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Report of Wireless Access & Multiple Antenna Technologies

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Author(s)	Albrecht Wolf, Andreas Festag, Jiancao Hou, Na Yi, Iqbal Hussain, Weiwei Jiang, Tad Matsumoto, Jiguang He
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Abstract: In this deliverable, we address several aspects related to physical transmission and medium access for the links-on-the-fly concept. After a brief review of *lossy forwarding* and RESCUE requirements on the physical and medium access control layers, we present three parts: First, we study multiple-input multiple-output (MIMO) beamforming to improve system reliability and spectrum efficiency in the context of *lossy forwarding*, specifically a MIMO multi-relay system with random beamforming and limited feedback. The approach exploits link correlation information in order to mitigate error propagation effects. Two user scheduling strategies are proposed and assessed by means of theoretical and numerical analysis. Second, we consider the relay network of toy scenario 1 as a virtual multiple-input single-output (MISO) system. Then, we evaluate the performance by employing *lossy forwarding* and investigate the tradeoff between high communication reliability (diversity gain) on the one side and high throughput for a fixed reliability level (multiplexing gain) on the other side. We compare the *lossy forwarding* scheme with the conventional decode-and-forward scheme in terms of diversity and multiplexing gain by means of theoretical and numerical analysis. Third, we extend the RESCUE system to a general multi-user multi-way relay network. Based on this model, we explore the use of coded random access as a promising wireless access technique and develop a framework that allows to investigate the combination of *lossy forwarding* and the coded random access schemes.

Keyword list: links-on-the-fly, distributed lossless/lossy source coding, multi-user multi-way relay network, random beamforming, MIMO, error propagation effects, diversity-multiplexing tradeoff, coded random access

Executive Summary

This deliverable provides results from the research on physical transmission and medium access for the links-on-the-fly concept in the RESCUE project. The results are related to three main topics: (i) evaluation of a multiple-input multiple-output (MIMO) multi-relay system with random beamforming (RBF), limited feedback and *lossy forwarding*, (ii) assessment of the diversity-multiplexing tradeoff for a three-node relay network with *lossy forwarding*, and (iii) combination of *lossy forwarding* and coded random access schemes. The work has been carried out in work package 1 *Theoretical analyses for limit and rate-distortion region*, specifically in task 1.3 *Wireless access & multiple antenna techniques*.

In the first part – *evaluation of a MIMO multi-relay system with RBF, limited feedback and lossy forwarding* – we study RBF to improve system reliability and spectrum efficiency in the context of *lossy forwarding*. It considers a system where multiple source nodes equipped with single antennas communicate with their corresponding single-antenna destination nodes with the help of two multiple-antenna based relays. For this MIMO multi-relay system, we assume a RBF technique with limited feedback from the destination users to the relays. The selected approach exploits source-relay (S-R) link correlation information in order to mitigate error propagation consequences. To limit the feedback from destination to relays, two strategies for joint scheduling are proposed: (i) the destination users send their selected channel indexes and the preferred beam indexes to the relay based on their initially predicted signal-to-interference-plus-noise ratio (SINR). (ii) The destination users send, as in the first strategy, the selected channel and preferred beam indexes, and in addition the undesired interference beams to the relay. This additional information helps to improve the accuracy of the predicted SINR. We present algorithms for both strategies along with methods to reduce their complexity. We show by means of theoretical and numerical analysis that the first strategy increases the number of active destination nodes compared to the conventional RBF. The second strategy exhibits a better system performance with more accurate SINR prediction at the costs of a moderately increased complexity and a slightly larger feedback overhead.

In the second part – *assessment of the diversity-multiplexing tradeoff with lossy forwarding* – we investigate the tradeoff between high communication reliability (diversity gain) on the one side and high throughput for a fixed reliability level (multiplexing gain) on the other side with *lossy forwarding*. Specifically, we consider a three-node one-way relay system (RESCUE toy scenario 1 (TS1), source coding with a helper). We formally define the problem for diversity-multiplexing tradeoff for finite signal-to-noise ratio (SNR) and compare the *lossy forwarding* scheme with the conventional decode-and-forward (DF) scheme with respect to diversity and multiplexing gain by means of by theoretical and numerical analysis. We find significant improvements of *lossy forwarding* over the conventional scheme. Within the multiplexing range *lossy forwarding* outperforms the conventional DF scheme with respect to diversity gain. In addition, significant multiplexing gain can be achieved by *lossy forwarding*, which leads to maximum 50% higher possible transmission rate compared to the conventional DF scheme.

In the third part – *combination of lossy forwarding and coded random access* – we characterize the RESCUE system to a generalized multi-user multi-way relay network. This model represents the most general approach that allows exploring random access schemes. Specifically, we consider random access as an underlying scheme that is an appropriate access scheme for unpredictable environments with massive number of uncoordinated transmitting devices. We specifically study coded random access that relies on the concepts of graph-based codes and successive interference cancelation (SIC). The combination of *lossy forwarding* and advanced random access scheme promises a high performance gain in throughput and robustness compared to conventional random access schemes. Based on the new model of the multi-user multi-way relay network and an analysis of the various variations of coded random access, we develop a framework that allows studying coded random access in the context of RESCUE. We present the preliminary theoretical and numerical results for a simplified scenario based on MIMO relaying. The detailed theoretical and numerical results for more complex scenarios will be provided in other deliverables, i.e. D1.2.2 and D2.1.2.

The three topics address key challenges of RESCUE scenarios: In unpredictable environments, such as devastated areas or dense networks with many links and highly mobile nodes, a robust operation of the network at a high performance cannot be guaranteed as it is not possible to manage interference properly and to keep synchronization among communicating nodes. The presented results on physical transmission and multiple access help to address these challenges.

Authors

Partner	Name	Phone/Fax/e-mail
Technical University Dresden (TUD)	Albrecht Wolf	EMail: albrecht.wolf@tu-dresden.de
	Andreas Festag	EMail: andreas.festag@tu-dresden.de
University of Surrey (UNIS)	Jiancao Hou	EMail: j.hou@surrey.ac.uk
	Na Yi	EMail: n.yi@surrey.ac.uk
University of Oulu (UOULU)	Iqbal Hussain	EMail: iqbal.hussain@ee.oulu.fi
	Jiguang He	EMail: jiguang.he@ee.oulu.fi
Japan Advanced Institute of Science and Technology (JAIST)	Tad Matsumoto	EMail: matumoto@jaist.ac.jp
	Weiwei Jiang	EMail: wjiang@jaist.ac.jp

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List of Acronyms and Abbreviations

Term	Description
AF	Amplify-and-forward
AWGN	Additive white Gaussian noise
CEO	Chief executive officer
CF	Compress-and-forward
CSI	Channel state information
CFO	Carrier frequency offset
CRC	Cyclic redundancy check
DF	Decode-and-forward
DMT	Diversity-multiplexing tradeoff
DoF	Degrees of freedom
DSC	Distributed source coding
DTC	Distributed turbo code
f-DMT	Finite-SNR diversity-multiplexing tradeoff
HBC	Hybrid broadcast
JD	Joint decoding
LLR	Logarithm likelihood ratio
MA	Multiple access
MAC	Multiple access channel
MIMO	Multiple-input multiple-output
MISO	Multiple-input single-output
MRT	Maximum ratio transmission
PHY	Physical layer
PTT	Push-to-talk
R-D	Relay-destination
RBF	Random beamforming
S-D	Source-destination
S-R	Source-relay
SCTC	Straightforward combining based turbo code
SIC	Successive interference cancelation
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal-to-noise ratio
TDBC	Time-division broadcast
TDMA	Time division multiple access
TC	Turbo code
TS1	Toy scenario 1
V2V	Vehicle-to-vehicle
ZF	Zero-forcing

1. Introduction

In unpredictable environments, wireless networks are faced with challenging requirements in terms of energy efficiency and reliable information transfer under a continuously changing network topology. Within the RESCUE project we address these requirements to enable wireless communication in devastated areas with a limited communication infrastructure or densely populated networks. Therefore, an innovative distributed source coding (DSC) technology, referred to as *lossy forwarding* was proposed. Unlike in the conventional DF relaying, with *lossy forwarding* a relay forwards a message regardless whether errors have been detected after decoding. At the destination, a joint decoding technique exploits the high correlation of the messages received via different network paths. With *lossy forwarding*, an increase of network capacity and a reduction of outage probability are expected. This deliverable incorporates *lossy forwarding* into wireless access and multiple antenna technique from different perspectives. In this chapter, we present requirements on wireless access and multiple antenna techniques for RESCUE scenarios and introduce the three main topics that will be presented in detail.

1.1 Requirements on Wireless Access and Multiple Antenna Techniques

In [D11], two main RESCUE application scenarios have been developed, i.e. public safety and vehicle-to-vehicle (V2V), and functional requirements on wireless access and multiple antenna techniques have been established. In the following, we summarize the requirements for the RESCUE application scenarios.

Simultaneous access of users: The transmission of several copies of a message over multiple routes strongly increases the load on the network. Since erroneous messages are not necessarily dropped, the network load is even further increased with the links-on-the-fly concept. Hence it is strongly required that the RESCUE multiple access control protocol allows several nodes to simultaneously transmit on a shared time-frequency resource in order to not increase transmit latency.

High spectral efficiency: Spectral efficiency is a main point for any wireless transceiver scheme as a low spectral efficiency increases delays and network load or required bandwidth. Therefore, we consider spectral efficiency as a performance indicator in the RESCUE project as considered the previously submitted deliverables..

Low latency transmission: In RESCUE application scenarios, several time-critical messages exist that need to be delivered within low delay. For example, in the V2V use case, messages for the electronic break light or accident alarms need to be delivered as fast as possible. Also, in public safety use cases, latency can become an issue, e.g., in the push-to-talk (PTT) communication case.

High system reliability: Providing a robust wireless communication system is an essential requirement for RESCUE scenarios. Public safety and V2V uses cases can only be addressed, if the wireless communication system can guarantee a very low outage probability.

Low power consumption: In RESCUE scenarios, we assume moving nodes with limited power resources. Consequently, energy efficient transmission and low power consumption are inevitable to ensure a long participation of all nodes in wireless networks.

1.2 Main Contributions of this Deliverable

Advanced wireless access techniques and multiple antenna technologies have a great potential to increase system performance. Their combination with the *lossy forwarding* concept in RESCUE promises to improve the performance gain and to meet the requirements from RESCUE application scenarios.

In multi-user communication systems, co-channel interference poses challenges to the wireless network as well. MIMO beamforming can be exploited to mitigate co-channel interference [God97]. Motivated by this, we introduce RBF with limited feedback. In MIMO multi-relaying networks, relays are provided with limited feedback of channel state information (CSI) from the destinations. With this information, the relays can determine qualified destination and thus, align beams accordingly. Two strategies to select qualified destination are proposed and evaluated by means of theoretical and numerical analysis. Moreover, both methods exploit the link correlation information in order to mitigate error propagation effects. It can be concluded that the proposed methods achieve significant improvements in terms of spectrum efficiency and system reliability.

It is challenging to achieve reliability and spectrum efficiency simultaneously in wireless sensor networks. The resilience of a network can be improved by multi-path routing (diversity), however more resources are required which impairs the spectrum efficiency (multiplexing). Thus, we evaluate the links-on-the-fly concept in a three-node one-way relay system and study the tradeoff between diversity gain and multiplexing gain for finite-SNR proposed in [Nar06]. Since the spatial topology of the three-node one-way relay system is equivalent to two input single output multiple-input single-output (MISO) system, we compare the performance of the proposed scheme with 2x1 MISO diversity multiplexing tradeoff limit and that with Alamouti scheme. It is found that with *lossy forwarding*, we can achieve close 2x1 MISO diversity multiplexing tradeoff bound, which is much better than the classical Alamouti scheme. Furthermore, the proposed lossy forwarding DF scheme shows improved performance as compared to the conventional DF schemes in terms of the outage probability.

In multi-user communication systems, the simultaneous access of users poses challenges to wireless networks. Therefore, we discuss advanced coded random access techniques, such as framed slotted ALOHA [Oka77]. In framed ALOHA, the link is divided into frames, and the user is allowed to transmit in a randomly chosen time slot of a given frame. This technique has been more enhanced over time, which resulted in variations of the basic scheme, such as contention resolution diversity slotted ALOHA, irregular repetition slotted ALOHA and coded slotted ALOHA. We map the RESCUE requirements to the existing wireless random access techniques and outline their limitations. To overcome this limitations, we extend the RESCUE system to a general multi-user multi way relay network and develop a framework which allows to combine *lossy forwarding* with advanced coded random access schemes. We present the preliminary theoretical and numerical results for a simplified scenario of two-user two-relay network based on the MIMO relaying.

2. Random Beamforming Assisted Error Propagation Mitigation with Limited Feedback

2.1 Motivation and Objective

Cooperative communication in wireless network has potential to obtain frequency, temporal, and/or spatial diversity gain by providing independent or moderately correlated fading [CG79]. In practice, there are many relaying strategies which can be used to exploit the diversity gain, e.g., amplify-and-forward (AF) relaying [LTW04; BZG07], DF relaying [LTW04; KGG05], and compress-and-forward (CF) relaying [LLG06; Kim08]. On the other hand, due to its simplicity and practicality, the DF relaying has been deemed as the most implementable strategy. In order to enjoy the full cooperative diversity gain and mitigate the effects of error propagation, the conventional DF relaying implements the cyclic redundancy check (CRC) codes at relay node, and the erroneous frame is prevented to forward if CRC check fails [HN06]. However, such scheme may reduce system's spectral efficiency, where adaptive modulation can be used to improve the system throughput [ZMT08; Ma+11]. Alternatively, as shown in [AM12a; He+13], the error probability estimated at relay node can be treated as the S-R correlation information, and it can be used to update the extrinsic (or a posteriori) logarithm likelihood ratio (LLR) of the distributed turbo decoder at the destination node to mitigate the error propagation effect.

In recent years, accompanied with the significantly increased mobile terminals and the sacrificed spectrum resources, many cooperative communication systems allow multiple active users coexist within the same time period and the same frequency band [Tel99; Bol06]. In this case, in order to limit the decoding errors, the co-channel interference (or say multiuser interference) is the key that needs to be mitigated. This motivates people to consider MIMO relaying strategies to exploit the space domain degrees of freedom (DoF), and beamforming techniques thus can be used to mitigate the co-channel interference [God97]. In detail, for the receive beamforming, the receiver can directly estimate CSI and implement the well known multiuser detection techniques to mitigate multiuser interference [Ver98]. For the transmit beamforming, the transmitter has to obtain the CSI either through channel reciprocity or receiver's feedback, then it can design the precoding matrix to mitigate the interference. In practice, the ideal channel reciprocity hardly holds due to frequency mismatch [KJK10], and the feedback overhead of existing beamforming schemes are still not affordable [Lov+03; Jin06].

Motivated by the above observations, in this chapter, we introduce a RBF assisted error propagation mitigation method for MIMO multi-relay system with limited feedback, which is used to improve the system reliability and spectrum efficiency. Specifically, we assume that there are multiple single-antenna based source nodes communicating to their corresponding single-antenna based destination nodes with the help of two multi-antenna based relay stations. The total communication period is divided by three phases. In the first phase, source nodes broadcast their encoded messages to the two relay stations, and in order to eliminate the multiuser interference, zero-forcing (ZF) based detection technique is implemented at both relay stations. In the second and third phases, the relay stations decode the multiple data streams and forward the data streams of the qualified destination nodes regardless of the decoding errors, where the qualified destination nodes are selected based on the proposed RBF with limited channel feedback from the destination nodes to the two relay stations. Then, the distributed turbo decoding by exploiting the S-R links correlation information as in [He+13] is then implemented at the selected destination nodes in order to mitigate the error propagation effects. Simulation results show that, with the proposed scheduling strategies, the number of qualified destination nodes selected by the two relay stations can be increased, thus the chance of letting more destination nodes implement joint decoding process to mitigate error propagation effects has also been improved.

