The Impact of Channel State Information on Wireless Relay Networks

by

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This is to certify that I have examined this copy of a master's thesis by

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To my grandparents…

Büyükanne ve Büyükbabama..

ABSTRACT

In the last decade, rising demand for high data rate transmissions over wireless channels has led the wireless research to focus on new transmission schemes supporting high data rates. As a candidate structure that allows high date rate transmissions, wireless relay networks have attracted significant interest. The network capacity values achieved by relay networks increase when the nodes have multiple antennas for transmission. Thus, combining the effects of relaying and MIMO communications, MIMO relay networks promise high performance in terms of network capacity. Higher data rates are possible with MIMO relay networks when relay selection, power allocation and beamforming strategies are utilized.

Intelligent selection of relay nodes, power allocation and beamforming strategies require the knowledge of related channel conditions at the transmitting nodes. In this thesis, we propose novel transmission strategies and present the impact of channel state information availability at the transmitting nodes on the design of the proposed schemes. These schemes employ intelligent relay selection, power allocation and beamforming methods based on the available channel state information. We compare the system performances of different transmission models for amplify-and-forward and decode-and-forward MIMO relay networks using an information theoretic approach.

ÖZETÇE

Geçtiğimiz on yılda, kablosuz kanallar üzerinden yüksek veri iletim hızına artan talep, telsiz iletişim araştırmalarını yüksek veri iletim hızlarını destekleyebilen yeni iletim stratejileri bulmaya odakladı. Yüksek hızda veri iletimine olanak saglayan bir yapı olarak, kablosuz röle ağları, araştırma dünyasının yoğun ilgisini çekti. Kablosuz röle ağları kullanılarak ulaşılan kapasite değerleri, kullanıcılardaki anten sayılarının artmasıyla artar. Böylece, rölelerin ve çok-girdili çok-çıktılı sistemlerin etkilerinin birleştiği röleli çok-girdili çok-çıktılı sistemler, daha yüksek kapasite değerlerine ulaşmak için umut verici sistemler olarak karşımıza çıkıyor. Röle seçimi, güç paylaştırması ve hüzme oluşturma stratejileri kullanarak, röleli çok-girdili çok-çıktılı sistemlerde ulşılabilir veri iletim hızını arttırmak mümkün.

Akıllıca röle seçimi, güç paylaştırması ve hüzme oluşturma stratejileri iletim yapan kullanıcıların kanal koşulları hakkında bilgi sahibi olmalarını gerektirir. Bu tezde, yeni iletim stratejileri öneriyoruz ve iletim yapan kullanıcılardaki kanal durum bilgisinin önerilen iletim stratejileri üzerindeki etkilerini araştırdık. Önerdiğimiz iletim stratejilerinde, iletim yapan kullanıcılardaki kanal bilgisinden yaralanarak röle seçimi, güç paylaştırılması ve hüzme oluşturma tekniklerinden yararlandık. Bu tezde, bilişim kuramsal bir yaklaşımla, yükselt-ve-gönder ve kodçöz-ve-gönder röle çok-girdili çok-çıktılı sistemleri için değişik iletim modelleri ile ulaşılan veri iletim hızlarını karşılaştırdık.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

AWGN	Additive White Gaussian Noise
CCSCG	Complex Circularly Symmetric Complex Gaussian
BF	Beamforming
DT	Direct Transmission
MIMO	Multiple-Input Multiple-Output
CSI	Channel State Information
NCSI	No Channel State Information
MRC	Maximum Ratio Combining
AF	Amplify-and-Forward
DF	Decode-and-Forward
CF	Compress-and-Forward
MU	Multi-User
MAC	Multiple Access Channel
BC	Broadcast Channel
SNR	Signal-to-Noise Ratio
SLR	Signal-to-Leakage Ratio
SSLR	Sum of Signal-to-Leakage Ratio

Chapter 1

INTRODUCTION

We have witnessed a dramatic increase in the consumer demand for high data rate services over wireless networks, such as multimedia streaming applications on wireless channels, over the last decade, which has made it compulsory to design new transmission strategies that allow higher transmission rates. Because of the ability of supporting higher data rates, wireless relay networks, where the source node cooperates with a relay node to transmit its information to the destination node, have been studied extensively in the literature [1], [2]-[6] and the *IEEE 802.16j* task group was established to develop a new standard, which supports mobile multihop relaying in wireless broadband networks [7]. Recently, with the technological advances in the antenna design, MIMO networks, which consist of nodes with multiple antennas for transmission, have attracted significant interest. By combining the effects of MIMO technology and relaying transmission schemes, MIMO relay networks have the ability to offer higher data rates by spatial multiplexing and combat the fading effects of the wireless channels by using diversity techniques [2]-[6].

Several cooperation modes have been studied in the literature [1], [8], and [9]. AF and DF are the two fundamental relaying modes. In the AF mode, relay node simply amplifies the received signal according to a power constraint and transmits the amplified version of the signal to the destination node while noise is also amplified with the signal. In the DF mode, the relay node fully decodes the received signal, re-encodes it and retransmits the signal to the destination node with a possibility of decoding error propagation. The ergodic and outage capacity expressions for AF mode fading relay channels, where all nodes are equipped with single antennas were investigated in [10], [11]. In [2], rank deficient AF MIMO relay networks have been studied assuming no channel information at the source node. In [4], the authors presented upper and lower bounds on the ergodic capacity of the MIMO relay channel over Rayleigh fading.

Beamforming (BF) is a transmission technique that directs the signal energy in a chosen direction. Up to now, various aspects of BF for wireless relay channels have been studied in the literature. In [12] and [13], the authors have studied beamforming algorithms for DF and AF relay networks, respectively.

The system performance of relay networks is highly dependent on the channel conditions of the source-relay, source-destination and relay-destination channels. When a number of potential relay nodes exist, selecting the nodes with good channel conditions to both the source and the destination node provides significant performance gains since geographically distributed nodes face different path-loss and fading effects.

Intelligent relay selection and power allocation to data streams require the source node to have some information about the channel conditions of the network. When there is no CSI available at the source node, the relay nodes are selected randomly and equal power is allocated to each data stream at the source node.

When the source node has the knowledge of all channel states of the network, it is possible to choose the highest capacity achieving relay nodes and allocate power to data streams optimally, which maximizes the network capacity. But it is a well known fact that full CSI availability at the source node requires a large amount of feedback transmission, making it impracticable for populous relay networks.

To reduce the amount of feedback traffic, relay selection and power allocation algorithms, which require only quantized channel information or partial channel state information may be employed at the source node.

The effects of CSI on the capacity of point-to-point MIMO communication systems have been studied extensively in the literature [14]. But the effects of CSI availability on the capacity of MIMO relay networks have been studied in a limited fashion so far [15], [5].

In this study, the effects of CSI availability at the transmitting nodes on the capacity of MIMO relay networks for the two fundamental relaying nodes, AF and DF, have been studied extensively. We have proposed relay selection and power allocation methods for different CSI availability cases and presented the ergodic capacity expressions for the proposed transmission schemes.

In Chapter 2, we investigate the impact of source node CSI availability for a dense AF MIMO relay network that employs linear precoding. We consider the cases of partial CSI availability, quantized CSI availability, phase and magnitude only CSI availability at the source node. We also investigate the impact of CSI feedback errors on the network performance.

In Chapter 3, we derive relay selection and power allocation algorithms based on the available channel state information at the source and the relay nodes under individual and total relay power constraints for AF relaying mode. We investigate the effects of the number of selected relay nodes on the system capacity for both AF MIMO and Amplify-and-Forward with Multi-user Beamforming (AF MB) MIMO networks.

In Chapter 4, we present the effects of CSI availability on the system capacity of MIMO wireless relay networks under Decode-and-Forward (DF) transmission mode for both non-beamforming and eigen-mode beamforming cases. We propose strategies for relay selection and power allocation at the source node, based on the available channel state information. We also compare the performance of relay networks with V-BLAST ZF and ZF pre-filtering detection at the receiving nodes. We present ergodic channel capacity values for different CSI availability cases for the DF MIMO relay networks.

The thesis is concluded with a short summary of the performed study and future research work.

1.1 Contributions of the Thesis

In this thesis, we focus on the effects of CSI availability at the transmitting nodes on the system performance of MIMO relay networks and we propose transmission schemes to exploit the available channel information to achieve hiher performance results. The main contributions of this thesis may be summarized as follows:

- We derive ergodic capacity expressions for AF MIMO relay networks for non-beamforming and beamforming cases when the source node has no channel state information for fading channels.

- We derive ergodic capacity expressions for AF MIMO relay networks for non-beamforming and beamforming cases when the source node has the knowledge of all channel conditions (full CSI) of the network for fading channels.

- We derive ergodic capacity expressions for AF MIMO relay networks for non-beamforming and beamforming cases for fading channels when the source node has partial information about the channel conditions of the network. The partial information may be in the form of channel information corresponding to the source to relay node channels, information of quantized channels, only magnitude information of the channel conditions, only phase information of the channel conditions, or relay to source node low rate feedback information. We propose transmission schemes that make use of the available channel information for achieving high capacity values.

- We investigate the effect of channel state information errors on the system performance of AF MIMO relay networks.

- We derive ergodic capacity expressions for DF MIMO relay networks for non-beamforming and beamforming cases when the source node has no CSI, full CSI or partial CSI of the network. We compare the achievable data rates by using V-BLAST ZF detection and ZF pre-filtering at the receiving nodes. We consider path-loss and fading effects in this study.

- We investigate the effects of CSI availability on relay node selection when there are many possible relay nodes for both AF and DF relaying modes when different levels of channel state information are available at the source node.

1.2 Notation

In this paper, we use following notations. ^{T} , * and ^{H} stand for transposition, element-wise conjugate and conjugate transposition, respectively. Bold uppercase letters refer to matrices while bold lowercase letters refer to column vectors of appropriate dimensions. *tr*(**A**) and *det*(**A**) stand for trace and determinant of the matrix **A**. $\|\mathbf{a}\|$ denotes the Euclidean norm of the vector **a**. $\varepsilon[.]$ denotes the expectation operator, $\mathbf{I}_N$ is the N×N identity matrix, **0** stands for an all zeros matrix of appropriate dimensions. $|\chi|$ is the cardinality of the set χ. A circularly symmetric complex Gaussian random variable (RV) is a RV Z = X + *j*Y ~ $\mathcal{CN}(0,\sigma^2)$, where X and Y are independent and identically distributed (i.i.d.) random variables with ~ $\mathcal{CN}(0,\sigma^2/2)$. A→B denotes the link between nodes A and B. Throughout the paper all logarithms, unless specified otherwise, are of the base 2.

Chapter 2

THE IMPACT OF CSI AVAILABILITY IN MIMO AF NETWORKS

2.1 Overview

Wireless communication has enjoyed significant growth over the last decade. New services, such as high-quality voice, high-speed data, multimedia streaming and broadcast are being developed for wireless networks, all enabled by groundbreaking research in the field. One of such enablers is likely to be cooperative communications. It has been shown that cooperation amongst geographically distinct nodes in a wireless ad-hoc network may improve the network performance significantly [10]. This scheme effectively creates a virtual array of transmitters and/or receivers, providing more reliability in the transmission relatively to transmitting alone. Several different relaying schemes have been proposed for cooperation in the literature [1]. In amplify-forward (AF) relaying, the cooperating nodes amplify the received signal according to a power constraint and forward this signal to the destination node. In decode-forward (DF) relaying, the cooperating nodes fully decode, re-encode and re-transmit the received signal to the destination node. In compress-forward (CF) relaying, the cooperating nodes compress the received signal and re-transmit the compressed signal to the destination node. In selection relaying, (SR) the intermediate nodes cooperate (using AF, DF or CF) only if they receive the original signal with a high signal-to-noise ratio (SNR). Otherwise, the source re-transmits to the destination using repetition or more powerful codes. Finally, in incremental relaying, (IR) the intermediate nodes cooperate only if the destination node cannot successfully decode the signal from the source node. The destination node uses ARQ to inform the nodes about its need for retransmission in this case.

It is well-known that employing multiple antennas at both ends of the communication link provides substantial benefits. Such systems, commonly referred to as multiple-input multiple-output (MIMO) systems, allow a growth in the transmission rate linear in the minimum of the numbers of antennas at each end [16], enhance link reliability and improve service coverage [17]. It is no surprise then that MIMO has become part of the next generation cellular and wireless LAN standards. The performance enhancements of MIMO are realizable even when only the receiver has the channel state information (CSI). Such gains are further amplified when the transmitter also has access to the CSI. For example, in a 4-transmit 2-receive antenna system, the CSI knowledge at the transmitter can more than double the capacity at −5dB SNR and add 1.5bps/Hz to the system capacity at 5dB SNR relative to the receiver only CSI case [15].

In cooperative communications, employing multiple antennas at all of the nodes in the network enables more sophisticated encoding and decoding schemes, which in turn, lead to improved performance. So far, most research on MIMO relay networks has focused on information theoretic capacity calculations for different relaying protocols and transmission/reception strategies [5], [6]. In these networks, the impact of cooperation is dependent upon the availability of CSI. Indeed, the feasibility of cooperation, the selection of cooperating peers, transmission/reception strategies all depend on the extent of CSI availability at the source node. In this article, we attempt to provide a performance comparison of a dense MIMO relay network for different cases of CSI availability at the source node.

