of the wavelength λ to ensure that the transmitted copies by these antennas have uncorrelated channel responses (Chockalingam & Rajan, 2014; Kumbhani & Kshetrimayum, 2017). Although it has been proven MIMO systems can improve the QoS, there are some limitations, such as cost and size, that decrease the feasibility of MIMO systems in some applications. For instance, in cellular systems, it is quite difficult, if it is not impossible, to install MIMO antennas in handsets because of the antenna array size. For example, for MIMO systems that operate on 900 MHz and 2.5 GHz, the spacing between antennas must be greater than 16.67 cm and 6 cm (i.e., greater than $\frac{\lambda}{2}$), respectively. The wavelength is equal to $\lambda - \frac{c}{f}$, where c is the speed of light and f is the operating frequency (Kumbhani & Kshetrimayum, 2017). Therefore, the focus is partially shifted into cooperative communications, where virtual MIMO can be formed.

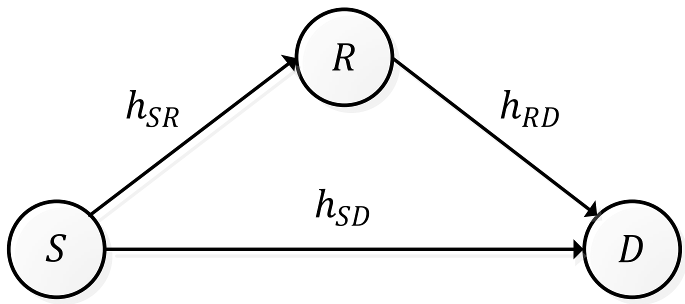

Figure 2.1: A simple cooperative relay network in which a relay node, *R*, assists a source node, *S*, to communicate with a destination node, *D*.

2.1 Cooperative Communications

Cooperative communication has received considerable interest as a promising strategy for future wireless networks. The fundamental concept is that relay nodes can act as virtual antenna array to assist in communication between a source node and destination node (Laneman et al., 2004). The distributed nodes replace the antenna array elements and form virtual MIMO. Figure 2.1 shows a simple cooperative relay network in which a relay node assists a source node to communicate with a destination node. The relay node can be an access relay point or another user. First, the source node broadcast its signal that will be received by both the relay and destination nodes. Then, the relay node retransmits the source signal to the destination. Thus, the destination will possess two copies of the source signal that have experienced independent fading channels. Cooperative communication exploits the spatial diversity to improve the QoS in many aspects such as capacity, coverage and total power expenditure (Cui et al., 2004; Hossain et al., 2011; Laneman et al., 2004; Zhong-Zhou et al., 2008).

Two relaying protocols are used in cooperative communications, namely, half-duplex (HD) and full-duplex (FD) relaying. In HD relaying protocols (e.g., (Azarian et al., 2005; Laneman et al., 2004; Rankov & Wittneben, 2007)), communication is established in two stages. In the first stage, the source node transmits its information to the relay nodes. In the second stage, relay nodes retransmit the source information to the destination node. In FD relaying, relay nodes have the ability to receive and transmit simultaneously over the same frequency band. The self-interference in FD systems degrades the performance significantly, which makes HD relaying protocols are preferable at present (Islam, 2014; Zafar, 2014). However, with the tremendous amount of researches have been carried out on FD communications, FD protocols may prevail in near future. In most recent studies on next-generation 5G wireless systems (Agiwal et al., 2016; Osseiran et al., 2014; Xiang-Wang et al., 2014), FD transmission is considered among competent technologies to be adopted in 5G wireless systems.

In addition, relaying protocols are also classified based on their data processing methods. The most widely used data processing methods are amplify-and-forward (AF) and decode-and-forward (DF) (Nosratinia et al., 2004). In AF relaying schemes (e.g., (Torabi et al., 2009; Yanwu-Ding et al., 2007; Yi-Zhao et al., 2006)), the source node transmits its information towards the relay node (or nodes) and the destination. The relay receives a noisy copy of the transmitted source signal, then, amplifies the signal and retransmits it to the destination node. Thus, the destination node receives two copies of the source signal. Despite the fact that noise has been amplified, the offered spatial diversity leads to a performance improvement as compare to non-cooperative communications. In DF relaying (e.g., (Hwang et al., 2008; Jin et al., 2011; Tairan-Wang et al., 2007)), the relay node (or nodes) decodes the received source signal before re-encodes and transmits the signal to the destination. Therefore, noise amplification is eliminated. However, it may cause error propagation especially in low SNR region over which decoding error is high.

