On Modeling and Analysis of Optimum Diversity Combining in Cooperative Relay Networks

by

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Abstract

The cancellation of co-channel interference (CCI) is extremely vital in the next-generation wireless systems, where universal frequency reuse is commonly used to maximize the capacity. The implementation of CCI cancellation at the receivers instead of the transmitters minimizes the additional overhead associated with CCI cancellation. Optimum combining (OC) enables the cancellation of CCI in multiple-antenna receivers. Cooperative relaying creates a virtual antenna array, which enables the cancellation of CCI using OC in single-antenna receivers.

The cancellation of CCI in cooperative relay networks using OC is the main focus of this thesis. More specifically, 1) the modeling and the application of optimum combining for cooperative relay networks 2) carrying out the performance analyses in different system and channel models to obtain performance metrics and 3) the evaluation of the robustness and the feasibility of practical implementation of OC in cooperative relaying, are carried out. The performance of OC in decode-and-forward and amplify-and-forward relay protocols, and in opportunistic relay selection is studied. The deterministic interference model, which can be used to model conventionally planned networks, and the random interference model, which can be applied for fourth-generation adhoc and heterogeneous networks, are considered in the performance analysis. The impact of imperfect estimations of the desired and interferer channels on OC in cooperative relaying is analyzed.

Optimum combining improves the performance of cooperative relay networks significantly with a minimum additional overhead, which allows the capacity to be maximized using universal frequency reuse at each transmitter.

Preface

The research in this thesis was carried out under the supervision of, and in collaboration with Professor Norman C. Beaulieu. For each publication listed below, Navod Devinda Suraweera carried out the problem formulation, development of the system model, the mathematical analysis, computer simulations and the preparation of the manuscript. Prof. Norman C. Beaulieu was the supervisory author and was involved with concept formation, manuscript edits and manuscript composition. The research results are published as the following co-authored journal articles and conference proceeding papers.

- Chapter 3 was published as
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To

my wife, my parents and Romeo

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List of Abbreviations

Abbreviation	Definition
2D	two-dimensional
3D	three-dimensional
3GPP	third generation partnership project
4G	fourth generation
AF	amplify-and-forward
AWGN	additive white Gaussian noise
BER	bit error rate
BPSK	binary phase shift keying
CCI	co-channel interference
CDF	cumulative distribution function
CoMP	coordinated multipoint transmission/reception
CSI	channel state information
DF	decode-and-forward
EGC	equal-gain combining
FDD	frequency division duplexing
FFR	fractional frequency reuse
FG	fixed-gain
IBFD	in-band full-duplex
IEEE	Institute of Electrical and Electronics Engineers
IID	independent and identically distributed
IMT-A	International Mobile Telecommunications Advanced
INID	independent and non-identically distributed
INR	interference-to-noise ratio
ITU-R	International Telecommunication Union Radio Communication Sector
LTE	Long Term Evolution

LTE-A	Long Term Evolution-Advanced
MGF	moment generating function
MIMO	multiple-input multiple-output
MMSE	minimum-mean-square estimation
MRC	maximal-ratio combining
MRT	maximal-ratio transmission
NICM	noise-plus-interference correlation matrix
OC	optimum combining
PDF	probability density function
PGFL	probability generating functional
PPP	Poisson point process
PSK	phase shift keying
RV	random variable
SC	selection combining
SER	symbol error rate
SIMO	single-input multiple-output
SINR	signal-to-interference-plus-noise ratio
SNR	signal-to-noise ratio
TPS	transmit point selection
VG	variable-gain

List of Symbols

- Basic arithmetic, set and calculus notations have standard notation.

Elementary & Special Functions

Notation	**Definition**
$\lceil \cdot \rceil$	ceiling function
$\exp(\cdot)$	exponential function
$\log(\cdot)$	natural logarithm
$\log_2(\cdot)$	logarithm base 2
$\Gamma(\cdot)$	gamma function
$\gamma(\cdot, \cdot)$	lower incomplete gamma function
$\Gamma(\cdot, \cdot)$	upper incomplete gamma function
$\mathrm{Ei}(\cdot)$	exponential integral function Ei
$\mathrm{E}_1(\cdot)$	exponential integral function E_1
$\mathcal{Q}(\cdot)$	Gaussian-Q function
${}_2F_1(\cdot, \cdot; \cdot; \cdot)$	Gauss hypergeometric function
$\mathcal{I}_0(\cdot)$	modified Bessel function of the first kind of order zero
$\mathcal{J}_0(\cdot)$	Bessel function of zeroth order

Probability & Statistics

Let X and Y be two random variables and A be an arbitrary event

Notation	**Definition**
$\mathcal{M}_X(s)$	moment generating function (MGF) of X
$\mathcal{M}_{X\|Y}(s)$	MGF of X given Y
$\Phi_X(\omega)$	characteristic function of X
$\Phi_{X\|Y}(\omega)$	characteristic function of X given Y
$f_X(x)$	probability density function (PDF) of X
$f_{X\|Y}(x)$	PDF of X given Y
$F_X(x)$	cumulative distribution function (CDF) of X
$X \sim \mathcal{CN}(\mu, \sigma^2)$	X is a complex Gaussian random variable with mean μ and variance σ^2

$\mathcal{P}(A)$	probability of A

Vectors & Matrices

Let $\mathbf{a} \in \mathbb{C}^{n\times 1}$ and $\mathbf{A} \in \mathbb{C}^{n\times m}$ denote a $n \times 1$ complex vector and a $n \times m$ complex matrix, respectively.

Notation	**Definition**
$\mathbf{a}^T$	transpose of $\mathbf{a}$
diag$[\mathbf{a}]$	a diagonal matrix with elements of $\mathbf{a}$ on the main diagonal in the same order
$\mathbf{A}^H$	conjugate transpose of $\mathbf{A}$
$\mathbf{A}^{-1}$	inverse of $\mathbf{A}$
tr$\mathbf{A}$	trace of $\mathbf{A}$
$\mathbf{I}_n$	identity matrix with rank n
$\mathbf{1}_n$	$n \times 1$ vector with each element is equal to 1

Miscellaneous

Notation	**Definition**
$k!$	factorial of k
$\begin{pmatrix} n \\ k \end{pmatrix}$	binomial coefficient n choose k
$\|X\|$	magnitude of a complex number X
$\mathcal{O}(x^n)$	the remainder in a series of a function of x after the x^n term
arg $\max_{n,i}(a_i)$	index corresponding to the n-th largest a_i
arg $\min_{n,i}(a_i)$	index corresponding to the n-th smallest a_i
$\min(\mathbf{a})$	value of the smallest element of the vector $\mathbf{a}$
$\mathcal{J}$	square root of -1

Chapter 1

Introduction

Wireless communications has made connectivity cheaper and easier, compared to wired communications. In December 2014, NASA e-mailed a three-dimensional (3D) design of a wrench to the International Space Station via a satellite communication link, where the astronauts had printed it using a 3D printer [1], which produced a real wrench. This is one of many instances where wireless communications have been used to save cost and lives.

Mobile wireless communications had improved the flexibility and the scalability of communications significantly. The popularity of social networking, video sharing and other data-intensive web applications, and the introduction of more data-oriented mobile devices has triggered an explosive growth in the demand for mobile data usage. In fact, the number of mobile devices exceeded the world population by the end of year 2014 [2] and the mobile data usage is expected to increase by 1000 between 2010 and 2020 [3]. Consequently, catering to the ever increasing demand for high-speed data for a large number of users, while maintaining the required quality-of-service levels for each user poses an enormous challenge for the standardization bodies and the mobile operators, since conventional wireless networks and standards are falling short of fulfilling these demands.

Fourth-generation (4G) or international mobile telecommunications-advanced (IMT-A) is the latest set of mobile standards designed to meet the ever increasing demand for mobile data. 3GPP Long Term Evolution-Advanced (LTE-A) [4] and IEEE 802.16m [5] are the candidate 4G wireless systems.

Fading[1] in wireless channels degrades the performance of wireless communications as it reduces the signal-to-noise ratio (SNR) at the receiver, which increases the probability of error. In small-scale fading, if the signals coming via multiple paths are added destructively, a deep fade occurs. Multiple-antenna receivers can be used to combat the detrimental effects of small-scale fading, which reduces the probability of a deep fade. Consequently, error rate and outage probability[2] are reduced. However, it may not be feasible to equip most mobile devices with multiple antennas while maintaining a sufficient separation between the antennas due to cost, space and power constraints. Alternatively, cooperative relaying has been proposed as an effective method to achieve diversity gains[3] without using multiple antennas at the nodes.

1.1 Cooperative Communications

In cooperative relaying, one or more relay nodes relay the message they have received from the transmitter (the source node) to the intended receiver (the destination node). A dual-hop cooperative relay network is shown in Fig. 1.1. Relay nodes can be infrastructure-based relays (fixed) or mobile relays.

A typical relay communication takes place in two phases. During Phase 1, the source node broadcasts its message to the relay nodes and to the destination node. Phase 2 is the relaying phase where the relay nodes forward the message to the destination node. In the scope of this thesis, it is assumed that the relays operate in the half-duplex mode, where transmission and reception take place in separate time

[1]Please refer Section 2.1 for a detailed introduction into fading.

[2]Outage probability is the probability of the capacity falling below the minimum desirable rate of the communication R_{min}bits/s/Hz. The SINR threshold corresponding to R_{min} is found by,

$$\gamma_T = 2^{R_{\text{min}}} - 1.$$

[3]Diversity gain is the number of independent branches that needs to be in deep fade in order to have the entire link in deep fade. Analytically, the diversity gain can be obtained by

$$G_d = -\lim_{\rho\to\infty} \frac{\log\left(\bar{\mathcal{P}}_e(\rho)\right)}{\log(\rho)} = -\lim_{\rho\to\infty} \frac{\log\left(\mathcal{P}_{\text{out}}(\rho)\right)}{\log(\rho)}$$

where $\bar{\mathcal{P}}_e(\rho)$ and $\mathcal{P}_{\text{out}}(\rho)$ are the average error probability and the outage probability corresponding to the SNR ρ, respectively.

slots. Furthermore, time-division multiple access is used by multiple relay nodes to forward the message to the destination node without encountering collisions.

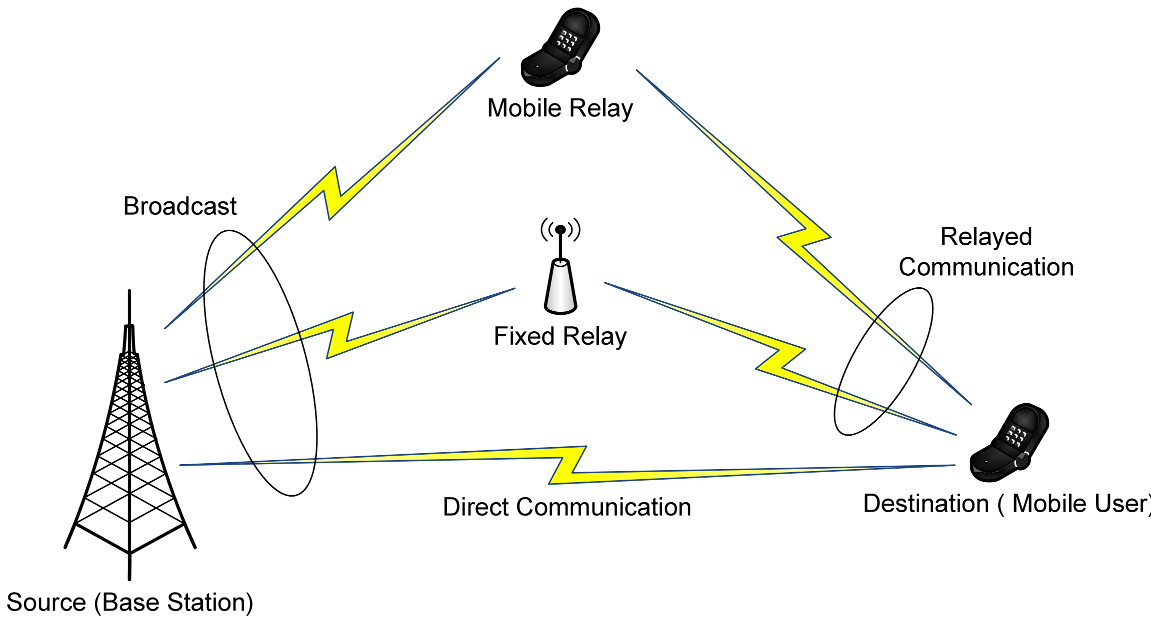

Figure 1.1: A cooperative relay network.

Cooperative relaying gained prominence in wireless communication research during the last decade [6–9] and features in both the LTE-A and IEEE 802.16m standards [10, 11] due to its advantages, which include but are not limited to

1. Increased diversity gain

   Using of relay nodes enables forming a virtual antenna array, which makes achieving diversity gains possible without using multiple antennas at the nodes. Furthermore, as the relays are geographically distributed, the fading coefficients are spatially uncorrelated, which is a key advantage over multiple-antenna receivers with co-located antennas.

2. Mitigation of shadowing

   Shadowing is the attenuation of signal power due to large obstacles (e.g. foliage, buildings, etc). Having multiple antennas at the receiver does not mitigate shadowing as the distance between the antennas is small. Since the relay nodes are geographically distributed in a larger area, at most one link is shadowed by a single obstacle.

3. Coverage extension

   In conventional cellular networks, cell-edge users generally experience a weak signal reception since they are located farthest from the base stations. Relay nodes can be used to improve the SNR of the cell-edge receivers.

The usage of relay nodes in the two 4G standards slightly differs from each other. In LTE-A, the relay node is defined as a network node without a wired backhaul, which is used to improve the coverage of cell-edge users [4]. Two types of relay modes are defined in IEEE 802.16m [10]. In the transparent mode, relays are used to improve the capacity within the same coverage area. The relays operating in the non-transparent mode are used for coverage extension.

1.2 Cellular Networks and Co-Channel Interference

The licensed frequency spectrum is a very expensive and scarce resource, which prompts the mobile operators to reuse the available spectrum. In order to facilitate frequency reuse, the coverage area is divided into non-overlapping areas termed as cells. The available frequency spectrum is allocated among a subset of cells called a cluster. A particular geographical area may consists of several clusters. Hence, the available frequency channels are reused by the cells in different clusters. Therefore, the system capacity, which is the number of concurrent channels being used in a given geographical area, can be increased by reducing the cell size and deploying more sectors in the given area.

Fig 1.2 depicts a large area divided into hexagonal cells. The number in each cell corresponds to the frequency channels assigned to that cell. Each cluster consists of the adjacent cells numbered from 1 to 7. The number of cells in a cluster is called the frequency reuse factor. Universal frequency reuse, where each cell reuses the complete frequency spectrum, is the ideal scenario in terms of the system capacity. However, reducing the frequency reuse factor increases the co-channel interference (CCI), which is the interference caused by the other cells using the same frequency channels (co-channel cells). The users located at the edge of the cells are the most

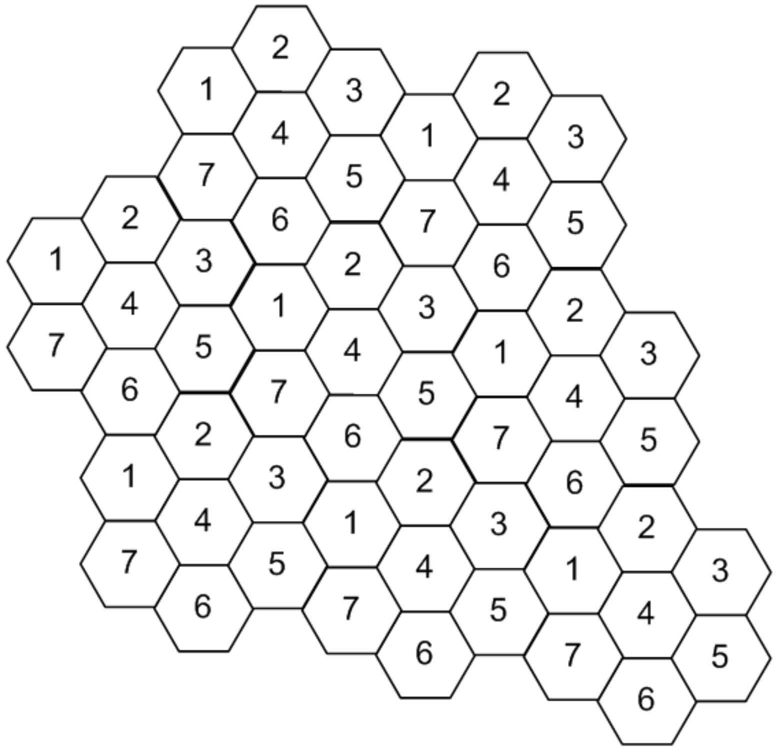

Figure 1.2: A large geographical area covered by hexagonal cells

vulnerable to CCI since compared to the other mobile users, they are located closer to the co-channel base stations and farther from their own base stations. A user in a given hexagonal cell is interfered by six co-channel cells in the first tier.

In fourth generation wireless systems, networks of cells of different sizes co-exist to maximize the system capacity. Typical transmitter nodes found in LTE-A heterogeneous networks [12] are shown in Fig. 1.3. Macro base stations are the conventional high-power base stations with transmit powers varying between 5 W and 40 W. Pico base stations are low-power base stations with the transmit powers between 250 mW to 2 W. Femtocells are consumer-deployed low-power access points for indoor usage with transmit powers below 100 mW. Small-scale transmitters use universal frequency reuse to maximize the capacity [13, 14]. Moreover, it is not feasible to plan the deployment of all the nodes in heterogeneous networks. Consequently, the impact of interference is far more severe in 4G heterogeneous networks.

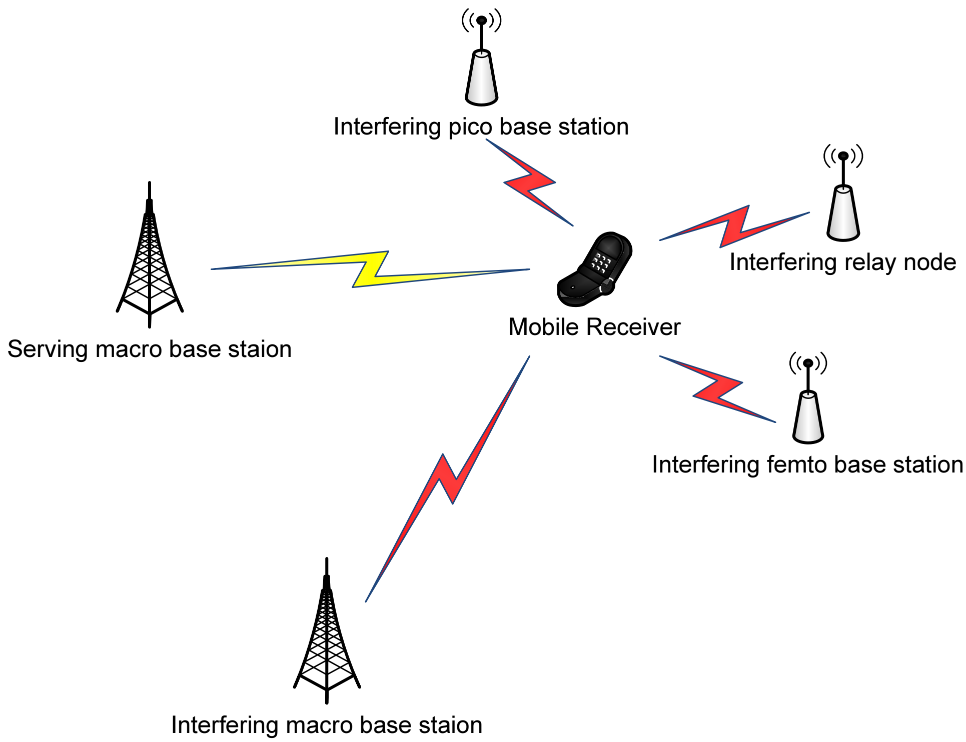

Figure 1.3: Interferers in LTE-A heterogeneous networks

1.2.1 Techniques to mitigate co-channel interference

Co-channel interference is the principle barrier for improving the capacity in cellular networks. Therefore, techniques to suppress the adverse effects of CCI have been investigated for a long time. The most obvious solution for CCI is to increase the frequency reuse factor. Nevertheless, this results in a reduced system capacity as the number of concurrent users served is reduced. The following are some of the techniques that are used / proposed to mitigate CCI.

- Using narrower beam antennas / sectorization
  Sectorization has been used for a long time in cellular communications to reduce CCI. With sectorization, the antenna beam is narrowed. Compared to isotropic antennas, the number of co-channel interferers for a given user is reduced with sectorization.

- Fractional frequency reuse
  In fractional frequency reuse (FFR), the frequency spectrum of a given cell is

partitioned such that the interference at the cell-edge users of the adjacent cells is minimized and the system capacity is maximized [15]. Hence, users located closer to the base station use universal frequency reuse, while the cell-edge users use a higher frequency reuse factor. However, FFR is a CCI mitigation technique: It does not cancel CCI.

- Coordinated multipoint (CoMP) transmission

  In CoMP, several base stations coordinate to minimize the co-channel interference for cell-edge users and to increase the capacity. CoMP is an integral component in the LTE-A standard. Following types of CoMP can be identified in the LTE-A standard [16].

  1. Coordinated scheduling / beamforming

     In this case, the user data is available to only one base station and the interference to the cell edge users is mitigated through coordinated beamforming and scheduling among several co-channel base stations.

  2. Transmission point selection

     In transmission point selection (TPS), the data of a given user is available for multiple base stations and a selected base station will transmit to the user equipment at a given time. The serving base station of a given user may change dynamically at the subframe level, based on the availability of resources and channel state information.

  3. Joint transmission

     Here, similar to TPS, the data destined for a given user is available in multiple cells. Unlike TPS, the joint processing and transmission by multiple base stations at a given time to a given user improves the diversity and multiplexing gains in Joint Transmission CoMP.

The major drawback of CoMP is the significant increase in system overhead and complexity. A central station, which is connected to the base stations via high-speed fiber optic links, is commonly used to compute the beamforming vectors for user scheduling and joint processing. Furthermore, the mobile devices are required to send the channel state information (CSI) feedback to the base stations when frequency division duplexing (FDD) is used, which necessitates reliable feedback links.

- Millimeter wave communications

  Millimeter wave communications is a key technology in the so-called fifth - generation wireless communications [17, 18]. Theoretically, carrier frequencies in the gigahertz range should reduce the CCI considerably as the propagation loss is higher. Moreover, more spectrum resources are available in the gigahertz frequency bands, which reduces the need for reusing frequency.

- Optimum combining

  Optimum combining (OC) is used at receiver nodes with multiple antennas to cancel the CCI component of the received signal using diversity combining [19, 20]. Unlike the previously mentioned techniques, which seek to mitigate the interference power received at the receiver, optimum combining suppresses the interference power after the signal with interference is received. A detailed introduction into OC is given in Section 2.4.

1.3 Motivation and Objectives

As the transmitters use universal frequency reuse to maximize network capacity, the impact of co-channel interference in fourth-generation wireless systems gets worsened. Therefore, the cancellation of interference is extremely vital for the performance improvement in 4G wireless systems. However, most interference mitigation schemes proposed in the literature are implemented at the transmitter, which requires the receiver node to feedback the channel state information of its interferers to the transmitter when frequency division duplexing is used. Furthermore, a central node may be necessary for interference coordination and cancellation, increasing the overhead considerably. Moreover, these techniques may be less effective in unplanned deployments of nodes, which is an important feature in fourth-generation wireless networks. Hence, cancellation of CCI at the receiver nodes is paramount to improve the capacity of wireless communications, while consuming a minimal overhead.

The cancellation of co-channel interference at multiple-antenna receivers using optimum combining has been extensively studied in the literature [19–24]. However, most mobile receivers cannot afford to have multiple antennas due to cost, space and power constraints.

Cooperative relaying, which is a key component in both 4G wireless standards, allows creating virtual antenna arrays at single-antenna receiver nodes with the aid of mobile and/or fixed relay nodes. This feature can be exploited to implement interference cancellation using optimum combining in cooperative relay networks, which allows maximizing the capacity while consuming a minimum additional overhead. This thesis analyzes the performance of optimum combining in cooperative relay networks. The key objectives of this research can be listed as follows.

1. To model and the application of optimum combining for cooperative relay networks

2. To carry out performance analyses of optimum combining across different relay protocols and system/channel models which suit different applications to obtain the performance metrics

3. To evaluate the impact of channel estimation imperfections on optimum combining in cooperative relaying to ascertain the robustness and the practical feasibility

1.4 Significance of the Thesis

Optimum combining enables the cancellation of co-channel interference in multiple-antenna receivers and the performance OC has been studied in single-input multiple-output (SIMO) systems comprehensively. However, due to the reasons discussed in Section 2.5 of the thesis, the performance results available for OC in SIMO systems cannot be directly applied for cooperative relaying. To the best of our knowledge, this is the first research that provides a comprehensive performance analysis of OC in cooperative relaying. The performance results obtained in this research can be applied in a wide variety of cooperative relay systems.

The performance results of this thesis suggest that OC in cooperative relaying results in a significant reduction of call-drop rates and increased data throughputs for the users, while consuming a minimum overhead. Moreover, the outcomes of this thesis enable implementing universal frequency reuse at each transmitter, thereby maximizing the system capacity. Thus, 4th generation wireless communications will be immensely benefited. Furthermore, a special attention is given to identifying the robustness of optimum combining to the channel estimation imperfections that exist in practical environments, in order to evaluate the feasibility of practical implementation.

1.5 Thesis Outline

In Chapter 2, a technical background of the main concepts studied in the thesis is provided. Furthermore, related state-of-the-art research contributions in the literature are briefly presented and their limitations are discussed. Chapters 3 to 8 contain the main contributions of this research and are written in the publication-based format. Each one of these chapters is a peer reviewed conference or a journal paper with its own introduction, literature review, system model description, conclusions and a list of references. The concluding remarks and the future research avenues generated by this thesis are presented in Chapter 9.

1.6 Novel Contributions of the Thesis

The major contributions and the insights of each contribution chapter can be summarized as follows.

- The performance of optimum combining in decode-and-forward[4] (DF) relaying in the presence of CCI at the destination node is analyzed in Chapter 3. Closed-form expressions for the probability density function (PDF) of signal-to-interference-plus-noise ratio (SINR) and the outage probability are derived for

[4]Please refer Section 2.3 for relay protocols.

the case of $N_I \leq M + 1$ where N_I is the number of interferers and M is the number of relay nodes. Moreover, a tight approximation for the average symbol error rate (SER) is derived. It is shown that OC results in a diversity gain of M, which is a significant advantage over MRC, where the diversity gain reaches zero with CCI.

- The performance of OC in DF relaying is studied in Chapter 4 for Nakagami-m fading with CCI present at all the relay nodes and the destination node. A closed-form expression for the outage probability is derived. It is shown that OC cannot be used to achieve diversity gains, if CCI present at the relays as the single-antenna relays with CCI act as a bottleneck for the end-to-end performance improvement. However, OC still achieves a significantly better performance than MRC and the performance gap between OC and MRC increases with the increase of the number of relay nodes.

- In Chapter 5, the impact of imperfect channel estimations on the performance of OC in DF relaying is investigated. The outage probability when the source-destination and relay-destination channel (desired channels) estimations are corrupted by a Gaussian error is derived. The diversity gain of OC is lost if the error variance of the desired channels is not changed with the source and relay power. Moreover, the impact of imperfect interferer channel estimations is studied and it is shown that if the destination node estimates only the variance of the interferer channel state information (CSI), instead of instantaneous interferer CSI, no performance loss is observed. This is a remarkable result as it reduces the additional channel estimation overhead associated with OC significantly, facilitating the practical implementation of OC.

- A solution for the problem raised in Chapter 4 when CCI present at the relay nodes is provided in Chapter 6. In the proposed system, multiple antennas are used at the relay nodes to cancel CCI. In Phase 2 of the communication, joint relay and antenna selection is used to transmit to the destination node. It is shown that the combination of OC with joint relay and antenna selection achieves positive diversity gains if $n > 0$, where n is the number of relays having $N_i < T_i$, where N_i and T_i are the number of interferers and the number of antennas at relay i, respectively. Furthermore, the diversity gain increases with increases in n.

- Amplify-and-forward (AF) relaying is more simple and secure than DF relaying. In Chapter 7, the performance of OC in AF relaying is analyzed using an approximation for SINR of the OC receiver. Two types of relaying schemes are considered: all-relay transmission and best-relay transmission. An approximation for the outage probability is derived and the diversity gain is obtained. It is shown that when CCI present at the destination, both relaying schemes achieve a diversity gain of M, which is a significant gain over MRC. Best-relay transmission maximizes the spectral efficiency as only two time slots are needed for a single communication. Furthermore, the performance of best relay transmission is studied when interference is present at both the relay nodes and the destination node using an approximation for SINR.

- The analyses in Chapters 3 to 7 are based on the deterministic interference model[5], where the number of interferers and their locations are assumed to be deterministic. A random interference model, which is more suitable to describe the more random nature of 4G network deployments, is adopted in Chapter 8 and the interferer distribution is assumed to follow a homogeneous Poisson point process. The performance analysis is carried out for both AF and DF relaying protocols. Tight approximations for the outage probability of each relay protocol are derived for both multi-relay transmission and relay selection. Moreover, an approximation for the outage probability of DF relaying with the limited estimation of the NICM, where the destination estimates only the CSI of the closest interferer, is obtained. When the relays are noise-limited and the destination is interference-limited, OC results in positive diversity gains in both protocols, provided that the destination node is able to estimate the noise-plus-interference correlation matrix (NICM) perfectly. Furthermore, relay selection outperforms multi-relay transmission in both relay protocols. Moreover, OC with limited estimation of the NICM outperforms MRC, though it fails to achieve diversity gains.

[5]Please refer Section 2.2 for co-channel interference models

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Chapter 2

Background

This chapter provides an overview of the subject matter and concepts investigated in this thesis. In Section 2.1, the characteristics of the mobile radio channel are discussed and Section 2.2 describes the cooperative communications protocols considered in the thesis. An overview into the co-channel interference models used is provided in Section 2.3. An introduction to optimum combining, the main interference cancellation technique used in this thesis, is given in Section 2.4 and a concise literature review of the related work is presented in Section 2.5.

2.1 Mobile Radio Channel

The mobile radio channel is the transmission medium of electro-magnetic waves between the transmitter and the receiver. Impairments that exist in the mobile radio channel cause variations and degradations in the signal power received. One can categorize these impairments into path loss, large-scale fading and small-scale fading.

Path loss

Path loss is the attenuation of signal power with the distance traveled by the waveform. In this thesis, following log-distance path loss model is frequently used [1, eq. (2.39)]

$$P_R = P_T K \left(\frac{d_0}{d}\right)^{\alpha} \tag{2.1}$$

where P_R is the received power, P_T is the transmitted power, d is the transmitter-receiver separation, d_0 is a reference distance, α is the path loss exponent, which determines the rate of decay of the signal power, and K is a constant. For free space propagation, $\alpha = 2$, but for practical wireless environments, α varies between 3 and 6. Typical values of α for different types of environments can be found e.g. in [1, Table 2.2].

Large-scale fading

In large-scale fading, the variations of the received signal power occur over larger distances compared to the wavelength of the signal. Shadowing, which is the attenuation of signal power due to large obstructions (e.g.: buildings, mountains and foliage), is the main source of large-scale fading. In this thesis, the effects of shadowing is not considered for simplicity.

Small-scale fading

The root cause of small-scale fading is the multipath propagation, where the same signal reaches the receiver in multiple paths with different delays / phases due to reflection, diffraction and scattering from the objects located in the signal's path. In fact, a line-of site path between the transmitter and the receiver does not exist in most urban environments and multipath propagation enables communication. These multipath components add together constructively or destructively depending on the phase of each multipath component, which results in rapid variations in the received signal power over very short distances, which is termed as small-scale fading.

Probability distributions are used to model the magnitude and the phase of the channel gain accounting for small-scale fading. Rayleigh distribution is commonly used to model the magnitude of the channel gain in the absence of a line-of-site path between the transmitter and the receiver. For Rayleigh fading, the probability density function (PDF) of the magnitude of the channel gain is

$$f_{|g|}(x) = \frac{2x}{\Omega}\exp\left(-\frac{x^2}{\Omega}\right), \quad 0 \leq x < \infty \tag{2.2}$$

where Ω is the mean signal power (envelope power) at the receiver, which is determined by large-scale fading. The Rayleigh fading model is advantageous due to its simplicity. However, this model may not be adequate to describe the small-scale fading in most environments. Alternatively, Nakagami-m fading model is a more general fading model. The PDF of the magnitude of the channel gain for Nagamami-m fading is

$$f_{|g|}(x) = \frac{2m^m x^{2m-1}}{\Omega^m \Gamma(m)} \exp\left(-\frac{mx^2}{\Omega}\right), \quad 0 \leq x < \infty \tag{2.3}$$

where m is the parameter that determines the severity of fading and $0.5 \leq m < \infty$. The severity of fading reduces with the increase of m. Note that for $m = 1$ this distribution reduces to Rayleigh distribution, and when $m \to \infty$ there is no fading.

2.2 Modeling of Co-Channel Interference

In order to analyze the impact of co-channel interference (CCI), the interference signal has to be mathematically modeled. Based on the number of interfering nodes and the node distribution, the co-channel interference models used in the literature can be divided into two main categories: the deterministic interference model and the random interference model.

2.2.1 Deterministic interference model

In this model, the number of interferers and the location of interferers are assumed to be deterministic. For this model, the aggregate interference power at the receiver node can be expressed as

$$I_D = \sum_{i=1}^{N_I} P_i r_i^{-\alpha} |f_i|^2 \tag{2.4}$$

where N_I is the number of interferers, P_i is the transmitted power of the i-th interferer, r_i and f_i are the distance and the fading channel coefficient between the i-th interferer and the receiver, respectively, and α is the path loss coefficient. In the deterministic interference model, N_I and r_i are assumed to be deterministic and f_i is random. This model has been widely used to analyze the impact of co-channel interference. Chapters 3, 4, 5, 6 and 7 of this thesis are based on the deterministic interference model.

The deterministic interference model is more suitable when the placement of the transmitters is well-planned. A conventional cellular network is an example of a well-planned wireless network, where this model can be applied.

2.2.2 Random interference model

As explained in Chapter 1, fourth generation wireless networks are heterogeneous in nature and the arbitrary deployment of transmitters by the operators and the consumers is common. Therefore, it is impractical to plan the whole network. Due to the adhoc / unplanned nature and the complexity of fourth-generation wireless networks, the deterministic interferer model is inadequate to model the interference.

Spatial point processes are used to model the node distribution due to the randomness of node locations in heterogeneous wireless networks. The most popular spatial point process used to model interference is the homogeneous Poisson point process (PPP) [2], since homogeneous PPP leads to more mathematically tractable expressions. Furthermore, this model accurately describes the interference in adhoc wireless networks when the node distribution is completely random. For this model, the aggregate interference power is

$$I_R = \sum_{i \in \Phi} P_i r_i^{-\alpha} |f_i|^2 \tag{2.5}$$

where Φ is a homogeneous PPP with node density λ. The probability of having n interfering nodes in area A is

$$\mathcal{P}(n \text{ nodes in } A) = \frac{(A\lambda)^n}{n!}\text{exp}(-A\lambda), i = 0, 1, 2, \dots \tag{2.6}$$

and the distribution of interferers over the area A is assumed to be uniform (constant node density λ). If A is a circle with radius R, the PDF of the distance r_i is

$$f_{r_i}(r) = \begin{cases} \frac{2r}{R^2}, & 0 < r < R \\ 0, & \text{otherwise} \end{cases}. \tag{2.7}$$

The PDF of the distance R_i to the i-th closest interferer can be found as [3]

$$f_{R_i}(r) = \frac{2(\lambda \pi r^2)^i}{r\Gamma(i)}\text{exp}(-\lambda \pi r^2). \tag{2.8}$$

It should be noted that the heterogeneous networks consist of multiple tiers of nodes, where the nodes with comparable transmit powers belong to a single tier [4]. The node distribution in each tier is modeled by a spatial point process. In the scope of this thesis, the analysis is confined to single-tier networks.