It is obvious that when multiple antennas are used in the system an increase in the number of channel state parameters is observed. Training signals or pilot channels can be used to estimate the channel at the receiver. In some cases, the transmit channel can be inferred from the receive channel, but more often channel state information needs to be sent back to the transmitter, often in a quantized fashion. This is not unreasonable. Indeed, in 2G and 3G cellular systems closed loop power control and adaptive coding and modulation parameters require some form of channel information feedback to the transmitter. However, the feedback requirements in a MIMO relay network grow very rapidly as a function of the product of transmit antennas, receive antennas, and number of cooperating nodes. For a dense network with many relay nodes, the feedback requirements become prohibitively high very quickly. For example, a relay network with 100 cooperating nodes each equipped with 4 antennas has 6400 parameters that needs to be fed back, compared with the single parameter needed in 3G 1xEV-DO systems. The resulting capacity increase from the employment of MIMO relay networks is certainly less than this tremendous increase in the required feedback. For this reason, the feedback necessary for optimal MIMO relay network operation is not feasible. In practice, transmitter CSI availability can at best be limited. Various options exist regarding the contents of this limited CSI. The CSI for the relay to destination channels may be made unavailable to the source node. The feedback channel may transmit only the magnitude, or only the phase information. Furthermore, the transmitted feedback signal may be quantized. Although the system performance and the effects of channel state information availability on the capacity of point-to-point MIMO communication systems have been studied extensively in the literature [14], the effect of CSI availability on the capacity of MIMO relay networks has been studied only in limited fashion so far [15], [5].

In this chapter, we investigate the impact of source node CSI availability for a dense amplify-and-forward MIMO relay network that employs linear precoding [15]. Here, the source node utilizes its spatial degrees of freedom by multiplexing the signal to be transmitted and assigning disjoint subsets of relay nodes to each of the signal streams. Each signal stream is multiplied by a corresponding precoding vector. The calculation of the precoder weights and allocation of available power to the multiplexed signal streams depend on the CSI availability at the source node. In this article we investigate different cases of limited CSI availability; no CSI, partial CSI, phase only CSI, amplitude only CSI and quantized CSI. In practice, since transmitter CSI is usually available through a feedback channel, some delay in obtaining the information is inevitable. In a rapidly changing MIMO channel, it is likely to encounter discrepancies between the actual observed channel information and the received CSI. Furthermore, there may be errors in the channel estimation process and/or the feedback channel. All such impairments result in erroneous CSI availability at the source node. In this article, we investigate the impact of imperfect CSI on the overall system performance as well.

This chapter is structured as follows. A brief description of the MIMO relay network model is provided. An overview of the linear precoding scheme for MIMO relay networks is given, identifying the calculation of precoder weights for different transmitter CSI availability scenarios. Comparative results are then reported illuminating the loss in the optimal system performance due to limited CSI availability.

2.2 System Model

In this article we consider a wireless communication system consisting of a single source node, S, a single destination node, D, and K cooperating relay nodes, R_k, $\forall k$, that employ AF relaying, as illustrated in Fig. 2.1. We assume that all nodes are located independently and equipped with multiple antennas. We consider a dense network. In other words, K is large.

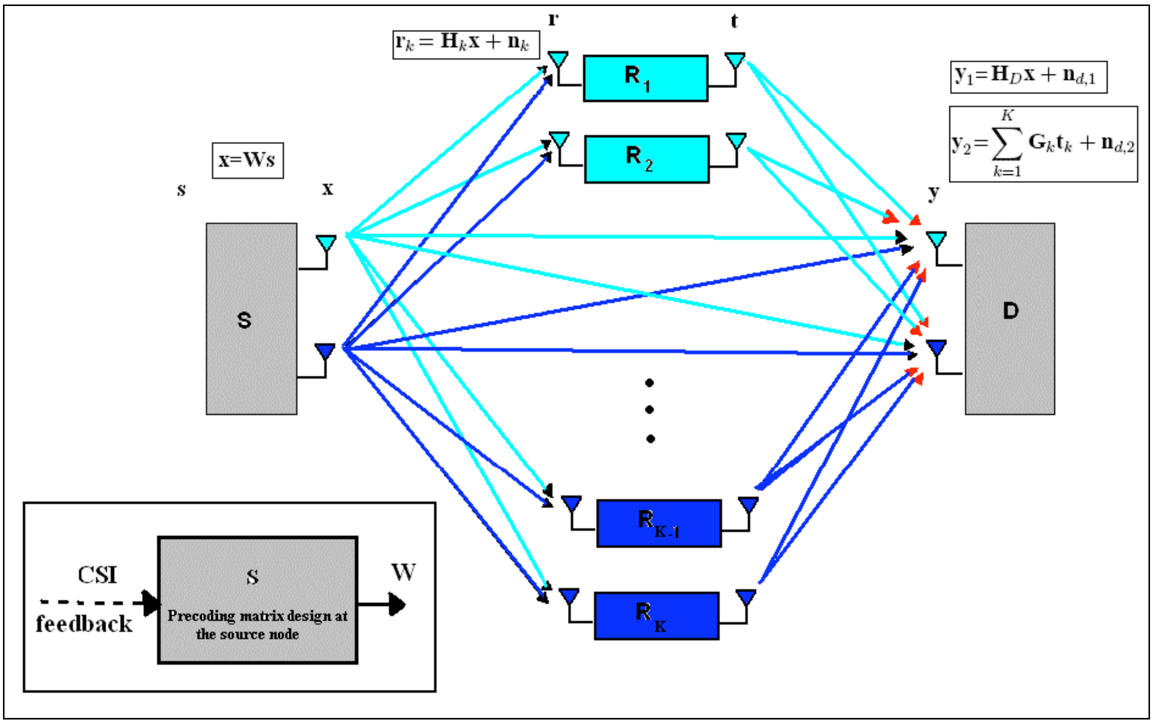

Fig. 2.1: Block diagram of the dense MIMO relay network.

Relaying Protocol: We consider the traditional two phase transmission for the relay network. In the first phase, the source node transmits *N* multiplexed signals, represented by the vector **x** having a covariance matrix of $\mathbf{Q}_s$, intended for the destination in a broadcast manner. All of the cooperating relays as well as the destination node receive the independently faded, noisy versions of these signals. In the second phase, the relays re-transmit an amplified version of their received signals, represented by the vectors $\mathbf{t}_k$, $\forall k$, having covariance matrices of t_k, to the destination node over the multiple access channel. The destination node combines the signals received from both phases to recover the signal.

Let us consider a direct transmission where the source node transmits at a rate of R symbols per second. For the two phase relay transmission that achieves the same end-to-end delay, the source node must transmit at a rate of $2R$ symbols per second, followed by the relay nodes' transmission of the same symbols in the second half period. In other words, the two phase transmission strategy for the relay network results in half the spectral efficiency of the direct transmission.

Channel Model: We represent the source to destination ($S \rightarrow D$), source to k-th relay ($S \rightarrow R_k$), and k-th relay to destination ($R_k \rightarrow D$) channels using the matrices $\mathbf{H_D}$, $\mathbf{H_k}$ and $\mathbf{G_k}$, respectively. We assume each channel in the relay network experiences frequency flat fading, captured by drawing the coefficients of the channels from a zero-mean, circularly complex Gaussian distribution with variance σ^2, $\mathcal{CN}(0,\sigma^2)$. Then, the magnitudes follow a Rayleigh distribution and the channel powers are exponentially distributed. We assume the channels remain constant for the duration of the two phase transmission. We take $S \rightarrow D$, $S \rightarrow R_k$, $\forall k$, and $R_k \rightarrow D$ channels to be independent of one another. The source, destination and relay nodes are assumed to have N, N and M antennas, respectively. The additive noise terms at the front end of each antenna of the relay nodes and the destination node are assumed to be independent random variables with $\mathcal{CN}(0,\sigma_{r_k}^2)$, $\forall k$, and $\mathcal{CN}(0,\sigma_n^2)$ distributions, respectively.

Power Constraints: We impose source and per-relay average power constraints $tr(\mathbf{Q}_S) = E_S$ and $tr(\mathbf{Q}_{r_k}) = E_{r_k}$, respectively. We should point out that imposing a total power constraint on the entire relay set with uniform power allocation does not change the conclusions drawn in this article.

CSI Availability: In this chapter, our goal is to investigate the impact of CSI at the source node. In this light, we compare the system performance under different levels of CSI availability. We assume that full forward ($R_k \rightarrow D$) and backward ($S \rightarrow R_k$) CSI is available at the relay nodes and full $S \rightarrow D$ and $R_k \rightarrow D$ CSI is available at the destination node. For the source node, the following cases are investigated:

o No CSI available

o Full CSI ($S \rightarrow D$, $S \rightarrow R_k$, $\forall k$, and $R_k \rightarrow D$) available

o Partial CSI ($S \rightarrow D$, $S \rightarrow R_k$, $\forall k$) available

o Quantized full/partial CSI available

o Phase-only full/partial CSI available

o Magnitude-only full/partial CSI available

o Imperfect full/partial CSI available

Transmission/Reception Strategy: Building on the model of [5], we consider a network where the source node multiplexes the signal to be transmitted into N parallel streams where N is the number of antennas at the source and destination nodes. We virtually pair each stream with a distinct receiver antenna at the destination node. Each cooperating relay node is assumed to be responsible for assisting for only one of the data streams. The relays that aid in the transmission of the l-th data stream form the relay subset χ_l. Note that χ_l, $\forall l$, are disjoint. During the first time slot, the source node broadcasts the N data streams and the relay nodes as well as the destination node listen. The relay nodes and the destination node receives the signals given by

$$\mathbf{r}_k = \mathbf{H}_k \mathbf{x} + \mathbf{n}_k \quad ,\forall k \tag{2.1}$$

$$\mathbf{y}_1 = \mathbf{H}_D \mathbf{x} + \mathbf{n}_{d,1} \tag{2.2}$$

Upon reception, each relay conducts matched filtering with respect to its backward channel to capture its assigned data stream. In accordance with the average per-relay power constraint, each relay then conducts transmit matched filtering with respect to its forward channel. In the second time slot, each relay directs its signals given by

$$\mathbf{t}_k = f_k \, u_k \frac{\mathbf{g}_{k,l}^{*}}{\left\|\mathbf{g}_{k,l}\right\|} \quad , \forall k \tag{2.3}$$

to the intended antenna at the destination node, where f_k is the power scaling factor given by

$$f_k = \sqrt{\frac{E_{r_k}}{\left\|\mathbf{H}_k \mathbf{w}_l\right\|^4 E_l + \sum_{\substack{i=1 \\ i \neq l}}^{N} \left|(\mathbf{H}_k \mathbf{w}_l)^H \mathbf{H}_k \mathbf{w}_i\right|^2 E_i + \left\|(\mathbf{H}_k \mathbf{w}_l)^H\right\|^2 \sigma_{r_k}^2}} \tag{2.4}$$

and u_k is the matched filtering output at the relay node that can be expressed as

$$u_k = \mathbf{w}_l^H \, \mathbf{H}_k^H \, \mathbf{r}_k \tag{2.5}$$

where $\mathbf{G}_k = \left[\, \mathbf{g}_{k,1} \, \mathbf{g}_{k,2} \cdots \mathbf{g}_{k,N} \,\right]^T$ is the $N \times M$ channel matrix corresponding to $R_k \to D$ link and $\mathbf{w}_l$ is the precoding vector corresponding to the data stream s_l.

In the second time slot, the destination node receives the signal

$$\mathbf{y}_2 = \sum_{k=1}^{K} \mathbf{G}_k \mathbf{t}_k + \mathbf{n}_{d,2} \tag{2.6}$$

and decodes signals at each of its antennas independently followed by Maximal Ratio Combining (MRC) of the signals from the two time slots. The received signals at the i-th antenna of the destination node at the first and second time slots are given, respectively, as

$$y_{1,i} = \mathbf{h}_{d,i}^T \, \mathbf{w}_i \, s_i + \mathbf{h}_{d,i}^T \sum_{\substack{j=1 \\ j \neq i}}^{N} \mathbf{w}_j \, s_j + n_{1,i} \tag{2.7}$$

$$y_{2,i} = h_i^{sig} \; s_i + \sum_{\substack{j=1 \\ j \neq i}}^{N} h_{i,j}^{\text{int}} \; s_j + N_{2,i} \tag{2.8}$$

where the first terms of the right hand side of the Eq. (2.7) and Eq. (2.8) are the intended signal terms, second terms are the interference terms and the third terms are the equivalent noise terms.

The SINR values at the first and second time slots are given by

$$SINR_{1.i} = \frac{\left| \mathbf{h}_{d,i}^T \; \mathbf{w}_i \right|^2 E_i}{\sum_{\substack{j=1 \\ j \neq i}}^{N} \left| \mathbf{h}_{d,i}^T \; \mathbf{w}_j \right|^2 E_j + \sigma_n^2} \tag{2.9}$$

$$SINR_{2.i} = \frac{\left| h_i^{sig} \right|^2 E_i}{\sum_{\substack{j=1 \\ j \neq i}}^{N} \left| h_{i,j}^{\text{int}} \right|^2 E_j + \sigma_r^2 \left(\sum_{k, R_k \in \chi_i} a_{k,i} + \sum_{\substack{n=1 \\ n \neq i}}^{N} \left(\sum_{k, R_k \in \chi_n} b_{k,i,n} \right) \right) + \sigma_n^2} \tag{2.10}$$

where $a_{k,i} = f_k^2 \left\| \mathbf{g}_{k,i} \right\|^2 \left\| \mathbf{H}_k \; \mathbf{w}_i \right\|^2$ and $b_{k,i,n} = \dfrac{f_k^2 \left\| \mathbf{H}_k \; \mathbf{w}_n \right\|^2 \left| \mathbf{g}_{k,i}^T \; \mathbf{g}_{k,n}^* \right|^2}{\left\| \mathbf{g}_{k,n} \right\|^2}$.

Then, the ergodic capacity of the AF MIMO relay network can be expressed as

$$C_{AF} = \sum_{i=1}^{N} \varepsilon_{\{H_D, H_k, G_k\}_{k=1}^{K}} \frac{1}{2} \left\{ \; \log\left(1 + SINR_{1,i} + SINR_{2,i}\right) \right\} \tag{2.11}$$

2.3 Linear Precoding

When CSI is available at the source node of a MIMO relay network, it is possible to exploit this information by means of precoding. For point-to-point MIMO links, it has been shown that linear precoding is optimal from an information theoretic point of view [15]. Linear precoder effectively acts like a beamformer and directs the multiplexed signal in such a way that water-filling over space is accomplished. It also allocates the available power to achieve water-filling over time. In other words, it optimally matches the input signal to the channel as described by the CSI. In practice, since channel conditions vary in time, regular updates of the CSI are necessary. In turn, the precoder weighting vectors should be adjusted accordingly. In MIMO relay networks, it is necessary for the source node to multiply the signal vector **s,** by a proper precoding matrix, **W** prior to transmission to obtain the signal to be transmitted, **x** as given by

$$\mathbf{x} = \mathbf{W}\,\mathbf{s} = \sum_{l=1}^{N} \mathbf{w}_l s_l = [\,\mathbf{w}_1\ \mathbf{w}_2\ \cdots\ \mathbf{w}_N\,] \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_N \end{bmatrix} \tag{2.12}$$

where $\mathbf{w}_k$ is the beamforming vector satisfying

$$\|\mathbf{w}_l\|^2 = 1\,, \quad l = 1, 2, \ldots, N \tag{2.13}$$

This clearly requires CSI from all of the relays at the source node.