A hybrid DF scheme is proposed in (Laneman et al., 2001) to mitigate decoding error propagation. In that work, based on the CSI, the relay either works on the DF mode or turns to non-cooperative mode and neglects the signal if the SNR is very low. Tairan-Wang et al.(2007) proposed a milestone DF relaying scheme referred to as cooperative maximal ratio combining (C-MRC). In which, a weighted combiner, which computes weights based on the direct source-destination path and source-relay-destination path, is used. The C-MRC has low complexity and offers diversity that is equal to the number of relays.

Cooperative relaying schemes can be categorized based on their selection policies into multi-relay selection and single-relay selection schemes (Ikhlef et al., 2012a; Nomikos et al., 2016). In multi-relay selection schemes (e.g., (Beibei-Wang et al., 2009; Juan-Zhang & Gong, 2009; Laneman & Wornell, 2003; Tairan-Wang et al., 2007; Vicky-Zhao & Su, 2010)), multiple relays participate in retransmitting the source information to the destination. In single-relay selection schemes (e.g., (Bletsas et al., 2006, 2007; Michalopoulos et al., 2008)), the best relay only is selected, based on the adopted selection criterion, to cooperate in the communication between the source and destination nodes. As only one relay is selected, the entire bandwidth can be exploited by the selected relay. An outage event occurs only if all relays cannot cooperate. These schemes offer a diversity that is equal to the number of relays, while better resource allocations are used. As compared with multi-relay selection schemes, single relay selection schemes have received more attention by virtue of their greater efficiency in resources without affecting performance (Ikhlef et al., 2012a; Nomikos et al., 2016).

A major drawback of both DF multi-rely selection and DF single-relay selection is that the system performance is restricted by the hop with lower quality (Zafar, 2014). The source node cannot use a data rate larger than what can be relayed successfully to the destination correctly. For single-relay selection schemes, if the source can communicate with the destination only through relays (i.e., the direct link is in state of deep fading), the system throughput is given by (Yuan-Liu, 2016)

$$\tau_{\text{single}} \leq \frac{1}{2}\min\left\{\log_2(1+\text{SNR}_{SR}), \log_2(1+\text{SNR}_{RD})\right\}, \tag{2.1}$$

where SNR_{SR} is the SNR of the *SR* link and SNR_{RD} is the SNR of the *RD* link of the selected relay. If the direct *SD* link is counted, the system throughput is given by (Laneman et al., 2004)

$$\tau_{\text{single}} \leq \frac{1}{2}\min\left\{\log_2(1+\text{SNR}_{SR}), \log_2(1+\text{SNR}_{RD}+\text{SNR}_{SD})\right\}. \tag{2.2}$$

For multi-relay selection schemes that use C-MRC method, if the direct link is in deep fading, the system throughput is given by (Yuan-Liu, 2016)

$$\tau_{\text{MRC}} \leq \frac{1}{2}\min\left\{\log_2(1+\text{SNR}_1), \log_2(1+\text{SNR}_2)\right\}, \tag{2.3}$$

where $\text{SNR}_1 = \min\{\text{SNR}_{SR_1}, \text{SNR}_{SR_1}, \cdots, \text{SNR}_{SR_N}\}$. SNR_{SR_i} is the SNR of the *SR* link of the *i*-th relay, while N is the number of relays. $\text{SNR}_2 = \sum_{i=1}^{N} \text{SNR}_{RD_i}$, where SNR_{RD_i} is the SNR of the *RD* link of the *i*-th relay. If the direct *SD* link is counted, the system throughput is given by (Laneman et al., 2004)

$$\tau_{\mathrm{MRC}} \leq \frac{1}{2}\min\left\{\log_2(1+\mathrm{SNR}_1), \log_2(1+\mathrm{SNR}_2+\mathrm{SNR}_{SD})\right\}. \tag{2.4}$$