Since cooperative relaying involves transmission in orthogonal time slots, the temporal correlation of the interferer distribution is an important factor to be considered. In [5], it was shown that the temporal correlation factor of a Poisson field of interferers is greater than zero since the members of the interferer set of each time slot share the common randomness of Φ. Moreover, the interference at different relay nodes are spatially correlated due to the same reason.

Even though modeling of interfering nodes as a homogeneous PPP simplifies the analysis considerably, it has several drawbacks. For example, the distance between any two interfering nodes may then be arbitrarily small, which is not realistic. Furthermore, the node distribution in practical networks is not purely random [6]. Moreover, in practical networks, it is not always correct to assume that the location of each transmitting node is independent of each other. Consequently, more general spatial point processes have been considered in the literature. A summary of spatial point processes used to model the network interference can be found in [7, Table 1]. Unfortunately, most of the general spatial point processes result in less mathematically tractable expressions.

2.3 Cooperative Communication Protocols

Two main types of cooperative communication protocols can be identified: amplify-and-forward (AF) and decode-and-forward (DF) [8]. In AF relaying, the relay nodes simply amplify the received signal by an amplification factor and forward to the destination node. The relay nodes decode, re-encode and forward the received signal to the destination node in DF relaying.

In AF relaying, the amplification gain can be either fixed or variable. In variable-gain (VG) AF relaying, the amplification factor is the inverse of the instantaneous received power. Another variant of VG AF relaying is channel state information

(CSI) assisted AF relaying, where the amplification factor is the inverse of the magnitude of the source-relay channel coefficient. Hence, the relay nodes are required to estimate the corresponding source-relay channel coefficient to implement the CSI-assisted AF relaying. Compared to DF relaying, AF relaying is simple to implement as the complexity at the relay nodes is minimal. Furthermore, AF relaying is more secure than DF relaying as the relay nodes do not decode the data. However, the noise and the interference at relay nodes are also amplified and propagated to the destination, thus degrading the performance.

Selection DF relaying is a variant of DF relaying, where the relay nodes are able to decode the received signals if the received SNR/SINR is above a given threshold γ_T. The threshold γ_T corresponds to the minimum desirable rate of the communication R_{min} [8]. This selection criterion ensures that the symbols transmitted by the relay nodes to the destination node are error-free. DF relaying is advantageous as noise and interference are not propagated towards the destination, at the expense of increased complexity at the relay nodes.

In dual-hop cooperative communications with multiple relay nodes, the relay-destination communication takes place in orthogonal time slots to avoid collisions, i.e., at a given time, the destination will receive a signal replica transmitted by only one relay node. The destination node uses diversity combining (e.g. selection combining (SC) [9], maximal-ratio combining (MRC) [10]) to combine the received signals in multiple time slots and to achieve receiver diversity. Diversity combining techniques are discussed in detail in Section 2.4.

Relay selection

The main drawback of cooperative relaying in orthogonal time-slots is the degradation of spectral efficiency as a single complete communication consumes up to $M + 1$ time slots, where M is the number of relay nodes. Alternatively, relay selection algorithms [11], [12] use only one relay for the communication. Relay selection significantly improves the spectral efficiency as only two time slots are required for a single communication, instead of $M + 1$ time slots.

The relay selection criterion varies with the relay protocol. In DF, the relay node with the best relay-destination SNR is selected for transmission and relay selection achieves a diversity gain of $M+1$, similar to relaying in orthogonal time slots [13]. Furthermore, the overhead associated with DF relay selection is minimal as the destination node conveys only the selected relay index to the relay nodes, instead of channel state information.

For AF relaying, two types of relay selection schemes can be identified, 1) opportunistic relay selection [11], and 2) partial relay selection [14]. In opportunistic relay selection, the relay node with the best end-to-end SNR is selected for the communication, and it achieves a diversity gain of $M + 1$. The main drawback of opportunistic relay selection is the increased system complexity as the instantaneous channel state information of both source-relay and relay-destination channels is required for the selection process. Furthermore, the performance of opportunistic relay selection is highly vulnerable to feedback delays [15], [16]. Hence, high-speed feedback links are required to achieve the performance advantages promised in opportunistic relay selection.

In partial relay selection, based on the relay selection criterion, the relay node with the best source-relay or relay-destination link amplifies the received signal and forwards to the destination node. Therefore, the overhead associated with partial relay selection is considerably reduced. Nevertheless, the diversity gain of partial relay selection is limited to one for Rayleigh fading [17] and m for Nakagami fading [18], where m is the Nakagami factor, regardless of the number of relays used.

2.4 Optimum Combining

As explained in Chapter 1, cooperative relaying enables creating virtual antenna arrays. For multiple-antenna receivers, optimum combining can be used to cancel co-channel interference. In this section, optimum combining is explained using a multiple-antenna receiver.

Fig. 2.1 shows a multiple-antenna receiver or a single-input multiple-output (SIMO) receiver with M_R receiver antennas using diversity combining, where $w_1, w_2, \ldots, w_{M_R}$ are the combiner weights, which are complex numbers. In the presence of

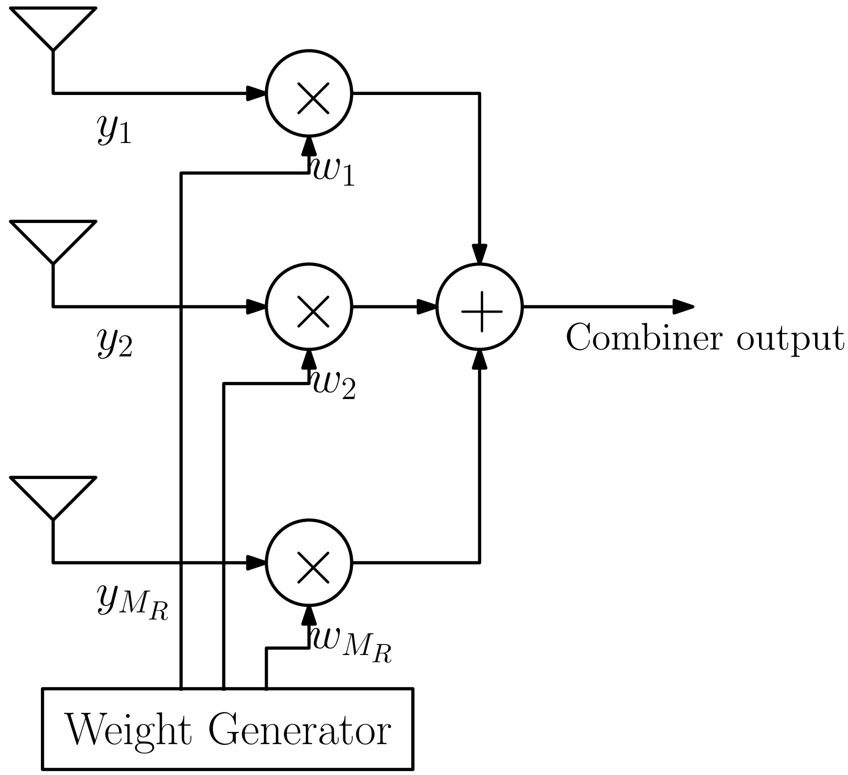

Figure 2.1: Structure of a diversity combiner.

CCI, the received signal vector is

$$\mathbf{y} = \sqrt{P_T}\mathbf{h}x_0 + \sum_{k=1}^{N_I} \sqrt{P_{I_k}}\mathbf{f}_k x_k + \mathbf{n} \tag{2.9}$$

where P_T is the transmitter power, N_I is the number of interferers, $\mathbf{h}$ is the transmitter-receiver channel vector, x_0 is the transmitted symbol, P_{I_k} are the interferer powers, $\mathbf{f}_k$ are the interferer-receiver channel vectors, x_k are the interferer symbols and $\mathbf{n} \sim \mathcal{CN}(0, N_0\mathbf{I}_{M_R})$ is the noise vector. The receiver node performs diversity combining and obtains the estimation of the transmitted symbol as

$$\hat{x}_0 = \mathbf{w}^H\mathbf{y} \tag{2.10}$$

where $\mathbf{w}$ is the combiner vector. Selection combining (SC), equal-gain combining (EGC) and maximal-ratio combining (MRC) are some of the well-known diversity combining schemes. MRC, where the combiner vector is obtained by $\mathbf{w} = \frac{\mathbf{h}}{N_0}$, is the optimal diversity combining technique when AWGN is the principle limiting factor. However, MRC is sub-optimal in the presence of co-channel interference since it does not suppress CCI. Therefore, diversity gains cannot be achieved using MRC in the presence of CCI.

When CCI present, optimum combining (OC) [19], [20] is the optimal diversity combining technique that maximizes the SINR at the receiver nodes. The combiner vector of OC is computed as

$$\mathbf{w} = \mathbf{R}_N^{-1}\mathbf{h} \tag{2.11}$$

where $\mathbf{R}_N$ is the noise-plus-interference correlation matrix, which is given by

$$\mathbf{R_N} = N_0\mathbf{I}_{M_R} + \sum_{k=1}^{N_I} P_{I_k}\mathbf{f}_k\mathbf{f}_k^H. \tag{2.12}$$

Note that the combiner vectors of MRC and OC are the same in the absence of CCI. It can be easily proved that the resulting SINR of OC is

$$\gamma = P_T\mathbf{h}^H\mathbf{R}_N^{-1}\mathbf{h} \tag{2.13}$$

If multiple antennas are used at the transmitter as well, the SINR at the output of the optimum combiner can be given as [21]

$$\gamma_{MIMO} = \frac{P_T}{M_T}\lambda_{max} \tag{2.14}$$

where M_T is the number of transmitter antennas, λ_{max} is the largest eigenvalue of the matrix $\mathbf{H}^H\mathbf{R}_{NN}^{-1}\mathbf{H}$, $\mathbf{R}_{NN} = N_0\mathbf{I}_{M_R} + \sum_{k=1}^{N_I}\frac{P_{I_K}}{M_{T_k}}\mathbf{F}_k\mathbf{F}_k^H$ and M_{T_k} are the number of transmit antennas at the k-th interferer.

2.5 Related Work and Limitations

2.5.1 Optimum combining for SIMO receivers in the presence of co-channel interference

Deterministic interference model

The performance of optimum combining (OC) in multiple antenna receivers has been extensively studied in the literature. In [19], it was shown that an interference-limited OC receiver with $M_R + 1$ antennas and a single strong interferer always outperforms a noise-limited MRC receiver with M_R antennas, which emphasizes the importance of using OC in the presence of CCI. The average bit error rate (BER) of OC was derived in [22] for $N_I = 1$ and 2, where N_I is the number of co-channel interferers. The outage probability of OC with an arbitrary number of equal-power interferers was derived in [23]. For this system model, approximations for the SER were derived in [24] when $N_I < M_R$, where M_R is the number of receiver antennas. The results further confirm the advantage of OC over MRC in the presence of interference.

Closed-form expressions for the average bit error rate (BER) of OC were derived for binary phase shift keying (BPSK) signaling in [25] and [26] for an arbitrary number of interferers with equal power and arbitrary powers, respectively. Performance analyses were carried out for both the underloaded ($N_I < M_R$) and the overloaded ($N_I \geq M_R$) systems. Accordingly, OC results in diversity gains only for underloaded systems in multiple antenna receivers. This work was extended for general PSK signaling in [27].

The above results were obtained based on the assumption that the interferer channel gains for different antennas of the same receiver are independent. However, due to the limited space between the antennas, independent channels are practically not realizable. In cooperative communications, even though the gains of desired channels are independent due to the geographical distribution of nodes, the interferer channel gains in different time slots are highly correlated. Hence the performance analysis of OC with correlated interferer channels is vital for cooperative communications.

In [28], the performance of OC with correlated fading of interferers was analyzed for an interference-only environment, assuming the same correlation matrix for the interferer and the desired channels. The impact of Gaussian noise was neglected. This work was generalized for different correlation matrices for the desired and the interferer channels in [29]. Both analyses were carried out for the case of $N_I \geq M_R$, since the interference correlation matrix is rank-deficient for $N_I < M_T$.

In [30], the average SER was derived for OC with a single correlated interferer, considering both interference and Gaussian noise. A closed-form expression for the outage probability of OC with multiple equal-power interferers with the same correlation matrix for the desired and the interferer channels was derived in [31] for both interference and Gaussian noise. For a single interferer, the asymptotic performance of OC with the increase of the number of antennas was studied in [32] using an average SINR analysis. The effects of spatial correlations on the performance of multiple-input multiple-output (MIMO) OC was analyzed in [33]. It was shown that the performance of OC improves with the increase of the interferer correlation factor and this effect gets more significant with the increase of the number of receiver antennas.

Random interference model

The outage probability of a multiple-antenna receiver using optimum combining in a homogeneous Poisson point process (PPP) was derived in [34]. The desired and the interferer channel gains were assumed to be spatially uncorrelated, separately. Furthermore, the receiver was assumed to be able to estimate the complete noise-plus-interference correlation matrix (NICM) perfectly. The performance of OC in a non-homogeneous PPP was studied in [35], where an expression for the cumulative distribution function was derived.

In a random field of interferers, the receiver may not be able to estimate the NICM perfectly. However, performance metrics of OC with the partial estimation of the NICM are not available in the literature.

Differences between the analyses of OC in SIMO and DF relaying

Since multiple relays create a virtual antenna array, decode-and-forward relaying is analogous to a distributed SIMO receiver. However, the performance metrics derived in the literature for SIMO receivers cannot be directly applied to DF cooperative relay networks due to the following reasons.

1. The majority of the general results derived for OC in SIMO systems are based on the assumption that the interferer channel gains of different antennas are independent. Even though the desired channel gains in cooperative relaying can

be assumed to be independent, the interferer channel gains in different time slots (equivalently, different antennas in SIMO) are highly correlated, unless the destination node is moving very fast with respect to the interferers. For SIMO systems with correlated interferers, the available results are mostly for specific cases (e.g. single interferer [30, 32], interference-only systems [28, 29, 33], the same correlations matrix for the desired and the interferer channels [31], etc.). Hence, it is necessary to derive performance metrics for a general system model with correlated interferer and uncorrelated desired channels, to be applied for cooperative communications.

2. For the performance analyses of OC in SIMO systems, it is commonly assumed that the desired channel coefficients are independent and identically distributed, which is not an accurate assumption for distributed antenna systems due to the large-scale fading effects (path loss and shadowing). Hence, fading of the desired channels should be independent and non-identically distributed (INID). In [36], the outage probability was derived for a SIMO system with an INID desired channel. However the interferer channel coefficients were also assumed to be independent, which is not the case with cooperative communications.

3. For multi-relay networks, the opportunistic relay selection improves the spectral efficiencies while maintaining diversity gains. For SIMO systems, the performance with antenna selection and OC has not been studied. Hence, the performance analysis of the joint effect of relay selection and OC is a novel and an important research area.

Furthermore, AF relaying is not analogous to a SIMO receiver and the performance of AF relaying with OC has not been studied in the literature. Compared to DF relaying, AF relaying is simple and more secure, which emphasizes the importance of studying the performance of OC in AF relaying. Consequently, the performance analysis of optimum combining in DF and AF cooperative relaying is a novel research area.

2.5.2 Cooperative communications in the presence of co-channel interference

Deterministic interference model

The performance of cooperative communications in the presence of interference has been investigated only for a limited number of system configurations. In [37], the outage performance of DF relaying was analyzed for interference-limited relay nodes and a noise-limited destination node with Nakagami-m fading. The performance of MRC in DF relaying was analyzed for Rayleigh fading in [38]. CCI was assumed to be present at both the relays and the destination. The effect of imperfect channel estimations on MRC was also analyzed. However, the effect of large scale fading was not considered and fading of all the links were assumed to be independent and identically distributed (IID). The outage performance DF relaying with MRC in the presence of CCI at both the relay nodes and the destination node was analyzed in [10] for Nakagami-m fading. Accordingly, in the presence of CCI, MRC results in positive diversity gains only if the interference-to-noise ratio (INR) remains constant. If the interferer powers increase with the source power, the diversity gains are lost.

The performance analyses of dual-hop AF relaying in the presence of CCI have been confined to single relay systems due to the complexity of the analysis. Furthermore, the direct link between the source and the destination has always been assumed to be shadowed. The performances of variable-gain (VG) and fixed-gain (FG) AF relaying in the presence of CCI were studied in [39–43] and [44, 45], respectively, for different channel and interferer configurations. However these configurations fail to achieve diversity gains in the presence of CCI.

In [46–48], the performance of AF relaying in the presence of CCI was analyzed for a relay network with multiple-antenna source and destination nodes and a single-antenna relay node. VG AF relaying with maximal ratio transmission (MRT) at the source node and MRC at the destination node was considered in [46]. The performance of VG AF relaying with transmit antenna selection at the source node, and MRC and SC at the destination node was studied in [47]. An FG AF relay network with MRT/MRC was studied in [48]. However, these systems are vulnerable to shadowing as the multiple antennas are co-located. Furthermore, diversity gains cannot be achieved using MRC or SC in the presence of CCI.

Random interference model

In [49], the performance of a dual-hop AF relay network was analyzed with the interferers at the destination node distributed according to a two-dimensional (2D) Poisson point process (PPP), where the outage probability and the average SER were derived. The performance of an N-hop AF cooperative relay network in a Poisson field of interferers was studied and the performance metrics were derived in [50] and [51] for Rayleigh and Nakagami-m fading, respectively. The direct link between the source node and the destination node was assumed to be shadowed in all these works, resulting in zero diversity gains. In [52], the direct link is present and MRC is used at the destination node to combine the signals received via the direct link and the relay-destination link. Nevertheless, interference cancellation was not applied.

The performance of DF relay network in a Poisson field of interferers was studied in [53] for SC and MRC at the destination. The spatial and temporal correlations of the interference in a Poisson interference field were considered here. However, the interference cancellation using OC was not considered. In [54], the performance of multihop DF relaying was studied for the same interference model.

2.5.3 Relay selection in the presence of co-channel interference

Deterministic interference model

The performance of opportunistic relay selection for DF relaying in the presence of CCI was analyzed in [55], where maximal-ratio combining (MRC) was used to combine the signals received from the source-destination link and the selected relay-destination link. The relay was selected based on the SINR of the relay-destination link. However, MRC is sub-optimal in the presence of CCI and does not cancel interference.

The performance of relay selection in the presence of CCI was analyzed in [56–59] for AF relaying. In [56] and [57], interference is present only at the relays.

In [58], both the relay nodes and the destination node are affected by CCI and the direct link between the source and the destination nodes was assumed to be shadowed. The direct link is available in [59] and interference is present only at the destination. However, the cancellation of CCI was not considered.

Random interference model

In [60], the outage performance and diversity gain of opportunistic relay selection in AF dual-hop relaying was analyzed in the presence of a Poisson field of interferers using an approximation for the instantaneous SINR expression of each source-relay-destination link. The authors of [61] used the exact instantaneous SINR expression of each source-relay-destination link to obtain the outage probability of AF opportunistic relay selection. The direct link was assumed to be shadowed in both these analyses and the interference mitigation was not considered.

2.5.4 Cooperative relaying with optimum combining

Deterministic interference model

A multiuser DF cooperative relay network was considered in [62], where intra-cell interference was assumed to be the main source of interference. Here, the SINR at output of the optimum combiner is

$$\gamma_{OC} = \frac{P_S|h_{SD}|^2}{N_0} + \frac{P_S|h_{RD}|^2}{N_0 + P_S|h_{SD}|^2} \tag{2.15}$$

where P_S is the source and relay power, and h_{SD} and h_{RD} are the source-destination and relay-destination channel coefficients, respectively.

Eq. (2.15) is different from the conventional SINR expression of OC as the two terms in the sum are not independent, resulting in a zero diversity gain. Furthermore, the practical cellular communications with the frequency reuse are limited by the inter-cell interference rather than the intra-cell interference. The performance further degrades if the inter-cell interference is also considered.

For AF relaying with a one multiple-antenna relay, the outage and capacity performances of CCI suppression at the relay node using OC were analyzed in [63] and [64], respectively. Here, the direct link is shadowed and the destination is interference free. For the same system model, the outage performance with CCI present at both the relay and the destination nodes was analyzed in [65]. Interference cancellation at the destination node was not considered here. Extending these results to multi-relay networks with a direct link is non-trivial and demands a separate analysis.

Random interference model

The performance of DF relaying with OC and MRC in a Poisson field of interference was studied in [66]. However, the interference cancellation capability of OC was not taken into consideration. Hence, the results obtained in this work are sub-optimal.

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Chapter 3

Optimum Combining in Decode-and-Forward Relaying

The performance of optimum combining in a decode-and-forward relay network with N equal-power interferers is analyzed. The probability density function of the output signal-to-interference-plus-noise ratio is obtained and a closed-form expression for the exact outage probability is derived for $N \geq M + 1$, where M is the number of relay nodes. An approximation for the symbol error rate (SER) is presented. The performance results and closed-form expressions for outage probability and for SER suggest that the asymptotic diversity gain of OC is equal to M, which is a significant improvement over maximal-ratio combining, whose asymptotic diversity gain is equal to zero when operating with co-channel interference[1].

3.1 Introduction

The advantages of cooperative relaying over non-cooperative wireless communications include increased diversity, coverage extension and mitigation of shadowing. Cooperative relaying protocols can be mainly divided into two categories: amplify-and-forward (AF) and decode-and-forward (DF) [1]. One can identify a wide rage of publications analyzing the performance for DF relaying in noise-limited environments for different channel and system models [2–4]. Maximal-ratio combining

[1] A version of this chapter was presented in the IEEE International Conference on Communications (ICC 2013), Budapest, Hungary.
N. Suraweera and N. C. Beaulieu, "Performance analysis of decode-and-forward relaying with optimum combining in the presence of co-channel interference," in *Proc. IEEE Conference on Communications (ICC 2013)*, pages 4968–4972, Jun. 2013.

(MRC) is the diversity combining technique that maximizes the signal-to-noise ratio (SNR) at the receiver in additive white Gaussian noise (AWGN) [5]. However, the performance of spectrally efficient practical wireless communication systems is limited by the co-channel interference, rather than by noise.

When co-channel interference is present, optimum combining (OC) is the diversity combining technique that maximizes the signal-to-interference-plus-noise ratio (SINR) [6]. Unlike MRC, OC reduces the interference power component at the receiver, enhancing the diversity gain. Bounds to the performance of OC for multiple-antenna receivers were analyzed in [7–9] and the references therein.

The outage and symbol error rate (SER) performance of DF cooperative relay networks using MRC were analyzed for an arbitrary number of equal-power Rayleigh fading interferers in [10]. The effect of imperfect channel estimation at the receiver on the performance was also studied. In [11], a detailed analysis of a DF relay system with non-identical Nakagami-m fading interferers with MRC at the receiver was carried out and a closed-form expression for the exact outage probability was derived.

In this chapter, we investigate the performance of OC in a DF relay network with co-channel interference and Rayleigh fading. The probability density function (PDF) of the output SINR of the optimum combiner is derived for the scenario where $N \geq M + 1$, where N is the number of interferers and M is the number of relay nodes. Moreover, a closed-form expression for the exact outage probability is derived and an accurate approximation for the SER is derived for the binary phase shift keying (BPSK) modulation scheme. The outage and SER expressions show that the asymptotic diversity gain of OC is equal to M, which is a significant improvement in performance compared to MRC.

The remainder of this chapter is organized as follows. Section 3.2 describes the system and channel models used for the DF relay network. In Section 3.3, we analyze the performance of DF relay networks with OC, where SINR PDF, exact outage probability and approximate SER are derived. In Section 3.4, numerical results are presented and discussed and Section 3.5 concludes this chapter.

3.2 System and Channel Models

A DF cooperative relay network with a source node (S), a destination node (D) and M relays ($R_i, i \in \{1, \ldots, M\}$) is considered. It is assumed that the co-channel interference is present only at node D, which is interfered by N signals with equal average power (Fig. 3.1). It is assumed that source-destination, source-relay, relay-destination and interferer-destination links are frequency-flat Rayleigh faded with $g_0 \sim \mathcal{CN}(0, \sigma_g^2)$, $h_i \sim \mathcal{CN}(0, \sigma_h^2)$, $g_i \sim \mathcal{CN}(0, \sigma_g^2)$ and $f_j \sim \mathcal{CN}(0, \sigma_f^2)$ where $i \in \{1, 2, \ldots, M\}$ and $j \in \{1, 2, \ldots, N\}$. We assume that the destination node is equipped with the exact channel state information of the relay-destination and interferer-destination links.

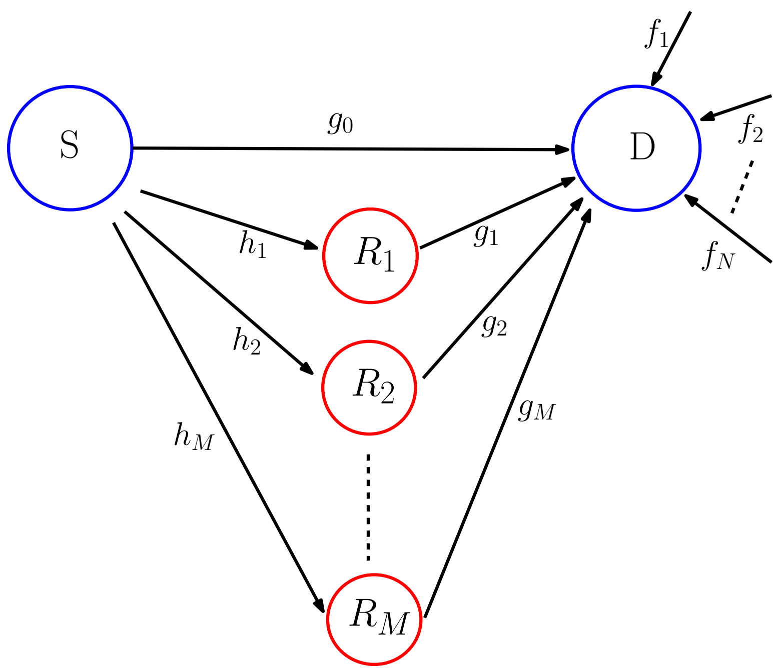


Figure 3.1: Decode-and-forward cooperative relay network with co-channel interference at the destination node.

During the first phase of the communication, the source node broadcasts its data symbols to the destination and to all the relays. The signal received at D in phase 1 is given by

$$y_{S,D} = \sqrt{P_S} g_0 x_0 + \sqrt{P_I} \sum_{i=1}^{N} f_i x_i + n_{S,D} \tag{3.1}$$

where P_S is the transmitter power and P_I is the interferer power, x_0 is the data symbol transmitted by node S and x_i $(i = 1, 2, \ldots, N)$ are the data symbols transmitted by the interferer nodes. $n_{S,D}$ is the noise at node D in the first phase and $n_{S,D} \sim \mathcal{CN}(0, N_0)$. The signal received at relay R_j in phase 1 is given by

$$y_{S,R_j} = \sqrt{P_S} h_j x_0 + n_{S,R_j} \tag{3.2}$$

where $n_{S,R_j} \sim \mathcal{CN}(0, N_0)$.

In the second phase, the relay nodes that correctly detect the transmitted data symbols will forward the data symbols to the destination in orthogonal time slots, i.e. at a given time, the destination will receive a signal replica transmitted by only one relay node. It is assumed that error detection coding is utilized to detect errors at relay nodes. The relays that encounter errors in decoding inform the destination node about the failure using a pre-defined sequence. Therefore, the destination node can identify the relay nodes that decoded the message correctly. We assume that interferer-destination channel states do not change during the second phase. Assuming that C relays out of M decode the symbols received from node S correctly, the received signal at the destination in the j-th time slot in phase 2 is given by

$$y_{R_j,D} = \sqrt{P_S} g_j x_0 + \sqrt{P_I} \sum_{i=1}^{N} f_i x_i + n_{R_j,D}, \qquad j \in \{1, \ldots, C\}. \tag{3.3}$$

The optimum combiner at node D combines the received signals at $C+1$ time slots to obtain the decision variable $x = \mathbf{w}^H \mathbf{y}$. The weight vector $\mathbf{w}$ is given by $\mathbf{w} = \mathbf{R}^{-1}\mathbf{g}$, where $\mathbf{R}$ is the noise+interference correlation matrix, which is defined by [6]

$$\mathbf{R} = N_0 \mathbf{I}_{C+1} + P_I \sum_{i=1}^{N} |f_i|^2 \mathbf{1}_{C+1} \mathbf{1}_{C+1}^H \tag{3.4}$$

where $\mathbf{1}$ is the $(C+1)$-dimension vector consisting of all ones.

The resulting SINR at the receiver is given by [12]

$$\gamma|C = P_S \mathbf{g}^H \mathbf{R}^{-1} \mathbf{g} \tag{3.5}$$

which can also be expressed as

$$\gamma|C = P_S \boldsymbol{\alpha}^H \boldsymbol{\Phi}^{-1} \boldsymbol{\alpha} \tag{3.6}$$

where $\boldsymbol{\alpha} = \mathbf{U}\mathbf{g}$ in which $\mathbf{U}$ is the matrix consisting of the eigenvectors of $\mathbf{R}$ and $\boldsymbol{\Phi}$ is the matrix of eigenvalues of $\mathbf{R}$. Since $\mathbf{U}$ is a unitary matrix, $\boldsymbol{\alpha}$ has the same statistics as $\mathbf{g}$. Hence, the output SINR given C can be reformulated as

$$\begin{aligned}\gamma|C &= P_S\left[\frac{|\alpha_0|^2}{N_0 + P_I(C+1)\sum_{i=1}^{N}|f_i|^2} + \sum_{j=1}^{C}\frac{|\alpha_j|^2}{N_0}\right] \\ &= P_S\left[\frac{X}{Y} + Z\right]. \end{aligned} \tag{3.7}$$

3.3 Performance Analysis

3.3.1 Probability density function of the SINR at the destination after optimum combining

The conditional moment generating function (MGF) of γ can be expressed as

$$\mathcal{M}_{\gamma|Y,C}(s) = \frac{N_0^C Y}{\left(\sigma_g^2\right)^{C+1}} \frac{1}{\left(s + \frac{Y}{\sigma_g^2}\right)} \frac{1}{\left(s + \frac{N_0}{\sigma_g^2}\right)^C}. \tag{3.8}$$

Hence, the conditional probability density function $f_\gamma(\gamma|Y, C)$ can be given as

$$f_{\gamma|Y,C}(\gamma) = K_1\left(\frac{\exp\left(\frac{-Y\gamma}{\sigma_g^2}\right)}{\left(\frac{N_0 - Y}{\sigma_g^2}\right)^C} + \frac{\sum_{i=1}^{C}(-1)^{i-1}\gamma^{C-i}\exp\left(\frac{-N_0\gamma}{\sigma_g^2}\right)}{\left(\frac{Y-N_0}{\sigma_g^2}\right)^i (C-i)!}\right) \tag{3.9}$$

where $K_1 = \frac{N_0^C}{\left(\sigma_g^2\right)^{C+1}}$. The conditional PDF of Y is given by

$$f_{Y|C}(y) = \frac{(y-N_0)^{N-1}\exp\left(-\frac{y-N_0}{\sigma_f^2 P_I(C+1)}\right)}{\left(\sigma_f^2 P_I(C+1)\right)^N (N-1)!}. \tag{3.10}$$

Therefore, the PDF of γ conditioned on C can be written as

$$\begin{aligned} f_{\gamma|C}(\gamma) = \int_0^\infty K_1(N_0 + y)\Bigg[&\frac{(\sigma_g^2)^C\exp\left(-\frac{N_0\gamma + y\gamma}{\sigma_g^2}\right)}{-y^C} \\ &+ \sum_{i=1}^{C}(-1)^{i-1}\frac{(\sigma_g^2)^i\gamma^{C-i}\exp\left(\frac{-N_0\gamma}{\sigma_g^2}\right)}{y^i(C-i)!}\Bigg]\frac{y^{N-1}\exp\left(-\frac{y}{\sigma_f^2 P_I(C+1)}\right)}{\left(\sigma_f^2 P_I(C+1)\right)^N (N-1)!}dy \end{aligned} \tag{3.11}$$

From (3.11), we can observe that if $N - 1 < M$ we are unable to obtain a closed-form solution for the PDF as the power of y in the integral becomes negative for some values of C. In order to perform further analysis we assume that $N-1 \geq M$. The conditional PDF $f_{\gamma|C}(\gamma)$ for the scenario when $N-1 \geq M$ can be presented as

$$f_{\gamma|C}(\gamma) = K_2 \text{exp}\left(\frac{-N_0\gamma}{P_S\sigma_g^2}\right)(g_1(\gamma)+g_2(\gamma)) \tag{3.12a}$$

where

$$K_2 = \frac{K_1}{P_S\left(\sigma_f^2 P_I(C+1)\right)^N (N-1)!} \tag{3.12b}$$

$$g_1(\gamma) = \sum_{i`=1}^{C} \gamma^{C-i} K_3(i) \tag{3.12c}$$

$$g_2(\gamma) = (-1)^C \left(\frac{\sigma_g^2 N_0 (N-1-C)!}{\left(\frac{\gamma}{P_S\sigma_g^2} + \frac{1}{\sigma_f^2 (C+1) P_I}\right)^{N-C}} + \frac{\sigma_g^2 (N-C)!}{\left(\frac{\gamma}{P_S\sigma_g^2} + \frac{1}{\sigma_f^2 (C+1) P_I}\right)^{N-C+1}} \right) \tag{3.12d}$$

and $K_3(i)$ is defined as

$$\begin{aligned} K_3(i) = \frac{(-1)^i \sigma_g^2}{P_S^{C-i}(C-i)!}\Bigg(& \left(\sigma_f^2 P_I(C+1)\right)^{N-i}(N-i-1)! \\ & + \left(\sigma_f^2 P_I(C+1)\right)^{N-i+1}(N-i)!\Bigg). \end{aligned} \tag{3.12e}$$

Based on the principle of total probability, the PDF of SINR at the output of the optimum combiner is expressed as [10]

$$\begin{aligned} f_\gamma(\gamma) &= \sum_{m=0}^{M} f_{\gamma|m}(\gamma)\mathcal{P}(C=m) \\ &= \sum_{m=0}^{R} \left(\begin{array}{c} M \\ m \end{array} \right) P_e^{M-m}(1-P_e)^m f_{\gamma|m}(\gamma) \end{aligned} \tag{3.13}$$

where P_e is the probability of error at a given relay station. For BPSK modulation with Rayleigh fading $P_e = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}}{1+\bar{\gamma}}}\right]$ [5] where $\bar{\gamma}$ is the average signal-to-noise ratio (SNR) at a given relay given by $\bar{\gamma} = \frac{P_S}{N_0}$. Fig. 3.2 shows the PDF of the output SINR of the optimum combiner, obtained using (3.13) for $M = 2, 4$ and 8 for ten co-channel interferers with $P_S = 10$ dB, $P_I = 0$ dB and $N_0 = 0$ dB.

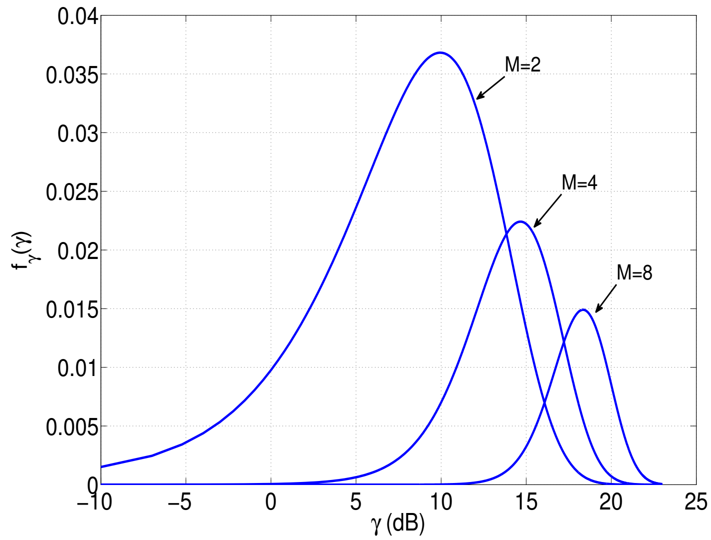


Figure 3.2: The PDF of the output SINR of the optimum combiner with $M = 2, 4$ and 8.