Various practical performance criteria have also been proposed in the literature for the precoder design in point-to-point MIMO systems [15]. Precoders minimizing the error probability, mean square error and maximizing the received SINR, canceling the co-channel interference for each user have been developed.

The impact of the precoder in the MIMO relay network is clearly dependent on the availability of the CSI at the source node. When there is no CSI, one cannot develop a precoder matrix. When there is partial CSI, (only for the source to relay and source to destination channels) precoders that attempt to match the transmitted signal to these channels may be developed. The value of precoding with partial CSI should be investigated. This is because; a relay that has a good channel with the source node does not necessarily have a good channel with the destination node. Thus, a precoder design that is blind to the channel between the relays and the destination may yield undesirable results. This article uses the above described network model to investigate the impact of partial CSI at the source node.

No CSI at the Source Node: The precoder uses the available CSI to adjust the transmitted signal to improve the overall system capacity. When the source node has no knowledge of the channel conditions, it has to be neutral to all data streams, effectively using an identity matrix for the precoder and allocating equal power to all data streams. In other words, the precoder matrix is $\mathbf{W} = \mathbf{I}_{N\times N}$, and equal power allocation is satisfied by setting the covariance matrix to $\mathbf{Q}_s = \mathcal{E}[\mathbf{xx}^*] = (E_S/N)\,\mathbf{I}_N$.

Partial CSI at the Source Node: When the source node has full CSI knowledge of the $S \rightarrow D$, $S \rightarrow R_k$, $\forall k$ channels, various practical design criteria may be employed in the precoder design. Though desirable, the design that maximizes the SINR at each of the relay nodes does not have a closed-form solution and can be obtained only iteratively due to the complexity of the optimization problem. Extending on the work of [19], we develop a precoder design that maximizes the sum of signal-to-leakage ratios (SSLR) for each data stream. For a given data stream, the SSLR is defined as the ratio of the sum of the received power at intended relays and the destination to the sum of the interference power observed by non-intended relays.

Mathematically, we can define the SSLR for the l-th stream as:

$$SSLR_l = \frac{\sum_{k,R_k \in \chi_l} \left\| \mathbf{H}_k \mathbf{w}_l \right\|^2 + \left| \mathbf{h}_{dl}^T \mathbf{w}_l \right|^2}{\sum_{k,R_k \notin \chi_l} \left\| \mathbf{H}_k \mathbf{w}_l \right\|^2 + \sum_{i=1, i \neq l}^{N} \left| \mathbf{h}_{di}^T \mathbf{w}_l \right|^2} \tag{2.14}$$

We choose the unit norm beamforming vectors $\mathbf{w}_l$ that constitute the columns of the precoding matrix $\mathbf{W}$ so that the SSLR is maximized for each data stream. Since no CSI for the $R_k \rightarrow D$ channels is available, equal power allocation needs to be employed across all data streams.

Full CSI at the Source Node: In this article we define full CSI at the source node to mean that the source node has the CSI of $S \rightarrow D$, $S \rightarrow R_k$, and $R_k \rightarrow D$, $\forall k$, channels. In this case, an information theoretic capacity optimal precoder design is possible where the source node matches the transmitted signal to the cascade of the source to relay and relay to destination nodes to maximize Eq. 2.11. As discussed in the overview, the CSI requirement for this design is prohibitively high.

Quantized CSI: The impractical CSI requirements for proper precoder design in dense MIMO relay networks may be eased somewhat by feeding back quantized versions of the channel matrices to the source node. Scalar or vector quantization techniques may be employed for this purpose. It has been shown that for the point-to-point MIMO system adaptive beamforming using a 6-bit vector quantizer outperforms the 40-bit scalar quantizer by approximately 1 dB [14]. In this article we consider vector quantization. To obtain the quantized CSI, the channel matrices are transformed to channel vectors and the vector quantization algorithm described in [19] is applied to the channel vectors. Using k-bit vector quantization, 2^k quantization vector levels are obtained. The quantized channel vectors are acquired by mapping the channel vectors to the closest quantization vector levels. It is assumed that the source node, the relay nodes and the destination node all have the same codebook, which contains the quantization vector level codewords. Therefore, it is sufficient to feedback only the *k*-bit indices of the codewords to the source node. Once the source node receives the indices, it can decode the quantized channel matrices and design the precoding matrix and power allocation scheme accordingly.

Phase-Only CSI: The coefficients of the Rayleigh fading channel are complex random variables. To reduce the feedback load, one may choose to feedback only the phase information for the channels in the network. When only the phase information is made available at the source node, it determines the precoder weights and the associated power allocation assuming that the channel matrices have the fed-back phase information and unit magnitude.

Magnitude-Only CSI: Similar to the phase-only CSI case, when only magnitude information of the channel coefficients is made available at the source node, it determines the precoder weights and the associated power allocation assuming that the channel matrices have the fed-back magnitude information and zero phases.

Imperfect CSI: In a practical wireless communication system, CSI at the source node is usually achieved via a feedback from the relay and destination nodes. The estimation of the channels by the destination and relay nodes is a noisy process in practice. Furthermore, the feedback channel used to transmit the information back to the source node is noisy as well. Therefore, at the source node, we only have a noisy estimate of the channel states. The noise in the estimation and feedback of the CSI matrix coefficients is usually modeled as independent, identically distributed random variables with distributions $\mathcal{CN}(0, \sigma_n^2)$ [18].

The source node has to create the precoder matrix and allocate the power among the streams using this noisy CSI. In this article, we investigate the degradation in the overall system performance due to imperfect CSI at the source node.

2.4 Performance Results

The impact of CSI availability at the source node on the capacity of the dense AF MIMO relay network is illustrated in three different performance plots, generated by Monte-Carlo simulations. We consider a network where N = 2, M = 1, $\sigma_{r_k}^2 = \sigma_n^2$ and $E_s / \sigma_n^2 = E_{r_k} / \sigma_n^2$ =10dB.

The first pair of plots in Fig. 2.2 illustrates the impact of imperfect CSI availability at the source node. The impact of noisy CSI is plotted as a function of number of cooperating relays for the cases of full CSI and partial CSI availability in the two plots. We observe that full CSI availability in the absence of noise provides a 0.5 bits/sec/Hz capacity increase over partial CSI availability and a 0.6 bits/sec/Hz capacity increase over no CSI availability. The impact of noise in CSI is significant even when it is low. For example, when $\sigma_n^2 / \sigma_{noise}^2$ =10, the noise in the available full CSI negates the gains achieved by such availability completely. If the feedback is noisier ($\sigma_n^2 / \sigma_{noise}^2$ =1 in the plots), the network is better of not using the CSI. The impact of partial CSI on the network capacity is not high. A gain of 0.1 bits/sec/Hz over no CSI availability is observed in the absence of noise. It is observed that in this case, the noise in the available CSI negates such gains.

The pair of plots in Fig. 2.3 illustrates how vector quantization of the CSI affects the ergodic capacity of AF MIMO relay networks. For the system where there is full CSI availability at the source node, quantization severely impacts the capacity. A system with 5-bit vector quantized full CSI available at the source performs similar to a network where there is no CSI availability at the source node. As the quantization levels decrease, the performance of the network becomes worse than the one with no CSI. A similar observation can be made for the network where there is partial CSI available at the source node. Quantization impacts the capacity of these networks to the extent that the performance becomes worse than the network with no CSI available at the source node.

Fig. 2.4 shows how the ergodic capacity of the dense MIMO relay network is impacted by the phase-only or amplitude-only CSI availability at the source node. As expected, the results illustrate that phase information is significantly more important than the amplitude information in the CSI that is fed-back to the source node. Indeed, we observe that basing the precoder design on the magnitudes of the channels always underperforms a network where there is no CSI availability at the source node by a wide margin. Phase information on the other hand, may be useful, provided that phase information for all channels is available. This case results in overall network capacities similar to the case where there is full partial CSI availability for moderate number of relays. As the network gets denser, knowledge of the channel phases alone is no better than no CSI knowledge.