2.2 Cooperative Buffer-Aided Relaying

In order to overcome the drawback mentioned earlier that the performance of the relaying network is limited by the hop with lower quality, the flexibility offered by the buffering capability has been exploited. Interestingly, most nodes are already equipped with buffers that mainly have used for network layer purposes. The basic idea is that in buffer-aided schemes, different relays can be selected for reception and transmission. The selected relay for reception can store the received buffer in its buffer and is not required to retransmit the packet in the next time slot. Hence, the relay with the best link to the source and the relay with the best link to the destination can be selected for reception and transmission, respectively.

Henceforth, the term "conventional" will be used to denote cooperative relaying schemes that do not exploit the buffering capability in agreement with the majority of the recent works in the literature. Furthermore, the best relay selection (BRS) scheme (denoted by max-min in some works) proposed in (Bletsas et al., 2006) is usually used to represent conventional relaying such as in (Ikhlef et al., 2012a; Krikidis et al., 2012; Zlatanov et al., 2014). The BRS scheme selects the link with the highest minimum quality for transmission. For example, between the two relays R_1 and R_2 with channels $\{h_{SR_1}=4, h_{R_1D}=6\}$ and $\{h_{SR_2}=9, h_{R_2D}=2\}$, the BRS scheme selects R_1 for transmission as its minimum channel (i.e., $h_{SR_1}=4$) has better quality than the minimum channel of R_2 (i.e., $h_{R_2D} = 2$).

The proposed vehicular communication system in (Grossglauser & Tse, 2001) was the first work in which the buffering capability is exploited for communication. In that work, mobile terminals can receive or transmit only within a range from the base station. Outside this range, mobiles can keep buffering their data until they return inside the range. In cooperative communications, the most renowned works with greatest influence on latest state-of-art buffer-aided schemes are the work in (Zlatanov et al., 2011) that is extended in (Zlatanov et al., 2013a), the MMRS scheme (Ikhlef et al., 2012a) and the max-link scheme (Krikidis et al., 2012).

Similar to conventional relaying schemes, the MMRS scheme proposed in (Ikhlef et al., 2012a) is using PTS for transmission. The MMRS scheme allocates the odd time slots for the reception from the source and the even time slots for the relaying of the received packets to the destination. In this scheme, as relay nodes are equipped with buffers, a relay that is selected for reception can store the received packet in its buffer and is not required to retransmit the packet in the next time slot. Hence, the relay with the strongest link to the source and the relay with the strongest link to the destination can be selected for reception and transmission, respectively. Accordingly, different relays may be selected for reception and transmission. As compared to the BRS scheme, the MMRS scheme offers the same diversity order that is equal to the number of relays, but it offers significant SNR coding gain.

The max-link scheme that uses DTS for transmission is proposed in (Krikidis et al., 2012). In this scheme, in each time slot, the available link that offers the strongest channel among all the available *SR* and *RD* links is selected. A relay has an available link to the source node if the relay's buffer is not full, while a link to the destination node is considered available if the corresponding relay's buffer is not empty. An outage occurs only if all links that are available for selection are in outage. The max-link scheme (Krikidis et al., 2012) can achieve a diversity up to twice the number of relays. The modelling of cooperative buffer-aided relaying systems based on Markov chain theory is used as framework by most of the buffer-aided schemes proposed later. For instance, the framework is used by the schemes in (Nomikos et al., 2015, 2016; Oiwa & Sugiura, 2016a) as well as the proposed scheme in Chapter 4. The proposed scheme in Chapter 5 is using a new modelling that depends on the max-link scheme's framework to some extent. In order to simplify the understanding of the modelling and analysis of the proposed schemes in Chapters 4 and 5, the max-link scheme's modelling and analysis will be introduced in brief.