2.2 System Model and Problem Formulation

The system model of a two-hop MIMO DF relaying network is given by Fig. 2.1. As shown in Fig. 2.1, there are K single-antenna based source nodes intend to communicate with their corresponding K single-antenna based destination nodes, respectively. Due to their geographical locations, the messages of the source nodes are relayed by the help of two M-antenna based relay stations via $N(=\lceil K/M \rceil)$ parallel frequency-domain sub-channels. The relay stations are performed in a half duplex mode, where the entire transmission process can be evenly divided into three phases. In the first phase, the source nodes are evenly distributed to N sub-channels and then broadcast their data streams to the two relay stations; In the second and third phases, the two relay stations are respectively

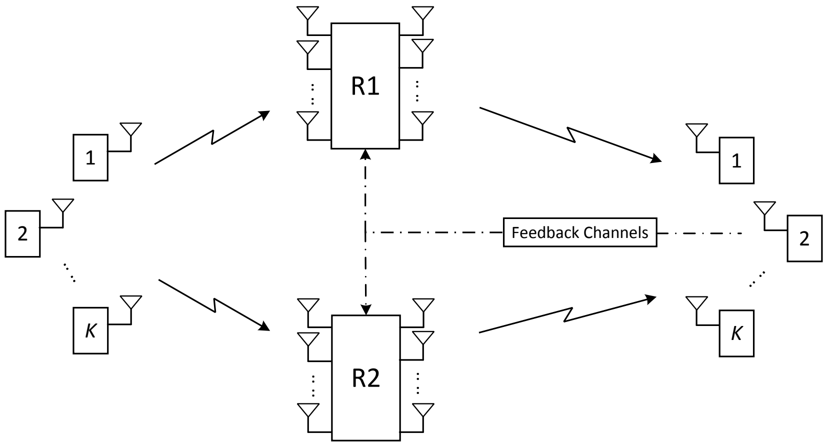

Figure 2.1.: System model of MIMO S-DF relaying network.

decoding their received data streams and forwarding certain qualified data streams to their corresponding destination nodes via efficiently scheduled sub-channels. Here, there are no direct links between the source nodes and the destination nodes.

2.2.1 Source-Relay Links

Consider that the system works in narrowband block fading environment. In the first phase, after turbo-like encoders and modulation, the k^{th} source node broadcasts its data stream to the two relay stations via the n^{th} sub-channel. The discrete-time equivalent form of received signal after the post-processing matrix at the i^{th} relay station in the n^{th} sub-channel can be expressed as

$$\begin{aligned} \widetilde{\mathbf{y}}_{r,n}^{(i)} &= \mathbf{U}_{r,n}^{(i)H}\mathbf{y}_{r,n}^{(i)} \\ &= \mathbf{U}_{r,n}^{(i)H}\mathbf{H}_{r,n}^{(i)}\mathbf{x}_{s,n} + \mathbf{U}_{r,n}^{(i)H}\mathbf{v}_{r,n}^{(i)}, \;\; i \in \{1,2\}, n \in \{1,\ldots,N\}, \end{aligned} \tag{2.1}$$

where $\mathbf{y}_{r,n}^{(i)}$ denotes the received signal before the post-processing matrix at the i^{th} relay station in the n^{th} sub-channel; $\mathbf{x}_{s,n} \in \mathbb{C}^{(\lceil K/M \rceil)\times 1}$ is the vector of transmitted data streams in the n^{th} sub-channel subject to the transmission power constraint $P_{s,n}$, i.e., $E\{\|\mathbf{x}_{s,n}\|^2\} \triangleq \sum_{k=1}^{\lceil K/M \rceil} \sigma_{k,n}^2 \leq P_{s,n}$, here, $\sigma_{k,n}^2$ is the transmission power allocated to the data stream of the k^{th} source node in the n^{th} sub-channel; $\mathbf{H}_{r,n}^{(i)} \in \mathbb{C}^{M\times(\lceil K/M \rceil)}$ is the channel matrix from the allocated $(\lceil K/M \rceil)$ source nodes to the i^{th} relay station in the n^{th} sub-channel; $\mathbf{U}_{r,n}^{(i)} \in \mathbb{C}^{M\times(\lceil K/M \rceil)}$ is the post-processing matrix at the i^{th} relay station in the n^{th} sub-channel for the multiuser interference mitigation; $\mathbf{v}_{r,n}^{(i)} \in \mathbb{C}^{(\lceil K/M \rceil)\times 1}$ is the independent and identically distributed (i.i.d.) additive white Gaussian noise (AWGN) vector with zero mean and variance σ_0^2 per element. In this case, the post-processing matrix $\mathbf{U}_{r,n}^{(i)}$ at the i^{th} relay station can be formulated based on ZF principle as

$$\mathbf{U}_{r,n}^{(i)} = \mathbf{H}_{r,n}^{(i)} \left(\mathbf{H}_{r,n}^{(i)H}\mathbf{H}_{r,n}^{(i)} \right)^{-1}. \tag{2.2}$$

After the ZF detection processing, the multiuser interference for each sub-channel can be completely eliminated. Thus, each data stream can be individually decoded without interfering by others. It is worthwhile to note that the decoded data stream may include certain errors, however, based on the proposed strategy, the erroneous data stream can still be forwarded, and the error propagation effects will be mitigated at the destination side.

2.2.2 Relay-Destination Links

In the second and third phases, due to the limited feedback channels from the destination nodes to the relay stations, a few bits feedback based RBF scheme is introduced in order to mitigate the multiuser interference among relay-destination (R-D) links. In detail, assume that both relay stations can send pilots to the destination nodes via all N sub-channels, but for the data transmission, the system only allows each active destination node to be scheduled to one beam and one sub-channel. Following the pre-processing matrix setup in [DSBN08], each relay station for the n^{th} sub-channel randomly generates M orthonormal beamforming vectors according to isotropic distribution [HM02], where its matrix form is expressed as $\mathbf{P}$ with the size of $M \times M$. $\mathbf{P}$ is assumed to be know at all destination nodes and keep the same for different sub-channels and relay stations.[1] Start from the user scheduling stage, the received signal of the kth destination node from the i^{th} relay station in the n^{th} sub-channel can be mathematically described as

$$y_{k,n}^{(i)} = \mathbf{h}_{k,n}^{(i)T} \mathbf{P} \mathbf{s}_n + v_{k,n}^{(i)}, \;\; i \in \{1,2\}, \forall k, \forall n, \tag{2.3}$$

where $\mathbf{s}_n \in \mathbb{R}^{M \times 1}$ is the vector of transmitted training symbols subject to the power constraint $P_{r,n}$, i.e., $\text{Tr}\left\{\mathbf{s}_n \mathbf{s}_n^H\right\} \leq P_{r,n}$; $\mathbf{h}_{k,n}^{(i)} \in \mathbb{C}^{M \times 1}$ is the channel vector from the i^{th} relay station to the k^{th} destination node in the n^{th} sub-channel; $v_{k,n}^{(i)}$ is the i.i.d. additive white Gaussian noise (AWGN) with zero mean and variance σ_0^2; Suppose all transmitted symbols experiencing the same transmit-power, i.e., $\sigma_{s,n}^2 \triangleq P_{r,n}/M$, and the m^{th} column of $\mathbf{P}$ is denoted by $\mathbf{p}_m$. The predicted SINRs of the k^{th} destination node from the i^{th} relay station in the n^{th} sub-channel are computed by

$$\widehat{\text{SINR}}_{k,m,n}^{(i)} = \frac{|\mathbf{h}_{k,n}^{(i)T} \mathbf{p}_m|^2}{\sigma_0^2/\sigma_{s,n}^2 + \sum\limits_{m' \neq m} |\mathbf{h}_{k,n}^{(i)T} \mathbf{p}_{m'}|^2}, \; m = 1, \ldots, M. \tag{2.4}$$

Then, this k^{th} destination node for the i^{th} relay station in the n^{th} sub-channel finds its preferred beam that provides the maximum SINR value based on

$$\hat{m}_{k,n}^{(i)} \triangleq \underset{m \in [1,M]}{\arg\max} \; \widehat{\text{SINR}}_{k,m,n}^{(i)}, \tag{2.5}$$

where if $\widehat{\text{SINR}}_{k,\hat{m}_{k,n},n}^{(i)}$ can pass the predetermined SINR threshold, which is defined as $\text{SINRT}_{k,n}^{(i)}$, the corresponding beam index $\hat{m}_{k,n}^{(i)}$ will be allowed to feed back to the i^{th} relay station. For other sub-channels, the same process will be carried out by the destination node. After receiving the feedback bits, based on the proposed scheduling method, the relay stations will decide which data steams can be relayed to their expected destination nodes. At each destination node, there are three options for the decoding process: 1) If the destination node is selected by both relay stations, it will receive two copy of the data stream, and then the distributed turbo decoding by exploiting S-R links correlation information can be implemented in order to mitigate the error propagation effects; 2) If the destination node is selected by one of the relay stations, the conventional turbo decoding technique is implemented to get the decoded information bits; 3) If the destination node is not selected by both relay stations, it will keep silence.

2.2.3 Problem Formulation

With only the beam (and sub-channel) indexes feedback from the destination nodes, the relay stations can either maximize the sum-rate of R-D links based on the destination nodes' predetermined SINR thresholds, which should be known by the relay stations, or maximize the number of the active destination nodes to be scheduled to the beams and the sub-channels. Specifically, if the relay stations intend to maximize the sum-rate, the cost function for the i^{th} relay station can be mathematically described by

$$(\hat{\mathcal{K}}^{(i)}, \hat{\mathcal{N}}^{(i)}) = \underset{\mathcal{K},\mathcal{N}}{\arg\max} \sum_{k \in \mathcal{K}, n \in \mathcal{N}} \log_2(1 + \text{SINRT}_{k,n}^{(i)}), \;\; i \in \{1,2\}, \tag{2.6}$$

where $\mathcal{K}$, $\mathcal{N}$ are the sets of indexes corresponding to the destination nodes, whose predicted SINRs can pass the predetermined threshold, and their operating sub-channels, respectively. It is shown that the problem (2.6) is an assignment problem in the area of computer science and can be solved by employing the brute-force search or the computationally efficient algorithms in the literature (e.g., the Hungarian method as in [BDM12]).

As we know, maximizing the sum-rate with the limited feedback at the relay stations cannot guarantee to maximumly mitigate the error propagation effects. This is because that maximizing the sum-rate may not necessarily maximize the number of the active destination nodes which can do the joint decoding by taking error propagation into account, except when all the destination nodes have the same predetermined SINR threshold. Thus, in this chapter, we mainly focus on the other objective, where the relay stations intend to maximize the number of the active destination nodes to be scheduled to the beams and the sub-channels. In this case, the probability that one

[1] Due to the randomness of $\mathbf{P}$, the performances of using $\mathbf{P}$ for different sub-channels and relay stations are the same.

destination node is selected by both relay stations can be increased, and then with the two copy of its data stream, the selected destination node can implement the distributed turbo decoding by exploiting S-R links correlation information as in [He+13] to mitigate the error propagation effects. In detail, define a utility function that

$$\operatorname{sgn}(x) \triangleq \begin{cases} 1, & x \geq 0, \\ 0, & \text{otherwise.} \end{cases} \tag{2.7}$$

Then, the cost function of the number of active destination nodes maximization for the i^{th} relay station can be mathematically described by

$$(\hat{\mathscr{K}}^{(i)}, \hat{\mathscr{N}}^{(i)}) = \underset{\mathscr{K}, \mathscr{N}}{\arg\max} \sum_{k \in \mathscr{K}, n \in \mathscr{N}} \operatorname{sgn}(\widehat{\text{SINR}}^{(i)}_{k,\hat{m}_{k,n},n} - \text{SINRT}^{(i)}_{k,n}), \;\; i \in \{1,2\}, \tag{2.8}$$

where $\mathscr{K}$, $\mathscr{N}$ have the same meaning as the ones in (2.6), and such problem is also called the system capacity maximization problem in the literature [CKH98]. In fact, the problem (2.8) is also an assignment problem in the area of computer science, which can be solved by employing the brute-force search over all destination nodes' feedback at the cost of exponential computational complexity [Lev11]. Motivated by this, in the following sections, we propose two complexity-reduced methods to solve the problem (2.8). Note that, because the scheduling process for both relay stations is the same and operated in the different time phases, for the sake of clarifying our key ideas, we will mainly focus on the scheduling process for one of the relay stations and eliminate the superscript (i) for all the following equations.

2.3 Strategy I: Joint Space-Frequency Scheduling Based on User Preferred Beam Index Feedback

In this section, the destination nodes are only allowed to send their preferred beam indexes (and sub-channel indexes) to the relay station based on their initially predicted SINR. Such assumption aims at simplifying the feedback strategy and in line with the scheme in [DSBN08]. However, at the relay station side, unlike the random based selection in [DSBN08], the proposed joint scheduling method here is able to maximize the number of active destination nodes.

2.3.1 Limited Feedback and Scheduling Matrix Formulation

After the relay station broadcasting the training symbols, the k^{th} destination node calculates its predicted SINRs, i.e., $\widehat{\text{SINR}}_{k,\hat{m}_{k,n},n}, \forall k, n$, and then produces up to N votes indicating its preferred beam indexes and the corresponding sub-channel indexes. Without loss of generality, we give an example assuming that the feedback produced by the k^{th} destination node is $(\hat{m}_{k,1}, \ldots, \hat{m}_{k,L_k})$, where L_k $(\leq N)$ is the sub-channel index that is incorporated in the feedback term. Then, the corresponding SINRs must satisfy

$$\widehat{\text{SINR}}_{k,\hat{m}_{k,1},1} \geq \text{SINRT}_{k,1}, \ldots, \widehat{\text{SINR}}_{k,\hat{m}_{k,L_k},L_k} \geq \text{SINRT}_{k,L_k}, \;\; k = 1, \ldots, K. \tag{2.9}$$

After collecting the feedback bits from all the destination nodes, the relay station aims to schedule the maximum number of active destination nodes to the different beams and sub-channels. Such scheduling process intuitively is described as solving an integer linear programming problem [PS98]. Mathematically, we can form a scheduling matrix $\mathscr{C}$ with the size of $K \times MN$. The column number of $\mathscr{C}$ stands for the beam and its corresponding sub-channel indexes, and the row number of $\mathscr{C}$ stands for the destination node index. The $(k,(n-1)N+m)^{\text{th}}$ entry of $\mathscr{C}$, denoted by $c^n_{k,m}$, is set to '1' (or otherwise '0') if the k^{th} destination node requests the m^{th} beam in the n^{th} sub-channel.

2.3.2 Complexity-Reduced Scheduling Process

In order to schedule the maximum number of active destination nodes to the beams and sub-channels, the brute-force search can be implemented to find the solution, however, such method costs exponential complexity [Lev11]. Moreover, the searching algorithm would probably yield multiple solutions. In such cases, arbitrary selection can be applied.