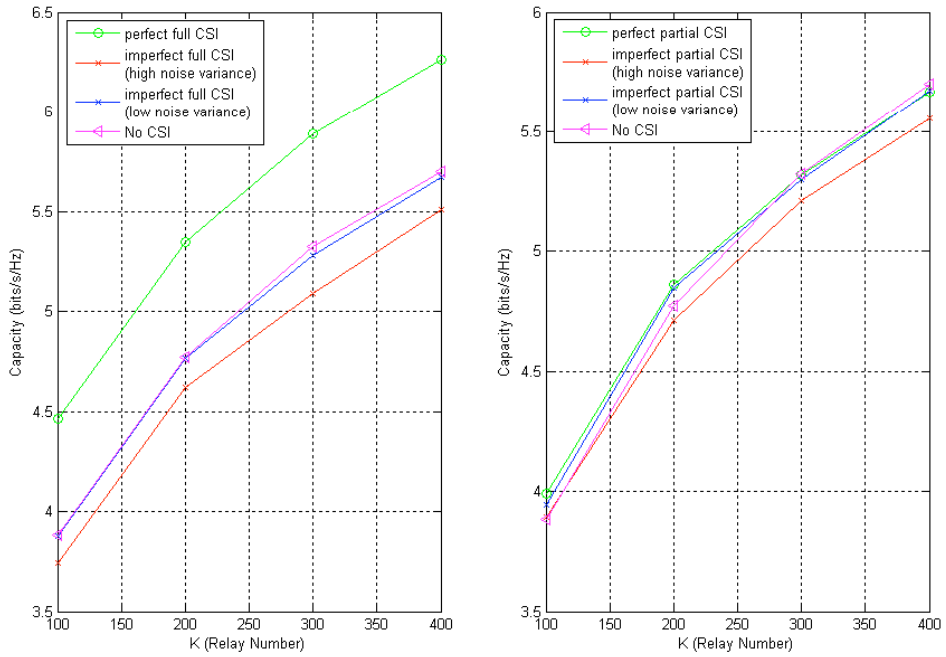

Fig. 2.2: Impact of noisy CSI on the ergodic capacity

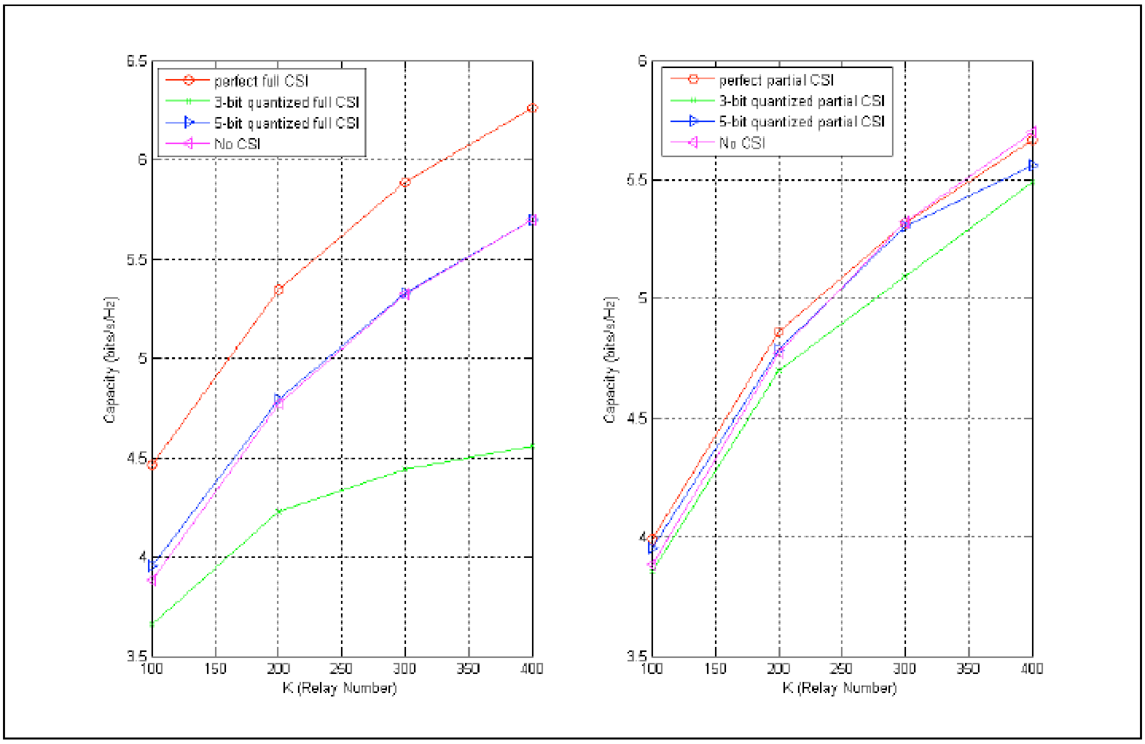

Fig. 2.3: Impact of vector quantized CSI on the ergodic capacity

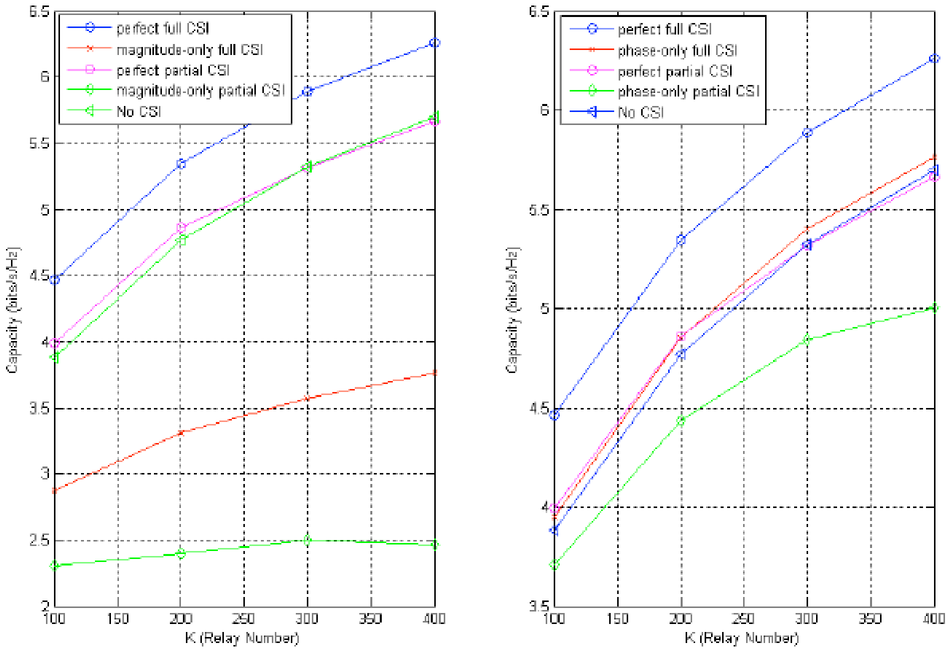

Fig. 2.4: Impact of phase-only/magnitude-only CSI on the ergodic capacity

Chapter 3

RELAY SELECTION AND POWER ALLOCATION IN AF MIMO NETWORKS

3.1 Overview

When there exists a set of potential relay nodes in the network, selecting the nodes with better channel conditions as relay nodes and utilizing power allocation schemes adapted to the channel conditions enhance the ergodic capacity of the system. Thus, CSI (Channel State Information) availability has a profound effect on the system capacity. In this chapter, we propose relay selection and power allocation schemes with different CSI availability cases at the source node for two different relaying modes and our simulations show that even for a small set of potential relay nodes, relay selection and power allocation increases the system capacity. When the number of the potential relay nodes increases, the capacity improvement provided by relay selection also increases. Since the source needs the CSI of all channels in the network for the optimal relay selection, the optimal relay selection becomes less practical for highly populated networks. Thus, we propose suboptimal relay selection methods, which need the CSI of only source to relay channels (partial-CSI) at the source node, and which does not need any CSI (no-CSI) at the source node.

3.2 System Model

We consider two-hop wireless MIMO relay networks as shown in Fig. 3.1. There exists a set of K potential relay nodes, which can assist the transmission from the source to the destination. The source node, the relay nodes and the destination node are equipped with *N*, *L*, and *M* antennas, respectively. $\mathbf{H_k}$, $\mathbf{D}$, and $\mathbf{G_k}$ correspond to the uncorrelated Rayleigh fading channel matrices for the source to the relay R_k, the source to the destination, and the relay R_k to the destination channels, respectively. The channels are assumed to be constant for two consecutive time slot blocks. The time-division multiple-access (TDMA) based transmission protocol is also illustrated by Fig. 3.1. This protocol assumes an orthogonality constraint such that the relay nodes can not transmit and receive at the same time slot. According to the transmission protocol, the source transmits data to the destination and the relay nodes over the first time slot, whereas only the selected relay nodes transmit data to the destination over the second time slot. We assume i.i.d random noise terms with $\mathcal{CN}(0,\sigma_{r_k}^2)$, $\forall k$, and $\mathcal{CN}(0,\sigma_n^2)$ at the receive antennas of the relay nodes and the destination, respectively. The transmit powers for the source and the relay nodes are E_s and E_{r_k}, $\forall k$, respectively. We assume that there is no cooperation among the relay nodes and the relay nodes have the perfect CSI of their forward and backward channels.

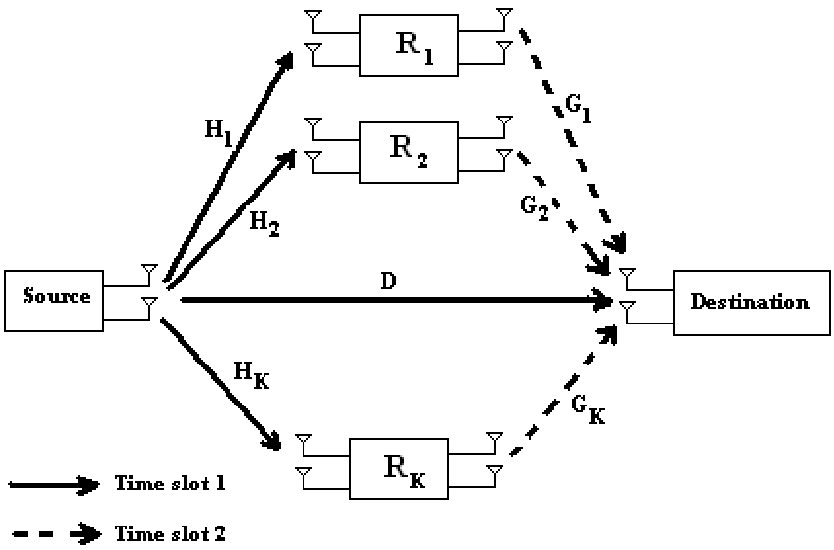

Fig. 3.1: Two-hop wireless MIMO relay network architecture

Received signal vectors at the destination and the relay nodes for the first time slot are given, respectively, by

$$\mathbf{y}_1 = \mathbf{D}\mathbf{x} + \mathbf{n}_{d,1} \tag{3.1}$$

$$\mathbf{r}_k = \mathbf{H}_k\mathbf{x} + \mathbf{n}_k \qquad \forall k. \tag{3.2}$$

where $\mathbf{n}_{d,1}$ and $\mathbf{n}_k$ denote the additive white Gaussian noise vectors at the destination and the relay node R_k, respectively.

Before the transmission at the second time slot, a subset Ω^* of relay nodes is selected to transmit to the destination.

At the second time slot, depending on the relaying mode, the selected relay node R_k computes the weighting matrix $\mathbf{B}_k$ and transmits $\mathbf{t}_k$ given by

$$\mathbf{t}_k = \mathbf{B}_k \mathbf{r}_k \qquad \forall R_k \in \Omega^* \tag{3.3}$$

and at the second time slot, the received signal at the destination can be expressed as

$$\mathbf{y}_2 = \sum_{\substack{k=1 \\ R_k \in \Omega^*}}^{K} \mathbf{G}_k \mathbf{t}_k + \mathbf{n}_{d,2} \tag{3.4}$$

where $\mathbf{n}_{d,2}$ denotes the additive white Gaussian noise vector at the destination for the second time slot.

In this chapter, we consider two relaying protocols: *AF MIMO* and *AFMB MIMO*. We propose relay node selection and power allocation methods based on the available CSI at the source for the two relaying protocols considered.

3.3 AF MIMO RELAYING

In the AF MIMO mode of relaying, we use the transmission protocol used by [2]. The selected relay nodes simply amplify the received signals according to the transmission power constraints and transmit the amplified signal vectors to the destination. Thus, the weighting matrix $\mathbf{B}_k$ is given by

$$\mathbf{B}_k = \sqrt{\frac{E_{r_k}}{L}}\, \mathbf{Q}_{r_k}^{-1/2}, \quad \forall k. \tag{3.5}$$

where $\mathbf{Q}_{r_k}$ is the covariance matrix of the received signal vector $\mathbf{r}_k$.

$$\mathbf{Q}_{r_k} = \mathbf{H}_k \mathbf{Q}_s \mathbf{H}_k^H + \sigma_{r_k}^2 \mathbf{I}_L, \quad \forall k. \tag{3.6}$$

At the second time slot, the received signal vector at the destination can be written as

$$\mathbf{y}_2 = \sum_{\substack{k=1 \\ R_k \in \Omega^*}}^{K} \mathbf{G}_k \mathbf{B}_k \mathbf{H}_k \mathbf{x} + \mathbf{n}_{eq} = \mathbf{H}_{eq}\mathbf{x} + \mathbf{n}_{eq} \tag{3.7}$$

where $\mathbf{n}_{eq}$ denotes the non-white equivalent noise vector at the destination. The corresponding whitening matrix is

$$\mathbf{W} = \mathbf{U}^{-1/2}\mathbf{V}^{H} \tag{3.8}$$

where the unitary eigenvectors matrix $\mathbf{V}$ and diagonal eigenvalues matrix $\mathbf{U}$ are defined by $\mathbf{\Lambda} = \mathbf{VUV}^{H}$ and the covariance matrix of the non-white equivalent noise is given by

$$\mathcal{E}\left[\mathbf{n}_{eq}\,\mathbf{n}_{eq}^{H}\right] = \sigma_n^2 \Lambda \tag{3.9}$$

After filtering at the destination, the equivalent received signal vector becomes

$$\mathbf{y}_{2,eq} = \mathbf{W}\mathbf{y}_2 = \mathbf{W}\mathbf{H}_{eq}\mathbf{x} + \mathbf{n}_{white} \tag{3.10}$$

where $\mathbf{n}_{white}$ is the filtered white noise with $\mathcal{CN}(\mathbf{0}, \sigma_n^2 \mathbf{I}_M)$.

We can write the received signals for the two time slots in a closed form

$$\underbrace{\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_{2,eq} \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} \mathbf{D} \\ \mathbf{W}\mathbf{H}_{eq} \end{bmatrix}}_{\mathbf{H}} \mathbf{x} + \underbrace{\begin{bmatrix} \mathbf{n}_{d,1} \\ \mathbf{n}_{white} \end{bmatrix}}_{\mathbf{n}} \tag{3.11}$$

Then, we can formulate the ergodic capacity of the AF MIMO relay network as

$$C_{AF} = \max_{tr(\mathbf{Q}_s)=E_s} \frac{1}{2} \mathcal{E}_{\mathbf{H}}\left[\log \det(\mathbf{I}_{2M} + \frac{1}{\sigma_n^2}\mathbf{H}\mathbf{Q}_s\mathbf{H}^{H})\right] \tag{3.12}$$

No CSI Case: When there is no CSI available at the source, we allocate equal power to all transmit antennas at the source, $\mathbf{Q}_s = (E_s/N)\mathbf{I}_N$, and for a given number of selected relay nodes, we select the relay node set Ω^* based on random selection.

Then, the ergodic capacity of no-CSI at the source case can be expressed as

$$C_{AF}^{noCSI} = \frac{1}{2}\varepsilon_{\mathbf{H}}\left[\log\det(\mathbf{I}_{2M} + \frac{E_s}{N\sigma_n^2}\mathbf{H}\mathbf{H}^H)\right] \qquad (3.13)$$

Partial CSI Case: When the source has the CSI of only the source to the potential relay channels, $\mathbf{H}_k$ for k=1,..., K, we propose a Signal-to-Noise Ratio (SNR) based relay selection method and an equal power allocation scheme to the transmit antennas at the source node. For a given number T of selected relay nodes, we select the potential relay nodes with the highest output SNR values as the elements of the relay node set Ω^* such that

$$SNR_k = \frac{E_s\|\mathbf{B}_k\mathbf{H}_k\|^2}{\sigma_{r_k}^2\|\mathbf{B}_k\|^2}, \forall k. \qquad (3.14)$$

$$\Omega^* = \arg\max_{\Omega} \sum_{R_k\in\Omega} SNR_k \qquad (3.15)$$

where Ω is the set of potential relay nodes with cardinality T. Then the ergodic capacity of partial-CSI at the source case is given by

$$C_{AF}^{partialCSI} = \frac{1}{2}\varepsilon_{\mathbf{H}}\left[\log\ \det(\mathbf{I}_{2M} + \frac{E_s}{N\sigma_n^2}\mathbf{H}\mathbf{H}^H)\right] \qquad (3.16)$$

Full CSI Case: When the source has the CSI of all channels in the relay network, the source employs a capacity maximizing power allocation and relay selection scheme. Thus, the relay selection, power allocation and the ergodic capacity of the system can be expressed as

$$\left[\Omega^*, \mathbf{Q}_s^*\right] = \arg \max_{\substack{tr(\mathbf{Q}_s)=E_s \\ \Omega}} C_{AF} \tag{3.17}$$

$$C_{AF}^{fullCSI} = \frac{1}{2} \varepsilon_{\mathbf{H}} \left[\log \quad \det(\mathbf{I}_{2M} + \frac{1}{\sigma_n^2} \mathbf{H}\mathbf{Q}_s^* \mathbf{H}^H) \right] \tag{3.18}$$

3.4 AFMB MIMO RELAYING

For the AFMB MIMO relaying mode, we use the same multi-user beamforming structure as in [3]. The source multiplexes N data streams, $s_1, s_2, \ldots s_N$. A set of relay nodes χ_n and the n-th receive antenna at the destination node are assigned to the data stream s_n, where $|\chi_1| = |\chi_2| = \ldots |\chi_N|$. The transmitted signal vector from the source node is given by

$$\mathbf{x} = \sum_{n=1}^{N} \mathbf{w}_n s_n = \mathbf{W}\mathbf{s} \tag{3.19}$$

where $\mathbf{w}_n$ is the unit-norm beamforming vector.