Markov chains (MC) modelling is widely used in science to analyse the long run performance of systems that include random phenomena due to its simplicity and precise results (Bolch et al., 2006; Norris, 1998). MC consists of states that represent all possible states of the system. The state transition matrix, denoted by $\boldsymbol{A}$, contains all probabilities of transitions from a state to another. The matrix element $\boldsymbol{A}_{i,j}$ represents the probability of transitioning from state s_j to state s_i ($\boldsymbol{A}_{i,j} = \Pr(X_{t+1} = s_i | X_t = s_j)$). Beside the state transition matrix, an important parameter is the time invariant state distribution, also called stationary distribution or equilibrium distribution (Norris, 1998), which represents the probability of occurrence of each state in long run of the system. For instance, if a state has stationary probability 0.5, the system will stay half of the time on that state. The stationary distribution is denoted by π henceforward. MC the-

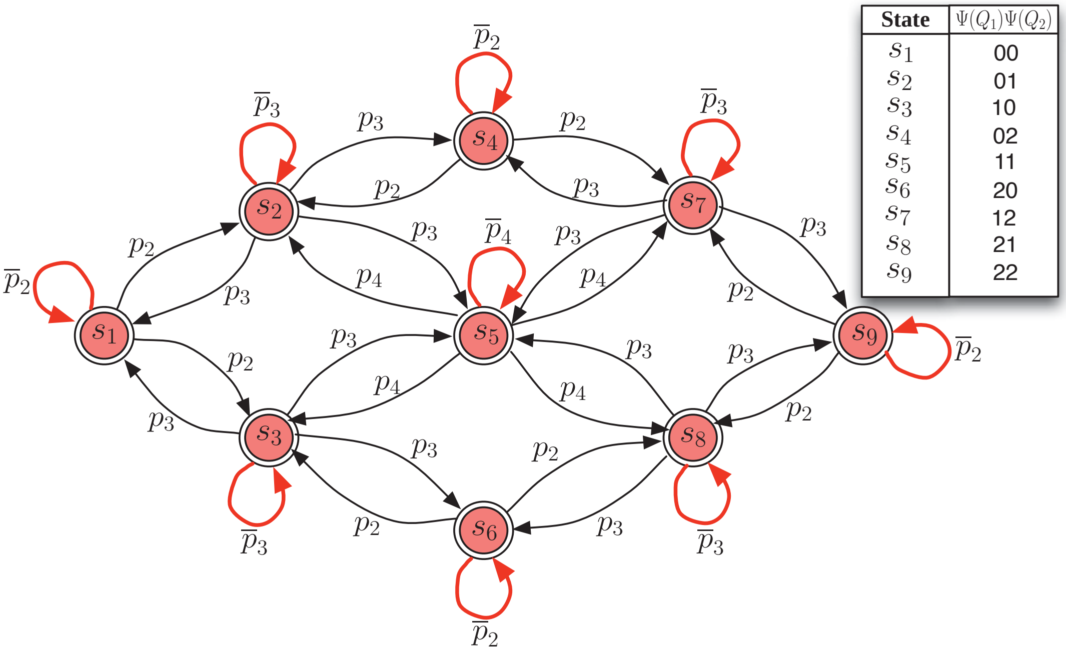

Figure 2.2: State diagram of the MC that represents the states of the buffers and transition probabilities for a network consists of $K = 2$ relays and buffer size $L = 4$ (Krikidis et al., 2012).

ory is a very wide science, and thus the description here only focuses on modelling cooperative buffer-aided relaying using MC. In the considered framework in (Krikidis et al., 2012), MC states represent the states of the relays' buffers (i.e., the number of filled elements in each buffer). In order to simplify the description of the framework, the illustrative example in (Krikidis et al., 2012) is used. In a simple cooperative network, the source can communicate with the destination only through one of two buffer-aided relays. The first (second) relay is equipped with a buffer Q_1 (Q_2) with size $L = 2$, where each element of the buffer can be used to store one packet. Based on the network architecture, there are nine possible combinations of the buffers states each of which represents a state on the MC as shown in Figure 2.2. For instance, $s_7 = 12$ means there is one filled element in the buffer Q_1 of the first relay R_1, while there are two filled elements in the buffer Q_2 of the second relay R_2. In Figure 2.2, the function

$\varphi(Q_i)$ returns the number of filled elements in the buffer Q_i. If one of the two relays in state s_7 is selected for reception or transmission, the number of filled elements in the buffer will be incremented or decremented by one, respectively. For example, if the relay R_1 is selected for reception, the number of filled elements in Q_1 will increment to two. That means, the system will transition from state s_7 to state s_9 in which both buffers have two filled elements. Likewise, in state s_7, if the relay R_1 is selected for transmission, the number of filled elements in Q_1 will decrease to zero. The system will transition from state s_7 to state s_4 in which the relay R_1 has no filled elements in its buffer, while the relay R_2 has two filled elements. In an outage event, buffers states remain without change and the system stays in the present state.