Motivated by these, we propose a complexity-reduced searching method, which can yield close performance to the brute-force search. In detail, form a set of destination node indexes, denoted by $\mathscr{U}_{(m,n)}$, by collecting the destination nodes who request the $(m,n)^{\text{th}}$ beam, and a set of beam indexes, denoted by $\mathscr{V}_k$, by collecting the beams with respect to the k^{th} destination node's preference. The proposed method is suggested to schedule the destination node start from the beam that has the largest number of requests. This is because that, after removing the scheduled destination node from the scheduling matrix, it can reserve the maximal number of residual beams to be allocated for the next loop. In other words, it will give the maximal DoF (the number of residual beams) for the next loop to perform resource allocation. Here, the index of such beam, denoted by (m_0,n_0), can be found by

$$(m_0,n_0) = \underset{m\in[1,M],n\in[1,N]}{\arg\max} \sum_{k=1}^{K} c_{k,m}^{n}. \tag{2.10}$$

Define that $U_{(m_0,n_0)} \triangleq \text{size}(\mathscr{U}_{(m_0,n_0)})$ is the number of destination nodes who request the $(m_0,n_0)^{\text{th}}$ beam, where $\text{size}(\mathscr{A})$ is the utility function to measure the size of the set $\mathscr{A}$. In addition, we have the u^{th} destination node request the $(m_0,n_0)^{\text{th}}$ beam (i.e., $u \in \mathscr{U}_{(m_0,n_0)}$) and also form the set $\mathscr{V}_u$. Given the beam index $(m_u,n_u) \in \mathscr{V}_u$, where (m_u,n_u) denotes the beam and the sub-channel requested by the u^{th} destination node, we are able to measure the size of $\mathscr{U}_{(m_u,n_u)}$ (i.e., $U_{(m_u,n_u)} = \text{size}(\mathscr{U}_{(m_u,n_u)})$) and obtain the minimum (denoted by U_u^*) via

$$U_u^* = \min_{(m_u,n_u)\in\mathscr{V}_u} U_{(m_u,n_u)}, \tag{2.11}$$

$$= \min_{(m_u,n_u)\in\mathscr{V}_u} \sum_{k=1}^{K} c_{k,m_u}^{n_u}. \tag{2.12}$$

Suppose there exist a destination node with the index u^* fulfilling the condition

$$u^* = \underset{u\in\mathscr{U}_{(m_0,n_0)}}{\arg\max}\,(U_u^*), \tag{2.13}$$

then, we will allocate this destination node to the $(m_0,n_0)^{\text{th}}$ beam. The above process is to select the destination node, whose requested beams have the largest number of destination nodes to request. This process follows the principle of leaving the maximal DoF for the next loop to perform resource allocation. Afterwards, the scheduled destination node needs to be removed from the scheduling matrix $\mathscr{C}$ by replacing each element of the column corresponding to the beam index (m_0,n_0) and the row corresponding to the destination node index u^* to be '0's. Then repeat the above process until there is no beam to allocate. Note that, (2.10) is possible to provide multiple solutions, and if such case happens, we select a beam with its term $\max(U_u^*)$ to be the maximum among all the candidates.

To sum up, start from the scheduling matrix formulation, the proposed scheduling method in this section (i.e., Stgy. I) can be described as:

Complexity-Reduced Scheduling Method for Stgy. I

I. Initialize the scheduling matrix $\mathscr{C}$ by collecting the feedback bits;
II. Set $i = 0$;
III. **While** $i \leq MN$:
  1. Increase i by 1;
  2. Form $\mathscr{U}_{(m,n)}, \forall m,n$, and $\mathscr{V}_k, \forall k$;
  3. Select the beam (m_0,n_0) based on (2.10);
  4. Schedule the destination node u^* to the beam (m_0,n_0) based on (2.11) to (2.13);
  5. Replace each element of the column corresponding to the beam index (m_0,n_0) with '0's in $\mathscr{C}$;
  6. Replace each element of the row corresponding to the destination node index u^* with '0's in $\mathscr{C}$;
  7. **If** $\mathscr{C}$ is a zero matrix, **break**.
IV. **End While**

According to above description, the computational complexity of Stgy. I mainly comes from the order statistics in

(2.10)-(2.13). Given the maximal DoF of (MN), the complexity of order statistics in (2.10) is upper bounded by $\mathscr{O}((MN)^2)$; the same upper bound applies also to the procedure from (2.11) and (2.13). Since the maximal number of loops is MN, the overall computational complexity is upper bounded by $\mathscr{O}((MN)^3)$, which is significantly lower than the exponential complexity offered by the brute-force search.

2.4 Strategy II: Joint Space-Frequency Scheduling Based on User Preferred & Interference Beam Indexes Feedback

As we know, Stgy. I presented in last section is based on pessimistic SINR prediction, where the initially predicted SINRs cannot well reflect destination nodes' actual SINRs if certain beams are not requested by any destination node. In this case, the destination node with small initially predicted SINRs may be switched off. Such strategy will result in inefficient exploitation of DoF . Motivated by this, a new scheduling strategy (i.e., Stgy. II) is proposed to improve the system performance by exploiting the more accurate destination node's SINR prediction method.

2.4.1 Limited Feedback and Scheduling Matrix Formulation

Unlike the feedback methods for Stgy. I, the proposed method here requires the destination nodes for their selected sub-channels to send back their preferred beam indexes and also indicate their undesired interference beams to the relay station.[2] Then, the relay station will schedule the maximal number of destination nodes with their condition of beam coexistence to be satisfied. By such means, we will show that the accuracy of predicted SINR can be improved.

In detail, assume that the n^{th} sub-channel is selected by the k^{th} destination node. The proposed method firstly requires the destination node to predict the SNR of each beam (denoted by $\widehat{\text{SNR}}_{k,m,n}$)

$$\widehat{\text{SNR}}_{k,m,n} \triangleq \frac{\left|\mathbf{h}_{k,n}^T \mathbf{p}_m\right|^2}{\sigma_0^2/\sigma_s^2},\ m = 1,\ldots,M, \tag{2.14}$$

and then select the preferred beam index in the n^{th} sub-channel by employing

$$\hat{m}_{k,n} = \underset{m\in[1,M]}{\arg\max}\ \widehat{\text{SNR}}_{k,m,n}. \tag{2.15}$$

All the rest beams in the sub-channel are considered as the interference beams. Then, the destination node needs to identify undesired interference beams with the number of which to be minimized. Such goal can be achieved by comparing the predicted SINR with the predetermined threshold when an interference beam is incorporated in the SINR computation. The detailed algorithm of undesired interference beam selection is summarized below:

Step 1: Compute the predicted SINR by incorporating $\mathscr{I}$ ($\mathscr{I} \leq M-1$) interference beams with the smallest interference power, i.e., those with smallest $|\mathbf{h}_{k,n}^T \mathbf{p}_{m'_{k,n}}|^2$, $\forall m'_{k,n} \neq \hat{m}_{k,n}$, where $m'_{k,n}$ denotes the beam index that is not equal to $\hat{m}_{k,n}$ in the n^{th} sub-channel. In the computation, assume equal power allocation over transmit-antennas subject to total power constraint per sub-channel. Set $\mathscr{I} = 1$ for the first loop.

Step 2: Compare the predicted SINR with the threshold $\text{SINRT}_{k,n}$. If it is not smaller than $\text{SINRT}_{k,n}$, then the considered $\mathscr{I}$ beams are counted as acceptable interference beams; or otherwise the algorithm ends, and the $\mathscr{I}^{\text{th}}$ beam and other residual interference beams are counted as undesired interference beams.

Step 3: Repeat *Step 1* and *Step 2* with $\mathscr{I} = \mathscr{I} + 1$.

The above process yields the indexes of the preferred beam and acceptable interference beams for the k^{th} destination node in the n^{th} sub-channel. Then, these indexes are sent to the relay station for performing the proposed joint

[2]The selected sub-channel is defined as that the destination node can give votes in that sub-channel, e.g., a destination node selects the interleaved sub-channels and gives votes.

scheduling method. It is clear that the undesired interference beams are not incorporated in the SINR prediction. Thus, the scheduling process based on the beam indexes of these predicted SINRs can closely reflect the destination nodes' actual SINR performances in comparison with the scheduling methods for Stgy. I.

Analogous to the previous section, the objective here is also to solve an integer linear programming problem. Mathematically, we form an $M \times K$ scheduling matrix $\mathscr{T}_n$ for the n^{th} sub-channel, $\forall n \in \{1,\ldots,N\}$. The column wise of $\mathscr{T}_n$ stands for the destination node index, and the row wise of $\mathscr{T}_n$ stands for the beam index. The $(m,k)^{\text{th}}$ entry of $\mathscr{T}_n$ is set to '1' when the k^{th} destination node considers the m^{th} beam as its preferred beam, '-1' when the k^{th} destination node considers the m^{th} beam as its acceptable interference beam, or '0' when the k^{th} destination node considers the m^{th} beam as its undesired interference beam or the k^{th} destination node does not have vote in this sub-channel.

2.4.2 Complexity-Reduced Scheduling Process

Scheduling method aims to find the maximal number of destination nodes whose preferred beams can coexist with each other in the same sub-channels. Optimum solution can be found by employing the brute-force search at the cost of exponential complexity, where the algorithm with such complexity is hard to implement especially when the network size is large. Hence, we introduce a complexity-reduced searching method, with which the exhaustive search only needs to be applied for some local areas.

The proposed method starts scheduling destination nodes from an arbitrarily selected scheduling matrix $\mathscr{T}_n$, $\forall n \in \{1,\ldots,N\}$.[3] Then, the aim of the method is to find a square matrix, $\overline{\mathscr{T}}_n$, which is formed by collecting appropriate rows and columns of $\mathscr{T}_n$. This matrix should have all the entries to be either '1' or '-1', and each row of the matrix should have only a single '1'. The row and column indexes of $\overline{\mathscr{T}}_n$ should remain the same as $\mathscr{T}_n$, and then the scheduling process can be done based on the row and column indexes corresponding to the entries of '1'. With the above description, we can guarantee all the active destination nodes in the sub-channel would not coexist with the undesired interferences. Note that, the method can yields multiple solutions of $\overline{\mathscr{T}}_n$. Then, it is suggested to select the solution with the size of the matrix to be the maximum. In this case, the number of active destination nodes for the sub-channel is maximized and thus achieves local optimality. The scheduled destination nodes are then removed from other scheduling matrices by replacing each element of the columns corresponding to the scheduled destination nodes with '0's. The above process is repeated until all the sub-channels are processed.

Specifically, assume that the scheduling matrix for the n^{th} sub-channel is selected, e.g., $\mathscr{T}_n$. Let's add additional two rows under $\mathscr{T}_n$: one is used to record the number of zeros of each column; one is used to record the destination nodes' indexes. Here, $\widetilde{\mathscr{T}_n}$ denotes the new generated scheduling matrix. Then, the scheduling method can be described as:

Complexity-Reduced Scheduling Method for Stgy. II

I. Set $i = 0$;
II. **While** $i \leq M$:
  1. Increase i by 1;
  2. Comprise a matrix $\mathscr{C}_i$, whose columns are made of the columns of $\widetilde{\mathscr{T}_n}$ with the second last elements less than i;
  3. **If** the number of columns of $\mathscr{C}_i$ is smaller than $(M-i+1)$, **goto** step II.1;
  4. Find an $(M-i+1)\times(M-i+1)$ matrix $\overline{\mathscr{C}}_i$ in $\mathscr{C}_i$, where its elements are no '0', and '1's are distributed in different rows;
  5. **If** such an $\overline{\mathscr{C}}_i$ is not exist, **goto** step II.1;
  6. Based on $\overline{\mathscr{C}}_i$, find the corresponding columns in $\mathscr{C}_i$, record the belonging destination nodes, **break**.

III. **End While**
IV. Remove the scheduled destination nodes from other sub-channels by setting up '0's.

In this case, if there exists a matrix $\overline{\mathscr{C}}_i$, such matrix is equivalent to the square matrix $\overline{\mathscr{T}}_n$, which was described above. Moreover, comparing with the exhaustive search directly to the scheduling matrix $\mathscr{T}_n$ with the size of $M \times K$, the proposed method only needs to apply the exhaustive search to the matrix $\mathscr{C}_i$ if the conditions in Step

[3]The reason of adopting arbitrary selection here is that $\mathscr{T}_n$, $\forall n \in \{1,\ldots,N\}$, are statistically identical.

II.3 to *II.5* of the proposed method are satisfied. Such method can reduce the computational complexity of the scheduling process as long as the matrix size of $\mathscr{C}_i$ is smaller than $M \times K$.

2.5 Performance Analysis of Proposed Schemes

2.5.1 Optimality

For Stgy. I, in each loop of scheduling process, one requested beam is allocated to a selected destination node. Therefore, the total number of loops is equal to the number of active (scheduled) destination nodes of the system. According to the objective of the number of active destination nodes maximization, the scheduling method is said to be optimum if the number of loops is maximized. However, in general, the proposed method cannot guarantee such global optimality. Instead, it can achieve local optimality by giving the maximal DoF (the number of residual beams) for the next loop to perform resource allocation.

With the condition of $2 \leq \max(U_u^*) \leq \sum_{k=1}^{K} c_{k,m_0}^{n_0}$, it is sufficient to guarantee the local optimality of the proposed method, where such condition is protected by (2.10). However, for the special case of $\max(U_u^*) = 1$, the proposed method cannot guarantee the goal of local optimality. A simple way of improving the proposed method is to compare the number of $U_{(m_u,n_u)} = 1$ instead of the minimum value of $U_{(m_u,n_u)}$ only. In order to give a clear story, we take a simple example, where the $(m_0,n_0)^{\text{th}}$ beam has been requested by two users: User 1 requests three beams in total, where the first beam (i.e., (m_0,n_0)) has 2 users to request and both the second and the third beams have 1 user to request; User 2 requests two beams in total, where the first beam (i.e., (m_0,n_0)) has 2 users to request and the second beam has 1 user to request. In this case, we have $\min(U_{(m_1,n_1)}) = \min(U_{(m_2,n_2)}) = 1$, User 1 has two elements equalling to 1, and User 2 has one element equaling to 1. Then, our decision is to allocate the $(m_0,n_0)^{\text{th}}$ beam to User 2 as such it removes only two requested beams; or otherwise we would have to remove 3 requested beams. In case, if User 1 and User 2 request the same amount of beams, the arbitrary selection is implemented.

For Stgy. II, due to the exhaustive search to the losslessly size-reduced scheduling matrix, the scheduling process can achieve the global optimality for the beam allocation step. However, for the sub-channel allocation step, because the statistical identity of the sub-channels leads to the arbitrarily selection of the first scheduling matrix, this will loss the global optimality of the scheduling process by comparing with the exhaustive search.

2.5.2 Feedback Overhead

Denote $\mathscr{B}$ to be the number of bits required for representing a beam index, and $\mathscr{S}$ to be the number of bits required for representing a sub-channel index. According to the above discussion, for Stgy. I, the k^{th} destination node is suggested to produce feedback bits for the L_k ($\leq N$) number of sub-channels, where (2.9) needs to be satisfied. With such feedback design, the overall feedback overhead for Stgy. I is

$$\mathscr{R}_{\text{FB}}^{(1)} = \sum_{k=1}^{K} L_k \mathscr{B}\mathscr{S} \leq KN\mathscr{B}\mathscr{S}. \tag{2.16}$$

For Stgy. II, besides the destination node's preferred beam index, the proposed method also requires extra feedback to indicate those acceptable interference beams. Denote that $Q_{k,n}$ ($\leq M-1$) is the number of the acceptable interference beams for the k^{th} destination node in the n^{th} sub-channel. Hence, the total number of feedback bits for Stgy. II is

$$\mathscr{R}_{\text{FB}}^{(2)} = \sum_{k=1}^{K} \sum_{n=1}^{N} (Q_{k,n}+1)\mathscr{B}\mathscr{S} \leq KNM\mathscr{B}\mathscr{S}. \tag{2.17}$$

In addition to these, for the conventional spatial domain RBF in [DSBN08], the total number of K destination nodes have been evenly distributed over N sub-channels. Hence, the overall feedback overhead is

$$\mathscr{R}_{\text{FB}}^{(3)} = K\mathscr{B}, \tag{2.18}$$

which provides the lowest feedback overhead, but the worst system capacity performance.

2.6 Simulation Results and Discussion

Computer simulations were used to evaluate the proposed user scheduling strategies in terms of bit error rate and the probability of attaining maximal number of active destination nodes normalized by the total number of destination nodes in the system. Here, the block Rayleigh fading channel was considered, and both relay stations were placed close to the source nodes. The SNR of S-R links were equal to the SNR of S-D links plus 10.6 dB, and the SNR of R-D links were equal to the SNR of source-destination (S-D) links plus 4.4 dB.[4] Meanwhile, all the destination nodes were placed in the same distance with the relay stations, thus the predetermined thresholds $\text{SINRT}_{k,n}^{(i)}, \forall i,k,n$, were considered equal for all the destination nodes (i.e., SINRT). Each relay station was equipped with $M = 8$ transceiver antennas serving $K = 64$ single antenna based transceiver pairs via $N = 8$ sub-channels. In addition, equal power allocation over the transmit antennas of the relay stations was implemented subject to the total power constraint per sub-channel. Simulation results were computed on an average over 10,000 independent channel realizations.