At time slot 1, the received signals at the destination and the relay node R_k can be expressed as

$$\mathbf{y}_1 = \mathbf{D}\mathbf{x} + \mathbf{n}_{d,1} \tag{3.20}$$

$$\mathbf{r}_k = \mathbf{H}_k \mathbf{x} + \mathbf{n}_k \tag{3.21}$$

After the selected relay node R_k, which is a relay node intended for data stream s_l, receives the signal $\mathbf{r}_k$ from the source, it applies a matched filter, scales the filter output and beamforms the scaled signal to the destination. The relay output $\mathbf{t}_k$ is given by

$$\mathbf{t}_k = f_k \mathbf{w}_l^H \mathbf{H}_k^H \mathbf{r}_k \frac{\mathbf{g}_{k,l}^*}{\left\| \mathbf{g}_{k,l} \right\|} \qquad \forall R_k \in \Omega^* \tag{3.22}$$

where f_k is the scaling factor for the transmission power of the relay node and $\mathbf{g}_{k,l}^T$ denotes the channel vector from the relay node R_k to the destination antenna *l.*

We can write the received signals at the destination antennas for the two time slots as

$$y_{1,i} = \mathbf{h}_{d,i}^T \mathbf{w}_i s_i + \mathbf{h}_{d,i}^T \sum_{j=1, j \neq i}^{N} \mathbf{w}_j s_j + \mathbf{n}_{1,i} \tag{3.23}$$

$$y_{2,i} = \sum_{n=1}^{N} \left(\sum_{k, R_k \in \mathcal{J}_n} \mathbf{g}_{k,i}^T \mathbf{t}_k \right) + \mathbf{n}_{2,i} \qquad \forall i. \tag{3.24}$$

where $\mathbf{h}_{d,i}^T$ is the channel vector from the source to the *i*-th receive antenna of the destination.

The ergodic capacity of the AFMB MIMO relaying mode is given by

$$C_{AFMB} = \sum_{i=1}^{M} \varepsilon_{\{\mathbf{D}, \{\mathbf{H}_k, \mathbf{G}_k\}_{k=1}^{K}\}} \left\{ \frac{1}{2} \log(1 + SINR_{1,i} + SINR_{2,i}) \right\} \tag{3.25}$$

where $SINR_{1,i}$ and $SINR_{2,i}$ are the signal-to-noise-and-interference-ratios of the signals $y_{1,i}$ and $y_{2,i}$, for i=1,2,…M, respectively.

No CSI Case: When the source has no CSI, we use a uniform beamforming, $\mathbf{W}=\mathbf{I}_N$, and equal power allocation scheme, $\mathbf{Q}_s= (E_s/N)\mathbf{I}_N$. The relay nodes are selected randomly since the source node has no knowledge about the channel conditions.

Partial CSI Case: The source node exploits the CSI of the source to the potential relay channels to select the relay nodes and compute the beamforming matrix. A Sum-of-Signal-to-Leakage-Ratio (*SSLR*) based beamforming structure has been proposed in [3], where the beamforming vectors are chosen such that the SSLR values for all the data streams are maximized. The SSLR value for the ℓ-th data stream is given by

$$SSLR_{\ell} = \frac{\sum_{k, R_k \in \mathcal{J}_\ell} \|\mathbf{H}_k \mathbf{w}_\ell\|^2 + |\mathbf{h}_{d,\ell}^T \mathbf{w}_\ell|^2}{\sum_{k, R_k \in \mathcal{J}_\ell} \|\mathbf{H}_k \mathbf{w}_\ell\|^2 + \sum_{i=1, i \neq \ell}^{N} |\mathbf{h}_{d,i}^T \mathbf{w}_\ell|^2} \quad (3.26)$$

We propose to select the set of relay nodes, Ω^*, and the beamforming matrix, $\mathbf{W}^*$, such that the sum of *SSLR* values is maximized.

$$[\Omega^*, \mathbf{W}^*] = \underset{\substack{\Omega \\ \mathbf{W} \in C^{N \times N}}}{\arg\max} \sum_{i=1}^{N} SSLR_i \quad (3.27)$$

Since the source node does not know the channel conditions of the relay to the destination channels, it allocates equal power to all data streams $\mathbf{Q}_s = (E_s/N)\mathbf{I}_N$.

Full CSI Case: When the source knows all the channel conditions of the network, the relay selection, power allocation and beamforming matrix are found such that the ergodic capacity expression of the AFMB MIMO network is maximized.

$$[\Omega^*, \mathbf{W}^*, \mathbf{Q}_s^*] = \underset{\substack{\Omega \\ \mathbf{W} \in C^{N \times N} \\ tr(\mathbf{Q}_s) = E_s}}{\arg\max} \; C_{AFMB} \quad (3.28)$$

3.5 SIMULATIONS

The impact of relay selection and power allocation on the system capacity is illustrated in the Figures 3.2-3.4, which are generated by Monte-Carlo simulations. These figures also show the effect of increasing the number of selected relay nodes on the system performance when there is a finite set of potential relay nodes in the network. For our simulations, we assume that there are 10 potential relay nodes, K=10, and all nodes are equipped with 2 antennas, N=L=M=2. In our simulations, we investigate the effect of individual and total relay power constrains on the system capacity. We assume that $E_{r_k} = E_R$ for individual relay power constraint, and $E_{r_k} = E_R / T$ for total relay power constraint, where T is the number of selected relay nodes. We provide numerical results for $\sigma_{r_k}^2 = \sigma_n^2$ and $E_s / \sigma_n^2 = E_R / \sigma_n^2$ =10dB for k=1, 2… K.

Fig. 3.2 shows the AF MIMO relay network ergodic capacity values achieved by the proposed relay selection and power allocation schemes for full CSI, partial CSI and no CSI feedback cases. We denote the individual and total power constraints as *Et* and *Er,* respectively, in Fig. 3.2. As we expect, relay selection and power allocation is most effective when the source has the full CSI of the network.

Fig. 3.3 and Fig. 3.4 illustrate the simulation results for AFMB relaying mode, where we use a multi-user beamforming scheme. Both figures show that, under the proposed relaying method, the network capacity increases with the number of selected relays for the no CSI and the partial CSI cases, whereas utilizing a smaller subset of potential relay nodes for relaying gives the highest capacity result for the full CSI case.

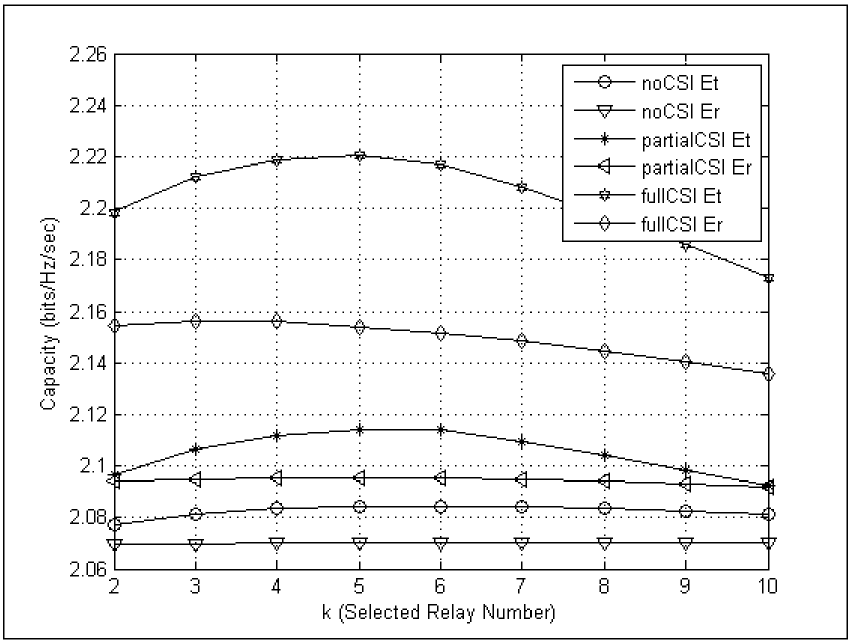

Fig. 3.2: AF MIMO relaying with individual (E_t) and total (E_r) relay power constraints

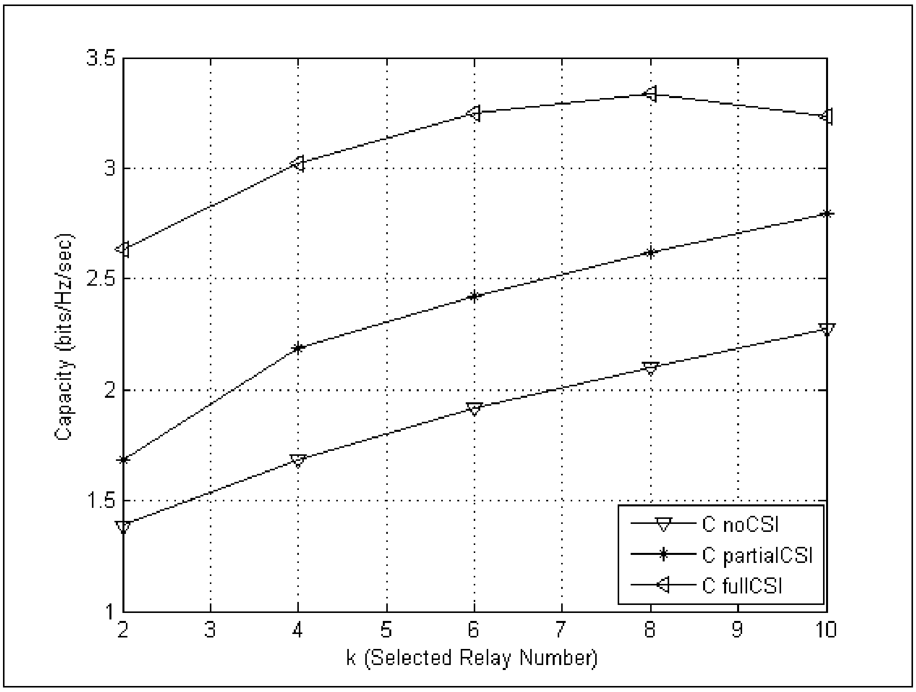

Fig. 3.3: AFMB relaying with total relay power constraint.

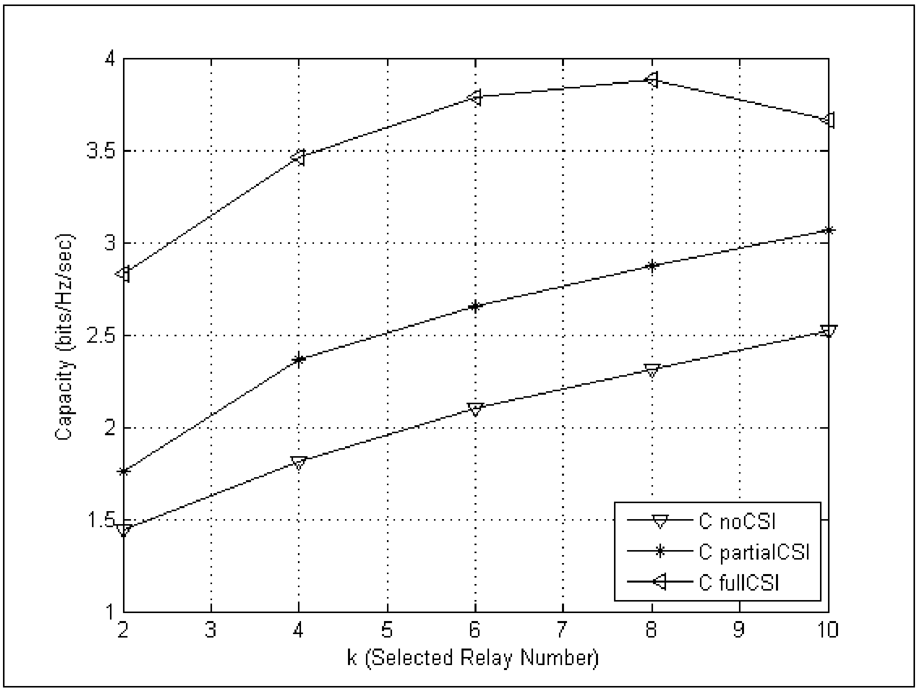

Fig. 3.4: AFMB relaying with individual relay power constraint.

Chapter 4

THE IMPACT OF CSI AVAILABILITY IN DF MIMO RELAY NETWORKS

4.1 Overview

In wireless communications, path-loss, shadowing and multi-path fading are the key factors affecting the transmitted signal. When the destination node is far away from the source node, the system performance suffers badly from the path-loss effect. To alleviate the effect of path-loss on the system performance, we may use relay nodes with better channels to the source and destination nodes. In the DF relaying mode, the relay nodes fully decode the received signal and re-encode it to re-transmit the signal to the destination node.

In this chapter, we examine fading relay channels where the source, the destination and multiple relay nodes are equipped with multiple antennas. We study the ergodic capacities of multiple relay networks based on the *Decode-and-Forward (DF)* mode. We consider system performances based on different CSI availability cases at the source node and the relay nodes. We assume that all receiving parts have their associated CSI. In the first scenario, we give the capacity expressions of multi-hop relay networks for no CSI at transmitter nodes. While in the second scenario, we examine the capacity of multi-hop relay networks when the source node has partial CSI and relay nodes have related channel information. We also examine the case when the source node has the knowledge of all channel states in the network. We propose transmission strategies using non-BF and best-eigen mode BF algorithms and derive the corresponding network capacity expressions. We compare the performance results for the V-BLAST ZF detector (successive decoding) and ZF pre-filtering (parallel decoding) at the receiving nodes. Allocating unequal power to the data streams at the source node regarding only first hop channel information does not achieve a higher performance compared to non-power allocation case, since randomness at the second hop will compensate the gain achieved by power allocation. We propose some relay selection algorithms to see the role of the number of transmitting relay nodes on the system performance assuming a total power constraint for relaying.

In the next section, we describe the system model and the protocol description used in this study. Then in Sec. III, we derive the network capacity upper bound expressions for DF mode of relaying. Next in Sec. IV and Sec. V, we derive the capacity expressions for the non-beamforming and beamforming DF relaying schemes. We give numerical results in Sec. VI.

4.2 System and Signal Model

In this section, we consider scenarios which include a single source node and a single destination node with multiple partnering relay nodes where the source node, relay nodes and the destination node are equipped with M, N_{Rk}, and N antennas, respectively. We assume that there exists no direct link between the source and the destination node. Source node, denoted as S, transmits multiplexed data streams to destination node, denoted as D, with assistance of K relay nodes, where relay k is denoted as R_k for $k \in \{1, 2, \ldots K\}$. The system model is depicted in Fig. 4.1.