A relay node has an available link to the source (destination) node if the relay's buffer is not full (empty). In state s_j, the number of links that are available for selection, denoted by D_j, is equal to the total number of available links of all relays (Krikidis et al., 2012, Eq. (5)). As Rayleigh fading is assumed, the outage probability of a link l_{mn} is equal to (Laneman et al., 2004)

$$P^{o}_{l_{mn}} = 1 - \exp\left(-\frac{2^{2r_0} - 1}{P^{t}_{mn}\sigma^{2}_{mn}}\right), \tag{2.5}$$

where P^{t}_{mn} is the transmission power, σ^{2}_{mn} is the variance of the fading channel of the link and r_0 is the target rate of the system. For simplicity, i.i.d. fading (all links have variances equal to one) and fixed transmission power P are assumed. Therefore, the outage probabilities of all links are equal. Accordingly, in state s_j, an outage event (in which all available links D_j cannot be selected and the system stays in state s_j) has a probability equals to

$$\overline{P}_{D_j} = {P^{o}_{l_{mn}}}^{D_j} = \left(1 - \exp\left(-\frac{2^{2r_0}-1}{P}\right)\right)^{D_j}. \tag{2.6}$$

The max-link scheme selects the link with the strongest channel among all SR and RD links that are available for selection. If the strongest channel is possessed by more than one link, the max-link scheme selects one of them uniformly. As i.i.d. fading is assumed, all available links have the same probability to be selected (i.e., have the same probability to enjoy the strongest channel). In state s_j, all the available links D_j have the same probability to be selected, which is equal to

$$p_{D_j} = \frac{1}{D_j}\left[1 - \left(1 - \exp\left(-\frac{2^{2r_0}-1}{P}\right)\right)^{D_j}\right]. \tag{2.7}$$

State s_7 has 3 available links $D_7 = 3$ (SR_1, R_1D and R_2D), where R_2 can be selected only for transmission because Q_2 is full. The relay R_1 can be selected for reception or transmission as the relay's buffer is not full and not empty. The probability of selecting SR_1, R_1D or R_2D is equal to p_3 that is given by Eq. (2.7). Thus, the probability of the transition from state s_7 to s_4, s_5 or s_9 is equal to p_3 (i.e., $\boldsymbol{A}_{4,7} = \boldsymbol{A}_{5,7} = \boldsymbol{A}_{9,7} = p_3$). An outage event may occur in state s_7 if the three available links are in outage, which has a probability equals $\overline{P}_3$ that can be determined by Eq. (2.6). Similarly, the entire transition matrix $\boldsymbol{A}$ can be found as in (Krikidis et al., 2012, Eq. (15)).

The state transition matrix $\boldsymbol{A}$ of the MC is a column stochastic and an irreducible matrix. The proofs of these properties are straightforward in (Krikidis et al., 2012).

Thus, the MC has a stationary distribution π (Norris, 1998) that can be found by

$$\pi = \boldsymbol{A}\pi, \tag{2.8}$$

where $\pi = (\pi_1, \pi_2, \cdots, \pi_N)^T$ and $(\cdot)^T$ gives the transpose of the matrix. In (Krikidis et al., 2012), another formula to find π is also derived. In that formula, $\pi = (\boldsymbol{A} + I + D)^{-1}C$, where I is the identity matrix and D and C are all ones matrices. Both I and D have the same size of $\boldsymbol{A}$ (i.e., $N \times N$, where N is the number of states), while C has the same size of π (i.e., $N \times 1$).