3.3.2 Outage probability

The outage probability is defined as $P_{out} = \mathcal{P}(\gamma \leq \gamma_T) = \int_0^{\gamma_T} f_\gamma(\gamma)d\gamma$ where γ_T is the SINR threshold. The resulting P_{out} can be given as

$$P_{out} = 1 - \sum_{m=0}^{M} \left(\begin{array}{c} M \\ m \end{array} \right) P_e^{M-m}(1-P_e)^m \int_{\gamma_T}^{\infty} f_{\gamma|m}(\gamma)d\gamma. \tag{3.14}$$

The solution of the integral $\int_{\gamma_T}^{\infty} f_\gamma(\gamma|m)d\gamma$ can be found as [13, 3.353.1]

$$\begin{aligned}\int\limits_{\gamma_T}^{\infty} f_{\gamma|m}(\gamma)d\gamma = K_2\Bigg\{&\exp\left(-\frac{\gamma_T N_0}{P_S\sigma_g^2}\right)\sum_{i=1}^{m} K_3(i)\sum_{k=0}^{m-i}\frac{(m-i)!\gamma_T^k}{k!\left(\frac{N_0\gamma_T}{P_S\sigma_g^2}\right)^{m-i-k+1}}\\ &+\left(-\sigma_g^2\right)^m\Bigg(N_0(N-1-m)!(P_S\sigma_g^2)^{N-m}\\ &\times\left(\exp\left(-\frac{\gamma_T N_0}{P_S\sigma_g^2}\right)\sum_{k=1}^{N-m-1}\frac{(k-1)!\left(-\frac{N_0}{P_S\sigma_g^2}\right)^{N-m-k-1}}{(N-m-1)!\left(\gamma_T+\frac{P_S\sigma_g^2}{\sigma_f^2(m+1)}P_I\right)^k}\right.\\ &-\frac{\left(-\frac{N_0}{P_S\sigma_g^2}\right)^{N-m-1}}{(N-m-1)!}\exp\left(\frac{N_0}{\sigma_f^2(m+1)P_I}\right)\\ &\left.\times\,\mathrm{Ei}\left[-\left(\gamma_T+\frac{P_S\sigma_g^2}{\sigma_f^2(m+1)P_I}\right)\right]\right)+(N-m)!(P_S\sigma_g^2)^{N-m+1}\\ &\times\left(\exp\left(-\frac{\gamma_T N_0}{P_S\sigma_g^2}\right)\sum_{k=1}^{N-m}\frac{(k-1)!\left(-\frac{N_0}{P_S\sigma_g^2}\right)^{N-m-k}}{(N-m)!\left(\gamma_T+\frac{P_S\sigma_g^2}{\sigma_f^2(m+1)}P_I\right)^k}\right.\\ &-\frac{\left(-\frac{N_0}{P_S\sigma_g^2}\right)^{N-m}}{(N-m)!}\exp\left(\frac{N_0}{\sigma_f^2(m+1)P_I}\right)\\ &\left.\times\,\mathrm{Ei}\left[-\left(\gamma_T+\frac{P_S\sigma_g^2}{\sigma_f^2(m+1)P_I}\right)\right]\right)\Bigg)\Bigg\}\end{aligned} \tag{3.15}$$

where $\mathrm{Ei}(x)$ is the exponential integral function defined in [13, 8.211.1].

By examination of the expression for P_{out}, we can deduce that the asymptotic diversity gain of the optimum combiner is equal to M, which is a significant improvement compared to MRC, where the asymptotic diversity gain equals zero when the signal-to-interference ratio (SIR) remains constant.

3.3.3 Average symbol error rate

For BPSK modulation, the average symbol error rate at the receiver can be approximated as [12]

$$\mathrm{SER} \approx \int\limits_{0}^{\infty} \mathcal{Q}\left(\sqrt{2\gamma}\right) f_\gamma(\gamma)d\gamma. \tag{3.16}$$

However, a closed-form expression for the SER based on the exact SINR PDF in (3.13) is difficult to obtain. Instead, we use an approximation for the SINR PDF, which is confirmed to be accurate for all values of P_S.

Recall $f_\gamma(\gamma|C)$ can be given as in (3.12a). Here, $g_1(\gamma) >> g_2(\gamma)$ for $\gamma > 1$. Furthermore, the term $K_2 \mathrm{exp}\left(\frac{-N_0\gamma}{P_S\sigma_g^2}\right) g_2(\gamma)$ does not contribute to the diversity gain of the optimum combiner as the power of P_S in this term is equal to zero. The diversity gain is determined by the term $K_2 \mathrm{exp}\left(\frac{-N_0\gamma}{P_S\sigma_g^2}\right) g_1(\gamma)$. Consequently, the approximate SINR PDF can be given as

$$f_\gamma(\gamma) \approx \sum_{m=1}^{M} \left(\begin{array}{c} M \\ m \end{array}\right) P_e^{M-m} K_2 \mathrm{exp}\left(\frac{-N_0\gamma}{P_S\sigma_g^2}\right) g_1(\gamma). \tag{3.17}$$

Fig. 3 shows comparisons between exact PDFs and CDFs and approximate PDFs and CDFs for transmit power levels of 5 dB and 10 dB with M =2, 4 and 8 and SIR of 10 dB. The results confirm that the approximation is accurate for all values of P_S considered.

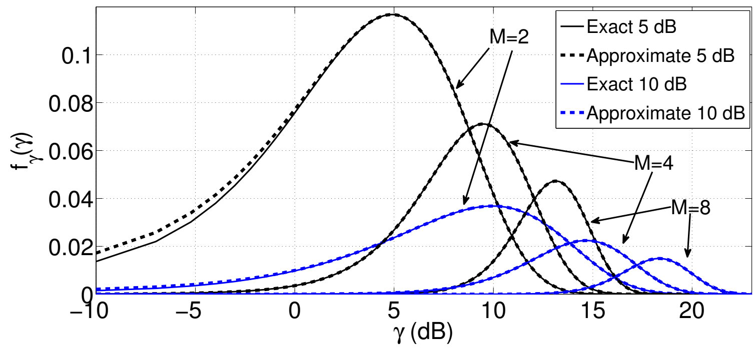
Based on the approximate SINR PDF given in (3.17), the asymptotic SER can be solved as [12]

$$\begin{aligned} \mathrm{SER} \approx \sum_{m=1}^{M} \left(\begin{array}{c} M \\ m \end{array}\right) P_e^{M-m}(1-P_e)^m K_2(m) \sum_{i=1}^{m} \frac{(-1)^{i-1}\sigma_g^2 K_3(i)}{4^{m-i+1}} \\ \times \left(\begin{array}{c} 2(m-i)+1 \\ m-i+1 \end{array}\right). \end{aligned} \tag{3.18}$$

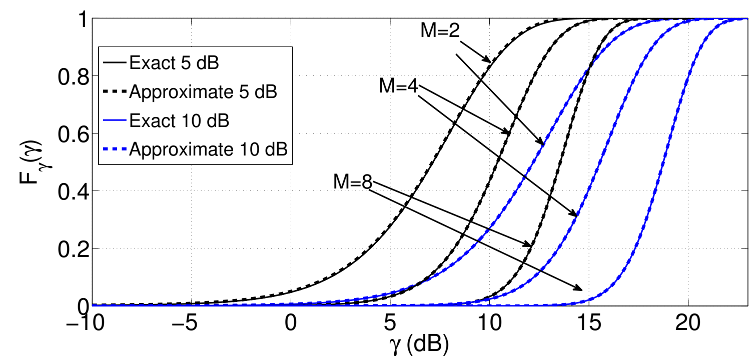
It is apparent from (3.18) and (3.12) that the maximum power of $1/P_S$ is M in the average SER expression. Hence, the asymptotic diversity gain of the optimum combiner is M.

3.4 Numerical Results and Discussion

In this section, we compare numreical results obtained from the analytical expressions derived for the outage probability and SER with simulation results. There are 10 interferers at the destination each having $P_I = 0.1P_S$. It is assumed that $\sigma_h^2 = \sigma_g^2 = \sigma_f^2 = 1$. The source and relay nodes are assumed to use BPSK modulation. Simulations are carried out until 10^3 outages / errors are obtained for each SNR value.



(a)



(b)

Figure 3.3: Comparison between exact and approximate SINR for (a) PDFs and (b) CDFs.

The outage probability performance results are shown in Fig. 3.4 for $\gamma_T = 5$ dB and in Fig. 3.5 for $\gamma_T = 3$ dB, 5 dB and 10 dB. One sees that the analytical expression derived for the outage probability coincides with the simulation results. Observe that a diversity gain of M is achieved using OC. As expected, the outage performance deteriorates with increase of the SINR threshold in Fig. 3.5. However, for a given number of relays the slope of the curve, which is the diversity gain of the system, does not change with the SINR threshold.

In Fig. 3.6, we investigate the accuracy of the approximation for the average SER by comparison with precise simulation results. It can be observed that the approximation for the average SER is accurate for $M = 4$ and 8. Furthermore, for $M = 2$, the approximated average SER is about 50% larger than the exact value. This is acceptable for system design, where a factor of 2 in the raw SER is tolerable.

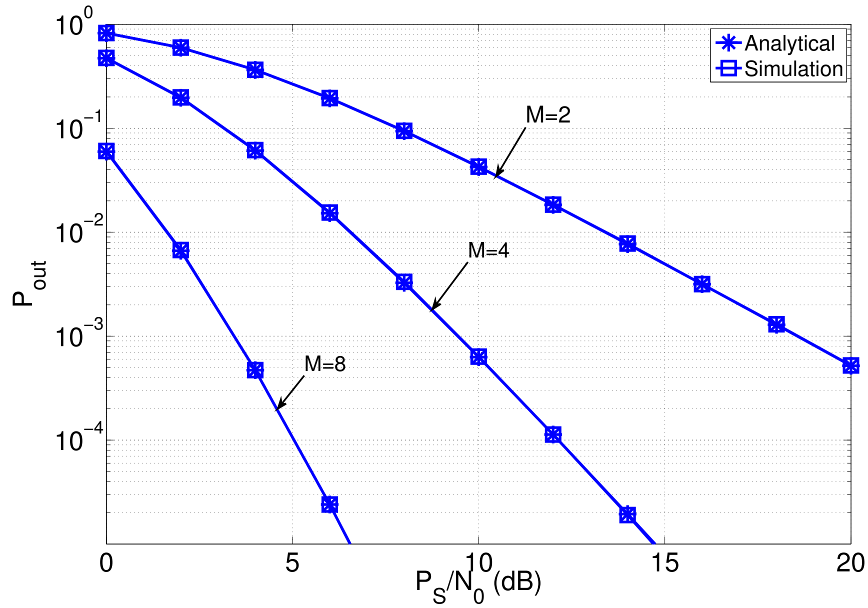


Figure 3.4: Outage performance of the optimum combiner for $M = 2, 4$ and 8.

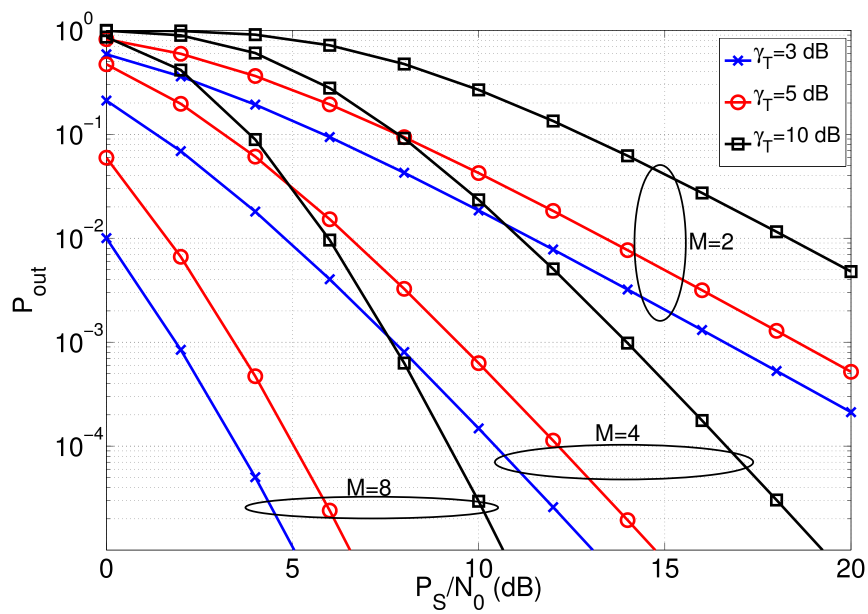


Figure 3.5: Outage performance of the optimum combiner for $M = 2, 4$ and 8 with variation of γ_T.

We compare the average SER performance of OC with MRC in Fig. 3.7. Ac-

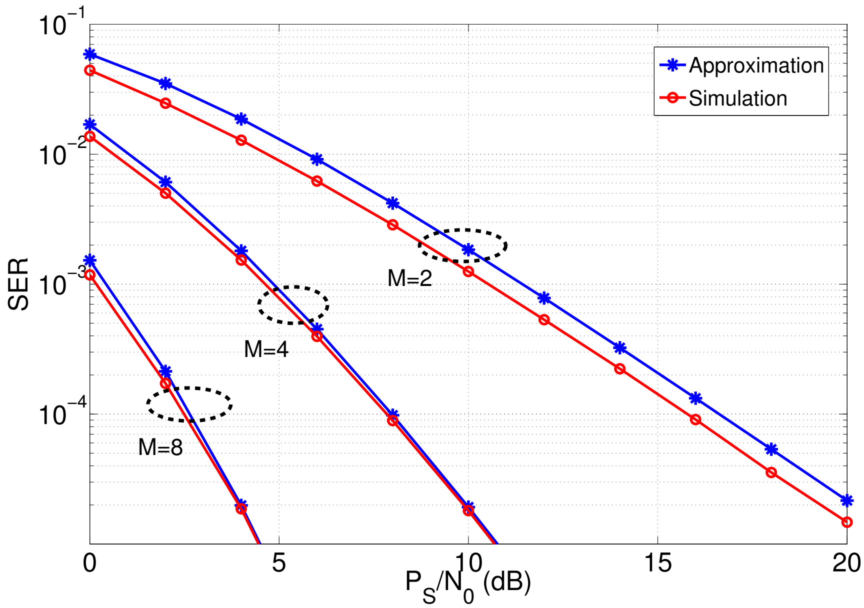


Figure 3.6: Average SER performance of the optimum combiner for $M = 2, 4$ and 8.

cordingly, we can observe that OC shows a significant performance gain over MRC. It is evident that MRC reaches an error floor, which can be explained using the instantaneous SINR expression for MRC, which is the sum of the SINR of each branch [10]. Importantly, OC always shows a positive diversity gain.

3.5 Conclusion

In this chapter, we studied the performance of optimum combining in DF relaying. We derived exact expressions for the PDF of the output SINR and outage probability for $N \geq M+1$. It was shown that the asymptotic diversity gain of OC is equal to M. Moreover, we derived an accurate approximation for the average symbol error rate for BPSK modulation. Furthermore, we compared the average SER performance of OC with MRC. It was shown that OC provides a significant performance gain over MRC, whose asymptotic diversity gain reduces to zero in the presence of co-channel interference.

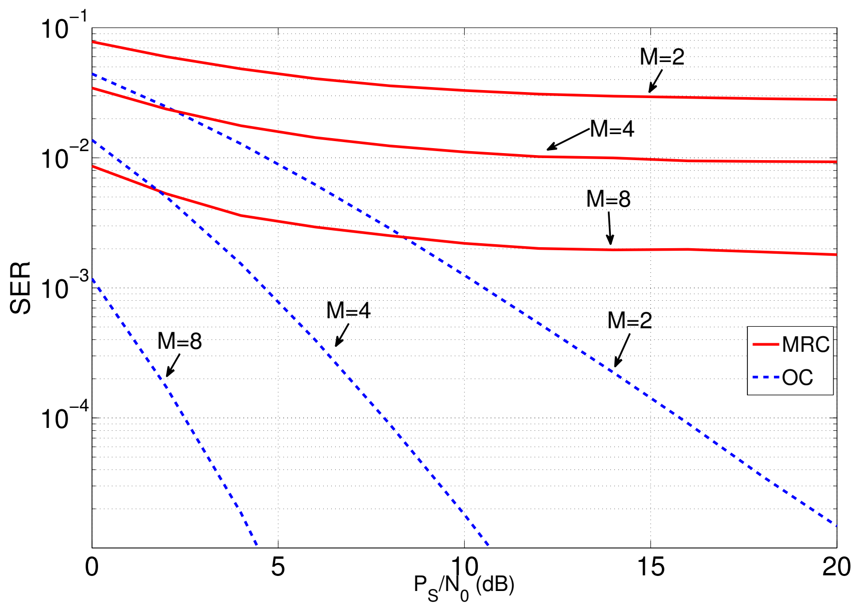


Figure 3.7: Comparison of the SER performance of the optimum combiner (OC) with that of maximal-ratio combiner (MRC) for $M = 2, 4$ and 8.

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Chapter 4

Decode-and-Forward Relaying with Optimum Combining in Nakagami Fading

The performance of optimum combining (OC) used in a decode-and-forward relay network over Nakagami-m fading channels in the presence of co-channel interference at the relay nodes and at the destination is analyzed. A closed-form expression is derived for the exact outage probability. It is found that OC cannot be used to achieve end-to-end diversity gain when interference is present at single-antenna relays, but the outage probability floor at the destination receiver is lowered by the OC. If the interference is present only at the destination, diversity gains can be achieved using OC. The performance of OC is compared with maximal-ratio combining (MRC) and OC achieves diversity gain if interference is present only at the destination node, whereas MRC does not[1].

4.1 Introduction

The performance analysis of decode-and-forward (DF) relaying has been carried out for a wide range of system and channel models [1, 2]. However, the majority of these studies are confined to a system model where thermal noise is the dominant limiting factor. Yet, in practical wireless communication networks with frequency

[1]A version of this chapter was published in IEEE Wireless Communications Letters, N. Suraweera and N. C. Beaulieu, "Outage Probability of Decode-and-Forward Relaying with Optimum Combining in the Presence of Co-Channel Interference and Nakagami Fading", *IEEE Wireless Communications Letters*, vol. 2, no. 5, pp. 495-498, Oct. 2013.

reuse, co-channel interference is the dominant limiting impairment.

When co-channel interference is present, optimum combining (OC) is the diversity combining technique that maximizes the signal-to-interference-plus-noise ratio (SINR) at the receiver [3]. In OC, higher diversity gains are achieved by suppressing the co-channel interference power component. The performance of OC with multiple-antenna receivers was analyzed in [4–6] and the references therein.

In this chapter, the outage performance of DF relay networks with OC in the presence of co-channel interference is analyzed. All the channels are subject to slow Nakagami-m fading. A closed-form expression is derived for the exact outage probability when interference is present at the relays and at the destination. Results indicate that, compared to the maximal-ratio-combiner (MRC) receiver, higher diversity gains are achieved using the OC receiver when the interference is present only at the destination node. When the interference is present at the relay nodes, the performance of both combining techniques degenerate to zero diversity gain, but OC outperforms MRC, resulting in lower outage probability floors.

The remainder of this chapter is organized as follows. Section 4.2 describes the system and channel models used for the DF relay network. In Section 4.3, a closed-form expression for the outage probability of the OC receiver is derived. Numerical results and simulation results are presented and discussed in Section 4.4, and Section 4.5 concludes this chapter.

4.2 System and Channel Models

See Fig. 4.1. A DF cooperative relay network with a source node (S), a destination node (D) and M number of relays ($R_i, i \in \{1, \ldots, M\}$) is considered. Each node is equipped with a single antenna. R_i is interfered by N_{R_i} number of co-channel interferers and the destination node is interfered by N_D interferers. The source-destination, source-relay, relay-destination, interferer-relay and interferer-destination links are slow Nakagami-m faded with m-factors m_g, m_h, m_g, m_f and m_l, respectively. All the m factors are assumed to be integers. The source-destination, source-relay, relay-destination, interferer-relay and interferer-destination channel coefficients are marked for each channel in Fig. 4.1. In this chapter, only slow small-scale fading is considered and pathloss and shadowing are ignored. It is assumed that the destination node is equipped with the exact channel state information of the relay-destination and interferer-destination links.

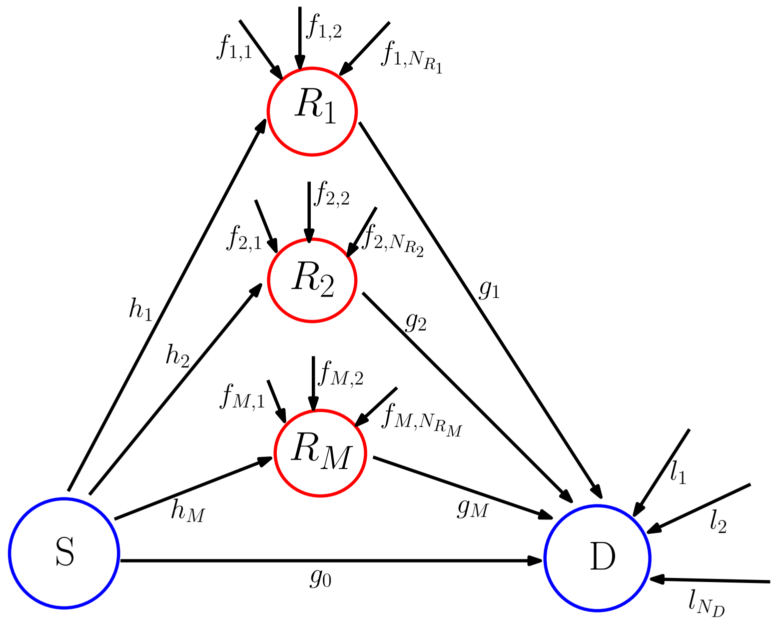

Figure 4.1: The decode-and-forward cooperative relay network with co-channel interference at the relay nodes and the destination node.

During the first phase of the communication, the source node broadcasts its data symbols to the destination and to all the relays. The signal received at D in phase 1 is given by

$$y_{S,D} = \sqrt{P_S} g_0 x_0 + \sum_{j=1}^{N_D} \sqrt{P_{ID_j}} l_j x_j + n_{S,D} \tag{4.1}$$

where P_S is the transmitter power, $\{P_{ID_j}\}$ are the average powers of the interferers at the destination, x_0 is the data symbol transmitted by node S and x_j ($j \in \{1, 2, \ldots, N_D\}$) are the data symbols transmitted by the interferer nodes. The noise at node D in the first phase, denoted by $n_{S,D}$, is complex and $n_{S,D} \sim \mathcal{CN}(0, N_0)$, where $\mathcal{CN}(0, N_0)$ denotes complex normal with mean zero and variance N_0. The signal received at relay R_i in phase 1 is

$$y_{S,R_i} = \sqrt{P_S} h_i x_0 + \sum_{j=1}^{N_{R_i}} \sqrt{P_{IR_{i,j}}} f_{i,j} t_{i,j} + n_{S,R_i} \tag{4.2}$$

where $P_{IR_{i,j}}$ is the average power of the j-th interferer at the i-th relay, $n_{S,R_i} \sim \mathcal{CN}(0, N_0)$ and $t_{i,j}$ is the symbol transmitted by the interferer j at R_i. The SINR at R_i is

$$\gamma_{R_i} = \frac{P_S|h_i|^2}{\sum_{j=1}^{N_{R_i}} P_{IR_{i,j}}|f_{i,j}|^2 + N_0} = \frac{X_{R_i}}{Y_{R_i} + N_0}. \tag{4.3}$$

In the second phase, the relay nodes that successfully decode the transmitted data symbols will forward the data symbols to the destination in orthogonal time slots, i.e. at a given time, the destination will receive a signal replica transmitted by only one relay node. It is assumed that the data symbols received at R_i are successfully decoded when $\gamma_{R,i} \geq \gamma_T$, where γ_T is the SINR value which corresponds to the minimum desirable rate R_{min} [7]. The interferer-relay and interferer-destination channel states are assumed to be unchanged during the second phase as the fading is assumed to be slow. Assuming C number of relays out of M decode the symbols received from node S correctly, the received signal at the destination in the i-th time slot in phase 2 is given by

$$y_{R_i,D} = \sqrt{P_S} g_i x_0 + \sum_{j=1}^{N_D} \sqrt{P_{ID_j}} l_j u_{i,j} + n_{R_i,D}, \quad i \in \{1, \ldots, C\} \tag{4.4}$$

where $u_{i,j}$ is the symbol transmitted by interferer j at the destination node in time slot i. The OC receiver at node D combines the received signals in $C+1$ time slots to obtain the decision variable $x = \mathbf{w}^H \mathbf{y}$, where $\mathbf{y} = [y_{S,D}, y_{R_1,D}, \ldots, y_{R_C,D}]^T$. The weight vector $\mathbf{w}$ is given by $\mathbf{w} = \mathbf{R}^{-1}\mathbf{g}$, where $\mathbf{g} = [g_0, g_1, \ldots, g_C]^T$ and $\mathbf{R}$ is the noise+interference correlation matrix, which is defined by [3]

$$\mathbf{R} = N_0 \mathbf{I}_{C+1} + \sum_{j=1}^{N_D} P_{ID_j} |l_i|^2 \mathbf{1}_{C+1} \mathbf{1}_{C+1}^H. \tag{4.5}$$

The resulting SINR of the OC receiver is given by [8, eq. (11.2)]

$$\gamma_D | C = P_S \mathbf{g}^H \mathbf{R}^{-1} \mathbf{g} = P_S \boldsymbol{\alpha}^H \boldsymbol{\Phi}^{-1} \boldsymbol{\alpha} \tag{4.6}$$

where $\boldsymbol{\alpha} = \mathbf{U}\mathbf{g}$ in which $\mathbf{U}$ is the matrix consisting of the eigenvectors of $\mathbf{R}$ and $\boldsymbol{\Phi}$ is the matrix of eigenvalues of $\mathbf{R}$. Since $\mathbf{U}$ is a unitary matrix, the elements of $\boldsymbol{\alpha}$ have the same statistics as the elements of $\mathbf{g}$ [8, eq. (11.44)]. Since $\boldsymbol{\Phi}$ is a diagonal matrix, for the $\mathbf{R}$ defined in (4.5) the inverse of the eigenvalue matrix $\mathbf{\Phi}$ can be given as

$$\mathbf{\Phi}^{-1} = \text{diag}\left[\frac{1}{(C+1)\sum_{j=1}^{N_D} P_{ID_j}|l_j|^2 + N_0}, \frac{1}{N_0}, \dots, \frac{1}{N_0}\right] \tag{4.7}$$

where diag$(\mathbf{v})$ represents the diagonalization of the vector $\mathbf{v}$. It should be noted that the only non-zero eigenvalue of the matrix $\sum_{j=1}^{N_D} P_{ID_j}|l_i|^2 \mathbf{1}_{C+1}\mathbf{1}_{C+1}^H$ is equal to $(C+1)\sum_{j=1}^{N_D} P_{ID_j}|l_j|^2$. Hence, the output SINR of the OC receiver given C relays successfully decode the message, can be reformulated as

$$\gamma_D|C = P_S\left[\frac{|\alpha_0|^2}{(C+1)\sum_{j=1}^{N_D} P_{ID_j}|l_j|^2 + N_0} + \sum_{i=1}^{C}\frac{|\alpha_i|^2}{N_0}\right] = \frac{X_D}{Y_D + N_0} + Z_D. \tag{4.8}$$

4.3 Exact Outage Probability

4.3.1 Outage probability at R_i

From (4.3), the outage probability at R_i can be given as [9]

$$\mathcal{P}(\gamma_{R,i} \leq \gamma_T) = P_{R_i} = 1 - \int_0^{\infty}\int_{y+N_0}^{\infty} f_{Z_R}(z) f_{Y_R}(y)\, dx\, dy \tag{4.9}$$

where $Z_R = X_R/\gamma_T$ and Z_R is a gamma distributed random variable (RV) with scale parameter $\frac{P_S}{m_h\gamma_T}$ and shape parameter m_h. Assuming the interferer powers are distinct, the probability density function (PDF) of Y_{R_i} can be found as [9, 10]

$$f_{Y_{R_i}}(y) = \sum_{m=1}^{N_{R_i}}\sum_{n=1}^{m_f}\frac{A_{mn} y^{n-1} \text{exp}\left(-\frac{m_f y}{P_{IR_{i,m}}}\right)}{(n-1)!} \tag{4.10a}$$

where

$$A_{mn} = (-1)^n\left(\frac{-m_f}{P_{IR_{i,m}}}\right)^{m_f}\sum_{\tau(m,n)}\prod_{k=1,k\neq m}^{N_{R_i}}\begin{pmatrix} m_f + q_k - 1 \\ q_k \end{pmatrix}\frac{\left(\frac{P_{IR_{i,k}}}{m_f}\right)^{q_k}}{\left(1 - \frac{P_{IR_{i,k}}}{P_{IR_{i,m}}}\right)^{m_f+q_k}} \tag{4.10b}$$

and where $\tau(m,n)$ denotes the set of N_{R_i}-tuples, such that $\tau(m,n) = \{(q_1,\dots,q_{N_{R_i}})|q_m = 0, \sum_{k=1}^{N_{R_i}} q_k = m_f - n\}$ and $(q_1,\dots,q_{N_{R_i}}) \in \mathbb{Z}^*$.

The outage probability at R_i can then be expressed as [11, eq. (3.351.2)]

$$P_{R_i} = 1 - \exp\left(-\frac{m_h \gamma_T N_0}{P_S}\right) \sum_{m=1}^{N_{R_i}} \sum_{n=1}^{m_f} \sum_{k=0}^{m_h-1} \frac{A_{mn}\left(\frac{m_h\gamma_T}{P_S}\right)^k}{\Gamma(n)k!} \times \sum_{r=0}^{k} \frac{\begin{pmatrix} k \\ r \end{pmatrix} N_0^{k-r}(n-1+r)!}{\left(\frac{m_f}{P_{IR_{i,m}}} + \frac{m_h\gamma_T}{P_S}\right)^{n+r}}. \tag{4.11}$$

4.3.2 Conditional outage probability of optimum combining

We use the SINR expression derived in (4.8) to determine the outage probability of OC at the destination, where X_D is a gamma RV with scale parameter $\frac{P_S}{m_g}$ and shape parameter m_g, and Z_D is a gamma RV with scale parameter $\frac{P_S}{N_0 m_g}$ and shape parameter Cm_g. Similar to (4.10a), the PDF of Y_D in (4.8) can be expressed as

$$f_{Y_D}(y) = \sum_{m=1}^{N_D} \sum_{n=1}^{m_l} \frac{B_{mn} y^{n-1} \exp\left(-\frac{m_l y}{P_{ID_m}(C+1)}\right)}{(n-1)!(C+1)^n} \tag{4.12a}$$

where

$$B_{mn} = (-1)^n \left(\frac{-m_l}{P_{ID_m}}\right)^{m_l} \sum_{\tau(m,n)} \prod_{k=1,k\neq m}^{N_D} \begin{pmatrix} m_l + q_k - 1 \\ q_k \end{pmatrix} \frac{\left(\frac{P_{ID_k}}{m_l}\right)^{q_k}}{\left(1 - \frac{P_{ID_k}}{P_{ID_m}}\right)^{m_l+q_k}} \tag{4.12b}$$

and $\tau(m,n)$ is defined as in (4.10b), but with m_f and N_{R_i} replaced by m_l and N_D, respectively.

For $C = 0$

If none of the relays decodes the received symbols successfully, $Pr(\gamma_D \geq \gamma_T | C = 0)$ is determined similar to (4.9) and can be expressed as

$$P_0 = \mathcal{P}(\gamma_D \geq \gamma_T | C = 0)$$
$$= \exp\left(-\frac{m_g\gamma_T N_0}{P_S}\right) \sum_{m=1}^{N_D} \sum_{n=1}^{m_l} \sum_{k=0}^{m_g-1} \frac{B_{mn}\left(\frac{m_g\gamma_T}{P_S}\right)^k}{\Gamma(n)k!} \sum_{q=0}^{k} \frac{\begin{pmatrix} k \\ q \end{pmatrix} N_0^{k-q}(n-1+q)!}{\left(\frac{m_l}{P_{ID_m}} + \frac{m_g\gamma_T}{P_S}\right)^{n+q}}. \tag{4.13}$$

For $C \geq 1$

For this scenario, the output SINR is given in (4.8). Hence,

$$P_C = \mathcal{P}(\gamma_D \geq \gamma_T | C \geq 1) = Pr\left(\frac{X_D}{Y_D + N_0} + Z_D \geq \gamma_T\right). \tag{4.14}$$

Based on the theorem of total probability, P_C can be expressed as

$$P_C = \int_0^{\gamma_T}\int_0^{\infty}\int_{(y+N_0)(\gamma_T - z)}^{\infty} f_{X_D}(x) f_{Y_D}(y) f_{Z_D}(z) dx dy dz + \int_{\gamma_T}^{\infty} f_{Z_D}(z) dz. \tag{4.15}$$

A closed-form expression for P_C is derived as [12, eq. (1.2.4.3)]

$$\begin{aligned} P_C = &\sum_{m=1}^{N_D}\sum_{n=1}^{m_l} K_1(m,n) \sum_{k=0}^{m_g-1} \frac{\left(\frac{m_g}{P_S}\right)^k \gamma_T^{k+Cm_g}}{k!} \sum_{q=0}^{k} \frac{\binom{k}{q} N_0^{k-q}(q+n-1)!}{\left(\frac{m_g K_2(m)}{P_S}\right)^{q+n}} \\ &\times \sum_{t=0}^{k} \frac{\binom{k}{t}(-1)^t}{(t+Cm_g)} {}_2F_1\left(q+n, t+Cm_g; t+Cm_g+1; \frac{\gamma_T}{K_2(m)}\right) \\ &+ \exp\left(-\frac{\gamma_T m_g N_0}{P_S}\right) \sum_{k=0}^{Cm_g-1} \frac{\left(\frac{m_g N_0 \gamma_T}{P_S}\right)^k}{k!} \end{aligned} \tag{4.16a}$$

where

$$K_1(m,n) = \frac{B_{mn}\left(\frac{N_0 m_g}{P_S}\right)^{Cm_g} \exp\left(-\frac{m_g N_0 \gamma_T}{P_S}\right)}{(C+1)^n \Gamma(n) \Gamma(Cm_g)} \tag{4.16b}$$

$$K_2(m) = \gamma_T + \frac{m_l P_S}{m_g P_{ID_m}(C+1)} \tag{4.16c}$$

and ${}_2F_1(a, b; c; d)$ is the Gauss hypergeometric function defined in [13, eq. (15.1.1)].

4.3.3 Outage probability of optimum combining

Based on the principle of total probability, the outage probability at the destination after optimum combining can be expressed as,

$$P_{out,D} = 1 - \sum_{k=0}^{M} \sum_{\substack{\forall T \subset S, \\ |T| = k}} \prod_{\forall i \in T}(1 - P_{R_i}) \prod_{\forall j \in (S \setminus T)} P_{R_j} P_k \tag{4.17}$$

where $S = \{1, 2, \ldots, M\}$ and T are the unique k-tuples which consist of the indexes of the nodes that successfully decode the message when $C = k$. P_k is found in (4.13) for $k = 0$ and in (4.16) for $k > 0$. For the special case of all the relays having the same outage probability ($P_{R_1} = \cdots = P_{R_M} = P_R$), the outage probability at the destination can be given as

$$P_{out,D} = 1 - \sum_{k=0}^{M} \left(\begin{array}{c} M \\ k \end{array} \right) (1 - P_R)^k P_R^{M-k} P_k \tag{4.18}$$

4.4 Numerical Results and Discussion

In this section, numerical results obtained from the closed-form expression for the exact outage probability of the OC receiver in (8.23) are compared with simulation results. In the examples, there are 5 distinct-power interferers at each relay node and at the destination node, having the power ratios $\frac{P_I}{P_S} = \{0.01, 0.02, 0.05, 0.08, 0.1\}$. Here, $\frac{P_I}{P_S} = 0.01$ and 0.1 correspond to a high frequency reuse factor (e.g. 7) and universal frequency reuse factor, respectively. It is assumed that $m_f = m_l = 1$ and $\gamma_T = 5$ dB.