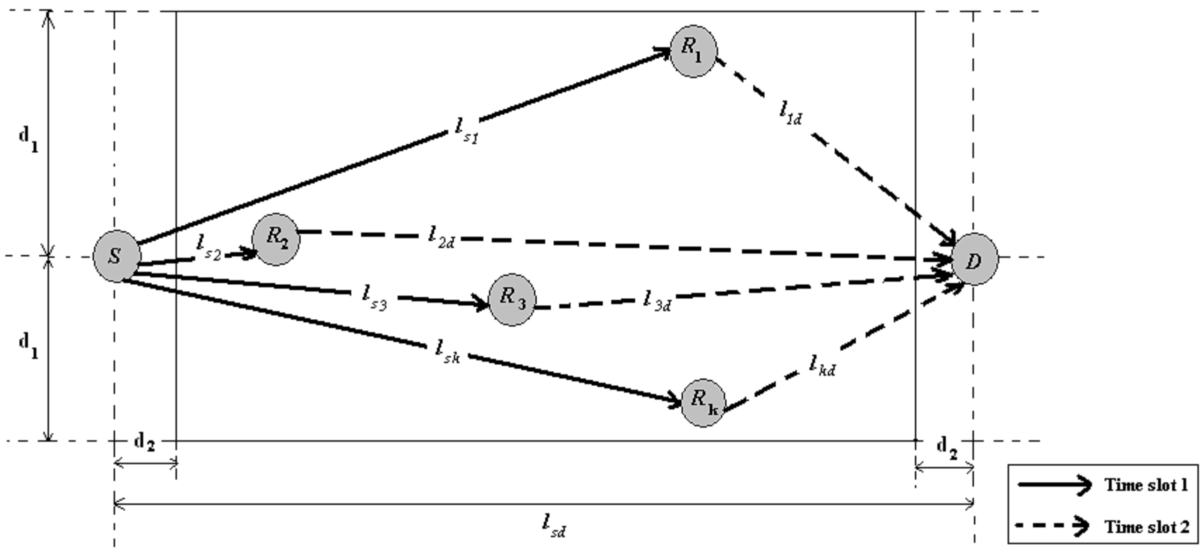

Fig. 4.1: System model with the two-hop relaying protocol

For realistic applications, we assume an orthogonality constraint such that the relay nodes can not transmit and receive at the same time slot. Hence, we divide the available channel into two orthogonal sub-channels in the time domain. Operation steps of this time-division multiple-access (TDMA) based transmission protocol is summarized in Table 4.1. Source node communicates with relay nodes over the first time slot. In the second time slot, relay nodes communicate with the destination node. We consider a multi-hop transmission protocol such that the source node can not transmit directly to the destination node due to the path loss phenomenon. As data transmission from the source node to the destination node overlaps two consecutive time slots, network capacity will be halved compared to the direct transmission with the same effective channel transfer function.

Table 4.1: The TDMA based transmission protocol

	Source Node (S)	**Relay Nodes (R_k)**	**Destination Node (D)**
Time Slot I	Broadcasts to R_k	Listens for S	Idle
Time Slot II	Idle	Transmits to D	Listens for R_k

The channels $S \rightarrow R_k$, and $R_k \rightarrow D$, for k = 1, 2. . . K, are modeled as Rayleigh block fading channels where the channels remain constant for the duration of two consecutive time slots. The channels are assumed to be independent of each other and between two consecutive time slot realizations.

We use $\mathbf{H}_k$ and $\mathbf{G}_k$ notations for channel matrices of $S \rightarrow R_k$, and $R_k \rightarrow D$ links, respectively. For each link, the channel coefficients are assumed to include path-loss exponent, such that the channel coefficient from the m-th transmit antenna to the n-th receiver antenna follows the general form of

$$h(n,m) = l^{-1}\phi(t) \tag{4.1}$$

where $\phi(t)$ is a complex Gaussian random variable with zero mean and unit variance and l is the distance between the transmitter and the receiver such that the path-loss satisfies the inverse square law.

Noise terms at the front end of relay nodes and destination node are assumed to be i.i.d. circularly symmetric complex Gaussian random variables with $\sim\mathcal{CN}(0,\sigma_r^2)$ and $\sim\mathcal{CN}(0,\sigma_n^2)$, respectively, where we assume that all relay nodes have the same noise variance for simplicity.

The total transmit power for the source node and the relay nodes are assumed to be the same and each relay node has the same power constraint, such that the total power is equally distributed among relay nodes. We assume that the total transmit power for the source node is P, and if L relay nodes are active in transmission, each active relay will have the power constraint of $P_r = P / L$.

In the first time slot, the source node transmits the symbol vector **x**, where $\mathbf{x} \in C^{M\times 1}$, with the covariance matrix $\mathbf{Q}_x = \varepsilon[\mathbf{x}\mathbf{x}^*]$ and P= $tr(\mathbf{Q}_x)$. The received signal vectors at the relay nodes are given by

$$\mathbf{r}_k = \mathbf{H}_k \mathbf{x} + \mathbf{n}_k \quad , \forall k \tag{4.2}$$

After reception, the selected relay nodes fully decode and re-encode the received signals and transmit the re-encoded signals under the relaying power constraint. At the second time slot, relay nodes transmit the vectors $\mathbf{t}_k$, where $\mathbf{t}_k \in C^{N_{Rk}\times 1}$, with covariance matrix $\mathbf{Q}_{t_k} = \varepsilon[\mathbf{t}_k \mathbf{t}_k^H]$ and $tr(\mathbf{Q}_{t_k}) \leq P_r$, $\forall k$. In the second time slot, the destination node receives the signal vector given by

$$\mathbf{y} = \sum_{k=1}^{K} \mathbf{G}_k \mathbf{t}_k + \mathbf{n}_d \tag{4.3}$$

4.3 DF Relaying Mode with Multiple Antennas

In this section, we examine the capacity of decode-and-forward MIMO relay networks with the previously specified transmission protocol. In DF mode, signal vectors received by the relay nodes at the first time slot are decoded and re-encoded before transmission with respect to the transmit power limitations. The signal vectors received by relay nodes and the destination node have the same structure as in (4.2) and (4.3), respectively.

The *max-flow min-cut* theorem of network information theory gives us the capacity upper bound of the DF mode relay network [23]. The cut set around the source node forms a Broadcast Channel (BC) and the cut set around the destination node forms a Multiple-Access Channel (MAC). The system capacity is the minimum value of the two cut-set capacities. For the BC part, if the source node has the CSI between $S \rightarrow R_k$, Dirty Paper Coding (DPC) achieves sum capacity [24], [25]. When the nodes are all equipped with single antennas and CSI is available at the source node, the channel turns to degraded Gaussian BC for which the capacity region is known [23]. But for MIMO transmission, we can not say that channel is degraded [26]. As DPC is a non-linear transmission strategy, different non-optimal linear pre-coding techniques, i.e. ZF pre-coding, has been proposed up to now [17].

The capacity of the cut-set around the source node is given by

$$C_{BC} = \max_{p(\mathbf{x})} \ \mathrm{I}(\mathbf{x};\mathbf{r}_1,\ldots,\mathbf{r}_K) \tag{4.4}$$

and the capacity of the cut-set around the destination node is given by

$$C_{MAC} = \max_{p(\mathbf{t}_1,\ldots,\mathbf{t}_K)} \ \mathrm{I}(\mathbf{t}_1,\ldots,\mathbf{t}_K;\mathbf{y}) \tag{4.5}$$

The overall network information capacity can be expressed as

$$C = \max_{p(\mathbf{x},\mathbf{t}_1,\ldots,\mathbf{t}_K)} \frac{1}{2} \min\left\{C_{BC} \ , C_{MAC}\right\} \tag{4.6}$$

The expected value of C over all channels gives us the ergodic capacity of the relay network. To achieve this upper bound, we need joint encoding at the source node, cooperative decoding and encoding at the relay nodes, i.e. all relay nodes act as a common receiver and transmitter, and ML decoding at the destination node.

Next, we are going to propose relay selection and power allocation schemes for the non-BF case and relay selection, power allocation and beamforming schemes for the BF case based on the available CSI at the source and the relay nodes. Then, we are going to present the achievable capacity expressions obtained by using V-BLAST ZF detection and ZF pre-filtering detection for both the non-BF and BF cases.

When L relay nodes out of K relay nodes are selected for transmission, the selected subset of relay nodes are indicated by the array $\pi \in \mathbf{R}^L$, where the array π keeps the indices of the selected relay nodes. In the non-BF case, each relay node in π tries to decode all multiplexed data streams, and if number of decoded streams, M, is less than relay node antenna number, N_{Rk}, the relay node transmits on M randomly selected antennas as in [6]. On the other hand, for BF transmission case, where one data stream is multiplexed for each relay node, each relay node tries to decode only the intended data stream regarding the other data streams as interference. Only the relay nodes in π will be active in the second time slot, while the rest of the relay nodes will be silent.

4.4 DF Relaying Mode without Beamforming

In this section, we will give capacity expressions for relay networks operating on DF mode without using beamforming at the transmitting nodes. The source node transmits M independent data streams and each relay node in π decodes and re-encodes all the data streams. The source node selects the relay nodes based on the available CSI. Decodability at the relay nodes introduces constraints on the antenna numbers of the nodes. To be able to decode fully at the selected relay nodes, we assume that $M \leq N_{Rk} \leq N$, $\forall k \in \pi$ for the non-BF case. This antenna number constraint limits the system configuration to be applicable for some specific antenna sizes. One can design more flexible systems, in terms of antenna sizes, by considering different multiplexing, pre-coding and relay selection schemes at the source node and release the fully decoding paradigm at relay nodes to more convenient decoding cases, i.e., use of some threshold SINR decoding schemes where each relay node selects the best SINR supplying subset of data streams for decoding and re-encode these streams to transmit to the destination.

The source and the transmitting relay nodes transmit $\mathbf{x} \in \mathbf{C}^{M\times 1}$. If one of the transmitting relay nodes, R_k, has more antennas than M, it utilizes M randomly selected antennas to participate in the transmission. The channel matrix corresponding to the channel $R_k \rightarrow D$ will be denoted as $\tilde{\mathbf{G}}_k \in \mathbf{C}^{N\times M}$. When L relay nodes are selected to transmit in the second time slot, the destination node receives the signal vector given by

$$\begin{aligned} \mathbf{y} &= \sum_{k=1}^{L} \sqrt{\frac{P_r}{P}}\, \tilde{\mathbf{G}}_{\pi(k)}\, \mathbf{x} + \mathbf{n}_d \\ &= \tilde{\mathbf{G}}\, \mathbf{x} + \mathbf{n}_d \end{aligned} \tag{4.7}$$

where $\tilde{\mathbf{G}} = \sum_{k=1}^{L} \sqrt{\frac{P_r}{P}}\, \tilde{\mathbf{G}}_{\pi(k)}$ is the $N \times M$ equivalent channel matrix.

Random selection case: When there is no CSI available at the source node, L relay nodes are selected randomly out of K relay nodes to transmit in the second time slot and the source node allocates equal power to all data streams, $\mathbf{Q}_x$ = (P/M) $\mathbf{I}_M$.

Best subset selection case: When the source node has the CSI of all channels in the relay network, the relay selection and power allocation can be performed optimally, such that the subset of selected relay nodes provides the highest system capacity for the non-BF DF mode of relaying. The array π of the selected relay nodes is determined by

$$\pi = \arg\max \min\{I(\mathbf{x};\mathbf{r}_{\pi(1)}),\, I(\mathbf{x};\mathbf{r}_{\pi(2)}),\ldots,\, I(\mathbf{x};\mathbf{r}_{\pi(L)}),\, I(\mathbf{x};\mathbf{y})\} \tag{4.8}$$

where

$$I(\mathbf{x};\mathbf{r}_k) = \log_2 \det(\mathbf{I} + \frac{1}{\sigma_r^2}\mathbf{H}_k\mathbf{Q}_{\mathbf{x}}\mathbf{H}_k^H) \tag{4.9}$$

and

$$I(\mathbf{x};\mathbf{y}) = \log_2 \det(\mathbf{I} + \frac{1}{\sigma_n^2}\tilde{\mathbf{G}}\mathbf{Q}_{\mathbf{x}}\tilde{\mathbf{G}}^H). \tag{4.10}$$

The ergodic capacity upper bound for the non-BF DF mode of relaying is given by

$$C_{DF}^{UB} = \varepsilon_{\mathbf{H}_k,\mathbf{G}_k}\{\ \frac{1}{2}\min\{I(\mathbf{x};\mathbf{r}_{\pi(1)}),\ I(\mathbf{x};\mathbf{r}_{\pi(2)}),\ldots,\ I(\mathbf{x};\mathbf{r}_{\pi(L)}),\ I(\mathbf{x};\mathbf{y})\}\ \} \tag{4.11}$$

Threshold selection case: When the source node has the CSI of $S \rightarrow R_k$ channels, and the relay nodes have the CSI of $S \rightarrow R_k$ and $R_k \rightarrow D$ channels, selecting the relay nodes using only the CSI of $S \rightarrow R_k$ channels does not improve the system capacity, since the relay nodes with better $S \rightarrow R_k$ channel conditions may have worse $R_k \rightarrow D$ channel conditions compared to the other relay nodes. Thus, the source node needs information about both $S \rightarrow R_k$ and $R_k \rightarrow D$ channel conditions to choose the relay nodes in an intelligent way to improve the system performance. Since the feedback of $R_k \rightarrow D$ channel conditions from the relay nodes to the source node introduces a heavy overhead to the system, it becomes impractical to feedback the entire channel conditions in a multi-relay network. To decrease the amount of the feedback data, threshold and channel quantization algorithms have been proposed in the literature [14]. Here, we propose an on-off relay selection algorithm which requires only 1-bit of feedback from each relay node and uses a pre-determined threshold value to select relay nodes. The threshold value is given by

$$threshold = \varepsilon_{\mathbf{H}_k,\tilde{\mathbf{G}}_k}\left\{\min(\log_2 \det(\mathbf{I} + \frac{P}{M\sigma_r^2}\mathbf{H}_k\mathbf{H}_k^H),\ \log_2 \det(\mathbf{I} + \frac{P}{M\sigma_n^2}\tilde{\mathbf{G}}_k\tilde{\mathbf{G}}_k^H))\right\} \tag{4.12}$$

Each relay node in the network computes the instantaneous capacity value and compares it with the *threshold* value. The instantaneous capacity value for R_k is computed as

$$C_k^{inst} = \min(\log_2 \det(\mathbf{I} + \frac{P}{M\sigma_r^2}\mathbf{H}_k\mathbf{H}_k^H),\ \log_2 \det(\mathbf{I} + \frac{P}{M\sigma_n^2}\widetilde{\mathbf{G}}_k\widetilde{\mathbf{G}}_k^H)) \qquad (4.13)$$

and each relay sends a 1-bit feedback to the source node such that

$$feedback_k = \begin{cases} 1 & for\ C_k^{inst} \geq treshold \\ 0 & for\ C_k^{inst} < treshold \end{cases} \qquad (4.14)$$

After the source node receives the feedback signals from the relay nodes, the relay selection is performed as follows

$$\pi = \begin{cases} select\ L\ nodes\ with\ positive\ feedback\ values\ randomly & for \sum_{k=1}^{K} feedback_k > L \\ select\ L\ nodes\ with\ positive\ feedback\ values & for \sum_{k=1}^{K} feedback_k = L \\ select\ Z\ nodes\ with\ positive\ feedback\ values\ and & for \sum_{k=1}^{K} feedback_k = Z\ and\ Z < L \\ L - Z\ nodes\ with\ zero\ feedback\ values\ randomly & \end{cases} \qquad (4.15)$$

Since the source node still does not have the full channel information, it allocates equal power to the data streams.