In any state s_j, an outage event occurs if and only if all available links D_j in that state are in outage. None of the links will be selected and buffers states remain the same without any change (e.g., an outage in state s_7 has a probability $\boldsymbol{A}_{7,7} = \overline{P}_3$). The overall system outage probability is equal to the sum of outage events in all states, and thus can be given by

$$P_{out} = \text{diag}(\boldsymbol{A})\pi. \tag{2.9}$$

The understanding of the max-link scheme's modelling and analysis is very important and represents an entrance key for more complicated MC analysis in Chapters 4 and 5.

The MMRS scheme (Ikhlef et al., 2012a) outperforms the BRS (Bletsas et al., 2006) due to the freedom offered by the buffering capability. The max-link scheme (Krikidis et al., 2012) outperforms both the MMRS and BRS schemes by virtue of the DTS used in its selection policy. In order to simplify the understanding of that, an illustrative example is presented. A simple network that consists of one source, two DF relays and one destination is considered as shown in Figure 2.3. The instantaneous

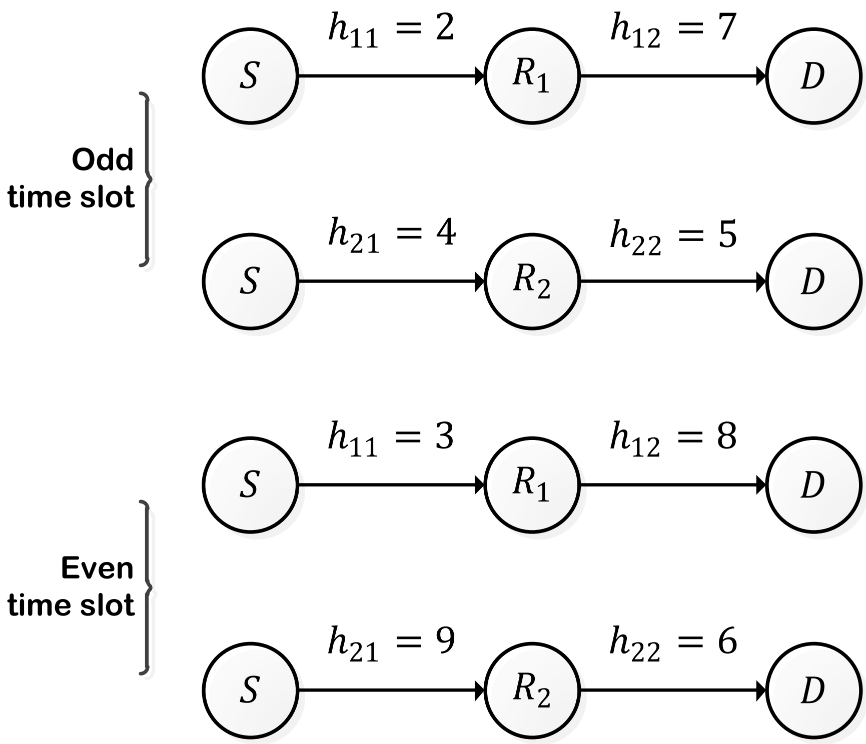

Figure 2.3: a simple cooperative relay network in which two relay nodes, R_1 and R_2, assists a source node, S, to communicate with a destination node, D.

SNR of each link in the odd time slot $2i-1$ and the following even time slot $2i$ are illustrated in Figure 2.3. The parameter h_{i1} denotes the fading coefficient of the *SR* link of the i-th relay, while the parameter h_{i2} denotes the fading coefficient of the *RD* link of the i-th relay. The BRS scheme (Bletsas et al., 2006) selects the relay with the maximum minimum channel quality using PTS for transmission. The relay R_1 has $h_{11} = 2$ in the odd time slot and $h_{12} = 8$ in the even time slot, while the relay R_2 has $h_{21} = 4$ in the odd time slot and $h_{22} = 6$ in the even time slot. Thus, the relay R_2 has the maximum minimum channel quality (i.e., $h_{21} > h_{11}$) and will be selected for transmission. On the other hand, the MMRS scheme (Ikhlef et al., 2012a) selects the *SR* (*RD*) link with the strongest channel in odd (even) time slots. Therefore, the links SR_2 and R_1D will be selected. Lastly, in each time slot, the max-link scheme (Krikidis et al., 2012) selects the link with the strongest channel quality among all the *SR* and *RD*