The outage performance of the optimum combiner when interference is present at the relays and destination is shown in Fig. 4.2 for $m_g = m_h = 2$. Accordingly, we can conclude that the overall diversity gain is equal to zero, irrespective of the number of relays used. The OC receiver can be used to suppress the interference component at the destination node only, as a virtual antenna array of M antennas is created at the destination node only. The interference at each relay node cannot be suppressed when each relay node only employs a single antenna. Therefore, a single-antenna relay node represents a bottleneck for improving the diversity gain of the overall system using optimum combining, forcing the overall diversity gain to zero.

Fig. 4.3 shows the performance when the interference is present only at the destination node. It is evident that the outage probability floors of the previous instance disappear as the relay nodes become free of interference and the end-to-end diversity gain of the optimum combiner increases as the number of relays increases.

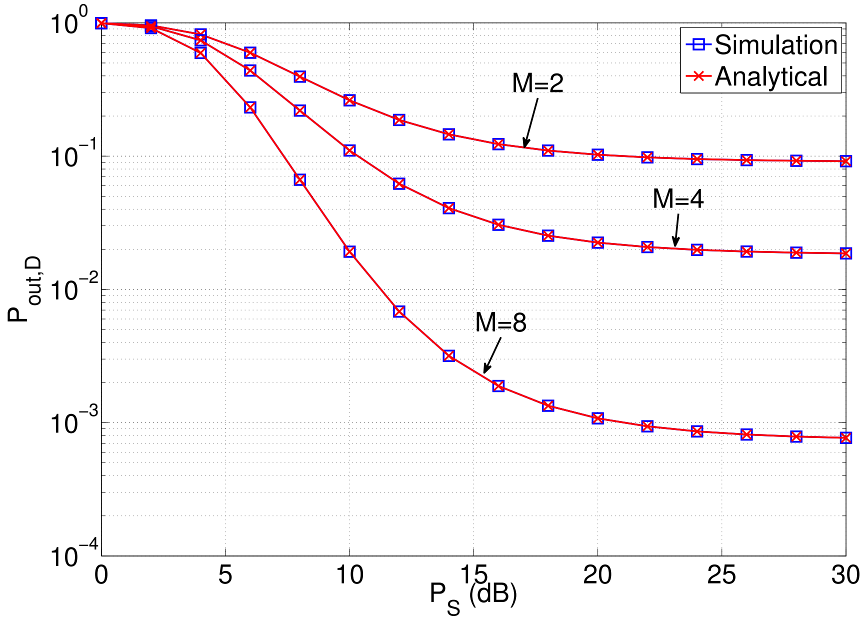

Figure 4.2: The outage performance of OC when interference is present at the relays and the destination.

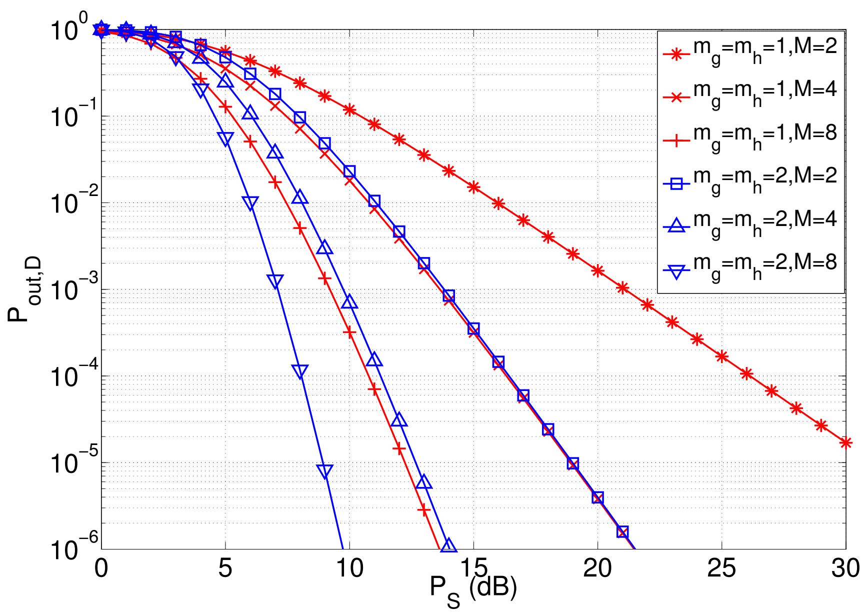

Figure 4.3: The outage performance of OC when interference is present at the destination only.

In Fig. 4.4, the outage performance is compared for MRC and OC when interference is present at the relays and at the destination for $m_g = m_h = 2$ and it can be seen that both combining techniques suffer outage probability floors when the SINR is increased. Even though there is no diversity gain, OC shows superior performance over MRC in lowering the outage probability floor. In the presence of interference, the performance of MRC is weakened as the output SINR is the sum of the SINRs of each branch. MRC fails to mitigate the co-channel interference at the destination, whereas OC does.

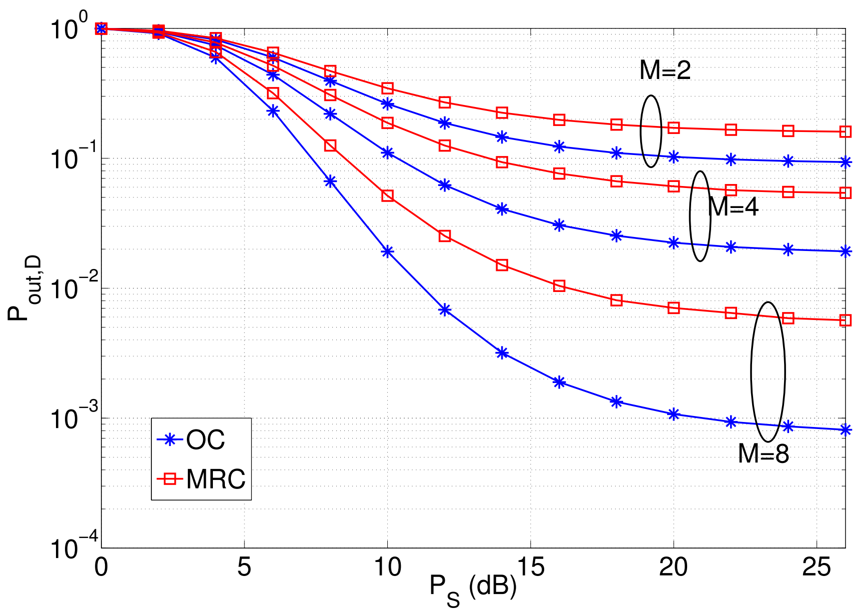

Figure 4.4: Comparison of the outage performances of OC and MRC when interference is present at the relays and destination.

The outage performances of MRC and OC are compared when interference is present only at the destination for $m_g = m_h = 2$ in Fig. 4.5. It can be observed that the overall performance shows a significant improvement when co-channel interference is present only at the destination. Furthermore, the outage probability floors of OC disappear and the end-to-end diversity gain of OC increases as the number of relays increases while the outage probability floors of MRC are lowered. This can be explained by interpreting the instantaneous SINR expressions for OC given in (4.8) and the interference cancelling behaviour of OC. For a DF relay network with

M relays and $m_g = m_h = 1$, the end-to-end diversity gain is equal to M when OC is used and interference is present at the destination node only. The diversity gain further increases with the increase of m_g.

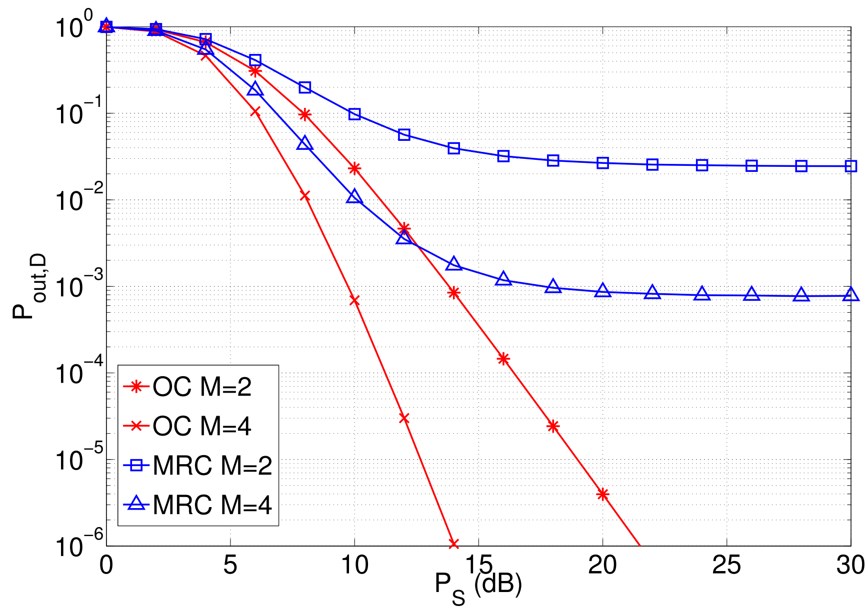

Figure 4.5: Comparison of the outage performances of OC and MRC when interference is present at the destination only.

4.5 Conclusion

A simple closed-form expression was derived for the exact outage probability of the optimum combiner in DF relaying in the presence of co-channel interference at the relay nodes and at the destination. All the channels were subject to Nakagami-m fading. It was evident that, when interference is present at the relays, end-to-end diversity gain cannot be achieved using the OC receiver. Nevertheless, the performance of OC is superior to MRC in this scenario lowering the outage probability floors. Moreover, it was shown that OC achieves end-to-end diversity gain while MRC does not achieve any diversity gain when the the co-channel interference is present only at the destination.

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Chapter 5

The Impact of Imperfect Channel Estimations on the Performance of Optimum Combining

Optimum combining (OC) in cooperative relaying enables achieving a diversity gain of M in the presence of co-channel interference (CCI), where M is the number of relay nodes. The additional performance overhead of OC is the need for estimation of interferer channels. The impact of imperfect channel estimation on the performance of OC with decode-and-forward relaying is analyzed. When the source-destination and relay-destination channel estimations are imperfect, the diversity gains of OC deteriorate and the performance further degrades with increase of the error variance. When the destination node accurately estimates the variances of the interferer channel state information (CSI), instead of instantaneous CSI, no performance loss is observed. Thus, the overhead associated with the interferer channel estimation in OC can be significantly reduced[1].

5.1 Introduction

Due to frequency reuse, the performances of cellular wireless communication systems are primarily limited by co-channel interference (CCI). The performance of decode-and-forward (DF) relaying with maximal-ratio combining (MRC), in the

[1]A version of this chapter was published in IEEE Wireless Communications Letters, N. Suraweera and N. C. Beaulieu, "The Impact of Imperfect Channel Estimations on the Performance of Optimum Combining in Decode-and-Forward Relaying in the Presence of Co-Channel Interference", *IEEE Wireless Communications Letters*, vol. 3, no. 1, pp. 18-21, Feb. 2014.

presence of CCI has been thoroughly analyzed in the literature [1, 2]. However, in the presence of CCI, MRC is suboptimal and the diversity gains disappear when the interferer powers scale with the source and relay powers.

In the presence of CCI, optimum combining (OC) [3] is the optimal diversity combining technique that maximizes the signal-to-interference-plus-noise ratio (SINR). The performance of OC with DF relaying in the presence of CCI at the destination node was analyzed recently in [4] and [5], where it was shown that OC enables achieving a diversity gain of M with Rayleigh fading, where M is the number of relay nodes. In OC, the destination node is required to estimate the channel state information (CSI) of interferer channels, in addition to source-destination and relay destination channels (user channels), which is the main additional overhead of OC over MRC. The above mentioned work all assumes that the destination node is provided with instantaneous CSI of the interferers.

In this chapter, the impact of imperfect CSI estimations on the performance of OC with DF relaying is analyzed. To the best of authors' knowledge, this has not been investigated in the existing literature. The novel contributions and the important results of this chapter can be listed as follows.

1. The effect of the estimation errors of the user channels on the performance is investigated using an outage probability analysis. In the presence of user channel estimation errors, the diversity gains of OC disappear and the performance further degrades with the increase of the estimation error variance.

2. The performance is studied when the destination node accurately estimates the variances of the interferer CSI, instead of the instantaneous interferer CSI. Using an approximation to the SINR of the OC receiver, it is shown that there is no loss in the diversity performance when the destination node is only provided with the variances of the interferer CSI. Hence, the channel estimation overhead of OC is significantly reduced.

The chapter is organized as follows. Section 5.2 explains the system and channel models used and in Section 5.3, the impact of user channel estimation errors on the outage and diversity performances is analyzed. Section 5.4 investigates the outage performance when the destination node is only aware of the variances of the interferer CSI. Numerical and simulation results are presented Section 5.5, and Section 5.6 concludes this chapter.

5.2 System and Channel Models

A DF relay network similar to Fig 3.1 is considered. The destination node is assumed to be located at the edge of the cell and is affected by N_I number of co-channel interferers with different average powers. The relay nodes are assumed to be located well inside the cell, such that the effect of CCI is negligible. The source-relay, relay-destination, source-destination and interferer-destination channel coefficients are given in Fig. 3.1.

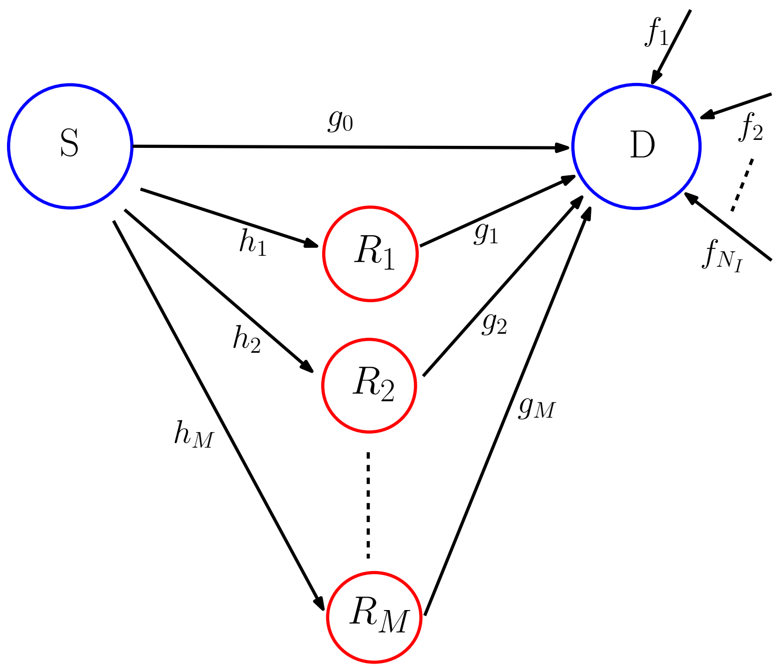

Figure 5.1: A decode-and-forward cooperative relay network with co-channel interference at the destination node.

The cooperative communication protocol consists of two phases. During the first phase, the source node broadcasts its data symbols to the relay nodes and to the destination node. The signal received at each relay node is

$$y_{S,R_i} = \sqrt{P_{S_i}} h_i x_0 + n_{R_i} \quad i \in \{1, \ldots, M\} \tag{5.1}$$

where P_{S_i} is the average power received from the source at relay i, $h_i \sim \mathcal{CN}(0, \sigma_{h_i}^2)$, x_0 is the transmitted data symbol and the noise at relay node i, $n_i \sim \mathcal{CN}(0, N_0)$. The signal received at the destination node in Phase 1 is

$$y_{S,D} = \sqrt{P_{S_D}} g_0 x_0 + \sum_{j=1}^{N_I} \sqrt{P_{I_j}} f_j t_{0_j} + n_{D_0} \tag{5.2}$$

where P_{S_D} is the average power received from the source at the destination node and P_{I_j} is the average power of interferer j at the destination node. The interferer channel coefficients $f_j \sim \mathcal{CN}(0, \sigma_{f_j}^2)$, t_{0_j} are the interferer symbols in Phase 1 and $n_{D_0} \sim \mathcal{CN}(0, N_0)$.

In the second phase, the relay nodes that successfully decode the received symbols will forward the data symbols to the destination node in orthogonal time slots. It is assumed that each relay node correctly decodes its received symbols if $\gamma_{R,i} \geq \gamma_{T,R}$, where $\gamma_{R,i}$ is the signal-to-noise ratio (SNR) at relay i and $\gamma_{T,R}$ is the SNR threshold corresponding to the minimum desirable rate of the communication R_{min} [6]. Assuming the interferer-destination channels remain unchanged during a single cooperative communication, the received signal at the destination in time slot k is given as

$$y_{R_k,D} = \sqrt{P_{R_k,D}} g_k x_0 + \sum_{j=1}^{N_I} \sqrt{P_{I_j}} f_j t_{k_j} + n_{D_k} \quad k \in \{1, \ldots, C\} \tag{5.3}$$

where C is the number of relay nodes that successfully decode the received symbols. If $C = 0$, there is no transmission in the second phase. $P_{R_k,D}$ is the average power of the $R_k - D$ link, $g_k \sim \mathcal{CN}(0, \sigma_{g_k}^2)$ and $n_{D_k} \sim \mathcal{CN}(0, N_0)$.

The OC receiver at the destination node combines the signals received in $C+1$ time slots to obtain the decision variable $\hat{x}_0 = \mathbf{w}^H \mathbf{y}$, where $\mathbf{y} = [y_{S,D}, y_{R_1,D}, \ldots, y_{R_C,D}]^T$. The combiner weight vector $\mathbf{w} = \mathbf{R}^{-1}\mathbf{g}$, where $\mathbf{R} = N_0 \mathbf{I}_{C+1} + \lambda \mathbf{1}_{C+1} \mathbf{1}_{C+1}^H$ [3], $\lambda = \sum_{j=1}^{N_I} P_{I_j} |f_j|^2$ and $\mathbf{g} = [g_0, g_1, \ldots, g_C]^T$. Hence, two types of channel estimations are involved in OC, interferer channel estimations and user channel estimations.

In the performance analysis that follows, the imperfections of these two types of channel estimations are considered separately. First, the user channel estimations are assumed to be described by a complex Gaussian error. In the latter part of the analysis, the destination node is assumed to be capable of estimating the variances of the interferer CSI accurately, but not the instantaneous interferer CSI. In order to simplify the analysis, it is assumed that the user channels are independent and identically distributed (IID), i.e. $\sigma_{h_1} = \cdots = \sigma_{h_M} = \sigma_h$, $\sigma_{g_0} = \sigma_{g_1} = \cdots = \sigma_{g_M} = \sigma_g$, $P_{S_1} = \cdots = P_{S_M} = P_S$ and $P_{S_D} = P_{R_1} = \cdots = P_{R_M} = P_S$. Thus, the effect of large-scale fading of user channels is not considered. However, it should be emphasized that the main insights derived in this work are directly applicable to independent and non-identically distributed (INID) user channels as well.

5.3 Performance Analysis with User Channel Estimation Errors

In this section, the effect of imperfect estimation of source-destination and relay-destination channels on the performance of the OC receiver is analyzed. It is assumed that the source-destination and relay-destination channel estimations ($\hat{\mathbf{g}}$) are described by a complex Gaussian error vector, i.e. $\hat{\mathbf{g}} = \mathbf{g} + \tilde{\mathbf{g}}$, where $\tilde{\mathbf{g}} \sim \mathcal{CN}(\mathbf{0}, \sigma_e^2 \mathbf{I}_{C+1})$. Hence, the actual channel vector g is expressed in terms of the estimated channel vector [7]

$$\mathbf{g} = \rho \hat{\mathbf{g}} + \acute{\mathbf{g}} \tag{5.4}$$

where $\rho = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_e^2}$ and $\acute{\mathbf{g}} \sim \mathcal{CN}(\mathbf{0}, \frac{\sigma_g^2 \sigma_e^2}{\sigma_g^2 + \sigma_e^2} \mathbf{I}_{C+1})$. It is assumed that $\hat{\mathbf{g}}$ and $\acute{\mathbf{g}}$ are independent, which is true for minimum-mean-square estimation (MMSE) of the channel vector. Based on (5.4), the expressions for the conditional SINR for the cases of $C = 0$ [8] and $C > 0$, in terms of $\hat{\mathbf{g}}$ and $\boldsymbol{\sigma}_{\mathbf{e}}^{\mathbf{2}}$ can be derived as

$$\gamma_e | (C = 0) = \frac{P_S |\hat{g}_0|^2 \sigma_g^4}{(\sigma_g^2 + \sigma_e^2) \left[P_S \sigma_g^2 \sigma_e^2 + (\sigma_g^2 + \sigma_e^2)(N_0 + \lambda) \right]} \tag{5.5a}$$

$$\gamma_e | (C > 0) = \frac{P_S \rho^2 \left(\hat{\mathbf{g}}^H \mathbf{R}^{-1} \hat{\mathbf{g}} \right)^2}{P_S \frac{\sigma_g^2 \sigma_e^2}{\sigma_g^2 + \sigma_e^2} \hat{\mathbf{g}}^H \left(\mathbf{R}^{-1} \right)^2 \hat{\mathbf{g}} + \hat{\mathbf{g}}^H \mathbf{R}^{-1} \hat{\mathbf{g}}} \tag{5.5b}$$

$$\approx \frac{P_S \rho^2 \hat{\mathbf{g}}^H \mathbf{R}^{-1} \hat{\mathbf{g}}}{P_S \frac{\sigma_g^2 \sigma_e^2}{\sigma_g^2 + \sigma_e^2} + 1} = \frac{\frac{\hat{X}}{\lambda(C+1) + N_0} + \hat{Z}}{\nu(\sigma_g^2 + \sigma_e^2)} \tag{5.5c}$$

where $\nu = \frac{P_S\sigma_g^2\sigma_e^2+\sigma_g^2+\sigma_e^2}{\sigma_g^4}$, $\hat{X}_D$ is an exponential random variable with parameter $P_e = P_S(\sigma_g^2+\sigma_e^2)$ and $\hat{Z}_D$ is a gamma random variable with scale parameter $\frac{P_e}{N_0}$ and shape parameter C. Note that the expression in (5.5c) is a tight approximation for $\gamma_e|(C>0)$.

The probability density function of λ can be given as [9]

$$f_\lambda(\lambda) = \sum_{k=1}^{r}\sum_{l=1}^{\nu_k}\frac{\phi_{kl}\lambda^{l-1}}{\Gamma(l)P_k^l}\exp\left(-\frac{\lambda}{P_k}\right) \tag{5.6}$$

where $P_1,\ldots,P_r$ are the distinct values of the average interferer powers $P_{I1}\sigma_{f_1}^2,\ldots,P_{IN_I}\sigma_{f_{N_I}}^2$, with multiplicities $\nu_1,\ldots,\nu_r$, respectively and $\sum_{i=1}^{r}\nu_r = N_I$. The partial fraction coefficients ϕ_{kl} are given in [9, eq. (10)].

The values $P_{0,e}$ and $P_{C,e}$ are defined as $P_{0,e} = \mathcal{P}\left(\gamma_e \geq \gamma_T|(C=0)\right)$ and $P_{C,e} = \mathcal{P}\left(\gamma_e \geq \gamma_T|(C>0)\right)$, respectively. Following the analysis in [5], these values are derived as

$$P_{0,e} = \sum_{k=1}^{r}\sum_{l=1}^{\nu_k}\frac{\phi_{kl}\exp\left(-\frac{\gamma_T\sigma_e^2}{\sigma_g^2}-\frac{N_0\gamma_T(\sigma_g^2+\sigma_e^2)}{P_S\sigma_g^4}\right)}{\left(1+\frac{P_k\gamma_T(\sigma_g^2+\sigma_e^2)}{P_S\sigma_g^4}\right)} \tag{5.7a}$$

$$\begin{aligned}P_{C,e} \approx{}& \sum_{k=1}^{r}\sum_{l=1}^{\nu_k}\frac{\phi_{kl}\exp\left(-\frac{N_0\gamma_T\nu}{P_S}\right)\left(\frac{N_0\gamma_T\nu}{P_S}\right)^C}{\Gamma(C)C\left(\frac{\gamma_T\nu P_k(C+1)}{P_S}+1\right)^l}{}_2F_1\left(l,C;C+1;\frac{\gamma_T\nu P_k(C+1)}{\gamma_T\nu P_k(C+1)+P_S}\right)\\ &+\exp\left(\frac{-N_0\gamma_T\nu}{P_S}\right)\sum_{i=0}^{C-1}\frac{\left(\frac{N_0\gamma_T\nu}{P_S}\right)^i}{i!}.\end{aligned} \tag{5.7b}$$

The end-to-end outage probability is found as [1]

$$P_{out} \approx \sum_{C=0}^{M}\binom{M}{C}(1-P_{out,R})^C P_{out,R}^{M-C}(1-P_{C,e}) \tag{5.8}$$

where $P_{out,R}$ is the outage probability at each relay node with $P_{out,R} = 1-\exp\left(\frac{-\gamma_{T,R}}{P_S\sigma_g^2}\right)$.

Diversity Gain

Here, the asymptotic diversity gain of OC with DF relaying is derived based on the approximate outage probability expression given in (5.8) for the case of imperfect estimation of the source-destination and relay-destination channels. The interferer powers are assumed to scale with the source and relay powers.

Using the power series expansion of the exponential function, the asymptotic value of $1 - P_{C,e}$ is expressed as

$$1 - P_{C,e}^{\infty} \approx \left(1 + \mathcal{O}\left(P_S^{-1}\right)\right) \left(K_1 + \mathcal{O}\left(P_S^{-1}\right)\right) \sum_{k=1}^{r} \sum_{l=1}^{\nu_k} G_{k,l} + K_2 + \mathcal{O}\left(P_S^{-1}\right) \tag{5.9}$$

where K_1, K_2 and $G_{k,l}$ are constants, which can be determined from (5.7b). Using the power series expansion of the exponential function, the asymptotic outage probability can be given as

$$\begin{aligned} P_{out}^{\infty} \approx \sum_{C=0}^{M} \begin{pmatrix} M \\ C \end{pmatrix} \left(1 + \mathcal{O}\left(P_S^{-1}\right)\right)^C \left(\frac{\gamma_T}{P_S} + \mathcal{O}\left(P_S^{-2}\right)\right)^{M-C} \\ \times \left[\left(1 + \mathcal{O}\left(P_S^{-1}\right)\right) \left(K_1 + \mathcal{O}\left(P_S^{-1}\right)\right) \sum_{k=1}^{r} \sum_{l=1}^{\nu_k} G_{k,l} + K_2 + \mathcal{O}\left(P_S^{-1}\right) \right]. \end{aligned} \tag{5.10}$$

From (5.10), it is evident that the asymptotic diversity gain with any user channel estimation errors is equal to zero. Hence, the destination node should be provided with perfect CSI of the user channels to achieve diversity gains with OC.

5.4 Performance Analysis with Only the Knowledge of Interferer CSI Variances at the Destination Node

When the destination node is provided only with the variances of the interferer CSI instead of the instantaneous CSI, the noise-plus-interference covariance matrix [3, eq. (8)] can be expressed as

$$\hat{\mathbf{R}} = N_0 \mathbf{I}_{C+1} + \hat{\lambda} \mathbf{1}_{C+1} \mathbf{1}_{C+1}^H \tag{5.11}$$

where $\hat{\lambda} = \sum_{i=1}^{N_I} P_{Ii} |\hat{f}_i|^2$ and $\hat{f}_i \sim \mathcal{CN}(0, \sigma_{f_i}^2)$ are complex Gaussian random variables generated at the destination node, which are independent of the interferer channel coefficients. The combiner vector is now $\hat{\mathbf{w}} = \hat{\mathbf{R}}^{-1}\mathbf{g}$. Hence, the resulting conditional signal-to-interference-plus-noise ratio (SINR) at the destination node can be derived as

$$\gamma|C = P_S \frac{\left(\mathbf{g}^H \hat{\mathbf{R}}^{-1} \mathbf{g}\right)^2}{\mathbf{g}^H \hat{\mathbf{R}}^{-1} \mathbf{R} \hat{\mathbf{R}}^{-1} \mathbf{g}}. \tag{5.12}$$

Theorem 5.1. *For high interferer powers, a tight approximation for the conditional SINR $\gamma|C$ can be given as*

$$\gamma|C \approx P_S \mathbf{g}^H \hat{\mathbf{R}}^{-1} \mathbf{g}. \tag{5.13}$$

The proof is given in Appendix 5.A.

The approximate conditional SINR expression with only interferer CSI statistics at the destination node given in (5.13) has the same statistical properties as the conditional SINR expression with instantaneous interferer CSI at the destination node $\gamma_2|C = P_S \mathbf{g}^H \mathbf{R}^{-1} \mathbf{g}$ [3] since λ and $\hat{\lambda}$ have the same distribution. This result is directly applicable for both IID and INID user channels. The conditional outage probability expressions can be easily obtained by substituting $\sigma_e^2 = 0$ in (5.7).

Importantly, the performance results given in [4] are achievable even when the destination node is only aware of the variances of the interferer CSI. Thus, the interferer channel estimation overhead of optimum combining can be significantly reduced without a loss of outage or diversity performance, which enables the practical implementation of OC in cooperative networks.

5.5 Numerical Results

In this section, the insights derived in Sections 4.3 and 4.4 are further confirmed using numerical and simulation results. There are 5 interferers at the destination node with the power ratios $\frac{P_S}{P_I} = \{20, 15, 10, 5, 3\}$ dB and $\sigma_h^2 = \sigma_g^2 = \sigma_f^2 = 1$. The SINR threshold $\gamma_T = 5$ dB

The effect of the user channel estimation error is demonstrated in Fig. 5.2 for $M = 4$. It can be observed that the SINR expression derived in (5.5c) is a very tight approximation for the exact conditional SINR expression given in (5.5b). Moreover, it can be concluded that the diversity gains of OC disappear in the presence of user channel estimation error. As expected, the outage performance degrades with increase of the error variance.

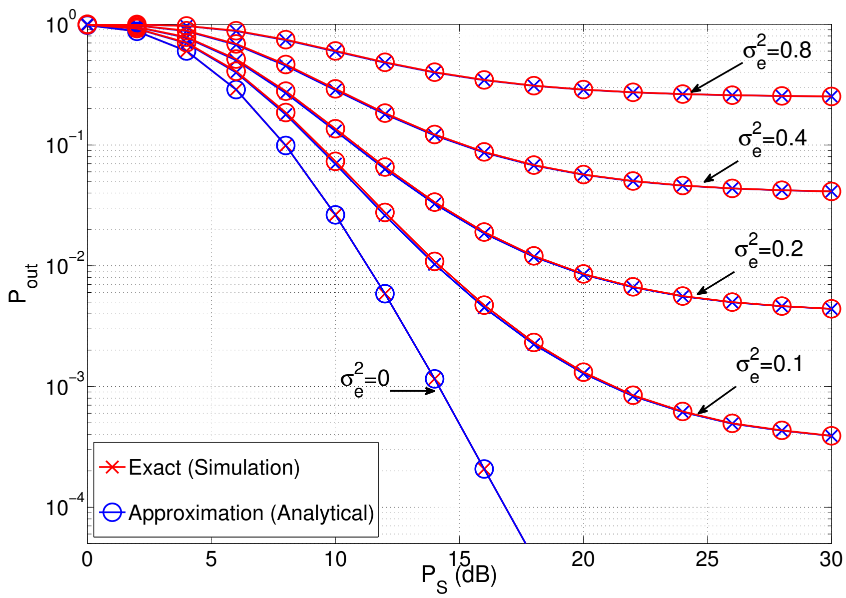

Figure 5.2: Outage performance with user channel estimation error at the destination node for $M = 4$.

The outage performance when the destination node is only aware of the variances of the interferer CSI is illustrated in Fig. 5.3 and in Fig. 5.4 for the noise variances of 0 dB and 20 dB, respectively. It is evident that the SINR expression (5.13), is a very tight approximation for the exact conditional SINR given in (8.16). Furthermore, there is no diversity loss resulting from using only the knowledge of interferer CSI variances at the destination node, instead of values of instantaneous CSI. The outage performance loss resulted in using only the variance of interferer CSI is negligible for the case of $N_0 = 0$ dB and is very small for $N_0 = 20$ dB.

Based on these results, it can be seen that the destination node only needs to estimate the statistics of the interferer CSI, which change slowly compared to the instantaneous CSI. This reduces the performance overhead of OC considerably, significantly furthering the practical implementation of OC with cooperative relay networks, which results in significant performance advantages over MRC [4], with a minimal additional performance overhead.

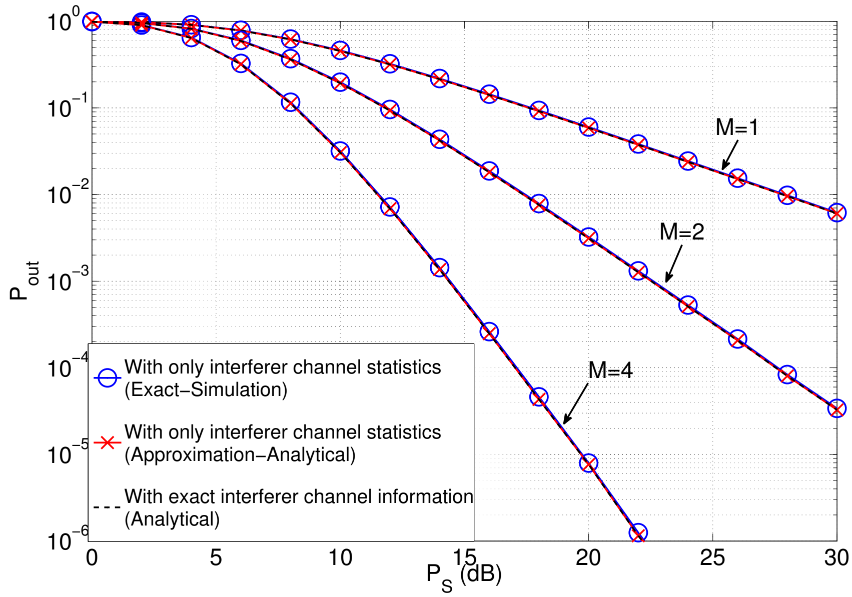

Figure 5.3: Outage performance of OC with knowledge of instantaneous and statistical CSI of the interferers at the destination node for $N_0 = 0$ dB.

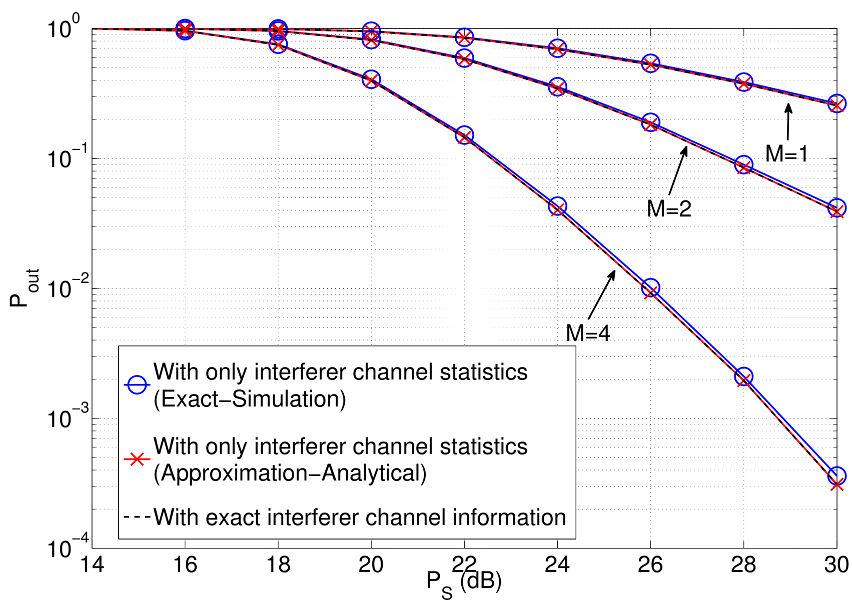

Figure 5.4: Outage performance of OC with knowledge of instantaneous and statistical CSI of the interferers at the destination node for $N_0 = 20$ dB.