Up to now, we have provided the relay selection algorithms based on the channel information available at the source node and expressed the ergodic capacity upper bound for the non-beamforming DF relaying mode with equal power allocation over transmit antennas. In the next subsections, we are going to give the achievable ergodic capacity expressions for random relay selection, threshold relay selection and best subset relay selection cases using V-BLAST ZF detection based on the successive decoding and ZF pre-filtering detection built upon parallel decoding at the receiving nodes.

4.4.1. Achievable rates using ordered V-BLAST ZF detection

In this section, we present achievable rates for DF relaying mode in which receivers are equipped with V-BLAST detectors that perform ZF nulling and successive cancellation as in [27], [28]. We assume optimal decoding order at receiving nodes. The source node selects L relay nodes out of K relay nodes based on the available CSI as explained in the previous section. Each selected relay node in π decodes all data streams multiplexed at the source node. It is worth to stress that to achieve system capacity, adaptive rate transmission should be used at the source node depending on the instantaneous channel capacities, which are fed back to the source via low rate feedback channels from the relay nodes and the destination node.

The source node transmits $\mathbf{x} \in \mathbf{C}^{M \times 1}$ with covariance matrix $\mathbf{Q}_{\mathbf{x}}$. Then, the received signal vectors at relay nodes in the first time slot are passed through V-BLAST ZF decoder and then each decoded signal is re-encoded for transmission to the destination node in the second time slot. To avoid error propagation in decoding, ordering is very important. We used the optimal ordering proposed in [27], [28]. Due to the multi-cast transmission scheme, achievable capacity for each data stream is limited by the minimum of the capacities for that stream in each relay node. The achievable V-BLAST ZF detection capacity from the source node to the selected relay nodes can be expressed as

$$C_{MC} = \sum_{i=1}^{M} \min\left\{ \log_2(1+\Gamma^i_{\mathbf{H}_{\pi(1)}}), \log_2(1+\Gamma^i_{\mathbf{H}_{\pi(2)}}), \ldots, \log_2(1+\Gamma^i_{\mathbf{H}_{\pi(L)}}) \right\} \tag{4.16}$$

where $\Gamma^i_{\mathbf{H}_{\pi(k)}}$ is the output SNR for the i-th data stream in the V-BLAST ZF detector at the k-th relay node. When i-th data stream is decoded in the φ_i-th order with the nulling vector $\mathbf{w}_{\varphi_i}$, the output SNR can be given by

$$\Gamma^i = \frac{\alpha_i \, P}{\sigma_r^2 \left\| \mathbf{w}_{\varphi_i} \right\|^2} \tag{4.17}$$

where $\alpha_i \, P$ is the power allocated to the i-th data stream. At the second time slot, the re-encoded signal vectors are transmitted according to the power constraint of the relay nodes, $P_r = P / K$ for $\forall \; \in \pi$. In the second time slot, the received signal vector at the destination node is given by (4.7). The detection at the destination node is the same as in relay nodes. The overall network capacity is the summation of the capacity of all data streams, which is given by

$$C_{vblast} = \frac{1}{2} \sum_{i=1}^{M} \min\left\{ \log_2(1+\Gamma^i_{\mathbf{H}_{\pi(1)}}), \log_2(1+\Gamma^i_{\mathbf{H}_{\pi(2)}}), \ldots, \log_2(1+\Gamma^i_{\mathbf{H}_{\pi(L)}}), \log_2(1+\Gamma^i_{\tilde{\mathbf{G}}}) \right\} \tag{4.18}$$

In order to achieve this capacity, $\Gamma^{i}_{\mathbf{H}_k}$ and $\Gamma^{i}_{\tilde{\mathbf{G}}}$ need to be fed back to the source node for rate adaptive transmission. Interested readers may refer to [27] and [28] for more details about the V-BLAST ZF decoding structure.

4.4.2. Achievable rates using ZF pre-filtering

In this section, we present achievable rates for DF relaying mode in which receivers are equipped with ZF pre-filtering. The source node selects L relay nodes out of K relay nodes based on the available CSI as explained in the previous section. Each selected relay node in π decodes all data streams multiplexed at the source node. It is worth to stress that to achieve the system capacity, adaptive rate transmission should be used at the source node.

The source node transmits $\mathbf{x} \in \mathbf{C}^{M\times 1}$ with covariance matrix $\mathbf{Q}_{\mathbf{x}}$. Then, the received signal vectors at relay nodes are passed through ZF filters, independently decoded and re-encoded. In the second time slot, the re-encoded signal vectors are transmitted according to the power constraint of $P_r = P / K$ for $\forall \in \pi$. Then the received signal vector at the destination node in the second time slot is given by (4.7). The ZF pre-filtering matrices at each relay node and the destination node are given as follows, respectively

$$\mathbf{H}_k^{\psi} = (\mathbf{H}_k^H \mathbf{H}_k)^{-1} \mathbf{H}_k^H \tag{4.19}$$

$$\tilde{\mathbf{G}}^{\psi} = (\tilde{\mathbf{G}}^H \tilde{\mathbf{G}})^{-1} \tilde{\mathbf{G}}^H \tag{4.20}$$

Then, the output sequences at relay nodes and the destination node are given by

$$\mathbf{r}'_k = \mathbf{H}_k^{\psi} \mathbf{r}_k = \mathbf{x} + \mathbf{H}_k^{\psi} \mathbf{n}_k \ , \ \ \forall k \in \pi \tag{4.21}$$

and

$$\mathbf{y}' = \tilde{\mathbf{G}}^{\psi}\mathbf{y} = \mathbf{x} + \tilde{\mathbf{G}}^{\psi}\mathbf{n}_d \tag{4.22}$$

respectively. The SNR terms for the relay nodes and the destination node for the *j*-th data stream can be expressed as follows

$$\Gamma_k^j = \frac{\alpha_j \; P}{\sigma_r^2 \; \left\|\mathbf{H}_k^{\psi}\right\|_j^2}, \quad j = 1, 2, \ldots, M \tag{4.23}$$

where Γ_k^j is the SNR term seen at the *k*-th relay node for the *j*-th data stream and

$$\Gamma_{des}^j = \frac{\alpha_j \; P}{\sigma_n^2 \; \left\|\tilde{\mathbf{G}}^{\psi}\right\|_j^2}, \quad j = 1, 2, \ldots, M \tag{4.24}$$

where Γ_{des}^j is the SNR term seen at the destination node for the *j*-th data stream and $\left\|\mathbf{A}\right\|_j^2$ is defined as the norm square of the *j*-th row of matrix **A.** The overall network capacity is the summation of the capacity of all data streams, which is given by

$$C_{zf} = \frac{1}{2}\sum_{i=1}^{M} \min\left\{\log_2(1+\Gamma_{\pi(1)}^i)\,,\, \log_2(1+\Gamma_{\pi(2)}^i)\,,\ldots,\, \log_2(1+\Gamma_{\pi(L)}^i)\,,\, \log_2(1+\Gamma_{des}^i)\right\} \tag{4.25}$$

In order to achieve this capacity, Γ_k^i and Γ_{des}^i need to be fed back to the source node for rate adaptive transmission.

4.5 DF Relaying Mode with Eigen-mode Beamforming

In this section, we propose a simple BF scheme where we assign single data streams to the selected relay nodes under the assumption that the number of selected relay nodes, L, is less than or equal to the number of antennas at the destination node. In the proposed BF transmission scheme, there is no constraint for the number of antennas at relay nodes which makes the scheme promising.

In the first time slot, the source node transmits the signal vector given by

$$\mathbf{x} = \sum_{k=1}^{L} \mathbf{w}_k s_k = [\,\mathbf{w}_1\ \mathbf{w}_2 \cdots \mathbf{w}_L\,] \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_L \end{bmatrix} \tag{4.26}$$

where $\mathbf{w}_k$ is the beamforming vector satisfying

$$\|\mathbf{w}_k\|^2 = 1, \quad k = 1, 2, \ldots, L \tag{4.27}$$

and s_k is the intended data stream for the $\pi(k)$-th relay node.

The transmit covariance matrix can be expressed as

$$\mathbf{Q}_{\mathbf{x}} = [\,\mathbf{w}_1\ \mathbf{w}_2 \cdots \mathbf{w}_L\,] \begin{bmatrix} \alpha_1 P & & & \\ & \alpha_2 P & & \\ & & \ddots & \\ & & & \alpha_L P \end{bmatrix} \begin{bmatrix} \mathbf{w}_1^H \\ \mathbf{w}_2^H \\ \vdots \\ \mathbf{w}_L^H \end{bmatrix} \tag{4.28}$$

where $\sum_{k=1}^{L} \alpha_k = 1$.

In the second time slot, the selected relay nodes transmit the signals given by

$$\mathbf{t}_k = \sqrt{\frac{P_r}{\alpha_k P}}\, \mathbf{v}_k s_k \tag{4.29}$$

where $\mathbf{v}_k$ is the beamforming vector at the $\pi(k)$-th relay node, which satisfies

$$\|\mathbf{v}_k\|^2 = 1, \quad k = 1, 2, \ldots, L \tag{4.30}$$

Depending on the available CSI at the source node and the relay nodes, relay selection, beamforming and power allocation are performed.

Random selection case: When there is no CSI available at the transmitting nodes, M relay nodes are selected randomly out of K relay nodes to transmit the intended data streams in the second time slot. The source node and the selected relay nodes perform uniform beamforming and equal power allocation.

Best subset selection case: When the source node and the relay nodes have the CSI of all channels in the relay network, the relay selection and power allocation can be performed optimally using exhaustive search, such that the subset of selected relay nodes and the power allocation scheme provide the highest system capacity for the DF mode of relaying with best eigen-mode corresponding beamforming at the transmitting nodes. Thus, $\mathbf{w}_k$ is the eigenvector corresponding to the maximum eigenvalue of the matrix $\mathbf{H}_{\pi(k)}^H \mathbf{H}_{\pi(k)}$, $k = 1, 2, \ldots, L$ and $\mathbf{v}_k$ is the eigenvector corresponding to the maximum eigenvalue of the matrix $\mathbf{G}_{\pi(k)}^H \mathbf{G}_{\pi(k)}$, $k = 1, 2, \ldots, L$.

$$(\pi, \alpha_1, \alpha_2, \ldots, \alpha_L) = \arg\max C_{bf} \tag{4.31}$$

Threshold selection case: When the source node has the CSI of $S \rightarrow R_k$ channels and 1-bit feedback information from the relay nodes, and the relay nodes have the CSI of $S \rightarrow R_k$ and $R_k \rightarrow D$ channels, we use the same threshold selection algorithm given by (4.15). We use best eigen-mode corresponding beamforming and equal power allocation at the transmitting nodes.

Unlike the non-BF case, in the BF case, we intend different data streams for different relay nodes as in a multi-user cellular system. Thus, in the first part of the transmission we can use sum-rate capacity achieving pre-coding techniques such as Dirty Paper Coding (DPC) and Block-Diagonalization (BD) [24]-[26], [29], [30]. Decoding at the destination node can be performed whether by considering parallel decoding at each antenna, i.e. by using ZF pre-filtering [17], or successive decoding, i.e., V-BLAST [27], [28], or by considering joint decoding, i.e., by using Maximum-Likelihood (ML) decoding [31].

Assuming arbitrary number, L ≤ N, of relay nodes participate in the communication between the source node and the destination node and $\pi \in \mathbf{R}^{L}$ keeps the indices of the active relay nodes, we can express the received signal at the destination node as

$$\begin{aligned}\mathbf{y} &= \sum_{k=1}^{L} \mathbf{G}_{\pi(k)} \mathbf{t}_{\pi(k)} + \mathbf{n}_d \\ &= \begin{bmatrix} \sqrt{\frac{P_r}{\alpha_1 P}} \mathbf{G}_{\pi(1)} \mathbf{v}_{\pi(1)} & \cdots & \sqrt{\frac{P_r}{\alpha_L P}} \mathbf{G}_{\pi(L)} \mathbf{v}_{\pi(L)} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_L \end{bmatrix} + \mathbf{n}_d \\ &= \mathbf{G}_{\pi} \mathbf{s} + \mathbf{n}_d \end{aligned} \tag{4.32}$$

where $\mathbf{s} = [s_1 \ s_2 \cdots s_L]^T$ is the transmit signal vector at the source node, and $\mathbf{G}_{\pi}$ is the $N \times L$ compound channel matrix. As each data stream is intended for a different relay node, all corresponding data rates from the source node to the relay nodes in the first time slot are given by the logarithm of SINR seen by each relay node. As the destination node has N receiving antennas, the number of utilized relay nodes should be less than this amount. With the given signal models for multi-user BF case, we can implement either successive or parallel decoding at the destination node. Next, we are going to give the capacity expressions for both V-BLAST and ZF pre-filtering cases without going into the details as the same procedures are applied in the previous sections.