In this simulation, both transmitter nodes and relay stations were implemented the turbo-like coding scheme, where the encoders were configured as the half rate memory-1 non-recursive systematic convolutional codes with a generator polynomial $G = [3,2]_8$, and the decoders were correspondingly configured with 20 iterations. The length of each transmitted frame is set up to 1024 for the coded bits. According to the work in [Hou+15], the error probabilities of S-R links $p_{e,k}, \forall k$ were estimated at the relay stations and then forwarded to the destination nodes in order to let the iterative error propagation mitigation process work. In terms of the decoding methods, four methods were presented in the experiments. In detail, turbo code (TC) method: only one relay station was selected to help the destination node forward the data stream, thus the conventional turbo-like decoder was implemented; distributed turbo code (DTC) method: both relay stations were selected to help the destination node forward the data stream, and distributed turbo code without taking error probabilities of S-R links into account was implemented; straightforward combining based turbo code (SCTC) method: both relay stations were selected to help the destination node forward the data stream, but straightforward LLR combining was implemented after the individual turbo decoding process; joint decoding (JD) method: both relay stations were selected to help the destination node forward the data stream, and joint decoding by exploiting error probabilities of S-R links was implemented to mitigate the error propagation effects.

As we know, the proposed joint space-frequency user scheduling scheme was used to increase the probability of letting both relay stations help the destination node forward its data stream, and then JD method can be implemented to mitigate the error propagation effects. In this case, the simulation experiments were carried out by comparing the conventional spatial domain RBF scheme in [DSBN08] with two proposed joint scheduling strategies in terms of both bit error rate and probability of active users performances. Fig. 2.2 and Fig. 2.3 show the performances of the conventional spatial domain RBF scheme when the predetermined SINR thresholds were set up to SINRT = 1 (i.e., equivalent to 1 bit/s/Hz) and SINRT = 3 (i.e., equivalent to 2 bit/s/Hz). As we can see in Fig. 2.2, in terms of bit error rate performance, both DTC method and SCTC method show better performance than TC method especially in high SNR range, and SCTC method is a bit better than DTC method through the whole SNR range. These are because that letting two relay stations help is better than letting only one relay help, and DTC method without taking error probability into account may iteratively enlarge the error prorogation by comparing with SCTC method. Moreover, JD method shows the best performance, and the bit error rate tends to zero when SNR of S-D link is above 10 dB. Fig. 2.3 show the performance of the probability of active users for TC and JD methods. As we can see, when SINRT=1, only TC method can have a bit less than 10 percentage active users, and there is very few active users for JD method. Meanwhile, when SINRT=3, almost no user can be active by both relay stations, and this is also why we didn't show the bit error rate performance for SINRT=3 case in Fig. 2.2.

In order to improve the performances, the proposed joint domains user scheduling methods were proposed. As shown in Fig. 2.4 and Fig. 2.5, the bit error rate and probability of active user performances of the first proposed strategy (i.e., Stgy. I) were presented. In Fig. 2.4, the bit error rate performances of different decoding methods were compared with each other for different SINRTs setup. Specifically, for SINRT=1, with the similar trends

[4]The way of deriving the SNR relationship among different channel links refers to the work in [AM12a].

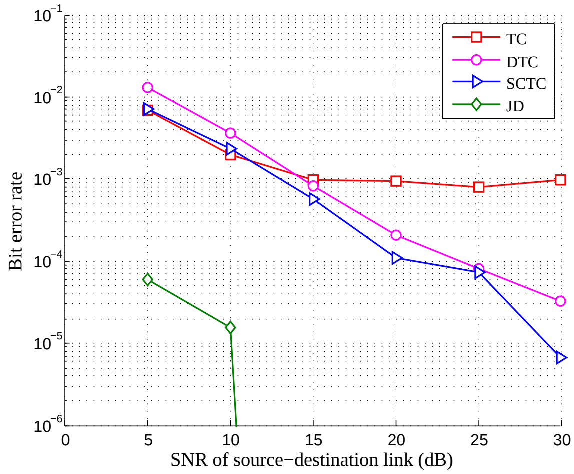

Figure 2.2.: Bit error rate vs. transmit-power normalized by noise for spatial domain RBF scheme, where the minimum SINR requirement is set up to $\mathrm{SINRT} = 1$**.**

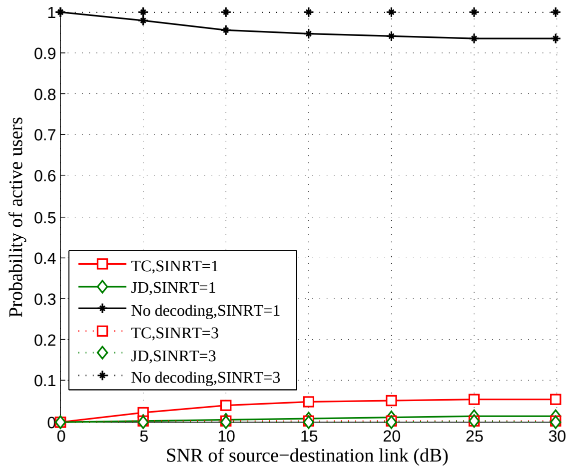

Figure 2.3.: The probability of attaining maximal number of active destination nodes vs. transmit-power normalized by noise for spatial domain RBF scheme, where the minimum SINR requirements are set up to $\mathrm{SINRT} = 1$ **and** $\mathrm{SINRT} = 3$**, respectively.**

as Fig. 2.2, the bit error rate performances of DTC method and SCTC method are better than TC method, and JD method shows the best bit error rate performance especially at low SNR of S-D link range in this case. Here, as the SNR of S-D link increasing, the bit error rate performances of different schemes are decreasing. This is because that, as the SNR of S-D link increasing, the number of active users are increasing, thus the multiuser interferences among the active users are increasing. In other words, by comparing with the performance of the space-domain RBF, although Stgy. I can let more destination nodes pass the predetermined threshold SINRT=1, the threshold SINRT=1 is still not big enough for destination nodes decoding the errors. For SINRT=3, in terms of bit error rate performance as shown in Fig. 2.4, only TC method can show some performances, but all the rest methods are abounded. This is because SINRT=3 is too high for the actual SINRs of destination nodes to pass. The performance of the probability of active destination nodes for both SINRT=1 and SINRT=3 can be seen in Fig. 2.5.

As we mentioned, Stgy. I was based on pessimistic SINR prediction, where the initially predicted SINRs cannot well reflect user's actual SINRs if certain beams were not requested by any destination node, especially for the high SINR threshold. This motivates us to present the performances of Stgy. II when the SINR threshold is high (i.e. SINRT=3). Fig. 2.6 and Fig. 2.7 present the bit error rate and the probability of active user performances of the second proposed strategy (i.e., Stgy. II) when SINRT=3. As shown in Fig. 2.6, the bit error rate performance of JD for SINRT=3 is much better than the other methods. This is because that, in this case, more destination nodes can be active and helped by two relay stations, and then error probability of S-R links can be taken into account for

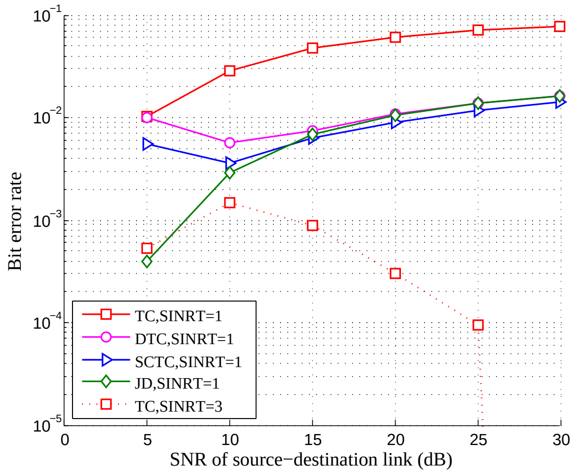

Figure 2.4.: Bit error rate vs. transmit-power normalized by noise for the proposed Stgy. I, where the minimum SINR requirements are set up to SINRT $= 1$ **and** SINRT $= 3$**, respectively.**

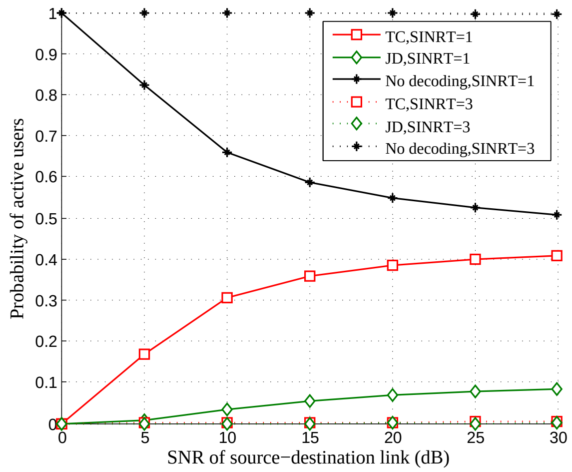

Figure 2.5.: The probability of attaining maximal number of active users vs. transmit-power normalized by noise for the proposed Stgy. I, where the minimum SINR requirements are set up to SINRT $= 1$ **and** SINRT $= 3$**, respectively.**

the joint iterative decoding process. Here, TC method offers the worst bit error rate performance especially when SNR of S-D link is high. Fig. 2.7 shows the probability of active destination nodes when SINRT=3. Comparing with the cases of spatial domain RBF and Stgy. I, Stgy. II can let much more destination nodes be active especially for high SINR threshold cases. Finally, since we have presented quite a few user scheduling methods, it might be interesting to have a summary of the performances comparison in terms of system capacity, feedback overhead and computational complexity. As shown in Table 2.1, the proposed joint space-frequency user scheduling methods can enjoy significantly improved system capacity at the price of the increased feedback overhead and computational complexity.

2.7 Summary

In this chapter, we have presented a novel joint space-frequency user scheduling approach with limited channel feedback to assist MIMO multi-relay system to mitigate the error propagation effects. Two strategies have been proposed in order to achieve the objective of the system capacity while the number of users in the system is small. The performances of proposed strategies have been carefully investigated through both theoretical and numerical analysis. It has been shown that, for Stgy. I, the complexity-reduced joint-domain user scheduling methods has been proposed to increase the number of active destination nodes by comparing with the spatial domain RBF

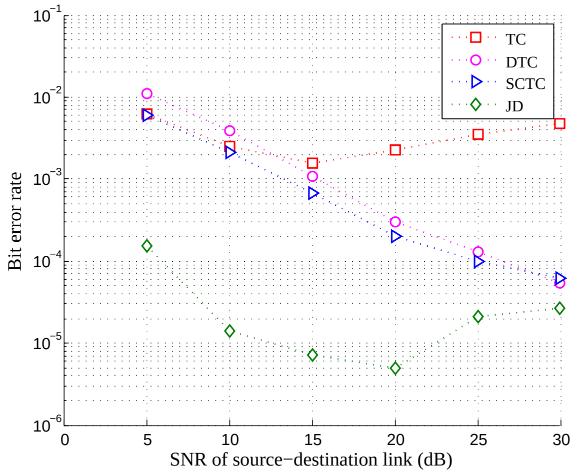

Figure 2.6.: Bit error rate vs. transmit-power normalized by noise for the proposed Stgy. II, where the minimum SINR requirement is set up to $\mathrm{SINRT} = 3$**.**

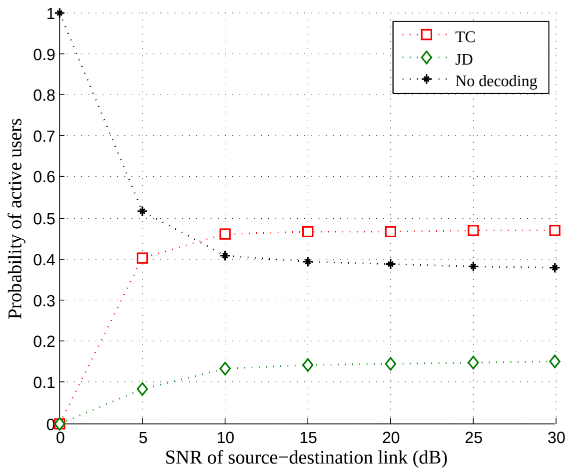

Figure 2.7.: The probability of attaining maximal number of active users vs. transmit-power normalized by noise for the proposed Stgy. II, where the minimum SINR requirement is set up to $\mathrm{SINRT} = 3$**.**

scheme. In addition, the proposed Stgy. II can exhibit even better system performances with more accurate SINR prediction at the price of relatively increased complexity and feedback overhead.

Table 2.1.: A comparison among the presented schemes in terms of system capacity, feedback overhead and computational complexity, when SNR $= 30\text{dB}$ and the predetermined threshold SINRT=1.

Different schemes	System Capacity (probability)	Feedback Overhead (bits)	Complexity
Spacial domain RBF in [DSBN08]	0.06 (0%)	$\leq$ 192	linear
The proposed Stgy. I	0.33 (+450.00%)	$\leq$ 3072	cubic
The proposed Stgy. II	0.64 (+966.67%)	$\leq$ 24576	exponential

3. Diversity-Multiplexing Tradeoff for Lossy Forwarding

Three-node relay network is spatially equivalent to 2x1 MISO system. By exploiting this analogy, we investigate the diversity-multiplexing tradeoff of three-node relay network (such as RESCUE TS1) in this chapter. We have analyzed the outage probability of TS1 in deliverable D1.2.1. More specifically, we investigate the diversity-multiplexing tradeoff diversity-multiplexing tradeoff (DMT) of TS1 based on lossy forwarding decode-and-forward DF technique. The DMT for TS1 based on lossy forwarding is derived according to the Slepian-Wolf theorem-based outage analysis. It is shown that the proposed system outperforms the conventional decode-and-forward system in terms of outage probability. Furthermore, additional 0.25 multiplexing gain is achieved for the proposed system based on lossy forwarding. Finally, the analytical results are verified by numerical examples.

3.1 Motivation and Objective

It is a challenging task to achieve high throughput and reliability simultaneously in wireless networks. The resilience of the system can be improved by lowering the throughput and vice versa. Therefore, a tradoff is required between the conflicting parameters for different applications. For example, the fundamental DMT was first introduced in [ZT03] for MIMO systems. This idea was then extended to multiple-access channels in [TVZ04].

Cooperative communication is considered as the backbone of the present and future wireless communication networks. Cooperative communication can be obtained via relay networks. Multiple relays communicating to a single destination can be viewed as a virtual MIMO system. As a result, spatial diversity can be achieved at the destination. The fundamental DMT limit of one-way relay channels was investigated for various relaying schemes [AEGS05; YE06; YE07] demonstrating that the virtual MIMO formed by cooperative wireless communications can never achieve diversity performance as a real MIMO system for large multiplexing gains. As a generalization, the DMT performance analysis for two-way relay channels was studied in [VH11; Sin+11; GGP08]. It is shown that in the scenarios of two-way relay channel with direct link, optimal DMT can be achieved by AF schemes [VH11]. By employing physical layer network coding, four-phase hybrid broadcast (HBC) protocol can be optimized by three-phase time-division broadcast (TDBC) protocol [Sin+11]. In multi-hop two-way relay channels without the direct link, the optimal DMT can be achieved by compress-and-forward relaying strategies [GGP08].

For MIMO systems, the DMT was obtained in [ZT03] as the SNR approaches infinity. Based on the fundamental DMT analysis, finite-SNR diversity-multiplexing tradeoff finite-SNR diversity-multiplexing tradeoff (f-DMT) was proposed to investigate DMT performance in more general and practical scenarios but asymptotic conditions. In [Nar; Nar06], f-DMT for rate-adaptive MIMO systems was first defined and analyzed, which shows that in finite SNRs, achievable diversity gains are significantly lower than the asymptotic cases. The f-DMT for relaying channels is further derived, in one-way relaying channels, by allowing the source to transmit constantly, improved multiplexing gain can be achieved at any SNRs [Sta+07]. In two-way multi-hop relaying channels, AF relying always outperforms decode-and-forward DF relaying [Lin+13].