5.6 Conclusion

The impact of imperfect channel estimations on the performance of OC with DF relaying was analyzed. Tight approximations for the outage probability were derived for the cases of 1) the user channel estimations are corrupted by errors and 2) the destination node is only provided with the variances of the interferer CSI. It was shown that the diversity gains of OC disappear with the user channel estimation errors. However, the diversity and outage performances of OC are preserved when the destination node is only aware of the variances of the interferer CSI, instead of instantaneous CSI. This reduces the channel estimation overhead of OC significantly, furthering the practical implementation of OC with DF relaying.

5.A Proof of Theorem 4.1

Using the matrix inversion lemma [10, eq. (2.1.4)], it can be shown that

$$\hat{\mathbf{R}}^{-1} = \frac{1}{N_0}\left(\mathbf{I} - \frac{\hat{\lambda}\mathbf{1}\mathbf{1}^H}{N_0 + \hat{\lambda}(C+1)}\right). \tag{5.14}$$

Hence, the product $\hat{\mathbf{R}}^{-1}\mathbf{R}$ can be found as

$$\hat{\mathbf{R}}^{-1}\mathbf{R} = \frac{1}{N_0}\left[N_0\mathbf{I} + \lambda\mathbf{1}\mathbf{1}^H - \hat{\lambda}\mathbf{1}\mathbf{1}^H\left(\frac{N_0 + \lambda(C+1)}{N_0 + \hat{\lambda}(C+1}\right)\right]. \tag{5.15}$$

When the noise power is insignificant with respect to the interferer powers, $\hat{\mathbf{R}}^{-1}\mathbf{R} \approx \mathbf{I}$, which completes the proof.

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Chapter 6

Optimum Combining With Joint Relay and Antenna Selection

The performance of optimum combining (OC) with joint relay and antenna selection is analyzed for decode-and-forward (DF) relaying when co-channel interference (CCI) is present at the relays and the destination. The combination of OC with joint antenna and relay selection results in positive diversity gains if at least one relay has $T_i > N_i$, where T_i is the number of relay antennas and N_i is the number of interferers at the relay, when the interferer powers are scaled with the source and the relay powers[1].

6.1 Introduction

In the presence of co-channel interference (CCI), optimum combining (OC) is the optimal diversity combining technique that results in diversity gains when interferer powers are scaled with the desirable signal powers [1]. For decode-and-forward (DF) cooperative relaying with CCI at the destination, OC results in a diversity gain of M for Rayleigh fading, where M is the number of relay nodes [2], [3]. However, the capacity of relaying in orthogonal time slots is degraded with M as $M + 1$ time slots are used to complete a single transmission.

Opportunistic relay selection [4] achieves the same diversity gains as conven-

[1]A version of this chapter was published in IEEE Communications Letters, N. Suraweera and N. C. Beaulieu, “Optimum Combining With Joint Relay and Antenna Selection for Multiple-Antenna Relays in the Presence of Co-Channel Interference”, *IEEE Communications Letters*, vol. 18, no. 8, pp. 1459-1462, Aug. 2014.

tional relaying in orthogonal time slots, while improving the capacity, since a single transmission uses only two time slots. The performance of opportunistic relay selection for DF relaying in the presence of CCI was analyzed in [5], where maximal-ratio combining (MRC) is used to combine the signals received from the source-destination link and the selected relay-destination links. However, MRC is sub-optimal in the presence of CCI and suffers from error floors.

The performance of OC in cooperative relaying when CCI is present at both the relays and the destination analyzed in Chapter 4. It was shown that if interference is present at the relays, OC fails to achieve diversity gains at the destination, since single-antenna relays with interference act as bottlenecks for performance improvement.

This chapter seeks to provide a solution for the above problem, highlighted in Chapter 4, by using multiple-antenna relays and using OC to suppress CCI at the relays. Furthermore, multiple-antenna relays enable using the combination of transmit antenna selection and opportunistic relay selection (termed joint relay and antenna selection), which further increases the diversity gain [6].

In this chapter, the performance of a multiple-antenna DF relay network using OC with joint relay and antenna selection is analyzed. When the source-destination and relay-destination links are independent and non-identically distributed due to path loss, an approximation for the outage probability of OC with joint antenna and relay selection is derived and the exact outage probability is expressed in terms of a single numerical integration, which can be solved very fast, compared to simulations. Accordingly, OC with joint antenna and relay selection achieves diversity gains if at least one relay has $T_i > N_i$, where T_i and N_i are the number of antennas and the number of interferers at relay i, respectively, and the diversity gain linearly increases with the number of relays having $T_i > N_i$.

This chapter is organized as follows. The system and channel models are presented in Section 6.2 and the performance analysis of joint relay and antenna selection is carried out in Section 6.3. In Section 6.4, the impact of feedback delay is analyzed. The numerical results are presented and discussed in Section 6.5 and Section 6.6 concludes this chapter.

6.2 System and Channel Models

The DF cooperative relay network with single-antenna source (S) and destination (D) nodes and M multiple-antenna relays ($R_i, i \in \Omega = \{1, \ldots, M\}$) in Fig. 6.1 is considered. The channel coefficients are marked on each link. CCI is present at the relays and at the destination. R_i has T_i number of antennas and is affected by N_i number of equal-power co-channel interferers. N_D arbitrary-power interfering signals are present at D. All the channel coefficients are Rayleigh faded.

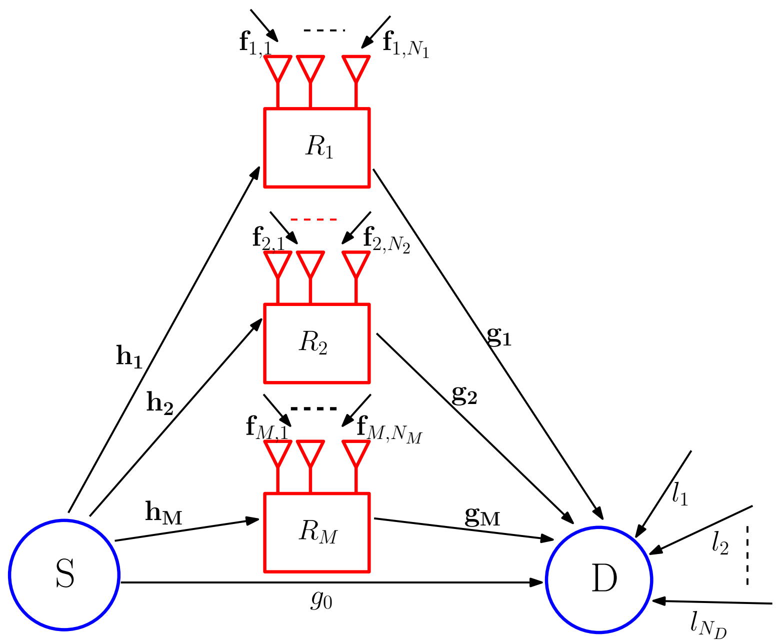

Figure 6.1: A decode-and-forward cooperative relay network with multiple-antenna relays and interference at the relays and at the destination.

In Phase 1 of the communication, the source broadcasts its symbols to all the relays and the destination. The signal received at the destination in Phase 1 is

$$y_{SD} = \sqrt{P_{SD}} g_0 x_0 + \sum_{j=1}^{N_D} \sqrt{P_{D_j}} l_j u_{1j} + n_{D_1} \tag{6.1}$$

where, P_{SD} is the average desired signal power at the destination in Phase 1, $g_0 \sim \mathcal{CN}(0, \sigma_g^2)$, x_0 is the transmitted symbol, $\sqrt{P_{D_j}}$ are the average interferer powers at the destination, $l_j \sim \mathcal{CN}(0, \sigma_{l_j}^2)$, u_{1j} are the interferer symbols in Phase 1 and $n_{D_1} \sim \mathcal{CN}(0, N_0)$ is the noise at the destination in Phase 1.

The signal received at R_i in Phase 1 is

$$\mathbf{y}_{R_i} = \sqrt{P_S}\mathbf{h}_i x_0 + \sqrt{P_{I_i}} \sum_{p=1}^{N_i} \mathbf{f}_{i,p} v_{i,p} + \mathbf{n}_i \tag{6.2}$$

where P_S is the average power of the desired signal at R_i, $\mathbf{h}_i \sim \mathcal{CN}(\mathbf{0}, \sigma_h^2 \mathbf{I}_{T_i})$, P_{I_i} is the average power of each interferer, $\mathbf{f}_{i,p} \sim \mathcal{CN}(\mathbf{0}, \sigma_i^2 \mathbf{I}_{T_i})$, $v_{i,p}$ are the interferer symbols and, $\mathbf{n}_i \sim \mathcal{CN}(\mathbf{0}, N_0 \mathbf{I}_{T_i})$ is the noise vector. R_i performs OC on $\mathbf{y}_{R_i}$ to estimate x_0. The signal-to-interference-plus-noise ratio (SINR) at R_i after OC is [1]

$$\gamma_{R_i} = P_S \mathbf{h}_i^H \mathbf{R}_{R_i}^{-1} \mathbf{h}_i \tag{6.3}$$

where $\mathbf{R}_{R_i} = N_0 \mathbf{I}_{T_i} + P_{I_i} \sum_{p=1}^{N_i} \mathbf{f}_{i,p} \mathbf{f}_{i,p}^H$. It is assumed that the data symbols received at R_i are successfully decoded if $\gamma_{R_i} \geq \gamma_T$, where γ_T is the SINR value corresponding to the minimum desirable rate R_{min} [7]. For $N_i = 1, \forall i \in \Omega$, the SINR at the relay i can be reformulated as [8, eq. (11.5)]

$$\gamma_{R_i} = P_S \left[\frac{|\alpha_{i,1}|^2}{N_0 + \lambda_i} + \sum_{k=2}^{T_i} \frac{|\alpha_{i,k}|^2}{N_0} \right] \tag{6.4}$$

where, $\lambda_i = \mathbf{f}_{i,1}^H \mathbf{f}_{i,1}$, $\boldsymbol{\alpha}_i = [\alpha_{i,1}, \ldots, \alpha_{i,T_i}]^T$, $\boldsymbol{\alpha}_i = \boldsymbol{\Phi}_i^H \mathbf{h}_i$ and $\boldsymbol{\Phi}_i$ is the unitary matrix consisting of eigenvectors of $\mathbf{R}_{R_i}^{-1}$.

The outage probability at R_i for $N_i = 1$ is [2, eq. (13)]

$$P_{O,R_i} = 1 - \exp\left(-\frac{\gamma_T N_0}{\bar{\gamma}_S}\right) \left[\frac{(\gamma_T N_0)^{T_i - 1} \bar{\gamma}_S}{\Gamma(T_i) \bar{\gamma}_i^{T_i} \left(\gamma_T + \frac{\bar{\gamma}_S}{\bar{\gamma}_i}\right)^{T_i}} {}_2F_1\left(T_i, T_i - 1; T_i; \frac{\gamma_T \bar{\gamma}_i}{\gamma_T \bar{\gamma}_i + \bar{\gamma}_S}\right) + \sum_{k=0}^{T_i - 2} \frac{\left(\frac{N_0 \gamma_T}{\bar{\gamma}_S}\right)^k}{k!} \right] \tag{6.5}$$

where ${}_2F_1(\cdot, \cdot; \cdot, \cdot)$ is the Gauss hypergeometric function [9, eq. (9.100)], $\bar{\gamma}_S = P_S \sigma_h^2$ and $\bar{\gamma}_i = P_{I_i} \sigma_i^2$. For $N_i > T_i$ with equal-power interferers, the outage probability is given in [10, eq. (39)]. For $2 \leq N_i \leq T_i$, a closed-form expression for the outage probability at the relay node is very difficult or impossible to derive when both noise and interference are considered. In [11], the eigenvalues of the matrix $\mathbf{R}_{R_i}$ were derived for $N_i = 2$ and $T_i > 2$, which can be used to derive the cumulative distribution function using a double numerical integration.

The decoding set C is defined as $C = \{i \in \Omega : \gamma_{R_i} \geq \gamma_T\}$. The corresponding joint relay and antenna set is

$$A_C = \{(q,k) : (k \in C), (1 \leq q \leq T_k), (q \in \mathbb{Z}^+)\}. \tag{6.6}$$

In the second phase, only the n-th best antenna in set A_C forwards the received symbols to the destination. The received signal at the destination node in phase 2 is

$$y_{RD} = \sqrt{P_R} g_{r,m} x_0 + \sum_{j=1}^{N_D} \sqrt{P_{D_j}} l_j u_{2j} + n_{D_2} \tag{6.7}$$

where P_R is the average power received by the destination from the selected relay, r and m are the antenna and the relay indexes of the n-th best antenna of A_C, respectively, which are obtained by

$$(r,m) = \arg \max_{n,(q,k)\in A_C} (\gamma_{D_{q,k}}) \tag{6.8}$$

where $\gamma_{D_{q,k}} = \mathbf{g}_{q,k}^H \mathbf{R}_D^{-1} \mathbf{g}_{q,k}$, $\mathbf{g}_{q,k} = [\sqrt{P_{SD}} g_0, \sqrt{P_R} g_{q,k}]^T$ and $g_{q,k}$ is the channel gain between the q-th antenna of the k-th relay and the destination. Furthermore, $\mathbf{R}_D = N_0 \mathbf{I}_2 + \lambda \mathbf{1}_2 \mathbf{1}_2^H$, where $\lambda = \sum_{j=1}^{N_D} P_{D_j} |l_j|^2$. The probability density function (PDF) of λ is [12]

$$f_\lambda(\lambda) = \sum_{j=1}^{p} \sum_{t=1}^{\nu_j} \frac{\phi_{jt} \lambda^{t-1}}{\Gamma(t) \eta_j^t} \exp\left(-\frac{\lambda}{\eta_j}\right) \tag{6.9}$$

where $\eta_1, \ldots, \eta_p$ are the distinct values of the average interferer powers $P_{D_1}\sigma_{l_1}^2, \ldots, P_{D_{N_D}}\sigma_{l_{N_D}}^2$, with multiplicities $\nu_1, \ldots, \nu_p$, respectively and $\sum_{j=1}^{p} \nu_j = N_D$. The partial fraction coefficients ϕ_{jt} are given in [12, eq. (10)]. It is assumed that the powers received by the destination from the source, from the relays and from the interferers are scaled with P_S, i. e. $P_R = \theta_1 P_S$, $P_{SD} = \theta_2 P_S$ and $\eta_k = \theta_{I_k} P_S, k \in \{1, 2, \ldots, p\}$, where θ_1, θ_2 and θ_{I_k} are positive constants. Hence, the interferer powers increase with an increase of the source and the relay powers.

6.3 Performance Analysis

For $|C| \geq 1$, using the approach given in [13], the conditional characteristic function of $\gamma_{D_{q,k}}$ is found as

$$\Phi_{\gamma_{D_{q,k}}|\lambda}(\omega) = \frac{N_0 + 2\lambda}{|\mathbf{D}| \left(N_0 + \lambda \mathrm{tr}(\mathbf{D}^{-1})\right)} \tag{6.10}$$

where $\mathbf{D} = \text{diag}\left[\left(1 - \frac{\mathcal{J}\omega\bar{\gamma}_{SD}}{N_0}\right), \left(1 - \frac{\mathcal{J}\omega\bar{\gamma}_R}{N_0}\right)\right]$, $\bar{\gamma}_{SD} = P_{SD}\sigma_g^2$, $\bar{\gamma}_R = P_R\sigma_g^2$ and $\mathcal{J} = \sqrt{-1}$.

For $\bar{\gamma}_{SD} \neq \bar{\gamma}_R$, i.e. source-destination and relay-destination links are independent and non-identically distributed due to path loss, the conditional PDF of $\gamma_{D_{q,k}}$ is found as

$$f_{\gamma_{D_{q,k}}|\lambda}(\gamma) = \frac{N_0(N_0 + 2\lambda)\left[\exp(-\gamma\beta) - \exp(-\gamma\alpha)\right]}{2\delta_2\bar{\gamma}_{SD}\bar{\gamma}_R} \tag{6.11}$$

where $\alpha = \delta_1 + \delta_2$, $\beta = \delta_1 - \delta_2$, $\delta_1 = \frac{(\lambda+N_0)}{2}\left(\frac{1}{\bar{\gamma}_{SD}} + \frac{1}{\bar{\gamma}_R}\right)$ and

$$\delta_2 = \frac{1}{2}\sqrt{(\lambda + N_0)^2\left(\frac{1}{\bar{\gamma}_{SD}} + \frac{1}{\bar{\gamma}_R}\right)^2 - \frac{4N_0(N_0 + 2\lambda)}{\bar{\gamma}_{SD}\bar{\gamma}_R}}. \tag{6.12}$$

Hence, the conditional outage probability is found as

$$P_{O,D_{q,k}} = 1 - \int_0^\infty \left(\frac{\alpha\exp(-\gamma_T\beta) - \beta\exp(-\gamma_T\alpha)}{2\delta_2}\right) f_\lambda(\lambda)d\lambda. \tag{6.13}$$

Due to the complexity caused by the square root operation in δ_2 (6.12), a single numerical integration is used to find $P_{O,D_{q,k}}$.

6.3.1 Large interferer power approximation for $P_{O,D_{q,k}}$

From (6.12), it can be observed that $\delta_2 \approx \frac{\lambda}{2}\left(\frac{1}{\bar{\gamma}_{SD}} + \frac{1}{\bar{\gamma}_R}\right)$ for high interferer powers. Hence, an asymptotic approximation for $P_{O,D_{q,k}}$ can be derived as

$$\begin{aligned} P_{O,D_{q,k}} \approx 1 - \exp\left(-\frac{N_0\gamma_T}{2}\left(\frac{1}{\bar{\gamma}_{SD}} + \frac{1}{\bar{\gamma}_R}\right)\right)&\left[1 + \sum_{j=1}^{p}\frac{N_0}{2}\right. \\ &\times\left\{\frac{\phi_{j1}}{\eta_j}\log\left(1 + \gamma_T\eta_j\left(\frac{1}{\bar{\gamma}_{SD}} + \frac{1}{\bar{\gamma}_R}\right)\right) + \sum_{t=2}^{\nu_j}\frac{\phi_{jt}}{(t-1)}\right. \\ &\left.\left.\times\frac{1}{\eta_j^t}\left(\eta_j^{t-1} - \frac{1}{\left(\frac{1}{\eta_j} + \gamma_T\left(\frac{1}{\bar{\gamma}_{SD}} + \frac{1}{\bar{\gamma}_R}\right)\right)^{t-1}}\right)\right\}\right]. \end{aligned} \tag{6.14}$$

For $\bar{\gamma}_{SD} = \bar{\gamma}_R$, $P_{O,D_{q,k}}$ is obtained in a manner similar to that leading to [2, eq.

(13)] and can be expressed as

$$\left(P_{O,D_{q,k}}\right)_2 = 1 - \exp\left(-\frac{N_0\gamma_T}{\bar{\gamma}_R}\right)\left[1 + \sum_{j=1}^{p}\sum_{t=1}^{\nu_j}\frac{\phi_{jt}\frac{N_0\gamma_T}{\bar{\gamma}_R}}{\left(1+\frac{2\gamma_T\eta_j}{\bar{\gamma}_R}\right)^t}\right.$$
$$\left.\times {}_2F_1\left(t, 1, 2, \frac{2\gamma_T\eta_j}{\bar{\gamma}_R + 2\gamma_T\eta_j}\right)\right]. \tag{6.15}$$

6.3.2 Outage probability for n-th best antenna selection

Without loss of generality, consider that only the first $|C|$ number of relays decode the received symbols successfully. The conditional SINR PDF for the selection of the n-th best antenna out of $\mu_C = \sum_{i=1}^{|C|} T_i$ antennas is

$$f_{\gamma_D}(\gamma|C) = \mu_C f_{\gamma_{D_{q,k}}}(\gamma)\begin{pmatrix}\mu_C - 1\\ n-1\end{pmatrix}\frac{(1-P_{O,D_{q,k}})^{n-1}}{(P_{O,D_{q,k}})^{n-\mu_C}}. \tag{6.16}$$

Hence, the conditional outage probability for the selection of the n-th best antenna is derived as [9, eq. (8.391)]

$$P_{O,D}|C = \begin{pmatrix}\mu_C\\ n-1\end{pmatrix} P^{\kappa}_{O,D_{q,k}}{}_2F_1(\kappa, 1-n; \kappa+1, P_{O,D_{q,k}}) \tag{6.17}$$

where $\kappa = \mu_C - n + 1$. For $|C| = 0$, the outage probability can be given as [2, eq. (11)]

$$P_{O,D}|(|C| = 0) = 1 - \exp\left(-\frac{N_0\gamma_T}{\bar{\gamma}_{SD}}\right)\sum_{j=1}^{p}\sum_{t=1}^{\nu_j}\frac{\phi_{jt}}{\left(1+\frac{\eta_j\gamma_T}{\bar{\gamma}_{SD}}\right)}. \tag{6.18}$$

The end-to-end outage probability is expressed as

$$P_{O,D} = \sum_{|C|=0}^{M}\sum_{\forall C\subset\Omega}\prod_{\forall i\in C}(1-P_{O,R_i})\prod_{\forall j\in(S\backslash C)}P_{O,R_j}$$
$$\times (P_{O,D}|C). \tag{6.19}$$

where C are all the unique $|C|$-tuples with the indexes of the decoding relays.

For the special case of all the relays having the same outage probability ($P_{O,R_1} = \cdots = P_{O,R_M} = P_{O,R}$), the outage probability at the destination can be given as

$$P_{out,D} = \sum_{|C|=0}^{M}\begin{pmatrix}M\\ |C|\end{pmatrix}(1-P_{O,R})^{|C|}P_{O,R}^{M-|C|}(P_{O,D}|C). \tag{6.20}$$

6.3.3 Diversity gain

Here, the diversity gain of joint relay and antenna selection with OC is obtained by finding the minimum exponent of $\frac{1}{P_S}$ in the outage probability expression given in (8.23) for large P_S values. The asymptotic outage probability for large P_S can be approximated as

$$P_{O,D}^{\infty} \approx \sum_{|C|=0}^{M} \sum_{\forall C \subset \Omega} \prod_{\forall j \in (S \backslash C)} P_{O,R_j}(P_{O,D}|C). \tag{6.21}$$

It is assumed that each relay is equipped with Tantennas. Moreover, the first m number of relays have $N_a < T$ interferers and the remaining $M-m$ relays have $N_b \geq T$ interferers. Hence, from [14], the diversity gain of OC at each multiple-antenna relay R_i can be given as

$$G_{D_{R_i}} = \begin{cases} T - N_a & \text{for} \quad i \in \{1, \ldots, m\} \\ 0 & \text{for} \quad i \in \{m+1, \ldots, M\} \end{cases}. \tag{6.22}$$

By applying the infinite series expansion of the exponential function in (6.14), it can be easily shown that the minimum exponent of $\frac{1}{P_S}$ in $P_{O,D_{q,k}}$ is equal to 1. Hence, from (6.17), the minimum exponent of $\frac{1}{P_S}$ in $P_{O,D}|C$ is equal to $|C|T-n+1$. Furthermore, by observation, the minimum exponent of $\frac{1}{P_S}$ is equal to zero in (6.18). By applying these exponent values of $\frac{1}{P_S}$ in (6.21) and after simple manipulations, it can be easily shown that

$$P_{O,D}^{\infty} \approx \sum_{|C|=0}^{M} \frac{K_C}{P_S^{\Lambda_C}} + \mathcal{O}\left(\frac{1}{P_S^{\Lambda_C+1}}\right) \tag{6.23a}$$

where K_C is independent of $\frac{1}{P_S}$ and

$$\Lambda_C = \begin{cases} m(T-N_a) + |C|N_a - n + 1 & \text{if} \quad |C| < m \\ |C|T - n + 1 & \text{if} \quad |C| \geq m \end{cases}. \tag{6.23b}$$

It can be observed that the minimum exponent of $\frac{1}{P_S}$ in $P_{O,D}^{\infty}$ is equal to $m(T-N_a)-n+1$ for all values of $|C|$, which is the diversity gain. Hence, OC with joint relay and antenna selection achieves diversity gains for $m > 0$, which is the number of relays with fewer interferers than the number of antennas. Extending this result to unequal numbers of interferers and antennas at different relays is straightforward. For $m = 0$, the diversity gain is zero.

6.4 Numerical Results

Here, the outage probability expressions derived in Sections III and IV are verified using simulations. For all simulations, $n = 1$ (i.e. best relay selection), $P_S = P_R$, $T_i = 2 \quad \forall i \in \Omega$, $\gamma_T = 5\ dB$ and $\sigma_h^2 = \sigma_g^2 = \sigma_i^2 = \sigma_j^2 = 1 \quad \forall i \in \Omega, \forall j \in \{1, \ldots, N_D\}$. There are 5 independent interferers at the destination with signal-to-interference ratios (SIR) $\frac{P_R}{P_{D_j}} = [20, 15, 10, 5, 3]\ dB$, respectively. The SIR of interferers at the relays is $\frac{P_S}{P_{I_i}} = 10\ dB$. Hence, the interferer powers are always scaled with the source and the relay powers.

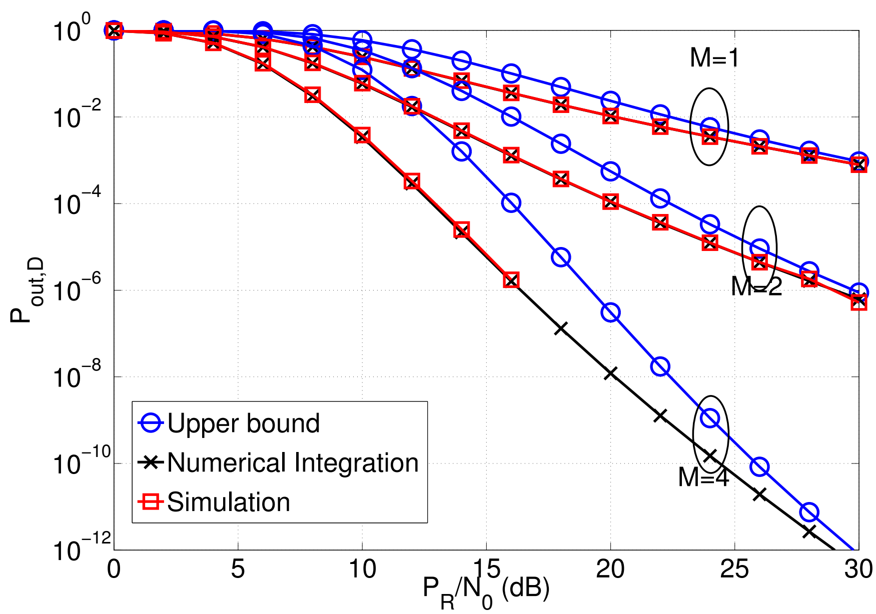

Figure 6.2: The outage performance of OC with joint relay and antenna selection for $m = M$, $N_a = 1$, $T = 2$, $P_{SD} = P_R/8$ and $n = 1$.

The performance of OC with joint relay and antenna selection for each relay having $N_a = 1(< T = 2)$ interferers is shown in Fig. 6.2 for $P_{SD} = P_R/8$ and $m = M$. The diversity gain is equal to $m(T - N_a)$. Hence, diversity gains of 1, 2 and 4 are achieved for $M = 1$, 2 and 4, respectively. Furthermore, the tightness of the proposed upper bound in (6.14) reduces with the increase of M. However, this approximation can be used to obtain the diversity gain as it shows the same diversity gain as the simulations. The exact performance can be obtained using a single numerical integration, which is computed significantly faster than the simulations.

Fig. 6.3 shows the performance degradation with the decrease of m, which is the number of relays having $N_a < T$ interferers at each relay, for $M = 4$ and $N_a = 1$. Each of the remaining $M - m$ relays have $N_b = 3 \geq T$ interferers. For $m = 0$, the diversity gain is equal to zero, which agrees with the value of diversity gain derived analytically. Hence the diversity performance is dependent on the number of antennas and the number of interferers at the relay nodes.

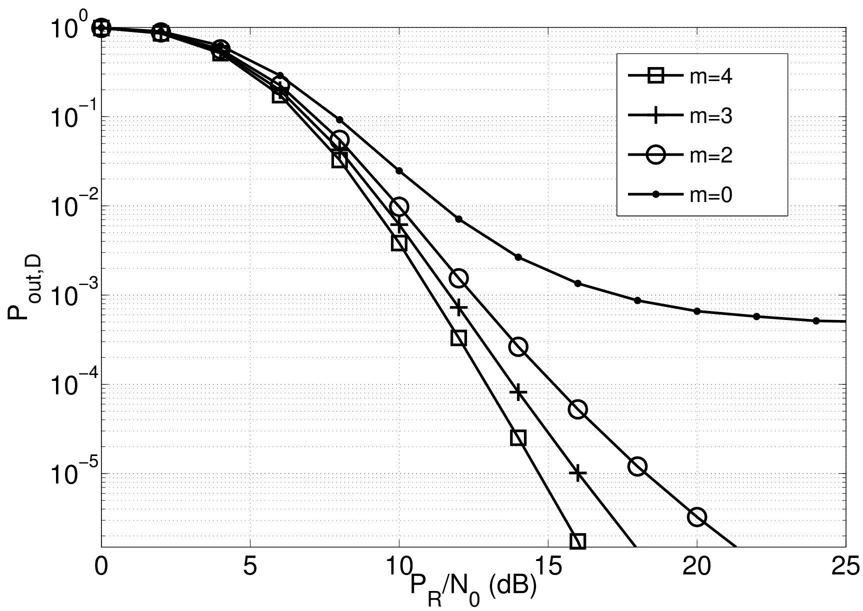

Figure 6.3: The outage performance for different values of m for $M = 4$, $T = 2$, $P_{SD} = P_R/8$, $N_a = 1$, $N_b = 3$ and $n = 1$.

The performances of OC at the relays and at the destination is compared with two schemes: (1) MRC at the relays and OC at the destination, and (2) OC at the relays and MRC at the destination in Fig. 6.4 for joint relay and antenna selection. The performances for $M = 2$ and $M = 4$ are shown in the curves with square markers and cross markers, respectively. Accordingly, the diversity gain is equal to zero for MRC as CCI is not suppressed by MRC. Furthermore, the performance with MRC at the relays only is significantly better than the performance with MRC at the destination only. Hence, having OC at the destination node is very critical to improve the performance in the presence of CCI. At low SNR values, the performance of MRC and OC are comparable as AWGN is the principle limiting factor at low power levels. However, at large SNR values, CCI becomes the principle limiting factor due to the increase of interferer powers, which is the reason for OC outperforming MRC at high SNR values.

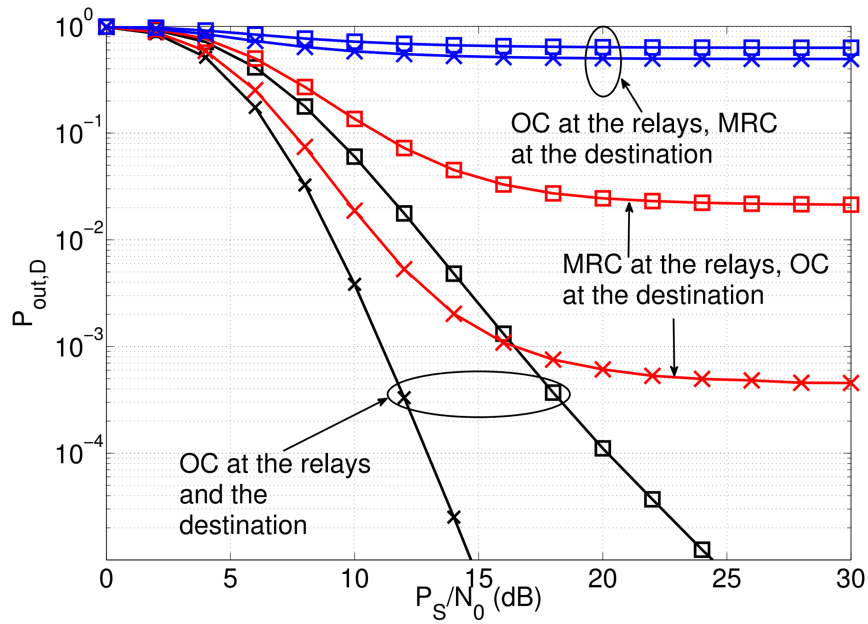

Figure 6.4: The outage performance comparison of OC and MRC with joint relay and antenna selection for $m = M$, $N_a = 1$, $T = 2$, $P_{SD} = P_R/8$ and $n = 1$.

Significantly, the combination of OC with joint relay and antenna selection achieves the same diversity gains as conventional relay transmission in orthogonal timeslots, in the presence of CCI. However, the capacity is improved as the communication uses only two time slots, instead of $M + 1$. Furthermore, the performance degradation due to CCI at the relays [2] is mitigated using multiple antennas and OC at the relays.

6.5 Conclusion

The performance of optimum combing in DF cooperative relaying with interfering signals present at the relays and the destination was analyzed. Joint relay and antenna selection was used in Phase 2 of the communication to improve the capacity.

OC with joint relay and antenna selection achieves diversity gains when the interferer powers are scaled with the source and the relay powers, given that at least one relay has $T_i > N_i$, where T_i and N_i are the number of antennas and the number of interferers at relay i, respectively.

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Chapter 7

Optimum Combining in Amplify-and-Forward Relaying

The performance of optimum combining (OC) in amplify-and-forward (AF) relaying systems in the presence of co-channel interference (CCI) is analyzed using a tight approximation for the signal-to-interference-plus-noise ratio (SINR) at the destination. Two types of relaying protocols are studied, all-relay transmission with OC and best-relay transmission with OC. When CCI is present only at the destination, both relaying protocols achieve diversity gains up to M when interferer powers are scaled with the source and the relay powers, where M is the number of relays. Best-relay transmission with OC maximizes the spectral efficiency as each communication consumes only two time slots[1]

7.1 Introduction

Compared to decode-and-forward (DF) relaying, amplify-and-forward (AF) relaying is less complex and more secure. When the distance between the source and the destination is such that dual-hop communication is possible, multiple relays can be used to transmit to the destination and diversity combining / relay selection techniques can be used to improve the system performance. Maximal-ratio combining (MRC) is the optimal diversity combining technique when additive white Gaussian

[1] A version of this chapter was published in IEEE Transactions on Communications, N. Suraweera and N. C. Beaulieu, "Optimum Combining in Dual-Hop AF Relaying for Maximum Spectral Efficiency in the Presence of Co-Channel Interference", *IEEE Transactions on Communications*, vol. 63, no. 6, pp. 2071-2080, Jun. 2015.

noise (AWGN) is the dominant limiting factor [1]. However, in practical wireless communications systems, co-channel interference (CCI) is the dominant limiting factor due to frequency reuse. The performance of MRC is degraded in the presence of CCI and diversity gains are achieved only if the average interferer power remains constant [2], [3]. However, it is not always reasonable to assume that average interferer powers remain constant when the source and the relay powers are increased.

The performance of dual-hop AF relaying with a single relay, in the presence of CCI was studied in several publications, including [4–7] for different channel models, without considering CCI suppression. It was always assumed that the direct link between the source and the destinations is completely shadowed. This mode of relaying operation only improves the coverage, and the diversity gains are not improved. Furthermore, the performance of transmission by multiple relays was not studied for AF relaying in the presence of CCI, except for relay selection.