In the first time slot, the SINR value seen at the $\pi(k)$-th relay node is given by

$$\psi_{\pi(k)} = \frac{\left\|\mathbf{H}_{\pi(k)}\mathbf{w}_{\pi(k)}\right\|^4 \alpha_k P}{\sum_{\substack{i=1 \\ i\neq k}}^{L} \left|\mathbf{w}_{\pi(k)}^H \mathbf{H}_{\pi(k)}^H \mathbf{H}_{\pi(k)} \mathbf{w}_{\pi(i)}\right|^2 \alpha_i P + \left\|\mathbf{H}_{\pi(k)}\mathbf{w}_{\pi(k)}\right\|^2 \sigma_r^2}, \quad k = 1, 2, \ldots, L \tag{4.33}$$

where $\sum_{k=1}^{L} \alpha_k = 1$.

The capacity expressions for both V-BLAST ZF and ZF pre-filtering decoding schemes have the same structure where the only difference is in the SNR term seen at the destination node. In general, the network capacity for multi-user BF structure is given by

$$C_{bf} = \frac{1}{2}\sum_{k=1}^{L} \min \left\{ \log_2(1+\psi_{\pi(k)}) \, , \, \log_2(1+\Gamma_{\mathbf{G}\pi}^k) \right\} \tag{4.34}$$

where $\Gamma_{\mathbf{G}\pi}^k$ corresponds to the SNR of the k-th data stream at the destination node for both V-BLAST ZF detector and ZF pre-filtering cases. The corresponding SNR terms for these schemes have been introduced in the previous section.

4.6 Simulations and Results

We conclude our discussion of the system performance of the proposed transmission protocols under decode-and-forward relaying mode with numerical results. Since we consider both path-loss and fading effects in our system model, the network capacities are highly dependent on the positions of the relay nodes in the geography. Thus, we performed Monte Carlo simulations and computed the ergodic capacity values for a large number of uniform geographical distributions on a rectangular region. To make sure that the inverse square law is a valid path-loss model, we used the rectangular region depicted in Fig. 4.1 for our simulations, where l_{sd} = 250m, d_1= 50m, and d_2 = 35m. We assume that there are 6 possible relay nodes in the network, K= 6, and all nodes are equipped with two antennas for transmission, M = N_{Rk} = N = 2.

In Fig. 4.2, ergodic capacity values for DF mode of relaying without beamforming case are plotted for different CSI availability cases and corresponding transmission schemes with V-BLAST ZF and ZF pre-filtering detection. The simulations are performed for $P / \sigma_n^2 = P_r / \sigma_r^2 = 5$ dB. Fig. 4.2 shows the change in the network performance when different numbers of relay nodes are chosen for participation in the transmission. As we can observe from the figure, using all relay nodes in the transmission degrades the network capacity, and selecting a subset of relay nodes for transmission is a better strategy in terms of system performance for all transmission schemes considered in this study. We can see that V-BLAST ZF outperforms ZF pre-filtering detection in terms of the system capacity for all CSI availability cases but this increase in the system performance costs higher decoding complexity. The performance gain achieved by relay selection decreases with the number of selected relay nodes. Fig. 4.2 also shows the DF upper bound for equal power allocation and non-BF case.

We plot the multi-user beamforming DF ergodic capacity values for different SNR values in Fig. 4.3, where we assume that L=2 relay nodes are chosen out of K=6 possible relay nodes for transmission. We can see that the CSI availability has crucial importance for the design of transmission strategies achieving higher network capacities. Using just forward CSI and extra 1-bit of feedback information from the relay nodes, we can double the capacity of no CSI availability case. And when the source node has full CSI and relay nodes have the CSI of their related channels, we can achieve network capacity values about four times achievable by the no CSI availability case. As in the non-BF case, V-BLAST ZF detection outperforms ZF pre-filtering detection for the cost of increased decoding complexity.

When we compare Fig. 4.2 and Fig. 4.3 at the 5dB SNR and 2-relay-node-selection case, we observe that multi-user BF scheme achieves higher ergodic capacity values than the non-BF scheme.

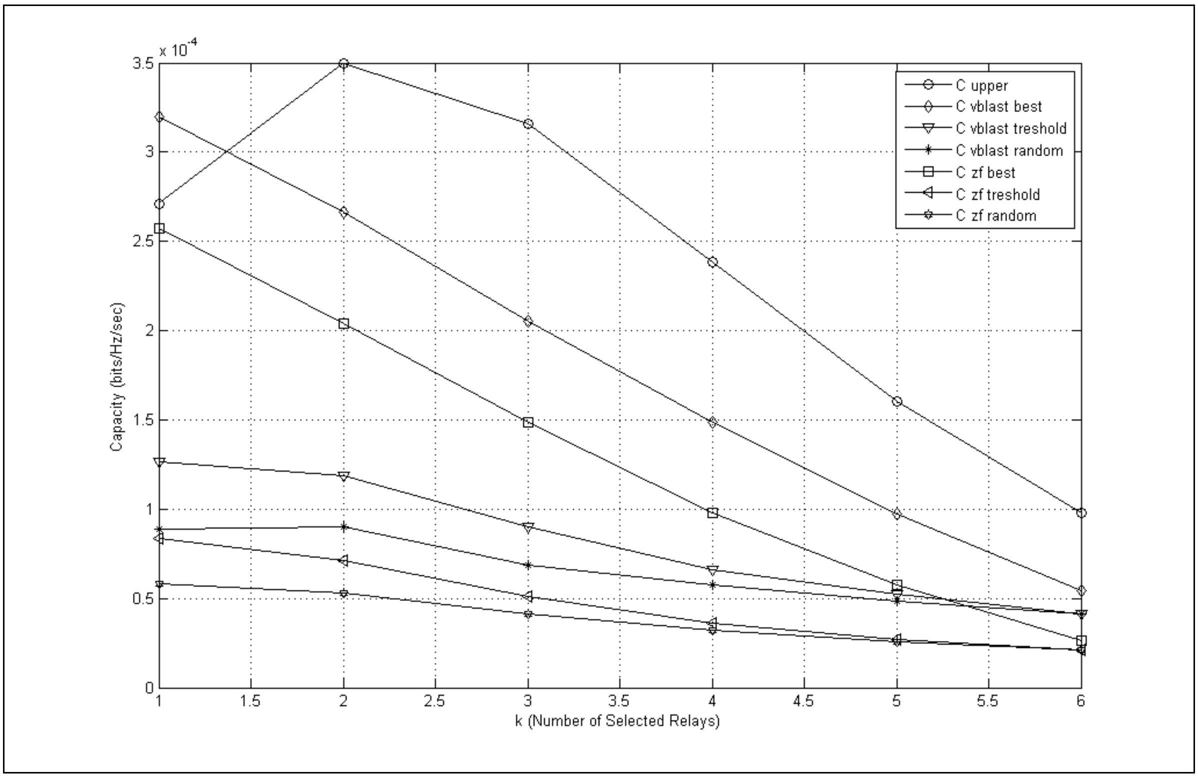

Fig. 4.2: Ergodic capacity values for the non-BF case

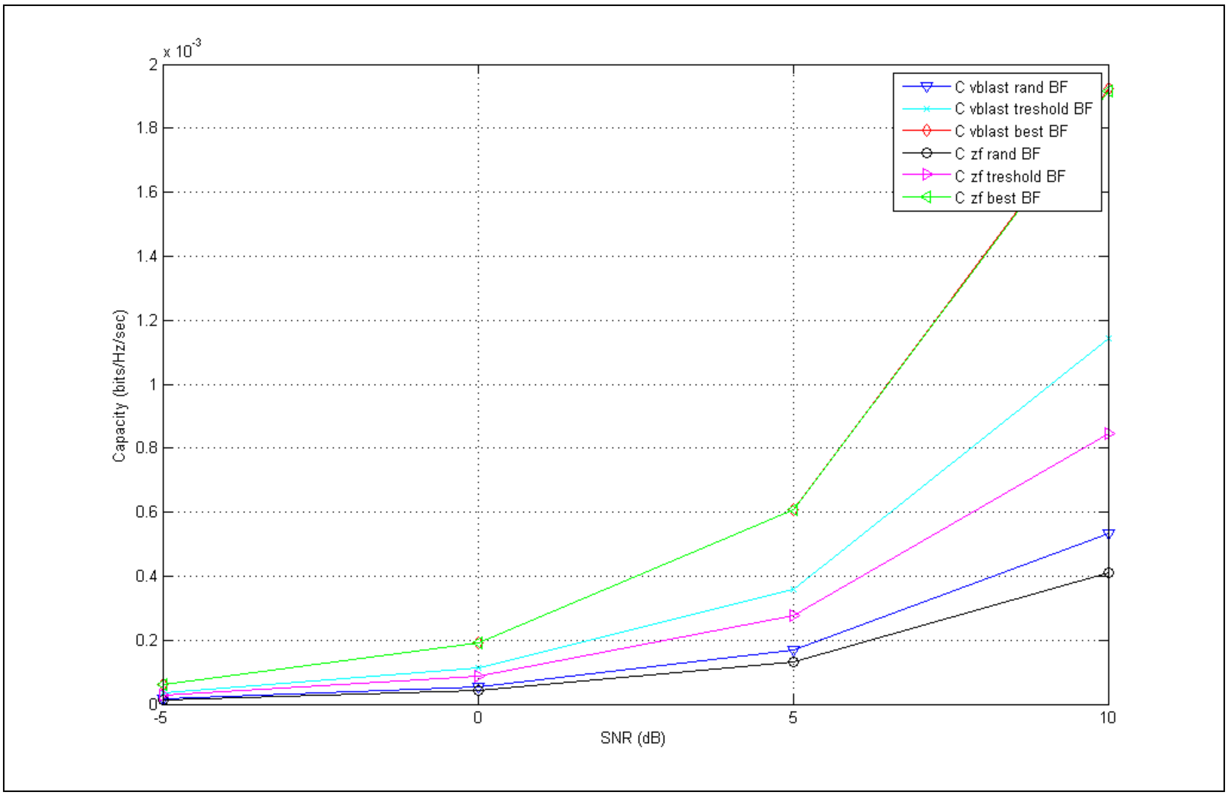

Fig. 4.3: Ergodic capacity values for the eigen-mode BF case

Chapter 5

CONCLUSIONS

5.1 Conclusion

In this thesis, we investigate the impact of CSI availability on the system performance and the ways to exploit the available CSI to achieve higher capacity values in wireless relay networks. We analyze the relay networks under the two fundamental relaying modes, i.e. AF and DF. We propose transmission schemes using non-beamforming and beamforming techniques.

Chapter 2 provides a comparative study of the impact of CSI availability at the source node of dense AF MIMO relay networks. The CSI, when available, is useful in constructing the linear precoder matrix as well as establishing the power allocation rule among the data streams. The relay network considered in this article provides two-hop communication links between the source and the destination nodes. A theoretically ideal precoder needs to match the transmitted signal vector to the composite channel matrix. This, however, requires CSI availability of all links, $S \rightarrow D$, $S \rightarrow R_k$, $\forall k$, and $R_k \rightarrow D$, to be available at the source node. However, for a dense MIMO relay network, the feedback requirements for this scenario are prohibitively high. This presents the need for developing networks that operate with limited feedback.

We investigate various limited feedback options in Chapter 2. We observe that when any form of quantization is made on the feedback information, a drastic drop in the ergodic capacity is unavoidable. Furthermore, we observe that the network that utilizes any form of CSI at the source node is sensitive to noise on the feedback information. The results indicate that utilization of source node CSI in MIMO relay networks is not always beneficial and systems that do not rely on any form of CSI at the source node may be preferable.

In Chapter 3, we present relay selection and power allocation schemes to enhance the ergodic capacity of two relaying modes, namely AF MIMO relaying and AFMB MIMO relaying. We show that CSI availability at the source node has a significant impact on the relay selection and power allocation policies, and consequently on the ergodic capacity of AF MIMO relay networks.

In Chapter 4, we study the DF relaying mode under different CSI assumptions, i.e., no CSI, partial CSI, and full CSI for different receiver structures, i.e., V-BLAST ZF detection (successive decoding) and ZF precoding (parallel decoding). We also consider the effects of relay node selection and power allocation on the network performance. Moreover, we compare performances of both non-BF and BF cases. At 5dB SNR, BF case achieves better capacity results than non-BF case for both decoding strategies. We show that using the CSI available at the source node, higher capacity achieving transmission strategies can be designed. We propose a transmission scheme which requires only partial CSI and 1-bit feedback from relay nodes, which outperforms the no CSI transmission case. For the non-BF case, we illustrate that selecting one relay node for transmission rather than using all relay nodes in the network achieves higher capacity values under a total power constraint for relaying.

Complexity and practicability are important design issues. Although we can achieve higher performance results by using full CSI schemes, where the source node exploits the knowledge of all channel states in the network, it becomes impracticable for large networks. Similarly, V-BLAST ZF detection outperforms ZF pre-filtering, but V-BLAST is based on successive decoding, which is of higher complexity than parallel decoding based ZF pre-filtering.

5.2 Suggestion for Future Directions

Although we have considered the path-loss effect in our study of DF relay networks, we have not considered the path-loss effect in our analysis of AF relay networks. As a future extension to our study, system models including the path-loss effect may be used in the analysis of AF networks. When path-loss effect is included in the analysis, relay selection and power allocation have a higher impact factor on the system performance.

We have analyzed networks with single source, single destination and multiple relay nodes. When there are multiple source and destination pairs with multiple relay nodes, there exist many cooperation schemes to utilize the system resources in order to maximize the system performance. Such transmission schemes may also be studied in the future.

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