Since the spatial topology of the TS1 is equivalent to 2x1 MISO system, in this chapter, we investigate the f-DMT for TS1 based on lossy forwarding. However, the same analytical methodology should apply to toy scenario 3 and toy scenario 4. By deriving the f-DMT formula, we find significant improvement with lossy forwarding DF over conventional DF in f-DMT can be achieved. Within the multiplexing range of conventional DF systems, the lossy forwarding DF system outperforms in diversity gain. In addition, extra 0.25 multiplexing gain can be achieved by the lossy forwarding DF which leads to maximum 50% higher possible transmission rate compared to conventional DF systems.

3.2 System Model

We focus on analyzing the f-DMT of a one-way orthogonal half-duplex DF relaying system which is shown in Fig. 3.1, where a source node S transmits an information sequence to a destination node D, with help of a relay node R. All nodes are equipped with a single antenna. For orthogonal transmission, time division multiple access (TDMA) technique is adopted. The total time of one transmission is equally split into two slots. Within the first time slot, S encodes the original information sequence and broadcasts to R and D. Within the second time slot, R decodes, interleaves, re-encodes, and transmits the information sequence to D. Finally, D performs joint decoding

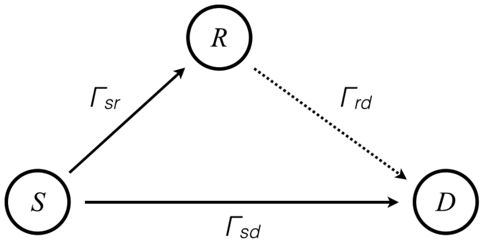

Figure 3.1.: System model.

to recover the original information sequence. Note that the decoded information sequence at R may contains error which is referred as intra-link errors with the definition of

$$p \triangleq \Pr((x_r = \hat{x}_s) \neq x_s), \tag{3.1}$$

where x_r, $\hat{x}_s$ and x_s denote the information sequence of R, decoded information sequence of S at R, and the information sequence of S, respectively. Each link suffers from frequency-flat and quasi-static block Rayleigh fading, and it is assumed to be independently, identically distributed among all the links. Perfect channel state information CSI is assumed at receivers while no channel information is required for transmitters. The channel model is formulated as

$$y_{sd} = h_{sd} \cdot x_s + n_{sd}, \tag{3.2}$$
$$y_{sr} = h_{sr} \cdot x_s + n_{sr}, \tag{3.3}$$
$$y_{rd} = h_{rd} \cdot x_r + n_{rd}, \tag{3.4}$$

where h_x and n_x denote complex channel coefficient, and zero-mean additive white Gaussian noise AWGN with variance σ_x^2 per dimension, where $x \in \{sd, sr, rd\}$ denotes the *SD*, *SR* and *RD* links, respectively. Without losing generality, it is assumed $\sigma_{sd}^2 = \sigma_{sr}^2 = \sigma_{rd}^2 = N_0/2$, where N_0 is the noise power. Hence, the instantaneous SNR γ_{sd} and average SNRs of *SD* link are expressed as

$$\gamma_{sd} = |h_{sd}|^2 \cdot \frac{E_s}{N_0}, \tag{3.5}$$
$$\Gamma = \frac{E_s}{N_0}, \tag{3.6}$$

where Γ is referred as average SNR, and E_s is the transmit power per symbol.

3.3 Finite-SNR Diversity-Multiplexing Tradeoff Analysis

We first define the multiplexing gain, diversity gain, and diversity-multiplexing tradeoff in Subsection 3.3.1. Then in Section 3.3.2, we provide the corresponding detailed calculations of the the diversity-multiplexing tradeoff.

3.3.1 Definition of Finite-SNR Diversity-Multiplexing Tradeoff

The finite-SNR multiplexing gain r and diversity gain d, defined in [Nar; Nar06] as

$$r = \frac{R_{sys}}{\log_2(1+\Gamma)}, \tag{3.7}$$

$$\begin{aligned} d(r,\Gamma) &= -\frac{\partial \log[P_{out}(r,\Gamma)]}{\partial \log(\Gamma)} \\ &= -\frac{\Gamma}{P_{out}(r,\Gamma)} \frac{\partial P_{out}(r,\Gamma)}{\partial \Gamma}, \end{aligned} \tag{3.8}$$

where R_{sys} denotes the spectrum efficiency (in $bits/sec/Hz$) and $P_{out}(r,\Gamma)$ is the outage probability given multiplexing gain r. By this definition, multiplexing gain r is a ratio of system spectrum efficiency to the capacity of an

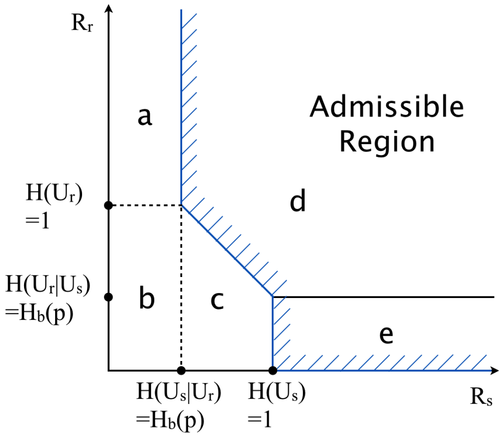

Figure 3.2.: The approximated admissible rate region for S and R determined by the Slepian-Worlf theorem.

AWGN channel at Γ, which indicates how aggressively the system raises the transmission speed with SNR. On the other hand, given a fix multiplexing gain r, diversity gain d indicates how gradually the transmission reliability is increased with SNR. Diversity gain can also be used to estimate additional SNR required to decrease a specified amount of outage probability.

3.3.2 Calculation of Finite-SNR Diversity-Multiplexing Tradeoff for Lossy Forwarding System

For simplicity, we assume S and R take the same spectrum efficiency R_c to transmit sequences, and channel input dimensionality N_D is two. According to [Zho+14], source rate-distortion of intra-link and its inverse function can be expressed as

$$R_d(D) = \Phi(\gamma) = \frac{1}{R_c}\log_2(1+\gamma), \tag{3.9}$$

$$\Phi^{-1}(R_d) = 2^{R_d R_c} - 1, \tag{3.10}$$

where $R_d(D)$ and $\Phi(\gamma)$ denote the binary rate-distortion function and the instantaneous intra-link channel capacity given γ. Note since S and R take only one time slot, the spectrum efficiency $R_c = 2R_{sys}$. Using (3.7), we have

$$\Phi(\gamma, r, \Gamma) = \frac{\log_2(1+\gamma)}{2r\log_2(1+\Gamma)} = \frac{\ln(1+\gamma)}{2r\ln(1+\Gamma)}, \tag{3.11}$$

$$\Phi^{-1}(R_d, r, \Gamma) = (1+\Gamma)^{2rR_d} - 1. \tag{3.12}$$

To compute the outage probability, we adopt the approximated bound for the lossy forwarding DF system derived in [Zho+14]. It is shown in [Zho+14] that the approximated outage probability bound based on Slepian-Wolf theorem is very close to the exact outage probability bound based on source coding with side information problem. The corresponding rate region is shown in Fig 3.2. The outage probability is expressed as

$$\begin{aligned} P_{out}^{SW}(r,\Gamma) =& Pr[(R_s,R_r) \text{ is in region } a,\ b \text{ or } c] \qquad (3.13)\\ =& P_{out1}(r,\Gamma) + P_{out2}(r,\Gamma) + P_{out3}(r,\Gamma)\\ =& \Pr\{p=0, (R_s,R_r) \in \mathscr{R}_c^{SW}\}\\ &+ \Pr\{0<p<0.5, (R_s,R_r) \in \mathscr{R}_{ab}^{SW}\}\\ &+ \Pr\{0<p<0.5, (R_s,R_r) \in \mathscr{R}_c^{SW}\}, \qquad (3.14)\end{aligned}$$

where $\mathscr{R}_i^{SW}$ is the region in Fig. 3.2 for $i \in \{a,b,c,d,e\}$, p is the intra-link error probability. By computing the partial derivative in terms of average SNR Γ, the diversity gain of the lossy forwarding DF system is defined as

$$d(r,\Gamma) = \frac{\Gamma}{P_{out}(r,\Gamma)}\left(\frac{\partial P_{out1}(r,\Gamma)}{\partial\Gamma} + \frac{\partial P_{out2}(r,\Gamma)}{\partial\Gamma} + \frac{\partial P_{out3}(r,\Gamma)}{\partial\Gamma}\right). \tag{3.15}$$

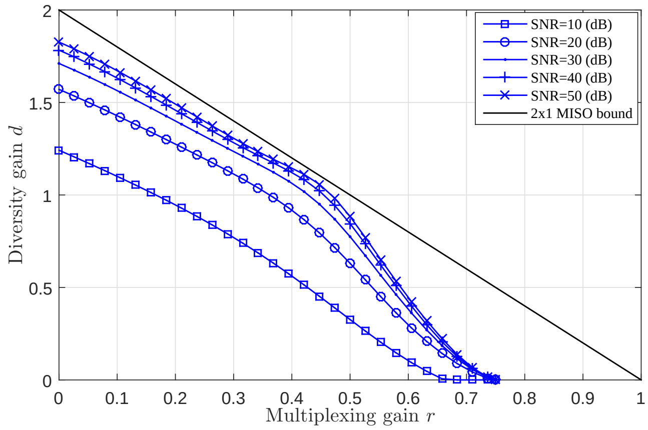

Figure 3.3.: Finite-SNR diversity-multiplexing tradeoff for lossy forwarding system.

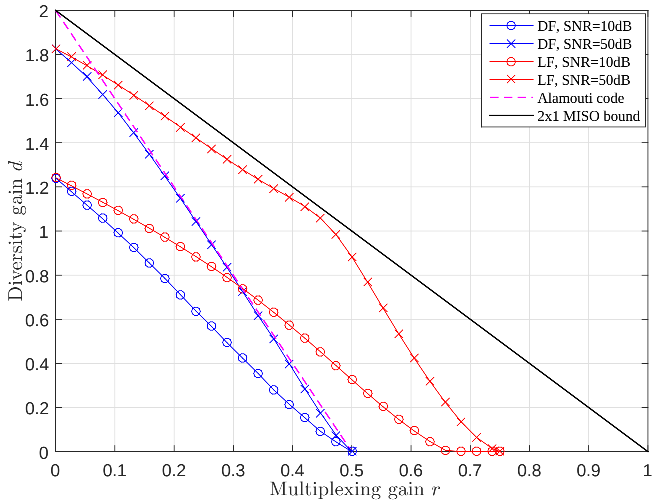

Figure 3.4.: Comparison of finite-SNR diversity-multiplexing tradeoff for LF and conventional DF systems.

The right hand side of the (3.15) requires calculations for the derivatives of three terms. Appendix A shows their derivations in detail.

3.4 Numerical Results

Here, we demonstrate numerical results of finite-SNR diversity-multiplexing tradeoff for the lossy forwarding DF system. Fig. 3.3. demonstrates the f-DMT curves with respect to different Γ for the lossy forwarding DF system. For reference, we also plot the bound for 2x1 MISO DMT in Fig. 3.4. Compared with conventional DF system, in which the finite-SNR diversity-multiplexing tradeoff was investigated in [Sta+07], the lossy forwarding DF system surpasses the conventional DF system in both diversity gain and multiplexing gain, as shown in Fig. 3.4. In Fig. 3.4, the bound for 2x1 MISO DMT and the DMT line with the Alamouti scheme is shown for reference. It is found that with the lossy forwarding technique, we can achieve close 2x1 MISO DMT bound, which is much better than the Alamouti scheme [Ala06]. For a fixed value of r, the lossy forwarding system achieves higher diversity gain than the conventional DF system. Otherwise, if multiplexing gain $r = 0$, i.e., the spectrum efficiency is fixed, the lossy forwarding DF system achieves the same diversity gain with conventional DF system. In addition, the maximum multiplexing gain $r_{\max} = 0.5$ can be achieved by the conventional DF system, while $r_{\max} = 0.75$ by the lossy forwarding DF system. The result shows that given a fixed outage probability, for S and R, the conventional DF system can transmit information sequences with spectrum efficiency $R_c = 1.0 \times \log_2(1+\Gamma)$, while the lossy forwarding DF system is able to transmit with $R_c = 1.5 \times \log_2(1+\Gamma)$.

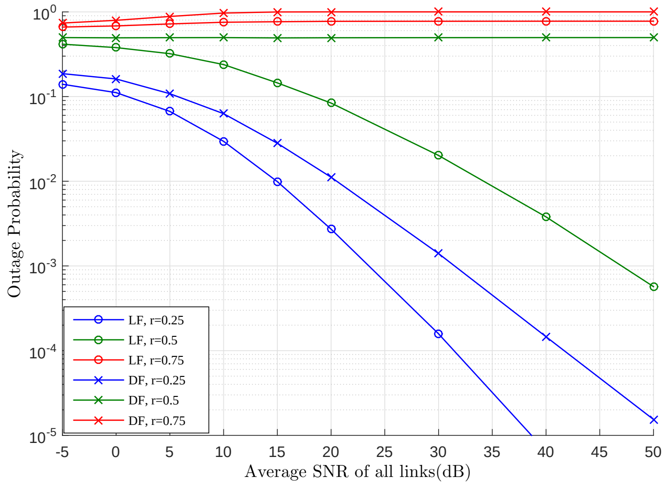

Figure 3.5.: Comparison of outage probability for lossy forwarding DF and conventional DF systems for different values of multiplexing gain.

As a verification, we conduct Monte Carlo simulation to compare the outage performance between the conventional DF system and the lossy forwarding DF system as shown in Fig. 3.5. For different values of r, Fig. 3.5 shows that the lossy forwarding DF system has better outage performance than the conventional DF system, the diversity gain is extremely close to the corresponding points shown in Fig. 3.3 and Fig. 3.4. Note that in the case of $r = 0.5$, no diversity gain can be achieved by the conventional DF system with approximately fixed 0.5 outage probability, while a diversity gain can be achieved by the lossy forwarding DF system. Furthermore, given multiplexing gain $r = 0.75$, reliable transmission is not possible for the conventional DF system because of the outage probability approaching to 1, while the lossy forwarding DF system still can transmit with lower outage probability.

3.5 Summary

Multiple-node relay network can be virtually considered as a MISO system. Therefore, we have investigated the diversity-multiplexing gain of the TS1 based on lossy forwarding RESCUE concept. In particular, we have derived finite-SNR diversity expressions for a given a specific value multiplexing gain r. It had been shown that the lossy forwarding DF system outperforms the conventional DF system in diversity performance. Furthermore, an extra multiplexing gain had been achieved by the lossy forwarding DF system compared to the conventional DF system, which leads to a significant transmission improvement.

4. Coded Random Access Technique

In this chapter, we briefly discuss the coded random access technique which is one of the emerging wireless access techniques in the multi-user communication. The RESCUE system model can be characterized by a multi-user multi-way multi-relay network. Therefore, it is interesting to investigate with a major focus on how we can efficiently combine the lossy forwarding techniques in the random access scenarios. The coded random access technique is used to efficiently exchange information among users which have no direct links. Thus the users can exchange information via relays which makes it possible to utilize the lossy forwarding techniques. We start this chapter by a motivation of the relay networks and cooperative relaying communications. Then, we highlight that the RESCUE system model can be characterized by a multi-user multi-way multi-relay network. Subsequently, we provide the existing coded random wireless techniques and their limitations. To overcome these limitations and to retrieve the beneficial properties of the lossy forwarding techniques, we establish an improved framework for improving the transmission efficiency, reliability, and reducing the complexity in the multi-users multi-way relay networks. Finally, we present the preliminary results for multi-relay networks based on MIMO relaying and outline the future work for upcoming deliverables.

The primary goal of this chapter is to identify the problems, limitation and drawbacks of the current coded random access techniques, and to provide potential solutions based on lossy forwarding techniques to the problems in the framework of RESCUE project. Following this approach, we obtained preliminary results for the multi-user multi-relay networks assuming that the relays have multiple antennas. However, in-depth analysis assuming more complex scenarios such as in the case multi-user detection performes at the relays, and numerical results for such scenarios will be provided in D1.2.2 and D2.1.2.