The main limitation of transmission in orthogonal time slots is the degradation of spectral efficiency as multiple time slots are used for a single communication. Relay selection [8] enables achieving higher spectral efficiencies, while maintaining the diversity gains as only one relay forwards its received signal to the destination. The performance of relay selection in the presence of CCI was analyzed in [9–12] for AF relaying. In [9] and [10], interference was assumed to be present only at the relays. In [11], both the relays and the destination were assumed to be affected by CCI. The direct link was assumed to be shadowed. The direct link was assumed to be available in [12] and interference was present only at the destination. However, the cancellation of CCI was not considered.

When co-channel interference is present, optimum combining (OC) (also known as minimum mean-square-error combining) is the diversity combining technique that maximizes the signal-to-interference-plus-noise ratio (SINR) at the receiver [13]. It enables achieving diversity gains by suppressing the co-channel interference component of the received signal as well as the ambient noise component, thus outperforming MRC. The performance of OC in multiple-antenna receivers has been widely investigated in the literature (e.g. [14–17] and the references therein) for different system and channel models. For AF relaying with a single multiple-antenna relay, CCI suppression at the relay using OC was studied in [18] and [19], where the direct link was assumed to be shadowed and the destination is interference free.

The additional performance overhead of OC over other diversity combining techniques is the estimation of interferer channel state information (CSI). In [20], it was shown that the performance of OC in DF relaying is not affected if the destination is only provided with the variance of interferer CSI, instead of instantaneous interferer CSI. This reduces the channel estimation overhead significantly as the CSI variance changes less frequently, compared to instantaneous CSI.

In this chapter, the performance of AF relaying with OC is analyzed in the presence of CCI. In the first part of the analysis, CCI is assumed to be present at the destination only. Two types of relaying protocols are considered, all-relay transmission with OC, where each relay amplifies and forwards its received signal to the destination in orthogonal time slots [21], and best-relay transmission with OC, where only the best available relay amplifies and forwards its received signal. Next, the performance of best-relay transmission is briefly studied when CCI is present at the relays and at the destination. The main contributions and insights in this chapter are listed as follows.

1. For all-relay transmission with OC in the presence of CCI only at the destination, the outage probability is derived using a tight approximation for SINR at the destination. It is proved that a diversity gain of M is achieved, where M is the number of relays. However, the spectral efficiency of all-relay transmission with OC is degraded with an increase of the number of relays.

2. For best-relay transmission with CCI present only at the destination, it is proved that a diversity gain up to M is achieved using OC. Furthermore, the capacity is maximized as only two time slots are used for a single communication.

3. Similar to [20], it is proved that for AF relaying, the performance of all-relay transmission and best-relay selection are not affected if the destination node is only provided with the distribution information of interferer CSI, instead

of instantaneous interferer CSI. This reduces the interferer channel estimation overhead of OC significantly.

4. The performance of best-relay selection when CCI is present at the relays and at the destination is studied using an approximation for SINR. The outage performance degrades and the diversity gain reduces to zero as OC at the destination fails to cancel the interference at the relays.

The rest of the chapter is organized as follows. The system description when CCI is present only at the destination is presented in Section 7.2 and in Section 7.3, the performance of OC with CCI present only at the destination is analyzed. The performance of best-relay transmission with OC when CCI present at the relays and at the destination is studied in Section 7.4. Numerical results are presented and discussed in Section 7.5, and Section 7.6 concludes this chapter.

7.2 System Description with CCI at the Destination only

An AF relay network with a source node (S), a destination (D) and M relays ($R_i, i \in \Omega = \{1, 2, \ldots, M\}$) is considered (Fig. 7.1). In this part of the analysis, it is assumed that the effect of CCI on the relays is negligible. The destination is interfered by N_D co-channel interferers having average powers $P_{ID_j}, j \in \{1, , 2 \ldots, N_D\}$. This model is relevant when the destination is located closer to the edge of the cell and the relays are located far from the edge of the cell. The average powers of the source-relay, source-destination and relay-destination links are P_S, P_{SD} and P_R, respectively. The source-relay, source-destination, relay-destination and interferer-destination links are assumed to be frequency-flat Rayleigh faded with $h_i \sim \mathcal{CN}(0, 1)$, $g_0 \sim \mathcal{CN}(0, 1)$, $g_i \sim \mathcal{CN}(0, 1)$ and $l_j \sim \mathcal{CN}(0, 1)$, respectively, where $i \in \Omega = \{1, 2, \ldots, M\}$ and $j \in \{1, 2, \ldots, I_D\}$.

The cooperative communication protocol consists of two phases. During the first phase, the source node broadcasts its message to all the relays and to the desti-

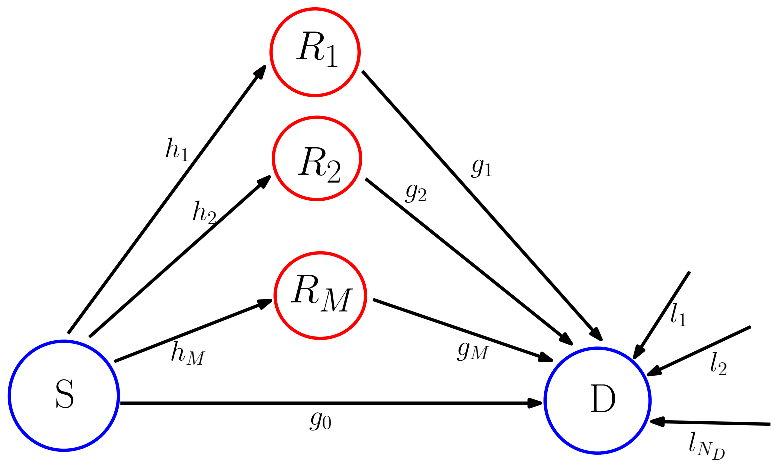

Figure 7.1: The AF relay network with co-channel interference at the destination.

nation. The signal received at the destination during phase 1 is given by

$$y_{SD} = \sqrt{P_{SD}} g_0 x_0 + \sum_{j=1}^{N_D} \sqrt{P_{ID_j}} l_j x_j + n_{SD} \tag{7.1}$$

where x_0 is the data symbol transmitted by the source and x_j are the data symbols transmitted by the interferer nodes. $n_{S,D}$ is the noise at the destination in the first phase and $n_{S,D} \sim \mathcal{CN}(0, N_0)$. The signal received at the R_i during phase 1 is given by

$$y_{SR_i} = \sqrt{P_S} h_i x_0 + n_{SR_i} \tag{7.2}$$

where $n_{SR_i} \sim \mathcal{CN}(0, N_0)$.

In Phase 2, amplify-and-forward relaying is used. For mathematical tractability, the amplification gains of relays are assumed to be channel state information (CSI) assisted, i.e. R_i estimates h_i correctly and inverts the amplitude of the received signal component ($\sqrt{P_S}|h_i|$). Two types of relaying protocols are considered, all-relay transmission and best-relay transmission.

7.2.1 All-relay transmission

Here, all the relays participate in the communication and each relay transmits an amplified version of its received signal to the destination in orthogonal time slots. Hence, $M + 1$ time slots are used to complete a single communication and the OC receiver combines the signals received in $M + 1$ branches.

It is assumed that the fading coefficients of interferer-destination links are quasi-static, i.e. the values of $\{f_j\}$ remain the same during a single cooperative communication cycle and are different between communication cycles. The signal received at the destination node from Relay i during Phase 2 is

$$y_{R_iD} = \frac{\sqrt{P_R} g_i h_i x_0}{|h_i|} + \sum_{j=1}^{I_D} \sqrt{P_{ID_j}} l_j x_j + \frac{\sqrt{P_R} g_i n_{SR_i}}{\sqrt{P_S} |h_i|} + n_{R_iD} \tag{7.3}$$

where $n_{R_iD} \sim \mathcal{CN}(0, N_0)$.

The OC receiver at the destination combines the signals received in $M+1$ time slots to detect the transmitted symbol $\hat{x}_0 = \mathbf{w}^H \mathbf{y}$, where $\mathbf{y} = [y_{SD}, y_{R_1D}, y_{R_2D}, \dots, y_{R_MD}]^T$ and the OC weight vector $\mathbf{w}$ is given by $\mathbf{w} = \mathbf{R}_{OC}^{-1} \boldsymbol{\alpha}$, where $\boldsymbol{\alpha} = \left[\sqrt{P_{SD}} g_0, \frac{\sqrt{P_R} g_1 h_1}{|h_1|}, \frac{\sqrt{P_R} g_2 h_2}{|h_2|}, \dots, \frac{\sqrt{P_R} g_M h_M}{|h_M|}\right]^T$. The noise-plus-interference correlation matrix $\mathbf{R}_{OC}$ is given by [13]

$$\begin{aligned} \mathbf{R}_{OC} = N_0 \mathbf{I}_{M+1} + \text{diag}\left[0, \frac{P_R |g_1|^2}{P_S |h_1|^2}, \frac{P_R |g_2|^2}{P_S |h_2|^2}, \dots, \frac{P_R |g_M|^2}{P_S |h_M|^2}\right] \\ + \sum_{j=1}^{I_D} P_{I_j} |l_j|^2 \mathbf{1}_{M+1} \mathbf{1}_{M+1}^T. \end{aligned} \tag{7.4}$$

It is assumed that the destination is provided with the channel state information of source-relay channels in Phase 1. In [22], the overhead associated with conveying the channel state information (CSI) of source-relay links to the destination is discussed. Accordingly, a potential training process consists of following two steps.

In Step 1, the destination obtains the CSI of the relay-destination links using pilot signals, transmitted by the relays in orthogonal time slots. Step 1 takes M time slots.

The source node broadcasts its pilot signal to the relays and to the destination in Step 2. Each relay, amplifies this signal using a fixed known amplification factor and forwards to the destination in orthogonal time slots, which is used to determine source-relay channel coefficients at the destination. Step 2 takes $M+1$ time slots. Hence, the training process takes $2M+1$ time slots.

The resulting SINR at the destination is given by [13]

$$\gamma_{D_{OC}} = \boldsymbol{\alpha}^H \mathbf{R}_{OC}^{-1} \boldsymbol{\alpha}. \tag{7.5}$$

It should be noted that the elements of $\boldsymbol{\alpha}$ have the same distribution as the elements of the vector $\mathbf{g} = \left[\sqrt{P_{SD}}g_0, \sqrt{P_R}g_1, \sqrt{P_R}g_2, \ldots, \sqrt{P_R}g_M\right]^T$. It is very difficult or impossible to analyze the performance of the AF relay network using OC based on the exact SINR expression given in (7.5). In order to further analyze the performance of the OC receiver in AF relaying , we propose a tight approximation for the SINR in (7.5), which is expressed as

$$\gamma_{D_{OC}} \approx \frac{P_{SD}|g_0|^2}{N_0 + \sum_{j=1}^{I_D} P_{I_j}|l_j|^2(M+1)} + \sum_{i=1}^{M} \min\left(\frac{P_R|g_i|^2}{N_0}, \frac{P_S|h_i|^2}{N_0}\right) \tag{7.6}$$

$$= \frac{X_D}{N_0 + Y_D} + \sum_{i=1}^{M} Z_i \tag{7.7}$$

where X_D is an exponentially distributed random variable with parameter P_{SD}. The probability density function (PDF) of Y_D is given by [23, eq. (9)]

$$f_{Y_D}(y) = \sum_{k=1}^{r}\sum_{l=1}^{\nu_k} \frac{\phi_{kl} y^{l-1}}{(l-1)!(\eta_k(M+1))^l} \exp\left(\frac{-y}{\eta_k(M+1)}\right) \tag{7.8}$$

where $\eta_1, \eta_2, \ldots, \eta_r$ are the distinct values of $P_{ID_j} (j \in \{1, 2, \ldots, I_D\})$ with multiplicities $\nu_1, \nu_2, \ldots, \nu_r$, respectively, such that $\sum_{k=1}^{r} \nu_k = I_D$. The coefficients ϕ_{kl} are defined in [23, eq. (10)]. The PDF of Z_i is given by [24, eq. (6-82)]

$$f_{Z_i}(z) = \frac{N_0}{P_T} \exp\left(\frac{-N_0 z}{P_T}\right) \tag{7.9}$$

where $P_T = \frac{P_R P_S}{P_R + P_S}$. Hence, the random variable $Z_D = \sum_{i=1}^{M} Z_i$ is gamma distributed with shape parameter M and scale parameter $\frac{P_T}{N_0}$.

The approximation in (7.6) is obtained by applying the SINR expression derived for DF relaying in [25, eq. (7)] into AF relaying. If the destination node is interference free, the signal-to-noise ratio (SNR) of the i-th relay-destination link is tightly bounded by

$$\gamma_i = \frac{\gamma_{i1}\gamma_{i2}}{1 + \gamma_{i1} + \gamma_{i2}} \leq \min(\gamma_{i1}, \gamma_{i2}) \tag{7.10}$$

where $\gamma_{i1} = \frac{P_S|h_i|^2}{N_0}$ and $\gamma_{i2} = \frac{P_R|g_i|^2}{N_0}$, which is used to get the approximation in (7.6).

For all-relay transmission, if MRC is used, the weight vector is found by $\mathbf{w}_{MRC} = \mathbf{R}_{MRC}^{-1}\boldsymbol{\alpha}$ where $\mathbf{R}_{MRC} = N_0\mathbf{I} + \text{diag}\left[0, \frac{P_R|g_1|^2}{P_S|h_1|^2}, \frac{P_R|g_2|^2}{P_S|h_2|^2}, \ldots, \frac{P_R|g_M|^2}{P_S|h_M|^2}\right]$, is the total noise covariance matrix. The resulting SINR is

$$\gamma_{D_{MRC}} = \frac{\left(\boldsymbol{\alpha}^H \mathbf{R}_{MRC}^{-1} \boldsymbol{\alpha}\right)^2}{\boldsymbol{\alpha}^H \mathbf{R}_{MRC}^{-1} \mathbf{R}_{OC} \mathbf{R}_{MRC}^{-1} \boldsymbol{\alpha}}. \tag{7.11}$$

7.2.2 Best-relay transmission

Here, only the best available relay amplifies and forwards the received signal to the destination. The general case of n-th best relay selection is considered as the best relay $(n = 1)$ may not always be available for the communication in Phase 2. Therefore, a single communication consumes only two time slots. Furthermore, the OC operation in best-relay transmission is simpler than in all-relay transmission as only two diversity branches are combined. Finding the best available relay is the additional overhead.

It is clear that the destination is the best node to make the selection decision with minimum additional overhead as it is provided with the necessary channel state information to perform OC. Feedback of $\lceil \log_2 M \rceil$ bits is sufficient to convey the selection decision to the relays and no channel state information feedback is necessary.

In relay selection, the received signal by the destination in Phase 2 is

$$y_{R_k D} = \frac{\sqrt{P_R} g_k h_k x_0}{|h_k|} + \sum_{j=1}^{I_D} \sqrt{P_{I_j}} f_j x_j + \frac{\sqrt{P_R} g_k n_{SR_k}}{\sqrt{P_S} |h_k|} + n_{R_k D} \tag{7.12}$$

where k is the index of the n-th best relay, which is obtained by

$$k = \arg\max_{n, i \in \Omega} \left\{ \gamma_{D_{OC,i}} = \boldsymbol{\alpha_i}^H \mathbf{R}_{OC,i}^{-1} \boldsymbol{\alpha_i} \right\} \tag{7.13a}$$

where

$$\mathbf{R}_{OC,i} = N_0 \mathbf{I} + \text{diag}\left[0, \frac{\sqrt{P_R} |g_i|^2}{\sqrt{P_S} |h_i|^2}\right] + \sum_{j=1}^{I_D} P_{I_j} |l_j|^2 \mathbf{1}\mathbf{1}^T \tag{7.13b}$$

and $\boldsymbol{\alpha}_i = \left[\sqrt{P_{SD}} g_0, \frac{\sqrt{P_R} g_i h_i}{|h_i|}\right]^T$. If best-relay transmission is used with MRC, the selected relay index is obtained as

$$q = \arg\max_{n, i \in \Omega} \left\{ \gamma_{D_{MRC,i}} = \frac{\boldsymbol{\alpha}_i^H \mathbf{R}_{MRC,i}^{-1} \boldsymbol{\alpha}_i}{\boldsymbol{\alpha}_i^H \mathbf{R}_{MRC,i}^{-1} \mathbf{R}_{OC,i} \mathbf{R}_{MRC,i}^{-1} \boldsymbol{\alpha}_i} \right\} \tag{7.14}$$

where $\mathbf{R}_{MRC,i}$ is the total noise covariance matrix.

7.3 Performance analysis of OC With CCI at the Destination only

7.3.1 All-relay transmission

Cumulative distribution function

Based on the principle of total probability, the cumulative distribution function (CDF) of SINR of the OC receiver at the destination can be expressed as

$$F_{\gamma_D}(\gamma) = 1 - (\mathcal{I}_1 + \mathcal{I}_2) \tag{7.15a}$$

where

$$\mathcal{I}_1 = \int_0^{\gamma} \int_0^{\infty} \int_{(\gamma-z)(N_0+y)}^{\infty} f_{X_D}(x) f_{Y_D}(y) f_{Z_D}(z) dx dy dz \tag{7.15b}$$

and

$$\mathcal{I}_2 = \int_{\gamma}^{\infty} f_{Z_D}(z) dz. \tag{7.15c}$$

Using [26, eq. (3.351.2)], the integral $\mathcal{I}_2$ is solved as

$$\mathcal{I}_2 = \exp\left(\frac{-\gamma N_0}{P_T}\right) \sum_{k=0}^{M-1} \frac{\left(\frac{\gamma N_0}{P_T}\right)^k}{k!}. \tag{7.16}$$

Substituting for $f_{X_D}(x)$, $f_{Y_D}(y)$ and $f_{Z_D}(z)$ and after some manipulations, $\mathcal{I}_1$ can be expressed as

$$\mathcal{I}_1 = \sum_{k=1}^{r} \sum_{l=1}^{\nu_k} \frac{\exp\left(\frac{-\gamma N_0}{P_T}\right) \phi_{kl} (-P_{SD})^l \left(\frac{N_0}{P_T}\right)^M}{(\eta_k (M+1))^l \Gamma(M)} \int_0^{\gamma} \frac{z^{M-1}}{\left(z - \gamma - \frac{P_{SD}}{\eta_k (M+1)}\right)^l} \times \exp\left(\frac{N_0 z}{P_{SD}} - \frac{N_0 z}{P_T}\right) dz. \tag{7.17}$$

For $P_{SD} \neq P_T$, after simple manipulations $\mathcal{I}_1$ can be expressed as

$$\mathcal{I}_1\Big|_{P_{SD} \neq P_T} = \sum_{k=1}^{r} \sum_{l=1}^{\nu_k} K_2(k,l) \exp(a K_1) \sum_{i=0}^{M-1} \binom{M-1}{i} K_1^{M-1-i} \times \int_{-K_1}^{\gamma - K_1} t^{i-l} \exp(at) dt \tag{7.18a}$$

where

$$K_2(k,l) = \frac{\exp\left(\frac{-\gamma N_0}{P_{SD}}\right)\phi_{kl}(-P_{SD})^l\left(\frac{N_0}{P_T}\right)^M}{(\eta_k(M+1))^l\Gamma(M)} \tag{7.18b}$$

and

$$K_1 = \gamma + \frac{P_{SD}}{\eta_k(M+1)}, \quad a = N_0\left(\frac{1}{P_{SD}} - \frac{1}{P_T}\right). \tag{7.18c}$$

For this scenario, $\mathcal{I}_1$ is solved as [26, eq. (2.324.2)]

$$\mathcal{I}_1\Big|_{P_{SD}\neq P_T} = \sum_{k=1}^{r}\sum_{l=1}^{\nu_k} K_2(k,l)\sum_{i=0}^{M-1}\left(\begin{array}{c} M-1 \\ i \end{array}\right) K_1^{M-1-i}\hat{\mathcal{I}}_1(i,l) \tag{7.19a}$$

$$\hat{\mathcal{I}}_1(i,l) = \begin{cases} \sum_{j=0}^{i-l}\frac{(-1)^j(i-l)!\left(\exp(a\gamma)(\gamma-K_1)^{i-l-j}-(-K_1)^{i-l-j}\right)}{(i-l-j)!a^{j+1}} & \text{if} \quad i>l \\ \frac{(\exp(a\gamma)-1)}{a} & \text{if} \quad i=l, \\ \frac{\exp(aK_1)a^{l-i-1}(\mathrm{Ei}(a(\gamma-K_1))-\mathrm{Ei}(-aK_1))}{(l-i-1)!} & \text{if} \quad i<l. \\ +\sum_{j=1}^{l-i-1}\frac{a^{j-1}(l-i-j-1)!}{(l-i-1)!}\left(\frac{1}{(-K_1)^{l-i-j}} - \frac{\exp(a\gamma)}{(\gamma-K_1)^{l-i-j}}\right) & \end{cases} \tag{7.19b}$$

where $\mathrm{Ei}(x)$ is the exponential integral function, defined in [26, eq. (8.211.1)].

If $P_{SD} = P_T = P$, $\mathcal{I}_1$ is obtained as [27, eq. (1.2.4.3)]

$$\mathcal{I}_1\Big|_{P_{SD}=P_T} = \sum_{k=1}^{r}\sum_{l=1}^{\nu_k}\frac{K_2(k,l)}{\left(\gamma+\frac{P}{\eta_k(M+1)}\right)^l M}\,{}_2F_1\left(l, M; M+1; \frac{\gamma}{\gamma+\frac{P}{\eta_k(M+1)}}\right) \tag{7.20}$$

where ${}_2F_1(\cdot,\cdot;\cdot,\cdot)$ is the Gauss hypergeometric function [26, eq. (9.100)].

Moment generating function

The conditional moment generating function (MGF) of γ_D can be found as

$$\mathcal{M}_{\gamma_D|Y_D}(s) = \frac{1}{\left(\frac{P_{SD}s}{N_0+Y_D}+1\right)\left(\frac{P_T s}{N_0}+1\right)^M}. \tag{7.21}$$

Averaging (7.21) over the PDF of Y_D given in (7.8), we obtain the unconditioned MGF of γ_D as

$$\begin{aligned}\mathcal{M}_{\gamma_D}(s) = & \sum_{k=1}^{r}\sum_{l=1}^{\nu_k}\frac{\phi_{kl}N_0^M}{(l-1)!(\eta_k(M+1))^l\left(P_T s+N_0\right)^M}\left[N_0\sum_{i=1}^{l-1}\left(\begin{array}{c} l-1 \\ i \end{array}\right)(-1)^{l-i-1}\right. \\ & \times\sum_{m=0}^{i-1}\frac{(i-1)!}{m!}\left(\eta_k(M+1)\right)^{i-m}\left(N_0+P_{SD}s\right)^{l-1-i+m}+\sum_{j=1}^{l}\left(\begin{array}{c} l \\ j \end{array}\right)(-1)^{l-j} \\ & \times\sum_{n=0}^{j-1}\frac{(j-1)!}{n!}\left(\eta_k(M+1)\right)^{j-n}\left(N_0+P_{SD}s\right)^{l-j+n}+\left(-N_0-P_{SD}s\right)^{l-1} \\ & \left.\times(-P_{SD}s)\mathrm{exp}\left(\frac{N_0+P_{SD}s}{\eta_k(M+1)}\right)\mathrm{E}_1\left(\frac{N_0+P_{SD}s}{\eta_k(M+1)}\right)\right]\end{aligned} \tag{7.22}$$

where $\mathrm{E}_1(z)$ is the exponential integral function defined in [28, eq. (5.1.1)]. Hence, the average symbol error rate (SER) is [29]

$$P_e = \frac{1}{\pi}\int_0^{\pi/2}\mathcal{M}_{\gamma_D}\left(-\frac{b^2}{2\mathrm{sin}^2\theta}\right)d\theta \tag{7.23}$$

where b is a constant based on the modulation scheme used.

Ergodic capacity

The ergodic capacity can be found as [30]

$$C_D = \frac{1}{(M+1)\mathrm{log}(2)}\int_0^{\infty}\frac{1-F_{\gamma_D}(\gamma)}{1+\gamma}d\gamma \tag{7.24}$$

or as [31]

$$C_D = \frac{\mathrm{log}_2(e)}{(M+1)}\int_0^{\infty}\frac{(1-\mathcal{M}_{\gamma_D}(s))}{s}\mathrm{exp}(-s)ds \tag{7.25}$$

using a single numerical integration. The division by $M+1$ is required as $M+1$ time slots are used for a single communication.

Diversity gain

The diversity gain is found by finding the minimum exponent of $\frac{1}{P_S}$ in (7.15). It is assumed that P_R, P_{SD} and the interferer powers are scaled with P_S, i.e. $P_{SD} =$

$\lambda_1 P_S$, $P_R = \lambda_2 P_S$ and $\eta_k = \lambda_{3,k} P_S$, where λ_1, λ_2 and $\lambda_{3,k}$ are constants. Hence, $P_T = \frac{\lambda_2 P_S}{(1+\lambda_2)}$ and $a = \frac{N_0}{P_S}\left(\frac{1}{\lambda_1} - \frac{\lambda_2+1}{\lambda_2}\right)$. From (8.22),

$$1 - \mathcal{I}_2 = \exp\left(\frac{-\gamma N_0}{P_T}\right) \sum_{k=M}^{\infty} \frac{\left(\frac{\gamma N_0}{P_T}\right)^k}{k!}. \tag{7.26}$$

Using the power series expansion of the exponential function, the asymptotic value of $1 - \mathcal{I}_2$ is found as

$$(1 - \mathcal{I}_2)^{\infty} = \frac{\left(\frac{\gamma N_0}{P_T}\right)^M}{M!} + \mathcal{O}\left(\frac{1}{P_T^{M+1}}\right). \tag{7.27}$$

Hence, the minimum exponent of $\frac{1}{P_S}$ in the asymptotic value of $1 - \mathcal{I}_2$ is M. For the special case of $P_{SD} = P_T$, using (7.20), the asymptotic value of $\mathcal{I}_1$ can be expressed as

$$\mathcal{I}_1^{\infty} = \left(\frac{\gamma N_0}{P_T}\right)^M K_3 + \mathcal{O}\left(\frac{1}{P_T^{M+1}}\right) \tag{7.28}$$

where the exponent of $\frac{1}{P_S}$ in K_3 is zero.

For $P_{SD} \neq P_T$, by applying the power series expansion of the exponential function in (7.18b), we observe that the minimum exponent of $\left(\frac{1}{P_S}\right)$ in $K_2(k,l)$ is equal to M. We now analyze the term $\hat{\mathcal{I}}_1(i,l)$ in (7.19) for different cases of i and l.

1. $i > l$ - For this case, using the power series expansion of the exponential function it can be shown that

   $$\hat{\mathcal{I}}_1(i,l)^{\infty}\Big|_{i>l} \approx K_4(i,l) + \mathcal{O}\left(a\right) \tag{7.29}$$

   where $K_4(i,l) = \frac{1}{i-l}\left((\gamma - K_1)^{i-l} - (-K_1)^{i-l}\right)$, is a constant for a given pair of i and l and a is proportional to $\left(\frac{1}{P_S}\right)$. Hence, the minimum exponent of $\left(\frac{1}{P_S}\right)$ in $\hat{\mathcal{I}}_1(i,l)$ is zero.

2. $i = l$ - Using the approximation $\exp(a\gamma) \approx 1 + a\gamma$ as $a \to 0$, for this case $\hat{\mathcal{I}}_1(i,l)^{\infty} \approx \gamma$. Thus, the minimum exponent of $\frac{1}{P_S}$ is zero.

3. $i < l$ - For this case, the asymptotic value of $\hat{\mathcal{I}}_1(i,l)$ can be expressed as

   $$\hat{\mathcal{I}}_1(i,l)^{\infty}\Big|_{i<l} \approx K_5(i,l) + \mathcal{O}(a) \tag{7.30}$$

where $K_5(i, l)$ is a constant for given i and l. The proof of (7.30) is given in Appendix 5.A.

Hence, the minimum exponent of $\frac{1}{P_S}$ in $\hat{\mathcal{I}}_1(i, l)$ is equal to zero for all values of i and l. Thus, the minimum exponent of $\frac{1}{P_S}$ in $\mathcal{I}_1$ is M.

Consequently, OC achieves a diversity gain of M in AF relaying when interferer powers are scaled with the source power and the relay powers. Note that there are $M+1$ diversity branches, including the direct link. It was shown that the diversity gain of OC reduces with the increase of the rank of the interference correlation component in $\mathbf{R}_{OC}$ [13,16]. From (7.4), when CCI is present only at the destination, the rank of interference correlation component in $\mathbf{R}_{OC}$ is equal to one. Due to the interference at the destination, the diversity gain is reduced by one and equal to M. This is the maximum achievable diversity gain in the presence of CCI, which is a significant improvement compared to MRC, where the diversity gain reaches zero when the interferer powers are scaled with the source and the relay powers.

The additional overhead associated with OC over MRC is the estimation of interferer channels. [20]

Theorem 7.1. *For AF relaying with high-power, quasi-static-fading interferers, the outage performance remains the same if the destination is provided with the average interferer powers and the variances of its interferer CSI, instead of the instantaneous interferer CSI.*

The proof is given in Appendix 7.B.

In [20] it was shown that the performance of OC in DF relaying is not affected if the destination estimates the average power and the variance of the interferers, instead of instantaneous interferer CSI. Following the steps used in [20], it can be easily proved that this result is applicable for AF relaying as well. Hence, the additional overhead associated with OC can be significantly reduced by exploiting this insight.

7.3.2 Best-relay transmission

As shown in (7.24), the capacity of relaying in orthogonal time slots degrades with the increase of the number of relay nodes, which is its primary drawback. Best-relay transmission, where only the best available relay transmits to the destination in Phase 2, can be used to improve the capacity.

The probability density function (PDF) of SINR for the selection of the n-th best relay is [24, eq. (7-14)]

$$f_{\gamma_{D\,sel}}(\gamma) = M f_{\gamma_{D_i}}(\gamma) \begin{pmatrix} M-1 \\ n-1 \end{pmatrix} \frac{(1-F_{\gamma_{D_i}}(\gamma))^{n-1}}{F_{\gamma_{D_i}}(\gamma)^{n-M}} \tag{7.31}$$

where γ_{D_i} is defined in (7.13) and $F_{\gamma_{D_i}}(\gamma)$ is found by substituting $M = 1$ in (7.15). Hence, the SINR CDF for the selection of the n-th best relay is [26, eq. (8.391)]

$$F_{\gamma_{D\,sel}}(\gamma) = \begin{pmatrix} M \\ n-1 \end{pmatrix} F_{\gamma_{D_i}}(\gamma)^{M-n+1} {}_2F_1\left(M-n+1, 1-n; M-n+2, F_{\gamma_{D_i}}(\gamma)\right). \tag{7.32}$$

It was shown that the minimum exponent of $\frac{1}{P_S}$ in $F_{\gamma_{D_i}}$ is equal to 1 for $M = 1$. Hence, (7.32) confirms that best-relay transmission results in a diversity gain of $M - n + 1$. The ergodic capacity of relay selection is found by substituting $M = 1$ and $F_{\gamma_{D\,sel}}(\gamma)$ in (7.24).

7.4 Performance of Best-Relay Transmission with CCI at the relays and at the destination

In this section, the general case of CCI present at the relays and at the destination as in Fig. 7.2 is studied. The interference at the relays is propagated to the destination in Phase 2 due to AF operation, which makes the analysis more complicated. Relay node i is affected by N_{R_i} co-channel interferers. The properties of the interferers at the destination are the same as in Section 7.2. It is assumed that the destination is not provided with the CSI of the relay interferers.

The received signal at R_i in Phase 1 is given as

$$y_{SR_i} = \sqrt{P_S} h_i x_0 + \sum_{\tau=1}^{N_{R_i}} \sqrt{P_{IR_{i\tau}}} f_{i\tau} t_{i\tau} + n_{SR_i} \tag{7.33}$$

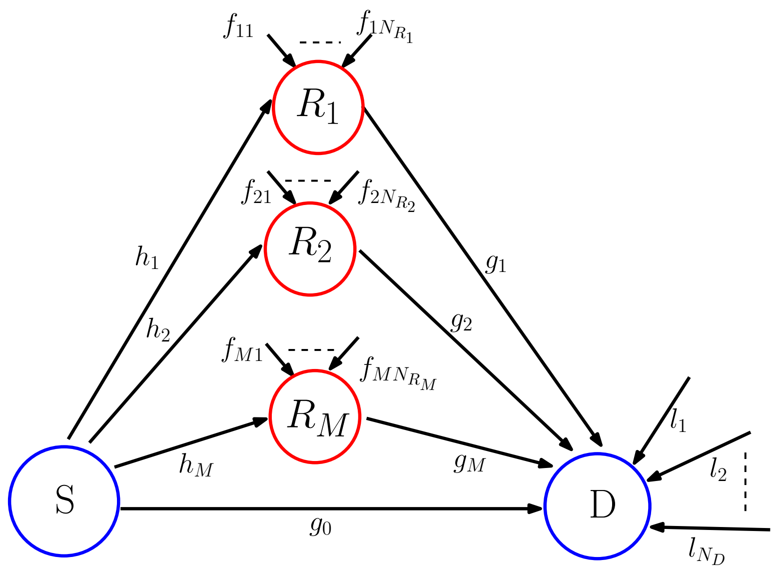

Figure 7.2: The AF relay network with co-channel interference at the relays and at the destination.

where $P_{IR_{i\tau}}$ is the average power received by the i-th relay from the τ-th interferer, $f_{i\tau}$ is the channel coefficient between the τ-th interferer and the i-th relay, $f_{i\tau} \sim \mathcal{C}N(0,1)$ and $t_{i\tau}$ is the symbol transmitted by the τ-th interferer.

For best-relay transmission, the signal received by the destination in Phase 2 is

$$\begin{aligned} y_{R_kD} =& \frac{\sqrt{P_R} g_k h_k x_0}{|h_k|} + \frac{\sqrt{P_R} g_k \sum_{\tau=1}^{N_{R_k}} \sqrt{P_{IR_{k\tau}}} f_{k\tau} t_{k\tau}}{\sqrt{P_S}|h_k|} + \sum_{j=1}^{N_D} \sqrt{P_{ID_j}} l_j u_j \\ &+ \frac{\sqrt{P_R} g_k n_{SR_k}}{\sqrt{P_S}|h_k|} + n_{R_kD}. \end{aligned} \tag{7.34}$$

where k is the index of the selected relay, given by

$$k = \text{arg}\max_{n,i\in\Omega} \gamma_{D_{2i}} \tag{7.35a}$$

where

$$\gamma_{D_{2i}} = \frac{\left(\boldsymbol{\alpha}_i^H \mathbf{R}_{OC,i}^{-1} \boldsymbol{\alpha}\right)^2}{\boldsymbol{\alpha}_i^H \mathbf{R}_{OC,i}^{-1} \boldsymbol{\alpha}_i + \psi_i} \tag{7.35b}$$

where $\psi = \boldsymbol{\alpha}_i^H \mathbf{R}_{OC,i}^{-1} \mathbf{f}_{R_i} \mathbf{f}_{R_i}^H \mathbf{R}_{OC,i}^{-1} \boldsymbol{\alpha}_i$, $\mathbf{f}_{R_i} = \left[0, \sqrt{\frac{P_R}{P_S}} \frac{g_i \beta_i}{|h_i|}\right]^T$, $\beta_i = \sum_{\tau=1}^{N_{R_i}} \sqrt{P_{IR_{i\tau}}} f_{i\tau}$ and $\mathbf{R}_{OC,i}$ is given in (7.13). Note that ψ_i is the total interferer power at the relay i, received at the output of the optimum combiner. Since the optimum combiner at the destination is not provided with the CSI of the relay interferers, it fails to suppress the interference received from the relays, which results in ψ_i. Due to the presence of ψ_i in the denominator, the diversity gain of OC should reach zero when the interferer powers are scaled with the source and the relay powers.