4.1 Motivation and Objective

Due to increasing demand of data rate and reliability, next generation wireless communication networks will go beyond point-to-point paradigm. The communication nodes in the future wireless communication networks will cooperate with one another to improve the performance of their own communication and that of the entire network. In multi-node network, there may be no direct reliable link between the source and the destination due to geographical location and power limitation. For examples, in applications such as communication for public safety in disaster areas and vehicle to vehicle communication which are the main focus of RESCUE project, information is gathered from the surrounding environment by a large number of users. The information are then delivered to the destination node via intermediate nodes called relays. Similarly, wireless sensor networks and teleconference calls where the information from sources are usually delivered to the destination through relays. Since the pioneer work of [CG79], relay techniques have received a lot of research interest for various applications. Relay-based communication is an emerging technology for future cellular communication networks [Vuk+14]. The presence of the relay nodes leads to a significant gain in performance especially for multicast transmission. In RESCUE project, toy scenario 2 is a typical example of such applications.

Even if the direct link between the source and destination exists, wireless networks that incorporate relaying can achieve high throughput, increase reliability, and improve spectral efficiency [CG79]. Cooperative relaying communication is used to obtain higher diversity, multiplexing gain and coverage extension. In the multi-source networks, relay combines data from multiple sources to obtain the benefits of larger blocklengths in graph-based codes. International mobile telecommunications-Advanced (IMT-Advanced) is another practical application of the relay-assisted wireless systems [AW05]. The relay station in IMT-Advanced assists the uplink transmissions originated from multiple user equipments simultaneously within its coverage. Multi-hop wireless mesh networks are other practical application of relay-assisted transmission where the Internet gateway connecting the mesh network of client stations to the core wired Internet [AW05]. RESCUE project has developed for applications in public safety and vehicle-to-vehicle communication where destination can receive data from the source with cooperation of relays. Therefore relaying cooperative communication is directly applicable to the RESCUE toy scenarios. For example, toy scenario 2, toy scenario 3, and toy scenario 4 of RESCUE project characterized cooperative relaying communication based on lossy forwarding. Furthermore, it has been shown in deliverable [D121] of the RESCUE project that the relaying communication based on lossy forwarding outperforms the existing relaying communication.

Two-way relay channel was introduced in [NCL08] where two users can communicate with each other via a

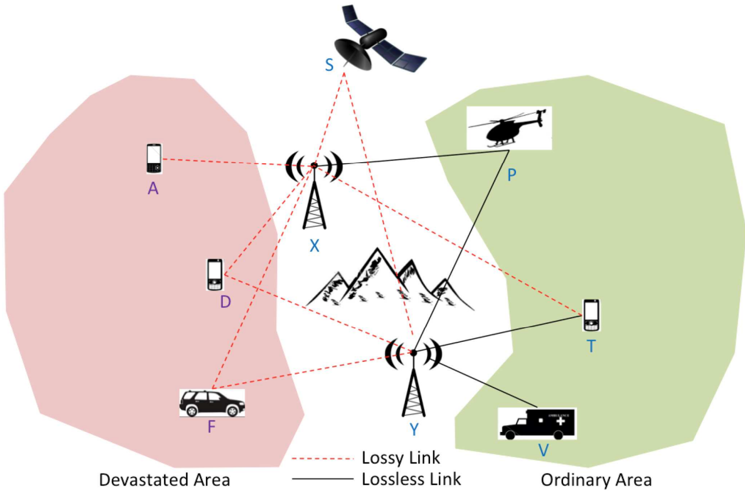

Figure 4.1.: Typical RESCUE diagram

single relay. By employing network coding, benefits in terms of higher throughput were achieved for the two-way relay channels [Wil+10]. As a generalization of two-way relay channels, multi-way relay channels have thoroughly investigated in [Gun+09]. Practical examples of the multi-way relay channels include transmission between multiple nodes via access point in the wireless sensor networks, conference call in cellular networks, and scattered users communicating with each other in the disaster areas. Multi-way relay channels were studied for Gaussian channels in [OKJ10] and for binary symmetric channels in [OJK10], when the channel state information is known to both users and relay. In addition to multi-way relay channel, multiple relay network is also used in large sensor network and disaster areas. Additional motivation is provided by the increasing practical interest in multiple-relay networks, as demonstrated by standards activities in IEEE 802.11 and upcoming improvements of cellular networks. Thus, it is beneficial to investigate the multi-users multi-relay networks to retrieve the benefits of lossy forwarding technique in the framework of RESCUE project.

The typical RESCUE diagram is shown in Fig. 4.1. From Fig. 4.1, we observe that multiple users communicate with each other via multiple relays in the RESCUE framework. Therefore, the RESCUE abstract system model can be represented by a more general multi-user multi-way multi-relay network. Our aim is to combine the lossy forwarding technique and network structure to gain in throughput and reliability. Further, we will improve the network capacity and reduce the complexity both at the users and relays. As a starting point, we obtain the rate region by considering this transmission as a non-orthogonal multiple access channel (MAC) transmission. From the rate region, we calculate the outage probability. Furthermore, by using the tools from graph theory, we will devise efficient transmission strategies from users to relays and from relays to users. Theoretical and numerical results for the simplified scenario of two users and two relays based on MIMO relaying are obtained and presented in this chapter. However, the in-depth analysis and results of these investigations will be presented in deliverable D1.2.2 and D2.1.2.

4.2 Background and Related Work

Multi-user communication has many applications in the current and future wireless communication network. For example, cellular network and wireless sensor networks consist of many users communicating with each other [Vuk+14; FKK10]. Recent development in the integrated circuit design will further boost multi-user applications. In the future wireless communication network, these devices will cooperate with each other to improve the performance of their own and the entire network. However, the coordination among the users in certain applications are not possible due to a large and random number of devices in the network. For instance, the number of active mobile users in a geographical cell in a cellular network and random number of devices in machine-to-machine communication.

For communication in uncoordinated applications, framed ALOHA random access is one of the pioneering approaches proposed in [Oka77], where the link is divided into frames containing predetermined time slots. The users are allowed to transmit in the randomly chosen time slots of a given frame. At the destination, the data of the user is recovered successfully from the time slots with a single user transmission. The time slots with no user or multiple user transmission are consider as collision. Hence, the receiver cannot recover data from these time slots resulting in a lower throughput. A further improvement was made in [CDGH07] to resolve the collision by interference cancelation called contention resolution diversity slotted ALOHA (CRDSA). In the CRDSA, a bipartite graph representation allows analyzing the convergence of the iterative interference cancellation. The CRDSA is based on the repetition of the same data within the same frame. A pointer is included in the header of the data to point to the replicas. The performance of framed ALOHA was improved significantly in [Liv11] by using the tools from the graph-based codes. This scheme is known as irregular repetition slotted ALOHA (IRSA) and improves the performance of CRDSA by allowing a variable repetition rate for each data packet. Subsequently, the user transmission profile was optimized in terms of throughput. For the collision resolution, successive interference cancelation (SIC) technique was applied to the iterative decoding on the developed bipartite graph between users and transmission time slots. Significant performance improvement was achieved when the number of the users in the network is large [Liv11; NP12]. As a generalization of the IRSA scheme, coded slotted ALOHA (CSA) was introduced in [PLC11b; PLC11a] by incorporating general linear codes at the users instead of repetition. Recently, further improvement was achieved in uncoordinated multi-way relaying systems in [AH15] by using multi-user detection at the relays.

For decoding at the relays and users, two approaches are mainly used. In the first approach, the SIC is realized by the factor graph made by users and relays in the network [Liv11]. To start decoding, all the singleton time slots are identified and the associated users are successfully decoded. Then using the pointers, all the recovered users, their replicas, and edges are removed from the time slots involving these users. As a result, new singleton time slots emerge and the process is repeated. The decoding process continues unless no singleton time slot remains, or certain predefined threshold of users are recovered. The remaining users are recovered in the next transmission. The second approach proposed in [AH15] used multi-user detection realized by the iterative demapping technique [AM12b]. Furthermore, multi-user detection based on code-division multiple access for irregular repetition slotted ALOHA presented in [GS13].

Although significant research has been made to improve the performance of the multi-users multi-relay networks, there are some limitations of the existing results. For example, most of the research attention has been directed towards improving transmission efficiency only for the uplink. Since, RESCUE project is based on end-to-end communication, investigation of the downlink transmission is relevant. Similarly, most the existing results are derived for high layers. Thus, the signalling and modulation of the physical layers are not considered. Furthermore, in the existing applications, all the users are assumed to be synchronized thus having the same channel gains at the destination. However, in RESCUE project, we consider all users at a different distances realizing the practical scenarios such public safety in disaster areas and vehicle-to-vehicle communication. Finally, the complexity and error propagation of the decoders both at the relays and users are not considered in the existing literature. The existing random access techniques are based on static channel conditions, fixed topology, and careful power controlled scenario such as satellite communication. However, RESCUE project is based on links-on-the-fly where topology, channels conditions, and power requirements are continuously changing. The requirements and differences between the wireless random access techniques for existing applications and RESCUE's links-on-the-fly are further elaborated in Table 4.1. In the next section, we propose our system model and outline how to overcome these problems.

4.3 Proposed Methodology

To characterize the RESCUE used case scenarios, we consider a multi-user multi-way multi-relay networks. More specifically, we consider K users and M relays scenario as shown in Fig. 4.2. Each user contending to receive the information from all other users. It is assumed that there are no direct links among the users. Hence, users exchange information via M relays as depicted in Fig. 4.2. All the nodes in the system operate in a half-duplex mode such that each node cannot transmit and receive simultaneously. We consider two phase transmission protocol, namely, uplink phase and broadcast phase. In the uplink phase, the randomly selected users broadcast information to the relays without coordination. The second phase is broadcast where relays decode and broadcast the decoded information back to the users. The broadcast phase by the relays to the users is explicitly illustrated in Fig. 4.2.

Table 4.1.: Requirements of static random access and dynamic (RESCUE) random access

S.No	Parameter	Stable-Network random access	Dynamically changing (RSECUE) random access
1	Topology	Static	Dynamic
2	Perfect packet synchronization	Possible	Impossible or Quasi-synchronization possible
3	Distances between communication nodes	Fixed	Varying
4	Error propagation in detection process	Not considered	Needs to be considered
5	Multi-user detection complexity	Not considered	Required
6	Received signal power	Stable	Dynamically changing
7	Research focus	Higher layer	Joint physical and higher layer
8	Channel models	Erasure channels	Fading channels
9	Channel conditions	Fixed	Varying
10	Impact on the industry	Mostly academic consideration	Needed practical consideration
11	Lossy forwarding	Not considered	Main technique

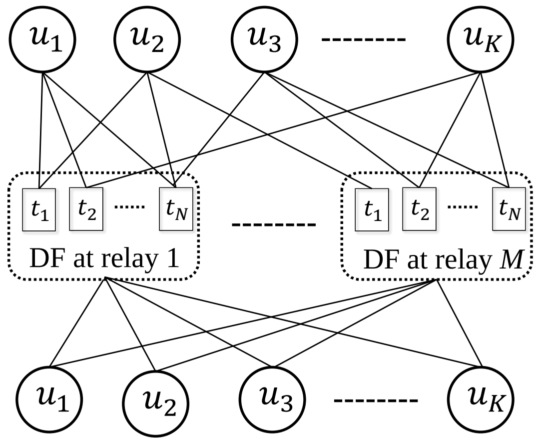

Figure 4.2.: System model of a Multi-user multi-way multi-relay network

The uplink phase is further divided into N time slots of equal duration. At each user, information packet is encoded to the coded packet by a linear block code. During each time slot , the users adopt a variable repetition rate, which is picked according to a predefined distribution. Hence, in each time slot, a number of active users broadcast their coded packets to the relays. In the uplink phase, each active user transmits the coded packet on a slot basis by a predefined distribution. A framework will be design to compute this predefined distribution which will be provided in deliverable D1.2.2.

Each user encodes its information vector $\mathbf{u}_i$ to the coded sequence $\mathbf{s}_i$ by a linear block code for $i = 1,2,\ldots,K$. If user i is active in a given time slot, then user i transmits $\mathbf{s}_i$. Note that several replicas of the same packet $\mathbf{s}_i$ is broadcasted by user i in different time slots of the uplink phase. Hence, the relays receive coded packets from different users simultaneously in a given time slot. The m-th relay receives the composite signal $\mathbf{y}_{R_m,j}$ in time slot j as

$$\mathbf{y}_{R_m,j} = \sum_{i=1}^{N} a(i,j)\sqrt{P_i}h_{i,m}^{j}\mathbf{s}_i + \mathbf{n}_{R_m,j},\ 1 \leq j \leq K, \text{ and } 1 \leq m \leq M, \tag{4.1}$$

where $\sqrt{P_i}$ is the average transmit power of user i and $\mathbf{n}_{R_m,j}$ is the additive white Gaussian noise with mean value zero and variance σ_j^2. The notation $h_{i,m}^{j}$ is the complex channel gain between i-th user and m-th relay in j-th time slot. Here, $a(i,j) = 1$ if user i transmits in time slot j and 0 otherwise. We assume that the channel coefficients between the users and the relays do not change during the uplink phase. The distances of the users and the relay are different. Therefore, their channel gains to the relay are different, that is, $h^j_{i,m} \neq h^j_{k,m}$ for $i \neq k$. Furthermore, we assume reciprocal channels such that the channel coefficients in the uplink and broadcast are the same.

The number of the replicas transmitted by user i is denoted as a user degree $|u_i|$ and the number of simultaneous transmission in time slot j is denoted as a slot degree $|s_j|$. Therefore, we have

$$|u_i| = \sum_{i}^{N} a(i,j), 1 \leq i \leq K, \tag{4.2}$$

$$|s_j| = \sum_{i}^{K} a(i,j), 1 \leq j \leq N. \tag{4.3}$$

Following [Liv11], the repetition rate of a user is denoted by a user-node degree. Therefore, the user-node degree distribution is represented by

$$\Lambda(x) = \sum_{i=1}^{I} \Lambda_i x^i, \tag{4.4}$$

where I is the maximum repetition rate, and Λ_i is probability that a user transmits i replicas. The slot-node degree distribution is not in the control of the system designer. The users randomly select the slots in which they transmit. Therefore, the slot degree distribution can be determined and subsequently approximated as [Liv11]

$$\Omega(x) = \sum_{i=0}^{N} \Omega_i x^i \approx e^{G\Lambda'(1)(x-1)}, \tag{4.5}$$

where $\Lambda'(1) =$ is the average repetition rate of users and $G = K/N$ is the normalized channel traffic [Liv11].

In the broadcast phase, the relays process and broadcast the received messages to all users according to a predetermined transmission profile. Each time slot is considered as MAC receiver at the relays where users are transmitting simultaneously. From the received signal at each relay, the relay first tries to decode all users' messages. The decoding at the relays can be performed either by the successive interference decoding presented in [Liv11] or multi-user detection based on iterative demapping outlined in [AM12b]. The decoding process at both the relays and users can also be performed by maximum a posteriori probability (MAP) decoding process. Thus the information of each user is decoded at each relays. The information from each user may be decoded error free or with some errors. The decoded sequences are then interleaved and re-encoded at each relay. Network coding [Ahl+00] can also be exploited at the relay. The coded sequences from each relay are broadcasted to the destinations according to a predetermined relay transmission strategy which needs to be optimized in terms of the throughput. The coded signals formed at the relays are always broadcasted to the destinations although the estimated information data may contains errors. According, the received signals at the users are decoded using MAP decoder or multi-user decoder [Liv11; AM12b].

4.4 Rate Region and End-to-end Outage Probability

There exist overall three cases/scenarios regarding the successfulness of the decoded data coming from users at the relays. In the first case, the relays to which user i has transmitted cannot fully recover the data of user i. Therefore, the decoded data at the relays can be regarded as noisy versions of the original data. Thus, the problem falls into the category of chief executive officer (CEO) problem in the broadcast phase. In the second case, the relays which receive data from user i, can fully recover the data of user i. Maximum ratio transmission (MRT) will be applied to achieve the maximum diversity gain, for which it is assumed that the relays can exchange the channel state information of the relay-destination links via back-haul network. For the third case, some of the relays can successfully decode the original data of user i depending on their admissible rate regions. The erroneously decoded message at these relays are correlated with the user data. In addition, the fully recovered message at the other relays is exactly the same with the user sequence. Therefore, the decoded sequences at the relays are correlated, entitled as relay-relay correlation. In this regards, the problem turns into the category of source coding with helper.

For the purpose of notational simplicity, we consider a simple structure composed of two users, two relay nodes, and one destination. In the uplink phase, the users are transmitting coded sequences to the relay nodes simultaneously (two nonorthogonal MACs), and the received signal in (4.1) at the relay nodes can be simplified by dropping the time slot index as [1]

$$y_{R_1} = \sqrt{P_1}h_{1,1}s_1 + \sqrt{P_2}h_{1,2}s_2 + n_{R_1}, \tag{4.6}$$

and

$$y_{R_2} = \sqrt{P_1}h_{2,1}s_1 + \sqrt{P_2}h_{2,2}s_2 + n_{R_2}. \tag{4.7}$$

The s_1 and s_2 are modulated symbols from the codewords[2] of two independent binary uniform sources u_1 (originated from user 1) and u_2 (originated from user 2) with $Pr(u_1 = 0) = Pr(u_1 = 1) = 0.5$ and $Pr(u_2 = 0) = Pr(u_2 = 1) = 0.5$. $E\{|s_1|^2\} = E\{|s_2|^2\} = 1$. The average signal to noise ratio of the user j to the relay i is $\gamma_{i,j} = P_j|h_{i,j}|^2$ for $i, j \in \{1,2\}$.

The relays decode the data from both of the users, re-encode, and forward it to the destination at the second transmission hop. We only focus on one user's (e.g., user 1) data transmission from the relays to the destination. Due to the symmetry, similar formulations can be derived for user 2. Let the decoded data of user 1 at relay 1 and relay 2 be denoted by $\hat{u}_{1,R_1}$ and $\hat{u}_{1,R_2}$, respectively. After re-encoding process at the relays, the corresponding coded and modulated versions are represented by $\hat{s}_{1,R_1}$ and $\hat{s}_{1,R_2}$, respectively, with $E\{|\hat{s}_{1,R_1}|^2\} = E\{|\hat{s}_{1,R_2}|^2\} = 1$. Further assuming orthogonal transmission, e.g., time division multiple access (TDMA), the received data at the destination can be expressed as

$$y_{D,t_1} = \sqrt{P_{R_1}}h_1\hat{s}_{1,R_1} + n_{D,t_1}, \tag{4.8}$$

and

$$y_{D,t_2} = \sqrt{P_{R_2}}h_2\hat{s}_{1,R_2} + n_{D,t_2}, \tag{4.9}$$

where n_{D,t_1} and n_{D,t_2} denote the AWGN noise for two adjacent time indices $\{t_1,t_2\}$ with distribution $\mathscr{CN}(0,1)$. The relay 1 transmits with power P_{R_1} while the relay 2 transmits with power P_{R_2}. The h_i denotes the channel coefficient from relay i to the destination, $h_i \sim \mathscr{CN}(0,1)$, for $i \in \{1,2\}$. The average SNR of the relay i to the destination is $\gamma_i = P_{R_i}|h_i|^2$, for $i \in \{1,2\}$.

It is of great challenge to find an optimal coding scheme that achieves the outer bound of the MACrate region if the relays are equipped with a single antenna. The Kasami codes presented in [KL76] are suboptimal, which can only achieve a point between the inner bound and outer bound of the rate region. To simplify the code design process, we introduce the concept of MIMO into the MAC channel, which can easily convert the MAC transmission into a point-to-point transmission by virtue of uncomplicated algebraic manipulations, for example, matrix inverse and singular value decomposition (SVD) at the relay nodes. As a result, the rate region is changed from a typical bounded pentagon into a bounded rectangle.

We further assume that the number of the antennas at each relay is equal to the number of users to simplify the problem. In our proposed topology, we assume that two antennas are equipped at each of the relay nodes. Therefore, by postulating equal power transmission, the received signal at the relay 1 can be expressed as

$$\mathbf{y} = \sqrt{P}\mathbf{H}\mathbf{s} + \mathbf{n}, \tag{4.10}$$

where $\mathbf{H} \in \mathbb{C}^{2\times 2}$ is the channel coefficient matrix with each entry i.i.d. normal Gaussian distributed, $\mathbf{s} = [s_1 \;\; s_2]^T$, and $\mathbf{n} \in \mathbb{C}^{2\times 1}$ is Gaussian vector with each component normal Gaussian distributed. We also assume that the channel state information is available at the relay side. By simply applying ZF filtering at the relay node, the post-detected signal can be written by

$$\hat{\mathbf{s}} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H\mathbf{y} = \sqrt{P}\mathbf{s} + \mathbf{H}^{-1}\mathbf{n}, \tag{4.11}$$

where $(\cdot)^H$ and $(\cdot)^{-1}$ stand for conjugate transpose and inverse, respectively. By using multiple antennas at the relay nodes, the multiple access transmission is transformed to a point-to-point transmission. Accordingly, the rate region becomes rectangular, as shown in Fig. 4.3

The singular value decomposition is applied to decompose $\mathbf{H} = \mathbf{U}\Sigma\mathbf{V}^H$, where $\mathbf{U} \in \mathbf{b}C^{2\times 2}$ and $\mathbf{V} \in \mathbb{C}^{2\times 2}$ denote the left and right singular (and unitary) matrices of $\mathbf{H}$, respectively. The $\Sigma \in \mathbb{C}^{2\times 2}$ is the diagonal matrix $\Sigma =$

[1] Even though the wireless channels are static and stationary within a period of coherence time (or a block/frame/codeword length, equivalently), we only deliver symbol-wise formulations to all the received signal in this chapter for the sake of simplicity.

[2] The encoding chain consists of source coding, channel coding, and modulation. The source coding rate of user i is denoted by R_{s_i} while the multiplication of channel coding rate and modulation order of user i is denoted by R_{c_i}, for $i \in \{1,2\}$. The notations R_{s_i} and R_{c_i} are also applied to the relay i, for $i \in \{1,2\}$.

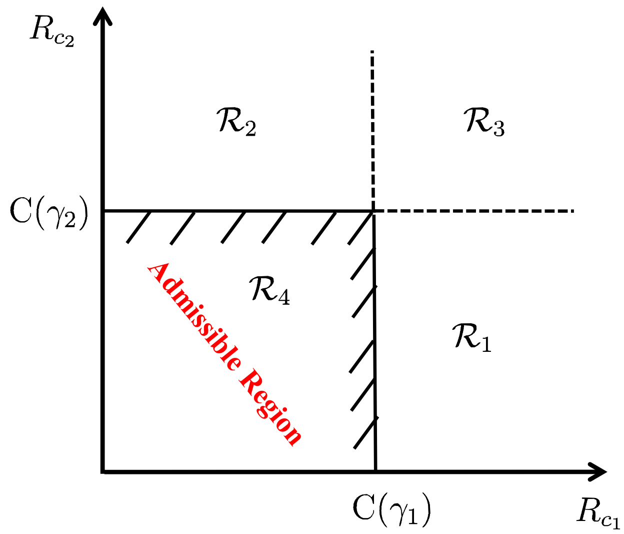

Figure 4.3.: Rate region of multiple-antenna relaying system for the source-to-relay transmission.

$\mathrm{diag}([\sigma_1, \sigma_2])$ with $\sigma_1 \geq \sigma_2 \geq 0$. The post-detection SNR for user i can be written as

$$\gamma_i = P\sigma_i^2. \tag{4.12}$$

We set $\lambda_i = \sigma_i^2$, for $i \in \{1,2\}$, which are eigenvalues of covariance matrix of $\mathbf{H}$ and mutually dependent. The joint probability density function (PDF) for the λ_i's can be expressed as [Tel99]

$$p(\lambda_1, \lambda_2) = K \exp(-\lambda_1 - \lambda_2)(\lambda_1 - \lambda_2)^2, \tag{4.13}$$

where K is a constant normalization factor ensuring that the $\int_0^\infty \int_0^\infty p(\lambda_1, \lambda_2) d\lambda_1 d\lambda_2 = 1$. The resultant value for K is 0.5. According to (4.13), we can calculate the marginal PDF for each λ_i and the result can be expressed as

$$p(\lambda_i) = \frac{1}{2}\exp(-\lambda_i)(\lambda_i^2 - 2\lambda_i + 2), \text{ for } i = 1,2. \tag{4.14}$$

The derived theoretical PDF of λ_i in (4.14) is verified by Monte-Carlo simulations, which is shown in Fig. 4.4. The Monte-Carlo simulation result almost overlaps with the its theoretical counterpart, except for the two tiny intervals [0, 0.1] and [9.8, 10]. This tiny mismatch can further be improved by using sufficient measurement data. Following the PDF from (4.14), the outage probability of user i at relay 1 can be further calculated by

$$\begin{aligned} P_{\text{out}}^{1,i} &= Pr(\gamma_i < 2^{R_{c_i}} - 1) = \int_0^{\frac{2^{R_{c_i}}-1}{P}} p(\lambda_i) d\lambda_i \\ &= 1 - \frac{\exp(-\frac{2^{R_{c_i}}-1}{P})((\frac{2^{R_{c_i}}-1}{P})^2 + 2)}{2}. \end{aligned} \tag{4.15}$$

Based on the outcome of data recovery of user 1 at the relays, we divide the analysis into three cases. In the following, we give further details of these cases.

Case 1 ($\hat{u}_{1,R_1} \neq u_1,\ \hat{u}_{1,R_2} \neq u_1$): In this case, both of the relays cannot fully recover the data from user 1. Therefore, the two decoded data at the relays can be regarded as noisy versions of the original data. Thus, the problem falls into the category of CEO problem at the second hop (i.e., relay-to-destination transmission). Therefore for the purpose of simplicity, we just set the outage probability to 1 at the second transmission.

Case 2 ($\hat{u}_{1,R_1} = u_1,\ \hat{u}_{1,R_2} = u_1$): Since both of the relays have two antennas. Hence the channels between relays and destination are supposed to be $\mathbf{h}_1 \in \mathbf{b}C^{1\times 2}$ and $\mathbf{h}_2 \in \mathbb{C}^{1\times 2}$. By using MRT, the received signal can be expressed

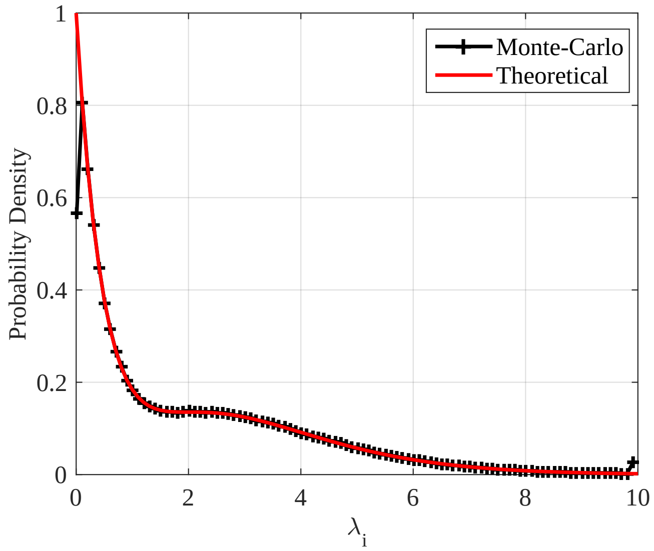

Figure 4.4.: Theoretical PDF of λ_i from (4.14) and numerical PDF of λ_i through Monte-Carlo simulations.

as

$$y = \sqrt{P}\mathbf{h}_1\mathbf{h}_1^H s_1 + \sqrt{P}\mathbf{h}_2\mathbf{h}_2^H s_1 + n. \tag{4.16}$$

By an abuse of notations $\{H_3, H_4\}$ and setting $\mathbf{h}_1\mathbf{h}_1^H = H_3$ and $\mathbf{h}_2\mathbf{h}_2^H = H_4$, H_3 and H_4 are Chi-square random variables, denoted by $H_3, H_4 \sim \chi^2(2)$. The PDF of H_i, for $i \in \{3,4\}$ can be expressed as

$$p(H_i) = \frac{\exp(-H_i/2)}{2}. \tag{4.17}$$

The corresponding outage probability can be computed by

$$P_{\text{out}}(\text{Case } 2) = Pr(R_c > \log_2(1 + P(H_3 + H_4))). \tag{4.18}$$

Then, the final expression for (4.18) can be written by

$$\begin{aligned} &Pr\{R_c > \log_2(1 + P(H_3 + H_4))\} \\ &= \int_0^{\frac{2^{R_c}-1}{P}} \int_0^{\frac{2^{R_c}-1}{P} - H_3} \frac{1}{4} \exp(-\frac{(H_3 + H_4)}{2}) dH_3 dH_4 \\ &= 1 - \exp(-\frac{2^{R_c}-1}{2P})(1 + \frac{2^{R_c}-1}{2P}). \end{aligned} \tag{4.19}$$

Case 3 ($\hat{u}_{1,R_1} \neq u_1$, $\hat{u}_{1,R_2} = u_1$) or ($\hat{u}_{1,R_1} = u_1$, $\hat{u}_{1,R_2} \neq u_1$): The outage probability of Case 3 can be expressed as

$$P_{\text{out}}(\text{Case } \ 3) = Pr(\mathscr{R}_2) + Pr(\mathscr{R}_3). \tag{4.20}$$

In this case, we use source coding with helper theorem to compute the two components of the outage probability as follows.

$$\begin{aligned} &Pr(\mathscr{R}_2) = Pr(R_{s_2} \geq 1, 0 \leq R_{s_1} \leq H_b(p)) \\ &= \int_{\mathrm{C}^{-1}(R_{c_2})/P}^{\infty} \int_0^{\mathrm{C}^{-1}(R_{c_1} H_b(p))/P} \frac{1}{4} \exp(-\frac{H_3 + H_4}{2}) dH_3 dH_3, \end{aligned} \tag{4.21}$$

and

$$\begin{aligned} &Pr(\mathscr{R}_3) = Pr(0 \leq R_{s_2} \leq 1, 0 \leq R_{s_1} \leq H_b(\alpha * p)) \\ &= \int_0^{\mathrm{C}^{-1}(R_{c_2})/P} \int_0^{\mathrm{C}^{-1}(R_{c_1} H_b(\alpha * p))/P} \frac{1}{4} \exp(-\frac{H_3 + H_4}{2}) dH_3 dH_4. \end{aligned} \tag{4.22}$$

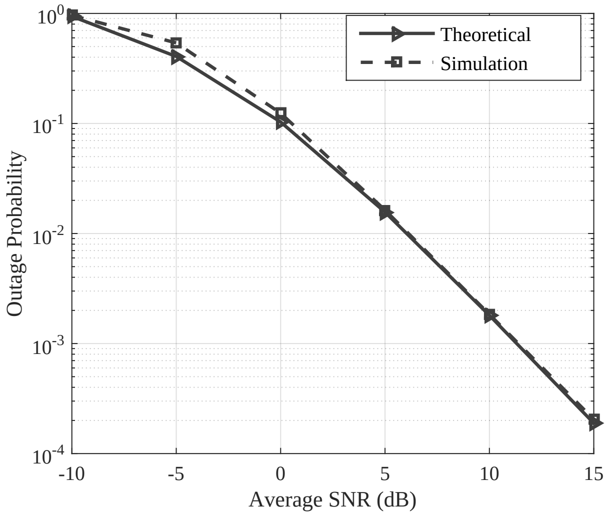

Figure 4.5.: End-to-end outage probabilities of user 1 in the multi-source multi-relay system.

As a future work, these analysis will be extended to the more generalized complex scenarios such as in the case multi-user detection performs at the relays. The in-depth analysis and results will be submitted in the future deliverables.