Further performance analysis based on the exact expression for $\gamma_{D_{2i}}$ in (7.35) is very difficult due to the complexity of the expression. Hence, following approximation is proposed.

$$\begin{aligned}\gamma_{D_{2i}} \approx& \frac{P_{SD}|g_0|^2}{N_0 + \sum_{j=1}^{I_D} P_{I_j}|l_j|^2} + \min\left(\frac{P_R|g_i|^2}{N_0}, \frac{P_S|h_i|^2}{N_0 + |\beta_i|^2}\right)\\ =& \frac{X_D}{N_0 + Y_D} + Z_i. \end{aligned} \tag{7.36}$$

The approximation given in (7.36) is based on (7.6). The fact that the CCI at the relay i is not suppressed by the OC receiver is incorporated to obtain Z_i [4, eq. (12)].

Similar to (7.8), the probability density function (PDF) of $V = |\beta_i|^2$ is given by

$$f_V(v) = \sum_{a=1}^{p}\sum_{b=1}^{\lambda_a} \frac{\mu_{ab} v^{b-1}}{(b-1)!\theta_a^b} \exp\left(\frac{-v}{\theta_a}\right) \tag{7.37}$$

where $\theta_1, \ldots, \theta_p$ are the distinct values of $P_{IR_{i\tau}} (\tau \in \{1, 2, \ldots, N_{R_i}\})$ with multiplicities $\lambda_1, \ldots, \lambda_p$, respectively, with $\sum_{a=1}^{p} \lambda_a = N_{R_i}$ and μ_{ab} are obtained by [23, eq. (10)].

It can be proved that the CDF and the PDF of Z_i are

$$F_{Z_i}(z) = 1 - \sum_{a=1}^{p}\sum_{b=1}^{\lambda_a} \frac{\mu_{ab} \exp\left(-N_0 z\left(\frac{1}{P_R} + \frac{1}{P_S}\right)\right)}{\theta_a^b\left(\frac{z}{P_S} + \frac{1}{\theta_a}\right)^b} \tag{7.38}$$

and

$$f_{Z_i}(z) = \sum_{a=1}^{p}\sum_{b=1}^{\lambda_a} \frac{\mu_{ab} \exp\left(-N_0 z\left(\frac{1}{P_R} + \frac{1}{P_S}\right)\right)}{\theta_a^b\left(\frac{z}{P_S} + \frac{1}{\theta_a}\right)^b} \left[N_0\left(\frac{1}{P_R} + \frac{1}{P_S}\right) + \frac{b}{P_S\left(\frac{z}{P_S} + \frac{1}{\theta_a}\right)}\right]. \tag{7.39}$$

Similar to (7.15), an approximation for the CDF of $\gamma_{D_{2i}}$ can be found as

$$F_{\gamma_{D_{2i}}}(\gamma) = F_{Z_i}(\gamma) - \mathcal{I}_3 \tag{7.40}$$

where,

$$\mathcal{I}_3 = \sum_{k=1}^{r}\sum_{l=1}^{\nu_k}\phi_{kl}\int_0^{\gamma}\frac{\exp\left(-\frac{N_0(\gamma-z)}{P_{SD}}\right)f_{Z_i}(z)}{\left(\frac{\eta_k(\gamma-z)}{P_{SD}}+1\right)^l}dz. \tag{7.41}$$

7.5 Numerical Results

In this section, numerical results obtained for the outage probability and ergodic capacity using analytical expressions and numerical integration are compared with simulation results. The destination is interfered by 5 co-channel interferers having signal-to-interference ratios (SIR) $\frac{P_S}{P_{I_j}} = \{3, 5, 7, 10, 15\}$ dB, unless specified otherwise. The SINR threshold for outage, $\gamma_T = 5$ dB.

The outage and ergodic capacity performances of all-relay transmission with optimum combining are shown in Figs. 7.3 and 7.4, respectively. The outage probability is obtained by substituting $\gamma = \gamma_T$ in (7.15). Accordingly, the outage performance and the diversity gain improves with the increase of the number of relays and it is verified that the diversity gain is equal to M. However, the ergodic capacity degrades as the number of relays increases as all-relay transmission consumes $M+1$ time slots to complete a single communication, which is its major drawback. It can be observed that the tightness of the approximation given in (7.6) slightly reduces with the increase of M. However, the difference between the simulation results and and the analytical results is always less than 2 dB for practical values of M. The tightness of this approximation is further investigated later in this section.

In Fig. 7.5, the outage performances when the destination is provided only with the average interferer powers and the variances of the interferer CSI, are compared with the performance when the destination is provided with the instantaneous CSI of interferers. Accordingly, there is almost no performance loss when the destination only has knowledge of the average interferer powers and the variances of the interferer CSI, instead of the instantaneous interferer CSI. The main additional overhead associated with OC is the estimation of interferer CSI and this result suggests that the overhead can be significantly reduced, since the average interferer powers and interferer CSI variances change less frequently, compared to the instantaneous

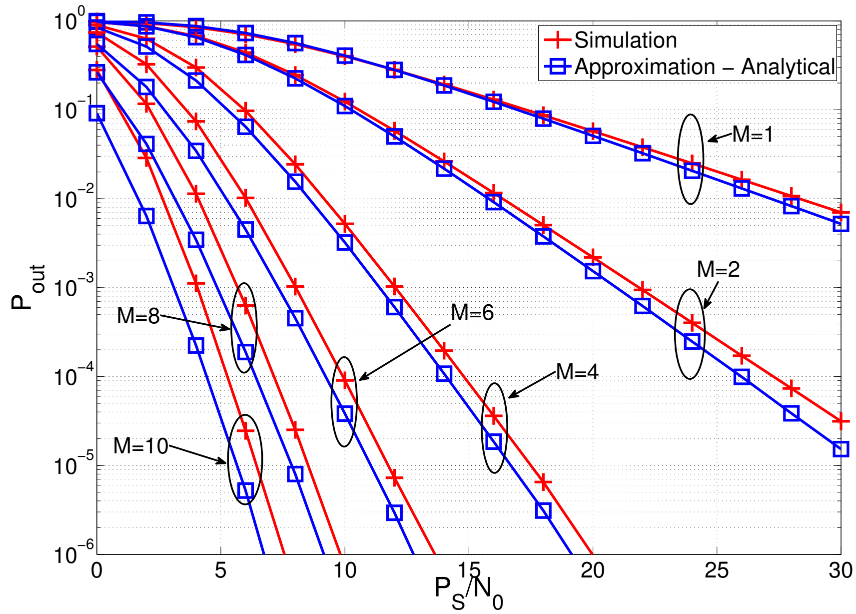

Figure 7.3: The outage performance with different numbers of relays in all-relay transmission for $P_{SD} = P_S = P_R$.

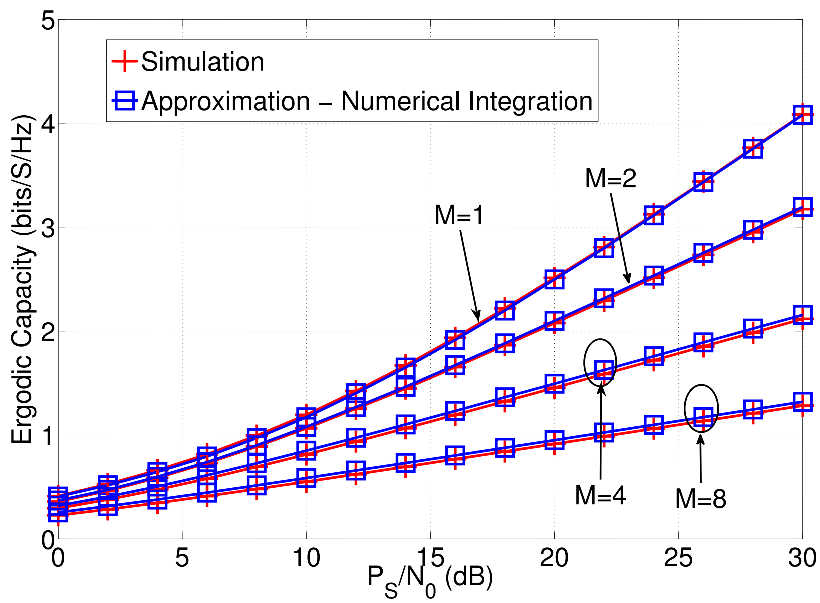

Figure 7.4: The ergodic capacity for different numbers of relays in all-relay transmission for $P_{SD} = P_S = P_R$.

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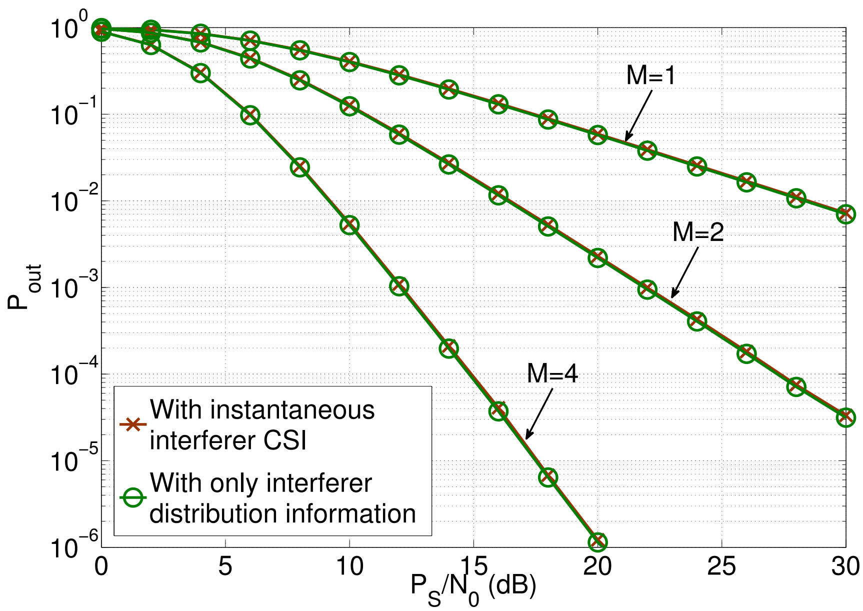


Figure 7.5: The outage performance of all-relay transmission when the destination is provided only with the average interferer powers and the variances of interferer CSI and when the destination is provided with the instantaneous interferer CSI for $P_{SD} = P_S = P_R$.

The outage performance and ergodic capacity of the combination of best-relay transmission and OC is shown in Figs. 7.6 and 7.7, respectively for $n = 1$. Accordingly, the combination of best-relay transmission and OC achieves a diversity gain up to M. Moreover, the capacity increases with M as the number of time slots used for the communication is always 2. However, the incremental increase in ergodic capacity when M is doubled, decreases as capacity depends on the logarithm of SINR at the destination and SINR only increases linearly, not exponentially with the increase of M. Hence, the combination of OC and best-relay transmission maximizes spectral efficiencies in the presence of CCI. It is evident that the approximation for SINR given in (7.6) is more suited for all-relay transmission than best-relay transmission.

In Figs. 7.8 and 7.9, the outage performances and capacities of four diversity techniques are compared, namely all-relay transmission with OC, best-relay transmission with OC, all-relay transmission with MRC, and best-relay transmission

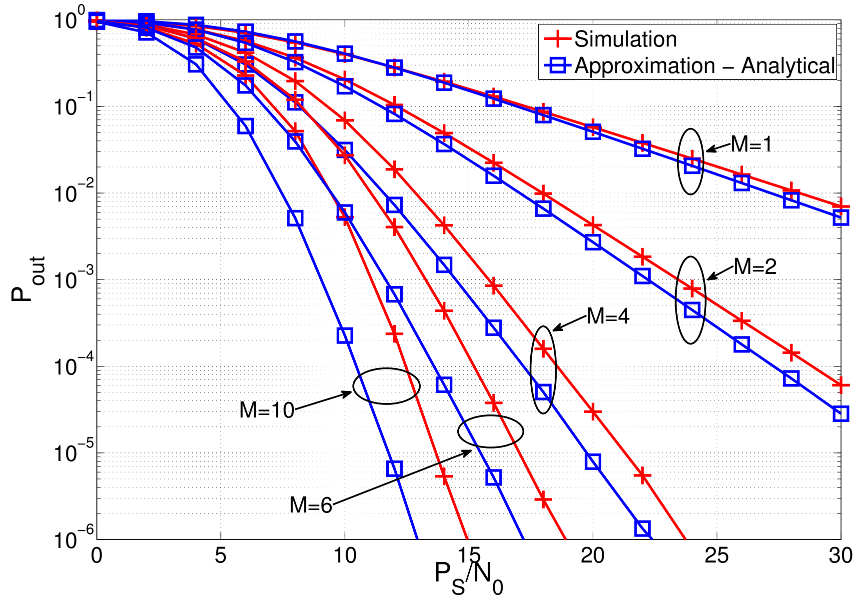


Figure 7.6: The outage performance of best-relay transmission with OC for $P_{SD} = P_S = P_R$ and $n = 1$.

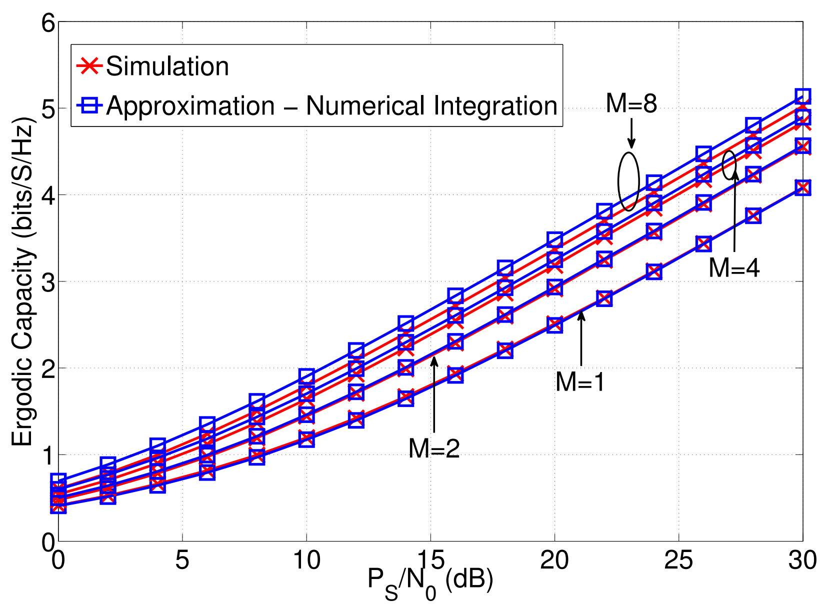


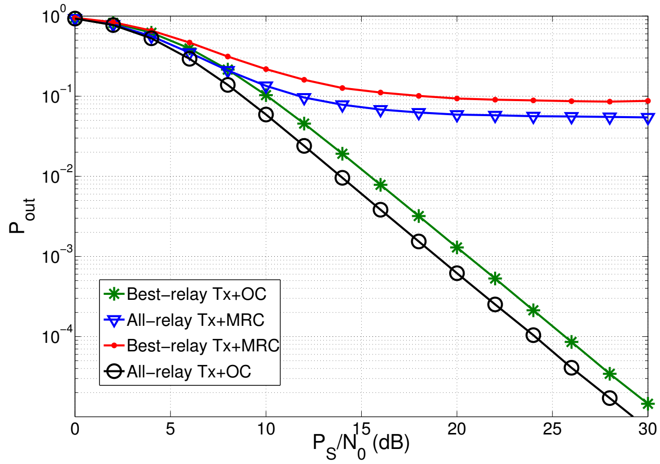
Figure 7.7: The ergodic capacity of best-relay transmission with OC for $P_{SD} = P_S = P_R$ and $n = 1$.

with MRC. For this comparison, it has been assumed that the destination is interfered by 3 co-channel interferers having SIRs $\frac{P_S}{P_{I_j}} = \{10, 15, 20\}$ dB. High SIR values are selected as the performance of MRC severely degrades in low SIR values. At very low SNR values, the performances of OC and MRC coincide as the interferer power is negligible. However, the diversity techniques using OC easily outperform techniques using MRC in medium-to-high SNR values. Techniques using MRC do not achieve diversity gains as they do not suppress CCI at the destination.

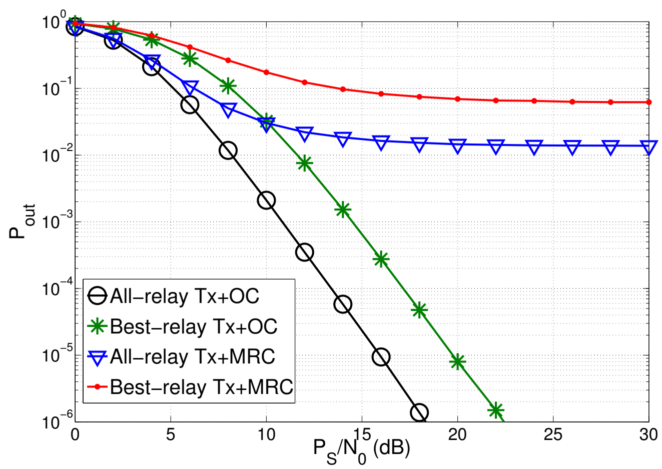
Moreover, the techniques using all-relay transmission shows a better coding gain compared to the diversity techniques using best-relay transmission. This can be explained by the array gain of the OC or MRC receiver, which increases with the increase of M. Furthermore, best-relay transmission with MRC outperforms the capacity of all-relay transmission with OC for $M = 4$. However, best-relay transmission with MRC shows the worst outage performance out of the four diversity techniques considered.

The tightness of more mathematically tractable approximation for the SINR of the OC receiver in (7.6) is investigated in Fig. 7.10 for $M = 4$ and $\frac{P_S}{P_R} = 0\ dB$. The variation of tightness with the decrease of P_{SD} is shown. Accordingly, the tightness worsens with the decrease of P_{SD}. It can be observed that the approximation converges with the decrease of P_{SD} as the term $\frac{P_{SD}|g_0|^2}{N_0+\sum_{j=1}^{I_D} P_{I_j}|\hat{l}_j|^2(M+1)}$ becomes insignificant with the decrease of P_{SD}. The exact performance also converges at very small P_{SD} values at a rate slower than the approximation. It can be concluded that the performance gap remains within 2 dB for the complete range of P_{SD}, which confirms that the approximation is tight in the whole range of P_{SD}.

In Fig. 7.11, the tightness of the SINR approximation is shown against the variation of the average relay power, P_R for $M = 4$ and $\frac{P_S}{P_{SD}} = 10\ dB$. Unlike with decrease of P_{SD}, the tightness of the approximation improves with decrease of P_R. Again, the performance gap is less than 2 dB for the complete range of P_R, confirming the tightness of the approximation. Furthermore, the outage performance is more dependent on P_R than P_{SD} and unlike with a decrease in P_{SD}, the performance does not converge with a decrease in P_R.



(a)

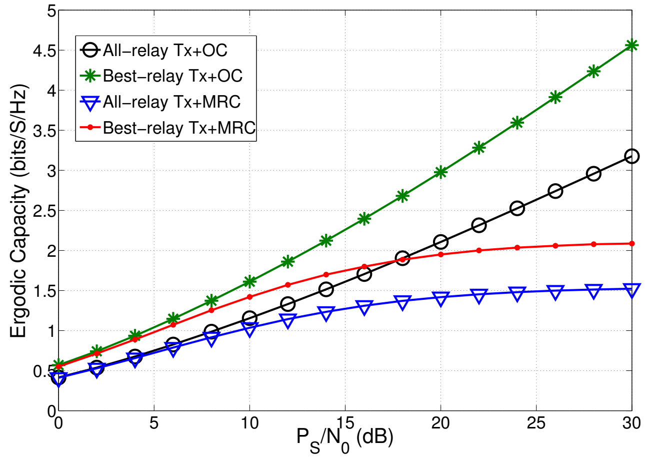


(b)

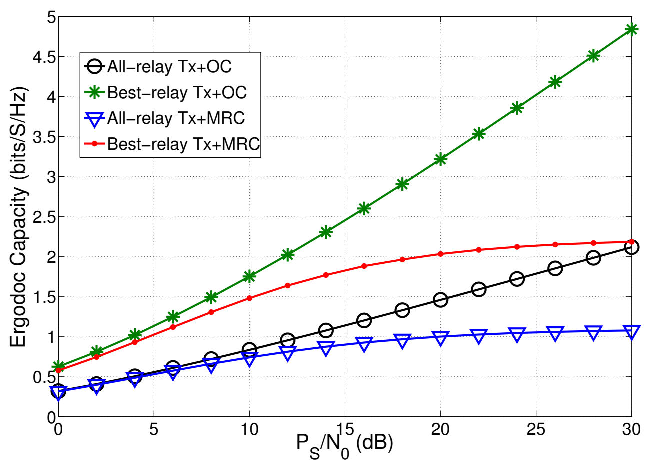
Figure 7.8: Outage performance comparison for different diversity techniques in the presence of CCI for (a) $M = 2$ and for (b) for $M = 4$.

In Fig. 7.12, the performance of best-relay selection when CCI is present at the relays and at the destination is demonstrated. It is assumed that each relay node is affected by 10 co-channel interferers, each having SIR of $\frac{P_S}{P_{IR_{i\tau}}} = 20\ dB$, $i \in \Omega$, $\tau \in \{1, \ldots, N_R\}$. A higher SIR at the relays is justified as the relays are located farther from the edge of the cell than the destination. However, the performance of OC degrades significantly in the presence of CCI at the relays and the destination, since the interference at the relays is not suppressed by the optimum combiner at the destination.

Theoretically, two approaches can be used to improve the performance in the



(a)



(b)

Figure 7.9: Capacity comparison for different diversity techniques in the presence of CCI for (a) $M = 2$ and for (b) for $M = 4$.

presence of CCI at the relays and the destination. First, multiple-antenna relays can be used , where OC is implemented at the relays to suppress interference at the relays [18, 19]. However, this approach increases the overhead and the complexity at the relay nodes significantly. For single-antenna relays, the performance can be improved by conveying CSI of all the relay interferers to the destination, where the total interference can be suppressed using OC. However, this approach is only of theoretical interest as the practical implementation is very difficult.

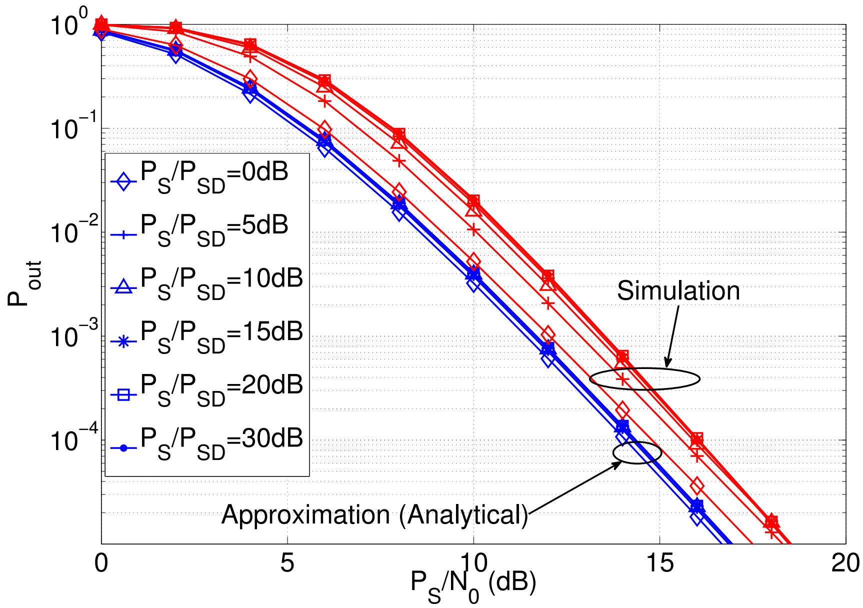


Figure 7.10: The tightness of the approximation in (7.6) to the exact SINR expression given in (7.5) for varying P_{SD} with $M = 4$ and $\frac{P_S}{P_R} = 0\,dB$.

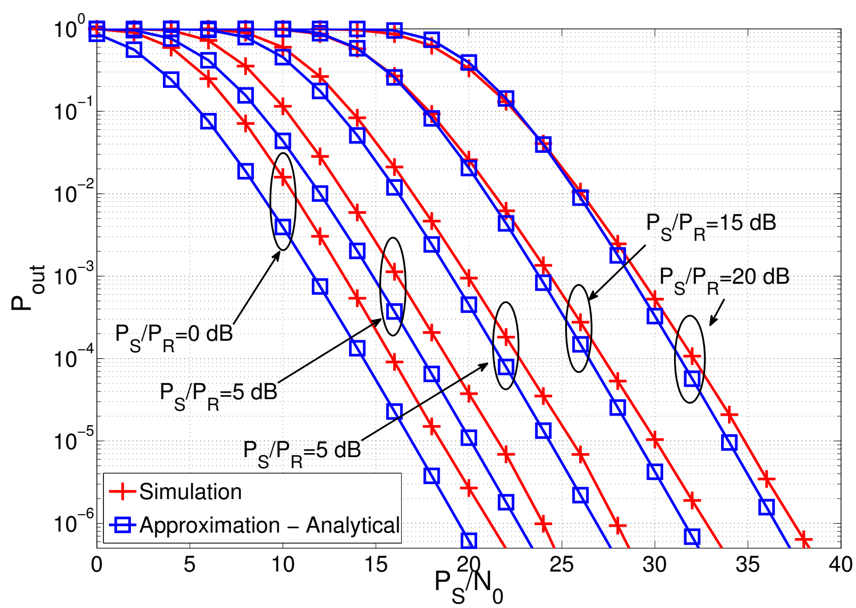


Figure 7.11: The tightness of the approximation in (7.6) to the exact SINR expression given in (7.5) for varying P_R with $M = 4$ and $\frac{P_S}{P_{SD}} = 10\,dB$.

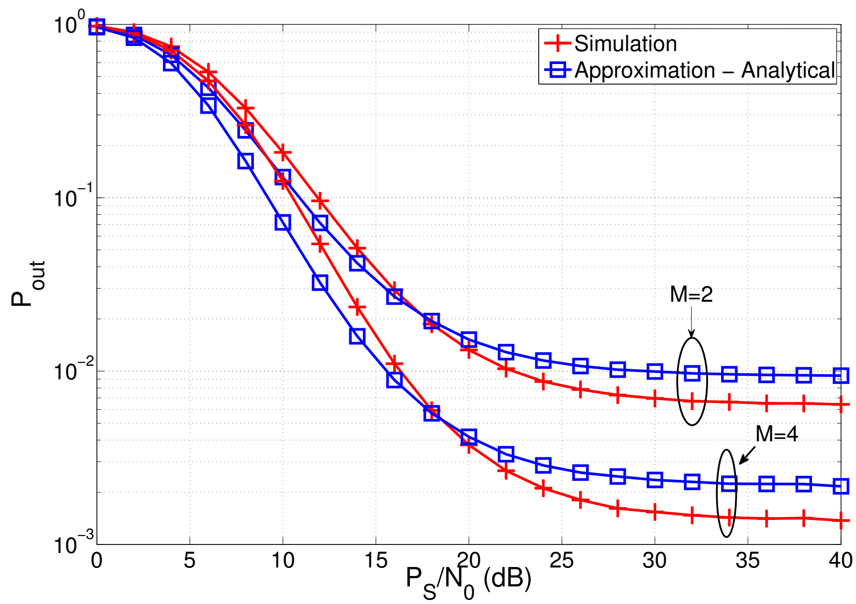


Figure 7.12: The outage performance of best-relay selection with OC in the presence of CCI at the relays and at the destination.

7.6 Conclusion

The performance of amplify-and-forward relaying with optimum combining in the presence of co-channel interference was analyzed. A tight and mathematically tractable approximation was proposed for the SINR at the destination. Two types of relaying protocols were considered: all-relay transmission with OC and best-relay transmission with OC. It was shown that both protocols achieve a diversity gain of M if CCI is present only at the destination and when the interferer powers are scaled with the source and the relay powers. Furthermore, best-relay transmission provides the best spectral efficiency in the presence of CCI, compared to other diversity techniques. Moreover, if CCI is present at the relays and at the destination, the performance degrades and the diversity gains are lost as the optimum combiner at the destination fails to suppress interference at the relays.

7.A The Derivation of (7.30)

The expansion of $\text{Ei}(x)$ is expressed as [28, eq. (5.1.10)]

$$\text{Ei}(x) = \alpha + \log(x) + \sum_{n=1}^{\infty} \frac{x^n}{nn!} \tag{7.42}$$

where α is the Euler's constant [28, eq. (6.1.3)]. Hence,

$$\text{Ei}(a(\gamma - K_1)) - \text{Ei}(-aK_1) = \log\left(\frac{K_1 - \gamma}{K_1}\right) + a\gamma + \mathcal{O}(a^2). \tag{7.43}$$

Using the approximation $\exp(a\gamma) \approx 1 + a\gamma$ as $a \to 0$,

$$\begin{aligned}\hat{\mathcal{I}}_1(i,l)^{\infty}\Big|_{i>l} \approx& \frac{(1+aK_1)a^{l-i-1}\left(\log\left(\frac{K_1-\gamma}{K_1}\right) + \mathcal{O}(a)\right)}{(l-i-1)!} \\ &+ \sum_{j=1}^{l-i-1} \frac{a^{j-1}}{(l-i-1)(l-i-2)\ldots(l-i-j)}\left(\frac{1}{(-K_1)^{l-i-j}} - \frac{1+a\gamma}{(\gamma-K_1)^{l-i-j}}\right).\end{aligned} \tag{7.44}$$

From (7.44), it is clear that the $\hat{\mathcal{I}}_1(i,l)^{\infty}\Big|_{i>l}$ can be expressed as in (7.30), which completes the proof.

7.B The Proof of Theorem 7.1

In this section, the proof of Theorem 2 is presented. When the destination is only provided with the the average interferer powers and the variances of interferer CSI, the noise-plus-interference covariance matrix can be expressed as

$$\begin{aligned}\hat{\mathbf{R}} =& N_0\mathbf{I} + \text{diag}\left[0, \frac{\sqrt{P_R}|g_1|^2}{\sqrt{P_S}|h_1|^2}, \frac{\sqrt{P_R}|g_2|^2}{\sqrt{P_S}|h_2|^2}, \ldots, \frac{\sqrt{P_R}|g_M|^2}{\sqrt{P_S}|h_M|^2}\right] \\ &+ \sum_{j=1}^{I_D} P_{I_j}|\hat{l}_j|^2\mathbf{1}\mathbf{1}^T\end{aligned} \tag{7.45}$$

where $\hat{l}_j$ and l_j are independent and identically distributed and $\hat{l}_j$ is the estimate of l_j at the destination. Now, the combiner vector is $\hat{\mathbf{w}} = \hat{\mathbf{R}}^{-1}\boldsymbol{\alpha}$. Hence, the resulting SINR at the destination is [20, eq. (12)]

$$\gamma_{D_2} = \frac{\left(\boldsymbol{\alpha}^H\hat{\mathbf{R}}^{-1}\boldsymbol{\alpha}\right)^2}{\boldsymbol{\alpha}^H\hat{\mathbf{R}}^{-1}\mathbf{R}\hat{\mathbf{R}}^{-1}\boldsymbol{\alpha}}. \tag{7.46}$$

Using the matrix inversion lemma [32, eq. (2.1.4)], it can be shown that

$$\hat{\mathbf{R}}^{-1} = \mathbf{A}^{-1} - \frac{\mathbf{A}^{-1}\hat{\lambda}\mathbf{1}\mathbf{1}^T\mathbf{A}^{-1}}{1+\hat{\lambda}\phi} \tag{7.47a}$$

where

$$\mathbf{A} = N_0\mathbf{I} + \text{diag}\left[0, \frac{\sqrt{P_R}|g_1|^2}{\sqrt{P_S}|h_1|^2}, \frac{\sqrt{P_R}|g_2|^2}{\sqrt{P_S}|h_2|^2}, \ldots, \frac{\sqrt{P_R}|g_M|^2}{\sqrt{P_S}|h_M|^2}\right] \tag{7.47b}$$

and

$$\hat{\lambda} = \sum_{j=1}^{I_D} P_{I_j}|\hat{l}_j|^2, \quad \phi = \text{tr}\left(\mathbf{A}^{-1}\right). \tag{7.47c}$$

Therefore,

$$\hat{\mathbf{R}}^{-1}\mathbf{R} = \mathbf{I} + \lambda\mathbf{A}^{-1}\mathbf{1}\mathbf{1}^T - \hat{\lambda}\mathbf{A}^{-1}\mathbf{1}\mathbf{1}^T\left(\frac{1+\lambda\phi}{1+\hat{\lambda}\phi}\right). \tag{7.48}$$

When the noise power is insignificant with respect to the interferer powers, $\hat{\mathbf{R}}^{-1}\mathbf{R} \approx \mathbf{I}$. Hence,

$$\gamma_{D_2} \approx \boldsymbol{\alpha}^H\hat{\mathbf{R}}^{-1}\boldsymbol{\alpha}. \tag{7.49}$$

As $\hat{\lambda}$ has the same average powers and variances as λ, γ_{D_2} is equivalent to γ_D in (7.5), which completes proof.

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Chapter 8

Optimum Combining For Cooperative Relaying in a Poisson Field of Interferers

Spatial point processes are commonly used to model the placement and the number of interferers in modern wireless networks, where the ad-hoc deployment of transmitters is common. The homogeneous Poisson point process (PPP) is the most popular spatial point process used to model co-channel interference. Optimum combining (OC) is the diversity combining technique that maximizes the signal-to-interference-plus-noise ratio at the receiver. The performance of OC in cooperative relaying in an interferer field modeled by a homogeneous PPP is analyzed. Both decode-and-forward (DF) and amplify-and-forward (AF) relay protocols are studied. Multi-relay transmission and relay selection techniques are considered. Accurate approximations for the outage probability are derived for DF and AF relaying when the destination is able to estimate the noise-plus-interference correlation matrix (NICM) perfectly. An approximation for the outage probability of DF relaying is obtained when the destination only estimates the channel state information of the closest interferer. Relay selection outperforms multi-relay transmission in both DF and AF relaying protocols. The interference correlation at the relays significantly degrades the outage performance. Limited estimation of the NICM results in better performance than conventional maximal-ratio combining, though it fails to achieve diversity gains[1].

8.1 Introduction

The advantages of cooperative relaying include, but are not limited to, increased diversity, coverage extension and mitigation of shadowing. Amplify-and-forward (AF) and decode-and-forward (DF) are two of the most commonly studied cooperative relaying protocols [1], which are so named based on the processing technique used at the relays. In dual-hop cooperative communications with multiple relays, diversity combining techniques are used to combine the signals received in multiple time slots and to achieve diversity gains. Maximal-ratio combining (MRC) is the optimal diversity combining technique when the receiver is additive white Gaussian noise (AWGN) limited [2].

Co-channel interference (CCI) is the primary performance limiting factor in multicell wireless communications. The performance of AF relaying in the presence of CCI was investigated in [3–7] and the references therein for relay networks with a single relay and the direct link between the source and the destination completely shadowed. In [8] and [9], the performance of DF relaying with MRC was analyzed for an interference-limited relay network and it was shown that MRC is suboptimal in the presence of CCI.

For multiple-antenna receivers with CCI, optimum combining (OC) [10] is the diversity combining technique that suppresses interference and maximizes the signal-to-interference-plus-noise ratio (SINR). In [11] and [12], the performance of OC was analyzed in AF and DF relaying, respectively and OC results in significant performance gains in the presence of interference, compared to conventional MRC.

In the above mentioned work, the locations of the interferers and the number of interferers were considered to be deterministic. This assumption is applicable for well-planned wireless networks. However, in modern heterogeneous wireless networks [13], small-scale transmitters are arbitrarily deployed by the operators

[1]A version of this chapter is accepted to be published in IEEE Transactions on Communications. N. Suraweera and N. C. Beaulieu, "Optimum Combining For Cooperative Relaying in a Poisson Field of Interferers", *IEEE Transactions on Communications*, Date of acceptance - July 2nd 2015, Number of pages - 11, DOI: 10.1109/TCOMM.2015.2453417.

and the users. Therefore, it is not practically feasible to plan the whole network. Consequently, the number and the location of the interferers can be assumed to be random. For such networks, stochastic geometry [14] can be employed to model the locations and the number of interferers. With stochastic geometry, it is commonly assumed that the interferer locations are distributed according to a Poisson point process (PPP) [15, 16]. The increased randomness of the interference model makes the analysis more complex, confining most of the available results to homogeneous PPPs. In a homogeneous Poisson field of interferers, the outage and error performances of MRC were studied in [17] and [18], respectively. In [19], the outage performance of OC in a Poisson field of interferers was analyzed. Nevertheless, the results in [19] cannot be directly applied for cooperative relaying as explained in Section 8.2.