4.5 Numerical Results

In this section, we provide Monte-Carlo simulations to calculate the end-to-end outage probabilities (only for user 1, the same results can be obtained for user 2 due to the symmetry property of the proposed topology.) and compare them with the derived theoretical results. For all the transmission links, we use the same transmit powers and multiplications of channel coding rate and modulation order. All the rates, including R_{c_1}, R_{c_2} and R_c, are set to be 0.5. We can clearly observe from the results presented in Fig. 4.5 that our numerical examples closely approach the theoretical analysis. It is depicted in Fig. 4.5 that second order diversity is achieved for the MIMO relaying systems in terms of end-to-end outage probabilities. Furthermore, the multiple-antenna relaying systems provide practical and optimal code design.

4.6 Summary

In this chapter, we have studied the coded random access which is one of the emerging wireless access techniques. First, we have briefly described the motivation of relay networks and its characterization in the RESCUE project. Then we have discussed the existing multi-users wireless random access techniques and their limitations. Furthermore, we characterized the RESCUE system model into a multi-user multi-way multi-relay network. To benefit from the the lossy forwarding techniques and realize realistic requirements, we provide our system model and detailed our approach. We also present the theoretical and numerical results of the two-users two-relays MIMO relaying system. Finally, we have outlined the potential future work, the results of which will be submitted in deliverables D1.2.2 and D2.1.2.

5. Conclusion

This document reported on the research of RESCUE regarding physical transmission and medium access for the links-on-the-fly concept. The three main contributions of this deliverable were: (i) evaluation of a MIMO multi-relay system with RBF, limited feedback and *lossy forwarding*, (ii) assessment of the diversity-multiplexing tradeoff for a three-node relay system with *lossy forwarding*, and (iii) combination of *lossy forwarding* and advanced random coded access schemes. The work has been carried out in work package 1 *Theoretical analyses for limit and rate-distortion region*, specifically in task 1.3 *Wireless access & multiple antenna techniques*.

In the first part – *evaluation of a MIMO multi-relay system with RBF, limited feedback and lossy forwarding* – we studied RBF as a tool to increase system reliability and spectrum efficiency to meet requirements for RESCUE use cases. We considered a MIMO multi-relay system with single-antenna equipped source nodes communicating with single-antenna equipped destination nodes with the help of two multiple-antena equipped relay nodes. The destination nodes provide limited feedback to the relays which allows joint scheduling. Two strategies were proposed: (i) the destination nodes indicate the preferred beam to the relay nodes based on their initially predicted SINR. (ii) The destination nodes indicate preferred and undesired beams to the relay nodes. The performances of the proposed strategies were carefully investigated through both theoretical and numerical analysis. In summary, we showed that the first strategy increases the number of active destination nodes compared to conventional RBF. In addition, the second strategy can exhibit even better system performances with more accurate SINR prediction at the price of relatively increased complexity and feedback overhead.

In the second part – *assessment of the diversity-multiplexing tradeoff with lossy forwarding for TS1* – we investigated the diversity-multiplexing gain based on the links-on-the-fly concept. Specifically, we considered a three-node one way relay system and derived finite-SNR diversity expressions for a given multiplexing gain by considering it equivalent to a 2x1 MISO system. Thus, we were able to investigate the tradeoff between high communication reliability (diversity gain) on the one side and high throughput for a fixed reliability level (multiplexing gain) on the other side. The proposed scheme based on *lossy forwarding* significantly outperformed the conventional DF scheme in terms of outage probability. In addition, we achieved additional 0.25 multiplexing gain of the proposed schemes, which leads to a maximum 50% higher possible transmission rate.

In the third part – *combination of lossy forwarding and advanced coded random access* – we extended the RESCUE system to a generalized multi-user multi-way relay network to exploited random access schemes. In detail, we studied the coded random access which is one of the emerging wireless access techniques for unpredictable environments with massive number of randomly transmitting devices. Coded random access relies on the concept of graph-based codes and SIC. We outlined limitations of the existing random access schemes in respect to RESCUE network requirements. Additionally, we presented the potential performance gain in throughput and robustness if advanced random access schemes are combined with *lossy forwarding*. We have presented theoretical and numerical results for a simplified scenario based on MIMO relaying. Finally, we outlined the potential future work, the results of which will be submitted in deliverables, i.e. D1.2.2 and D2.1.2.

The three presented topics play a major part to scope with RESCUE requirements in unpredicted environments. The presented results demonstrated significant performance improvements for *lossy forwarding* schemes in terms of system reliability and spectrum efficiency.

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Appendix A Derivation of Outage Probability Terms

The three different outage probabilities are given as

$$P_{out1}(r,\Gamma) = \frac{1}{\Gamma}\exp[-\frac{\Phi^{-1}}{\Gamma}]\int_{\Phi^{-1}(0)}^{\Phi^{-1}(1)}\exp(-\frac{\gamma_1}{\Gamma})[1-\exp(-\frac{\Phi^{-1}[1-\Phi(\gamma_1)]}{\Gamma})]d\gamma_1, \tag{A.1}$$

similarly,

$$P_{out2}(r,\Gamma) = \frac{1}{\Gamma}\int_{\Phi^{-1}(0)}^{\Phi^{-1}(1)}\exp(-\frac{\gamma_0}{\Gamma})[1-\exp(-\frac{\Phi^{-1}[1-\Phi(\gamma_0)]}{\Gamma})]d\gamma_0, \tag{A.2}$$

and

$$P_{out3}(r,\Gamma) = \frac{1}{\Gamma^2}\int_{\Phi^{-1}(0)}^{\Phi^{-1}(1)}\int_{\Phi^{-1}[1-\Phi(\gamma_0)]}^{\Phi^{-1}(1)}\exp(-\frac{\gamma_0}{\Gamma}-\frac{\gamma_1}{\Gamma})[1-\exp(-\frac{\Phi^{-1}[2-\Phi(\gamma_0)-\Phi(\gamma_1)]}{\Gamma})]d\gamma_1 d\gamma_0. \tag{A.3}$$

Then, their first order derivatives with respect to (Γ) are given as follows:

$$\frac{\partial P_{out1}(r,\Gamma)}{\partial\Gamma} = \frac{\partial P_{out1a}(r,\Gamma)}{\partial\Gamma}P_{out1b}(r,\Gamma) + P_{out1a}(r,\Gamma)\frac{\partial P_{out1b}(r,\Gamma)}{\partial\Gamma} \tag{A.4}$$

$$P_{out1a}(r,\Gamma) = \frac{1}{\Gamma}\exp\left(-\frac{\Phi^{-1}(1,r,\Gamma)}{\Gamma}\right), \tag{A.5}$$

$$\tag{A.6}$$

with which we get

$$\begin{aligned}\frac{\partial P_{out1a}(r,\Gamma)}{\partial\Gamma} = &-\frac{1}{\Gamma^2}\left(1+\frac{1}{\Gamma}\frac{\partial\left[\Phi^{-1}(1,r,\Gamma)\right]}{\partial\Gamma}+\frac{\Phi^{-1}(1,r,\Gamma)}{\Gamma}\right)\\ &\times\exp\left(-\frac{\Phi^{-1}(1,r,\Gamma)}{\Gamma}\right),\end{aligned} \tag{A.7}$$

$$\tag{A.8}$$

and

$$P_{out1b}(r,\Gamma) = \int_{\Phi^{-1}(0,r,\Gamma)}^{\Phi^{-1}(1,r,\Gamma)}[1-\exp(-\frac{\Phi^{-1}[1-\Phi(\gamma_1,r,\Gamma),r,\Gamma]}{\Gamma})]\exp\left(-\frac{\gamma_1}{\Gamma}\right)d\gamma_1, \tag{A.9}$$

$$\tag{A.10}$$

with which

$$\begin{aligned}\frac{\partial P_{out1b}(r,\Gamma)}{\partial\Gamma} = \frac{1}{\Gamma^2}\int_{\Phi^{-1}(0,r,\Gamma)}^{\Phi^{-1}(1,r,\Gamma)} & d\gamma_1\ \gamma_1[1-\exp(-\frac{\Phi^{-1}[1-\Phi(\gamma_1,r,\Gamma),r,\Gamma]}{\Gamma})]\exp(-\frac{\gamma_1}{\Gamma})\\ &+(\Gamma\frac{\partial\Phi^{-1}[1-\Phi(\gamma_1,r,\Gamma),r,\Gamma]}{\partial\Gamma}-\Phi^{-1}[1-\Phi(\gamma_1,r,\Gamma),r,\Gamma])\\ &\times\exp(-\frac{\gamma_1}{\Gamma}-\frac{\Phi^{-1}[1-\Phi(\gamma_1,r,\Gamma),r,\Gamma]}{\Gamma}).\end{aligned} \tag{A.11}$$

In the same way,

$$\frac{\partial P_{out2}(r,\Gamma)}{\partial\Gamma} = -\frac{1}{\Gamma^2}P_{out2b}(r,\Gamma) + \frac{1}{\Gamma}\frac{\partial P_{out2b}(r,\Gamma)}{\partial\Gamma} \tag{A.12}$$

with which

$$P_{out2b}(r,\Gamma) = \int_{\Phi^{-1}(0,r,\Gamma)}^{\Phi^{-1}(1,r,\Gamma)} [1-\exp(-\frac{\Phi^{-1}[1-\Phi(\gamma_0),r,\Gamma]}{\Gamma})]\exp(-\frac{\gamma_0}{\Gamma})d\gamma_0, \tag{A.13}$$

and

$$\begin{aligned}\frac{\partial P_{out2b}(r,\Gamma)}{\partial\Gamma} &= [1-\exp(-\frac{\Phi^{-1}(0,r,\Gamma)}{\Gamma})]\exp(-\frac{\Phi^{-1}(1,r,\Gamma)}{\Gamma})\frac{\partial\Phi^{-1}(1,r,\Gamma)}{\partial\Gamma}\\ &- [1-\exp(-\frac{\Phi^{-1}(1,r,\Gamma)}{\Gamma})]\exp(-\frac{\Phi^{-1}(0,r,\Gamma)}{\Gamma})\frac{\partial\Phi^{-1}(0,r,\Gamma)}{\partial\Gamma}\\ &+ \frac{1}{\Gamma^2}\int_{\Phi^{-1}(0,r,\Gamma)}^{\Phi^{-1}(1,r,\Gamma)} d\gamma_0[1-\exp(-\frac{\Phi^{-1}[1-\Phi(\gamma_0,r,\Gamma),r,\Gamma]}{\Gamma})]\exp(-\frac{\gamma_0}{\Gamma})\\ &+ (\Gamma\frac{\partial\Phi^{-1}[1-\Phi(\gamma_0,r,\Gamma),r,\Gamma]}{\partial\Gamma} - \Phi^{-1}[1-\Phi(\gamma_0,r,\Gamma),r,\Gamma])\\ &\times\exp(-\frac{\gamma_0}{\Gamma} - \frac{\Phi^{-1}[1-\Phi(\gamma_0,r,\Gamma),r,\Gamma]}{\Gamma})\gamma_0.\end{aligned} \tag{A.14}$$

Also for $P_{out3}(r,\Gamma)$,

$$\frac{\partial P_{out3}(r,\Gamma)}{\partial\Gamma} = -\frac{2}{\Gamma^3}P_{out3b}(r,\Gamma) + \frac{1}{\Gamma^2}\frac{\partial P_{out3b}(r,\Gamma)}{\partial\Gamma}, \tag{A.15}$$

$$\tag{A.16}$$

hence, we get

$$P_{out3b}(r,\Gamma) = \int_{\Phi^{-1}(0,r,\Gamma)}^{\Phi^{-1}(1,r,\Gamma)}\int_{\Phi^{-1}[1-\Phi(\gamma_0,r,\Gamma),r,\Gamma]}^{\Phi^{-1}(1,r,\Gamma)} [1-\exp(-\frac{\Phi^{-1}[2-\Phi(\gamma_0,r,\Gamma)-\Phi(\gamma_1,r,\Gamma),r,\Gamma]}{\Gamma})]\exp(-\frac{\gamma_0}{\Gamma}-\frac{\gamma_1}{\Gamma})d\gamma_1 d\gamma_0 \tag{A.17}$$

$$\tag{A.18}$$

and

$$\begin{aligned}\frac{\partial P_{out3b}(r,\Gamma)}{\partial\Gamma} &= \int_{\Phi^{-1}(0,r,\Gamma)}^{\Phi^{-1}(1,r,\Gamma)} \{1-\exp(-\frac{\Phi^{-1}[1-\Phi(\gamma_0,r,\Gamma),r,\Gamma]}{\Gamma})\}\exp[-\frac{\gamma_0}{\Gamma} - \frac{\Phi^{-1}(1,r,\Gamma)}{\Gamma}]\frac{\partial\Phi^{-1}(1,r,\Gamma)}{\partial\Gamma}\\ &- [1-\exp(-\frac{\Phi^{-1}(1,r,\Gamma)}{\Gamma})]\exp\{-\frac{\gamma_0}{\Gamma} - \frac{\Phi^{-1}[1-\Phi(\gamma_0,r,\Gamma),r,\Gamma]}{\Gamma}\}\frac{\partial\Phi^{-1}[1-\Phi(\gamma_0,r,\Gamma),r,\Gamma]}{\partial\Gamma}d\gamma_0\\ &+ \frac{\partial\Phi^{-1}(1,r,\Gamma)}{\partial\Gamma}\int_{\Phi^{-1}(0,r,\Gamma)}^{\Phi^{-1}(1,r,\Gamma)} \{1-\exp(-\frac{\Phi^{-1}[1-\Phi(\gamma_1,r,\Gamma),r,\Gamma]}{\Gamma})\}\exp(-\frac{\Phi^{-1}(1,r,\Gamma)}{\Gamma} - \frac{\gamma_1}{\Gamma})d\gamma_1\\ &+ \frac{1}{\Gamma^2}\int_{\Phi^{-1}(0,r,\Gamma)}^{\Phi^{-1}(1,r,\Gamma)}\int_{\Phi^{-1}[1-\Phi(\gamma_0,r,\Gamma),r,\Gamma]}^{\Phi^{-1}(1,r,\Gamma)} d\gamma_1 d\gamma_0\\ &(\gamma_0+\gamma_1)[1-\exp(-\frac{\Phi^{-1}[2-\Phi(\gamma_0,r,\Gamma)-\Phi(\gamma_1,r,\Gamma),r,\Gamma]}{\Gamma})]\exp(-\frac{\gamma_0}{\Gamma}-\frac{\gamma_1}{\Gamma})\\ &+ \{\Gamma\frac{\partial\Phi^{-1}[2-\Phi(\gamma_0,r,\Gamma)-\Phi(\gamma_1,r,\Gamma),r,\Gamma]}{\partial\Gamma} - \Phi^{-1}[2-\Phi(\gamma_0,r,\Gamma)-\Phi(\gamma_1,r,\Gamma),r,\Gamma]\}\\ &\times\exp(-\frac{\gamma_0}{\Gamma} - \frac{\gamma_1}{\Gamma} - \frac{\Phi^{-1}[2-\Phi(\gamma_0,r,\Gamma)-\Phi(\gamma_1,r,\Gamma),r,\Gamma]}{\Gamma}).\end{aligned} \tag{A.19}$$

When calculating (A.7), (A.11) and (A.19), it is required to derive

$$\frac{\partial \Phi^{-1}\left(R_d, r, \Gamma\right)}{\partial \Gamma} = 2rR_d(1+\Gamma)^{2rR_d-1}, \tag{A.20}$$

and

$$\frac{\partial \Phi^{-1}[1-\Phi(\gamma, r, \Gamma), r, \Gamma]}{\partial \Gamma} = 2r(1+\Gamma)^{2r-\frac{\ln(1+\gamma)}{\ln(1+\Gamma)}-1}. \tag{A.21}$$

After several mathematical manipulations, we have:

$$\frac{\partial \Phi^{-1}[2-\Phi(\gamma_0, r, \Gamma)-\Phi(\gamma_1, r, \Gamma), r, \Gamma]}{\partial \Gamma} = [\frac{\ln(1+\gamma_1)}{\ln(1+\Gamma)} + 4r - \frac{\ln(1+\gamma_1)}{\ln(\Gamma)}](1+\Gamma)^{4r-\frac{\ln(1+\gamma_0)}{\ln(1+\Gamma)}-\frac{\ln(1+\gamma_1)}{\ln(\Gamma)}-1} \tag{A.22}$$