In [20], the performance of a dual-hop AF relay network was analyzed with the interferers at the destination node distributed according to a two-dimensional PPP. The performance of an N-hop AF cooperative relay network in a Poisson field of interferers was studied and the performance metrics were derived in [21] and [22] for Rayleigh and Nakagami-m fading models, respectively. The direct link between the source node and the destination node was assumed to be shadowed in all these works, resulting in no diversity gains. In [23], the direct link was present and MRC was used at the destination node to combine the signals received via the direct link and from the relay node. However, multiple relays were not used to achieve diversity gains.

The performance of a DF relay network in a Poisson field of interferers was studied in [24] for selection combining and MRC at the destination, where spatial and temporal correlations of the interference in a Poisson interference field were considered. However, interference mitigation using OC was not considered. In [25], the performance of multihop DF relaying was studied for the same interference model. In [26], the performance of relay selection and OC was analyzed for ad-hoc networks. However, the interference cancellation capability of OC was not considered in that work.

In this chapter, the performance of OC in a dual-hop multi-relay network in the presence of a homogeneous Poisson field of interferers is analyzed for both AF and DF protocols. A direct link between the source and the destination nodes is assumed to be present. The main contributions and the insights of this work can be listed as follows.

1. The outage performance of OC in DF relaying is analyzed for the case when the relays and the destination are interference-limited and the destination node is able to estimate the noise-plus-interference correlation matrix (NICM) perfectly. The transmission techniques of multi-relay transmission and relay selection are considered. Close approximations for the outage probability are derived. When the relays are interference-limited, diversity gains are lost. Furthermore, the outage performance is significantly affected by the correlation among the interference signals at the relay nodes. Moreover, relay selection is the preferred transmission technique due to outage performance gains achieved over multi-relay transmission.

2. The outage performance of OC in AF relaying is analyzed when the relays are noise-limited and the destination is interference-limited with perfect estimation of the NICM for multi-relay transmission and relay selection. OC achieves positive diversity gains when the relays are noise-limited and the destination is interference-limited. Again, relay selection achieves superior outage performances over multi-relay transmission.

3. The performance of OC in DF relaying is analyzed with limited estimation of the NICM, where the destination node estimates only the channel state information (CSI) of the closest interferer. The diversity gains are lost with limited interferer channel estimation. However, the performance of OC with limited interferer channel estimation outperforms MRC.

The remainder of this chapter is organized as follows. Section 8.2 describes the system, interference and channel models used and in Section 8.3, the performance of DF relaying with OC is analyzed with perfect estimation of the noise-plus-interference correlation matrix. The performance of AF relaying with OC is studied in Section 8.4. In Section 8.5, the outage performance of OC in DF relaying with limited interferer channel estimation is studied. Numerical and simulation results are discussed in Section 8.6, and Section 8.7 concludes this chapter.

8.2 System, Interference and Channel Models

A dual-hop multi-relay cooperative relaying network similar to the one in Fig. 8.1 is considered, where S is the source node, D is the destination node and $\mathrm{R}_i, i \in \Omega = \{1, \ldots, M\}$ are the relay nodes. Each node deploys a single antenna. d_{SR_i}, $d_{\mathrm{R}_i\mathrm{D}}$ and d_{SD} are the distances between the nodes S and R_i, R_i and D, and S and D, respectively, which are assumed to be known constants.

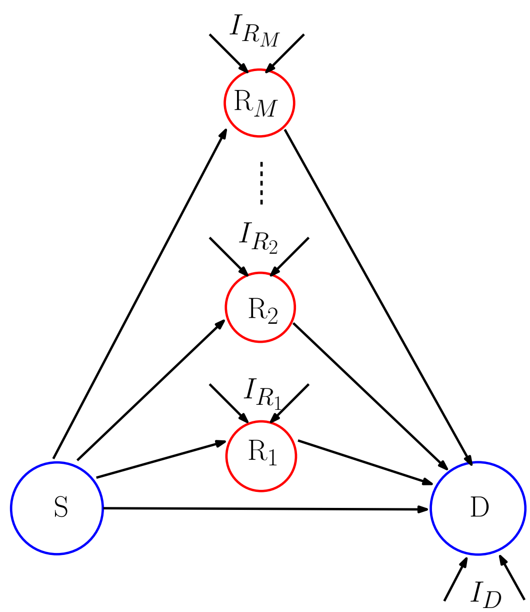

Figure 8.1: A multi-relay cooperative relay network with co-channel interference at the relays and the destination.

In this chapter, two system models with different relaying protocols are considered. First, decode-and-forward (DF) relaying with CCI present at both the relays and at the destination node, is considered. This system model is appropriate when the source-relay communication uses the same frequency resources as the other transmitters in the vicinity. Even though the AF protocol is the preferred relaying protocol in terms of simplicity and security, it is suboptimal in this scenario since the interference power at the relays is forwarded to the destination. The OC receiver at the destination is unable to mitigate the interference forwarded from the relays since the channel state information of the relay interferers is not provided to the destination. Amplify-and-forward (AF) relaying with noise-limited relays and interference-limited destination is studied subsequently. This model is suitable when the source-relay communication uses a dedicated set of frequency resources.

The numbers and the locations of the interferers at the relays and the destination are modeled by Φ_{R} and Φ_{D}, respectively, which are homogeneous Poisson point processes in the two-dimensional (2-D) plane. The node densities of Φ_{R} and Φ_{D} are λ_{R} and λ_{D}, respectively. Since the interference signals at different relays share the same source of randomness, they are correlated [27]. Moreover, the interferers of a given receiver node are assumed to be uniformly distributed in the 2-D plane.

In both protocols, the source node broadcasts its symbols to the relays and the destination in the first phase of the communication. The signal received by the destination in both DF and AF relaying in Phase 1 is

$$y_{\mathrm{SD}} = \sqrt{P_{\mathrm{S}}} d_{\mathrm{SD}}^{-\alpha/2} g_0 b_0 + \sqrt{P_I} \sum_{x \in \Phi_{\mathrm{D}}} \|x\|^{-\alpha/2} l_{0,x} t_{0,x} + n_{\mathrm{D}_0} \tag{8.1}$$

where P_{S} is the transmit power of the source node, P_I is the transmit power of each interferer, α is the path loss exponent, b_0 is the symbol transmitted by the source node and g_0 is the fading coefficient of the S-D channel. $\|x\|$ is the distance to the x-th interferer from the receiver node, $l_{0,x}$ is the fading coefficient of the channel between the x-th interferer and the destination in Phase 1, $t_{0,x}$ is the symbol transmitted by the corresponding interferer and n_{D_0} is additive white Gaussian noise (AWGN) at the destination node in Phase 1. Furthermore, it is assumed that all the desired and interferer channel fading coefficients follow a complex Gaussian distribution with zero mean and unit variance. Moreover, all the AWGN are assumed to follow a complex Gaussian distribution with zero mean and variance N_0.

8.2.1 DF relaying with interference-limited relays and destination

Here, it is assumed that CCI is present at both at the relays and the destination. Hence, the received signal at R_i in Phase 1 is

$$y_{\mathrm{S},\mathrm{R}_i} = \sqrt{P_\mathrm{S}} d_{\mathrm{SR}_i}^{-\alpha/2} h_i b_0 + \sqrt{P_I} \sum_{x \in \Phi_\mathrm{R}} \|x\|^{-\alpha/2} f_{i,x} t_{i,x} + n_{\mathrm{R}_i}, \quad i \in \Omega = \{1, \ldots, M\} \tag{8.2}$$

where h_i is the fading coefficient of the S-R_i channel, n_{R_i} is the AWGN at R_i in Phase 1, $f_{i,x}$ is the fading coefficient of the channel between the x-th interferer and R_i, and $t_{i,x}$ is the symbol transmitted by the x-th interferer at R_i.

In Phase 2, both multi-relay transmission and relay selection are studied.

Multi-relay transmission

Here, the relays that successfully decode the received signal forward to the destination node in orthogonal time slots. It is assumed that the relays are capable of decoding the received signal correctly if the signal-to-interference ratio (SIR) at each relay is above a given threshold γ_{min}, where γ_{min} is the SIR value which corresponds to the minimum desirable rate R_{min} [1]. To simplify the analysis, the impact of AWGN at the relay is assumed to be negligible. The SIR at relay i is

$$\gamma_{\mathrm{R}_i} = \frac{P_\mathrm{S} d_{\mathrm{SR}_i}^{-\alpha} |h_i|^2}{P_I \sum_{x \in \Phi_\mathrm{R}} \|x\|^{-\alpha} |f_{i,x}|^2}, \quad i \in \Omega = \{1, \ldots, M\}. \tag{8.3}$$

Since $|h_i|^2$ is an exponential random variable with unit variance, the probability of unsuccessful decoding at R_i can be given as

$$\mathbb{P}_{\mathrm{R}_i} = 1 - \left[\mathcal{M}_{Z_{\mathrm{R}_i}} \left(\frac{\gamma_{\text{min}}}{P_\mathrm{S} d_{\mathrm{SR}_i}^{-\alpha}} \right) \right] \tag{8.4}$$

where $Z_{\mathrm{R}_i} = P_I \sum_{x \in \Phi_\mathrm{R}} \|x\|^{-\alpha} |f_{i,x}|^2$. From [16, eq. (3.21)],

$$\mathbb{P}_{\mathrm{R}_i} = 1 - \exp\left(-\lambda_\mathrm{R} \Delta \left(\frac{\gamma_{\text{min}} P_I}{P_\mathrm{S} d_{\mathrm{SR}_i}^{-\alpha}} \right)^\delta \right) \tag{8.5}$$

where $\Delta = \pi \Gamma(1-\delta) \Gamma(1+\delta)$ and $\delta = \frac{2}{\alpha}$.

The signal received by the destination node in the i-th time slot of Phase 2 is

$$(y_{\mathrm{R}_i,\mathrm{D}})_{\mathrm{DF}} = \sqrt{P_{\mathrm{R}_i}} d_{\mathrm{R}_i\mathrm{D}}^{-\alpha/2} g_i b_0 + \sqrt{P_I} \sum_{x\in\Phi_\mathrm{D}} \|x\|^{-\alpha/2} l_{i,x} u_{i,x} + n_{\mathrm{D}_i}, \quad i \in C = \{k \in \Omega : \gamma_{\mathrm{R}_k} \geq \gamma_{\min}\} \tag{8.6}$$

where P_{R_i} is the transmit power of R_i, g_i is the fading coefficient of the $\mathrm{R}_i - \mathrm{D}$ channel, $l_{i,x}$ and $u_{i,x}$ are the fading coefficient of the channel between the x-th interferer in the i-th time slot and the destination node, and the symbol transmitted by the given interferer, respectively, and n_{D_i} is the AWGN at the destination node in time slot i of Phase 2. Hence, the destination has signals received in $K+1$ time slots, which are used for optimum combining, where K is the cardinality of the decoding set C given in (8.6).

Relay selection

In this technique, out of the decoding set C, the relay node that results in the best SINR at the destination is selected for transmission in Phase 2. The selection criteria is discussed in detail in Section 8.3.

8.2.2 AF relaying with noise-limited relays and interference-limited destination

For AF relaying, it is assumed that the interference is only present at the destination node. Hence, the signal received by R_i in Phase 1 is similar to (8.2), without the interference component. It is assumed that the the amplification gains of relay nodes are channel state information (CSI) assisted, i.e. R_i estimates h_i correctly and inverts the amplitude of the received signal component ($\sqrt{P_\mathrm{S}} d_{\mathrm{SR}_i}^{-\alpha/2} |h_i|$).

The signal received by the destination from the i-th relay in Phase 2 is

$$(y_{\mathrm{R}_i,\mathrm{D}})_{\mathrm{AF}} = \frac{\sqrt{P_{\mathrm{R}_i}} d_{\mathrm{R}_i D}^{-\alpha/2} g_i h_i b_0}{|h_i|} + \sqrt{P_I} \sum_{x\in\Phi_\mathrm{D}} \|x\|^{-\alpha/2} l_{i,x} u_{i,x} + \frac{\sqrt{P_{\mathrm{R}_i}} d_{\mathrm{R}_i\mathrm{D}}^{-\alpha/2} g_i n_{\mathrm{R}_i}}{\sqrt{P_\mathrm{S}} d_{\mathrm{SR}_i}^{-\alpha/2} |h_i|} + n_{\mathrm{D}_i}, \quad i \in \Omega. \tag{8.7}$$

Note that unlike DF relaying, all the M relays participate in the communication in Phase 2 when multi-relay transmission is used.

8.3 Performance Analysis of Optimum Combining in DF Relaying with Perfect Estimation of the NICM

In this section, the outage performance analysis is carried out for the DF relaying with interference-limited relays and destination for multi-relay transmission and relay selection. The outage probability is defined as the probability that the capacity falls below the minimum desirable rate of the communication R_{min}. Hence, for multi-relay transmission with DF relaying, the conditional outage probability can be expressed as

$$\begin{aligned}\mathbb{P}_{\text{DF,MR}}|C &= \mathcal{P}\left(\frac{1}{|C|+1}\log_2(1+\gamma_{\text{DF,MR}}) < \log_2(1+\gamma_{\text{min}})\right)\\ &= F_{\gamma_{\text{DF, MR}}|C}\left(\gamma_{T_{\text{DF,MR}}} = (1+\gamma_{\text{min}})^{|C|+1}-1\right)\end{aligned} \tag{8.8}$$

where $\gamma_{\text{DF,MR}}$ is the SINR at the destination and γ_{min} is the SINR threshold that corresponds to R_{min}. For best-relay transmission, the conditional outage probability is

$$\mathbb{P}_{\text{DF,RS}}|(C \neq \emptyset) = F_{\gamma_{\text{DF,RS}}|C}\left(\gamma_{T_{\text{DF,RS}}} = \gamma_{\text{min}}^2 + 2\gamma_{\text{min}}\right). \tag{8.9}$$

To evaluate the end-to-end outage probability, it is necessary to find the probability of K relays being able to successfully decode the received symbols. Without loss of generality, it is assumed that the first K relays are able to decode the received symbols correctly and the rest of the $M-K$ relays fail to decode the received signal. The probability of this event can be found as

$$\begin{aligned}&\Psi_{\text{R}_C} = \mathcal{P}(C = \{1,\ldots,K\}) =\\ &\sum_{j=1}^{2^{M-K}} (-1)^{\sum_{t=1}^{M-K}\tau_{j,t}} \exp\left(-2\pi\lambda_R \int_0^\infty \left(1 - \prod_{k=1}^{K} \frac{1}{\left(1+\frac{\gamma_{\text{min}}P_I r^{-\alpha}}{P_{\text{S}} d_{\text{SR}_k}^{-\alpha}}\right)}\right.\right.\\ &\qquad\qquad\left.\left.\times \prod_{k=K+1}^{M} \frac{1}{\left(1+\frac{\gamma_{\text{min}}P_I r^{-\alpha}\tau_{j,k-K}}{P_{\text{S}} d_{\text{SR}_k}^{-\alpha}}\right)}\right) r dr\right)\end{aligned} \tag{8.10}$$

where $\tau_j, j \in \{1,\ldots,2^{M-K}\}$ are all the $(M-K)$-tuples on the binary set $\{0,1\}$ and $\tau_{j,t}$ is the t-th element of τ_j. The proof of (8.10) is given in Appendix 8.A. For the special case of identically distributed S-R channels, i. e. $d_{\mathrm{SR}_1} = \cdots = d_{\mathrm{SR}_M} = d_{\mathrm{SR}}$, this probability is found as [28]

$$\Psi_{\mathrm{R}_{C\,\mathrm{corr,ID}}} = \sum_{j=1}^{2^{M-K}} (-1)^{\sum_{t=1}^{M-K} \tau_{j,t}} \exp\left(-\lambda_{\mathrm{R}} \Delta \left(\frac{\gamma_{\min} P_I}{P_{\mathrm{S}} d_{\mathrm{SR}}^{-\alpha}} \right)^{\delta} D_K(\delta) \right) \tag{8.11a}$$

where

$$D_K(\delta) = \frac{\Gamma\left(K + \sum_{k=1}^{M-K} \tau_{j,k} + \delta\right)}{\Gamma\left(K + \sum_{k=1}^{M-K} \tau_{j,k}\right) \Gamma(1+\delta)}. \tag{8.11b}$$

If the distributions of the interferers at the relays are modeled by separate independent PPPs, this probability is equal to

$$\Psi_{\mathrm{R}_{C\,\mathrm{ind,ID}}} = \sum_{j=1}^{2^{M-K}} (-1)^{\sum_{t=1}^{M-K} \tau_{j,t}} \exp\left(-\lambda_{\mathrm{R}} \Delta \left(\frac{\gamma_{\min} P_I}{P_{\mathrm{S}} d_{\mathrm{SR}}^{-\alpha}} \right)^{\delta} \left(K + \sum_{k=1}^{M-K} \tau_{j,k} \right) \right). \tag{8.12}$$

8.3.1 Multi-relay transmission

For multi-relay transmission and optimum combining at the destination, the weight vector can be given as [10]

$$\mathbf{w} = \mathbf{R}_{\mathrm{DF,MR}}^{-1} \mathbf{g} \tag{8.13}$$

where $\mathbf{g} = [\sqrt{P_{\mathrm{S}}} d_{\mathrm{SD}}^{-\frac{\alpha}{2}} g_0, \sqrt{P_{\mathrm{R}_1}} d_{\mathrm{R}_1\mathrm{D}}^{-\frac{\alpha}{2}} g_1, \ldots, \sqrt{P_{\mathrm{R}_K}} d_{\mathrm{R}_K\mathrm{D}}^{-\frac{\alpha}{2}} g_K]^T$. The noise-plus-interfer ence correlation matrix (NICM) $\mathbf{R}_{\mathrm{DF,MR}}$ is

$$\mathbf{R}_{\mathrm{DF,MR}} = N_0 \mathbf{I} + \boldsymbol{\eta}\boldsymbol{\eta}^H \tag{8.14}$$

where $\boldsymbol{\eta} = [I_0, I_1, \ldots, I_K]^T$, $I_0 = \sqrt{P_I} \sum_{x \in \Phi_{\mathrm{D}}} \|x\|^{-\alpha/2} l_{0,x}$ is the aggregate interference channel in Phase 1 and $I_i = \sqrt{P_I} \sum_{x \in \Phi_{\mathrm{D}}} \|x\|^{-\alpha/2} l_{i,x}$ is the aggregate interference channel in time slot i of Phase 2 at the destination node, where $i \in C$. In this section, it is assumed that the destination node is able to estimate NICM $\mathbf{R}_{\mathrm{DF}}$ perfectly. The NICM for multiple antenna receivers, $\mathbf{R}_{\mathrm{MA}}$, is given as [19]

$$\mathbf{R}_{\mathrm{MA}} = N_0 \mathbf{I} + P_I \sum_{x \in \Phi_{\mathrm{D}}} \|x\|^{-\alpha} \mathbf{l}_x \mathbf{l}_x^H \tag{8.15}$$

where $\mathbf{l}_x$ is the vector of fading coefficients for the channel between the x-th interferer and the receiver. Note the difference between $\mathbf{R}_{\mathrm{DF,MR}}$ and $\mathbf{R}_{\mathrm{MA}}$ matrices given in (8.14) and (8.15). By observation, the rank of the interference component in $\mathbf{R}_{\text{DF}}$ is equal to one. However, the interference component of $\mathbf{R}_{\text{MA}}$ has a higher rank. Furthermore, since the interferers at different time slots share the common source of randomness Φ_{D}, interferences at different time slots are correlated in DF relaying. However, interference correlation was not considered in [19]. Therefore, the results available for multiple-antenna receivers in [19] cannot be directly applied for unit DF relaying with single antenna receivers.

The resulting SINR at the OC receiver is [10]

$$\gamma_{\text{DF,MR}}|C = \mathbf{g}^H \mathbf{R}_{\text{DF,MR}}^{-1} \mathbf{g}. \tag{8.16}$$

To further analyze the performance of the OC receiver, we propose the following approximation for the exact SINR expression in (8.16).

$$\begin{aligned}\gamma_{\text{DF,MR}}|C &\approx \frac{P_{\text{S}} d_{\text{SD}}^{-\alpha} |g_0|^2}{N_0 + Z_{\text{D}_0} + Z_{\text{D}_1} + \cdots + Z_{\text{D}_K}} + \sum_{i=1}^{K} \frac{P_{\text{R}_i} d_{\text{R}_i\text{D}}^{-\alpha} |g_i|^2}{N_0} \\ &= \frac{X_1}{N_0 + Z_{\text{D}_T}} + Y_1 \end{aligned} \tag{8.17}$$

where $Z_{\text{D}_T} = \sum_{k=0}^{K} Z_{\text{D}_k}$, $Z_{\text{D}_0} = P_I \sum_{x \in \Phi_{\text{D}}} \|x\|^{-\alpha} |l_{0,x}|^2$ and $Z_{\text{D}_i} = P_I \sum_{x \in \Phi_{\text{D}}} \|x\|^{-\alpha} |l_{i,x}|^2$, $i \in C$.

It should be noted that the approximation in (8.17) is equal to the exact SINR expression given in (8.16) when the elements of the vector $\mathbf{g}$ are independent and identically distributed [29, eq. (11.5), eq. (11.8)]. When the elements of $\mathbf{g}$ are independent and non-identically distributed, the results in Section 8.6 indicate that (8.17) is still a very tight approximation for (8.16).

Similar to [30, eq. (9)], the probability density function (PDF) of Y can be found as

$$f_{Y_1}(y) = \sum_{k=1}^{r} \sum_{m=1}^{\nu_k} \frac{\phi_{km} y^{m-1}}{\Gamma(m)} \left(\frac{N_0}{\eta_k}\right)^m \exp\left(-\frac{N_0 y}{\eta_k}\right) \tag{8.18}$$

where $\eta_1, \ldots, \eta_r$ are the distinct values of the average powers, $P_{\text{R}_1} d_{\text{R}_1\text{D}}^{-\alpha}, \ldots, P_{\text{R}_K} d_{\text{R}_K\text{D}}^{-\alpha}$, with multiplicities $\nu_1, \ldots, \nu_r$, respectively and $\sum_{j=1}^{r} \nu_j = K$. The partial fraction coefficients ϕ_{km} are given in [30, eq. (10)].

The outage probabilities for the cases of empty decoding sets and non-empty decoding sets are found below.

Case 1: $C = \emptyset$

When all the relays fail to decode the received symbols correctly, the outage probability is derived in the same manner as the derivation of the outage probability at the relay nodes in (8.4) and can be expressed as

$$P_0 = \mathbb{P}_{\text{DF,MR}}|(C = \emptyset) = 1 - \exp\left(-\frac{\gamma_{T_{\min}} N_0}{P_{\text{S}} d_{\text{SD}}^{-\alpha}} - \lambda_{\text{D}} \Delta \left(\frac{\gamma_{T_{\min}} P_I}{P_{\text{S}} d_{\text{SD}}^{-\alpha}}\right)^{\delta}\right). \tag{8.19}$$

Case 2: $C \neq \emptyset$

Here, it is assumed that the decoding set C has K relays. Since $|g_0|^2$ is an exponential random variable with unit variance, using (8.17) and the total probability theorem, the outage probability given K can be expressed as

$$P_K = \mathbb{P}_{\text{DF,MR}}|(|C| = K > 0) =$$
$$1 - \Bigg[\underbrace{\int_{\gamma_{T_{\text{DF,MR}}}}^{\infty} f_{Y_1}(y)dy}_{\mathcal{I}_1} + \underbrace{\int_{0}^{\gamma_{T_{\text{DF,MR}}}} \mathbb{E}_{\Phi_{\text{D}}}\left[\exp\left(-\frac{(\gamma_{T_{\text{DF,MR}}} - y)(N_0 + Z_{D_T})}{P_{\text{S}} d_{\text{SD}}^{-\alpha}}\right)|Y_1\right] f_{Y_1}(y)dy}_{\mathcal{I}_2}\Bigg]. \tag{8.20}$$

The integral $\mathcal{I}_1$ in (8.20) can be found as [31, 3.351.2]

$$\mathcal{I}_1 = \sum_{k=1}^{r} \sum_{m=1}^{\nu_k} \frac{\phi_{km}}{\Gamma(m)} \Gamma\left(m, \frac{\gamma_{T_{\text{DF,MR}}} N_0}{\eta_k}\right) \tag{8.21}$$

where $\Gamma(\cdot, \cdot)$ is the upper incomplete gamma function [32, eq. (6.5.3)]. Furthermore, $\mathcal{I}_2$ can be evaluated as

$$\begin{aligned}\mathcal{I}_2 = \sum_{k=1}^{r} \sum_{m=1}^{\nu_k} \frac{\phi_{km}}{\Gamma(m)} \left(\frac{N_0}{\eta_k}\right)^m \int_{0}^{\gamma_{T_{\text{DF,MR}}}} y^{m-1} \exp\Bigg(&- \frac{y N_0}{\eta_k} - \frac{(\gamma_{T_{\text{DF,MR}}} - y) N_0}{P_{\text{S}} d_{\text{SD}}^{-\alpha}} \\ - \lambda_{\text{D}} \Delta \left(\frac{P_I \left(\gamma_{T_{\text{DF,MR}}} - y\right)}{P_{\text{S}} d_{\text{SD}}^{-\alpha}}\right)^{\delta} &\sum_{i=1}^{K+1} \binom{K+1}{i} \binom{\delta - 1}{i - 1} \Bigg) dy\end{aligned} \tag{8.22}$$

where $\delta = \frac{2}{\alpha}$. The proof of (8.22) is given in Appendix 8.B. Note that (8.22) requires only a single definite numerical integration.

It should be noted that the interferer powers at different time slots ($Z_{D_0}, Z_{D_1}, \ldots,$ Z_{D_K} in (8.17)) are not independent as the number of interferer nodes and their positions at different time slots share a common randomness Φ_{D} [27].

Using (8.4), (8.19), (8.20) and the theorem of total probability, the end-to-end outage probability of OC in DF relaying is obtained as

$$\mathbb{P}_{\text{DF,MR}} = \sum_{k=0}^{M} \sum_{\substack{\forall C \subset \Omega, \\ |C| = k}} \Psi_{\mathrm{R}_C} P_k. \tag{8.23}$$

8.3.2 Relay selection

For DF relaying with relay selection, the SINR can be given as

$$\gamma_{\text{DF,RS}}|(C \neq \emptyset) = \max_{i \in C} \left\{ \gamma_{\text{DF},i} = \mathbf{g}_i^H \mathbf{R}_{\text{DF},i}^{-1} \mathbf{g}_i \right\} \tag{8.24}$$

where $\mathbf{g}_i = \left[\sqrt{P_T} d_{\mathrm{SD}}^{-\frac{\alpha}{2}} g_0, \sqrt{P_{\mathrm{R}_i}} d_{\mathrm{R}_i\mathrm{D}}^{-\frac{\alpha}{2}} g_i \right]^T$, $\mathbf{R}_{\text{DF},i} = N_0 \mathbf{I} + \boldsymbol{\eta_i} \boldsymbol{\eta_i}^H$, $\boldsymbol{\eta_i} = [I_0, I_i]^T$ and $I_i = \sqrt{P_I} \sum_{x \in \Phi_{\mathrm{D}}} \|x\|^{-\alpha/2} l_{i,x}$. Since $\gamma_{\text{DF},i}$ is the SINR with a single relay, from (8.17), an approximation for $\gamma_{\text{DF},i}$ can be proposed as

$$\gamma_{\text{DF},i} \approx \frac{P_{\mathrm{S}} d_{\mathrm{SD}}^{-\alpha} |g_0|^2}{N_0 + Z_{D_0} + Z_{D_1}} + \frac{P_{\mathrm{R}_i} d_{\mathrm{R}_i\mathrm{D}}^{-\alpha} |g_i|^2}{N_0} \tag{8.25}$$

where $Z_{D_1} = P_I \sum_{x \in \Phi_{\mathrm{D}}} \|x\|^{-\alpha} |l_{1,x}|^2$.

Hence, the SINR of relay selection can be approximated as

$$\begin{aligned} \gamma_{\text{DF,RS}}|(C \neq \emptyset) &\approx \frac{P_{\mathrm{S}} d_{\mathrm{SD}}^{-\alpha} |g_0|^2}{N_0 + Z_{D_1} + Z_{D_2}} + \max_{i \in C} \frac{P_{\mathrm{R}_i} d_{\mathrm{R}_i\mathrm{D}}^{-\alpha} |g_i|^2}{N_0} \\ &= \frac{X_2}{N_0 + Z_{D_1} + Z_{D_2}} + Y_2. \end{aligned} \tag{8.26}$$

For relay-destination links with independent Rayleigh fadings, the CDF of Y_2 can be expressed as

$$F_{Y_2}(y) = \prod_{i \in C} \left(1 - \exp\left(\frac{N_0 y}{P_{\mathrm{R}_i} d_{\mathrm{R}_i\mathrm{D}}^{-\alpha}} \right) \right). \tag{8.27}$$

The conditional outage probability of relay selection can be given as

$$Q_K = \mathbb{P}_{\text{DF,RS}}|(|C| = K > 0) =$$

$$1 - \Bigg[\underbrace{\int_{\gamma_{T_{\text{DF,RS}}}}^{\infty} f_{Y_2}(y)dy}_{\mathcal{I}_3} + \underbrace{\int_{0}^{\gamma_{T_{\text{DF,RS}}}} \mathbb{E}_{\Phi_{\text{D}}}\left[\exp\left(-\frac{(\gamma_{T_{\text{DF,RS}}} - y)(N_0 + Z_{D_T})}{P_{\text{S}} d_{\text{SD}}^{-\alpha}}\right)|Y_2\right] f_{Y_2}(y)dy}_{\mathcal{I}_4} \Bigg]. \tag{8.28}$$

where $\mathcal{I}_3 = 1 - F_{Y_2}(\gamma_{T_{\text{DF,RS}}})$ and $\mathcal{I}_4$ can be obtained from (8.22) by using $K = 1$ and by obtaining the PDF of Y_2 from (8.27). An approximation for the end-to-end outage probability of relay selection can be obtained by the substitution of P_k by Q_k in (8.23).

8.4 Performance Analysis of Optimum Combining in AF Relaying With Perfect Estimation of The NICM

The outage performance of AF relaying is analyzed for noise-limited relays and an interference-limited destination node in this section. For AF relaying with multi-relay transmission, the outage probability can be defined as

$$\mathbb{P}_{\text{AF,MR}} = F_{\gamma_{\text{AF,MR}}}\left(\gamma_{T_{\text{AF,MR}}} = (1 + \gamma_{\min})^{M+1} - 1\right). \tag{8.29}$$

The noise-plus-interference correlation matrix for the optimum combiner in AF relaying is

$$\mathbf{R}_{\text{AF,MR}} = N_0\mathbf{I} + \boldsymbol{\kappa}\boldsymbol{\kappa}^H + \text{diag}\left[0, \frac{P_{\text{R}_1} d_{\text{R}_1 D}^{-\alpha}|g_1|^2}{P_{\text{S}}\, d_{\text{SR}_1}^{-\alpha}|h_1|^2}, \ldots, \frac{P_{\text{R}_M} d_{\text{R}_M\text{D}}^{-\alpha}|g_M|^2}{P_{\text{S}} d_{\text{SR}_M}^{-\alpha}|h_M|^2}\right] \tag{8.30}$$

where $\boldsymbol{\kappa} = [I_0, I_1, \ldots, I_M]^T$ and $I_i, i \in \Omega$ are defined in (8.14). The additional diagonal matrix in $\mathbf{R}_{\text{AF,MR}}$ is the covariance matrix of the noise forwarded from each relay to the destination. The first element of the relay-destination noise covariance matrix is zero since no noise is forwarded from the relays to the destination in Phase 1.

The resulting SINR of OC in AF relaying is

$$\gamma_{\text{AF,MR}} = \boldsymbol{\omega}^H \mathbf{R}_{\text{AF,MR}}^{-1} \boldsymbol{\omega} \tag{8.31}$$

where
$\boldsymbol{\omega} = \left[\sqrt{P_{\mathrm{S}}}d_{\mathrm{SD}}^{-\frac{\alpha}{2}}g_0, \frac{\sqrt{P_{\mathrm{R}_1}}d_{\mathrm{R}_1\mathrm{D}}^{-\frac{\alpha}{2}}g_1h_1}{|h_1|}, \ldots, \frac{\sqrt{P_{\mathrm{R}_M}}d_{\mathrm{R}_M\mathrm{D}}^{-\frac{\alpha}{2}}g_Mh_M}{|h_M|}\right]^T$. It is obvious that the elements of the vector $\boldsymbol{\omega}$ have the same distribution as the elements of the vector $\boldsymbol{\upsilon} = \left[\sqrt{P_{\mathrm{S}}}d_{\mathrm{SD}}^{-\alpha/2}g_0, \sqrt{P_{\mathrm{R}_1}}d_{\mathrm{R}_1\mathrm{D}}^{-\alpha/2}g_1, \ldots, \sqrt{P_{\mathrm{R}_M}}d_{\mathrm{R}_M\mathrm{D}}^{-\alpha/2}g_M\right]^T$.

Based on [11], the following approximation to the SINR of the OC receiver with AF relaying in (8.31) can be proposed,

$$\begin{aligned}\gamma_{\text{AF,MR}} &\approx \frac{P_{\mathrm{S}}d_{\mathrm{SD}}^{-\alpha}|g_0|^2}{N_0 + Z_{D_0} + Z_{D_1} + \cdots + Z_{D_M}} + \sum_{i=1}^{M} \min\left(\frac{P_{\mathrm{S}}d_{\mathrm{SR}_i}^{-\alpha}|h_i|^2}{N_0}, \frac{P_{\mathrm{R}_i}d_{\mathrm{R}_i\mathrm{D}}^{-\alpha}|g_i|^2}{N_0}\right) \\ &= \frac{X}{N_0 + Z_{D_T}} + Y_3.\end{aligned} \tag{8.32}$$

Similar to Y_1, the PDF of Y_3 can be expressed as

$$f_{Y_3}(y) = \sum_{k=1}^{t}\sum_{m=1}^{\zeta_k} \frac{\mu_{km}y^{m-1}}{\Gamma(m)}\left(\frac{N_0}{\beta_k}\right)^m \exp\left(-\frac{N_0 y}{\beta_k}\right) \tag{8.33}$$

where $\beta_1, \ldots, \beta_t$ are the distinct values of $P_{T_1}, \ldots, P_{T_M}$, with multiplicities $\zeta_1, \ldots, \zeta_t$, respectively, $\sum_{j=1}^{r}\zeta_j = M$ and $P_{T_i} = \frac{P_{\mathrm{S}}d_{\mathrm{SR}_i}^{-\alpha}P_{\mathrm{R}_i}d_{\mathrm{R}_i\mathrm{D}}^{-\alpha}}{P_{\mathrm{S}}d_{\mathrm{SR}_i}^{-\alpha}+P_{\mathrm{R}_i}d_{\mathrm{R}_i\mathrm{D}}^{-\alpha}}$ with $i \in \Omega$ [33, eq. (6-82)]. The outage probability can be derived similar to (8.20) with K replaced with M and the coefficients of the PDF of Y_1 replaced with corresponding values of the PDF of Y_2.

The performance analysis of AF relaying with relay selection follows the same steps as in Section 8.3.2.

8.5 Performance of DF Relaying with Limited Interferer Channel Estimation

In Sections 8.3 and 8.4, it is assumed that the destination node is able to estimate the noise-plus-interference correlation matrices perfectly. However, in a random interferer field, this may not be practically feasible. In this section, the outage performance of OC in DF relaying is studied for $M = 1$ when the destination node perfectly estimates only the CSI of the closest interferer, instead of all the interferers. Hence, the NICM with limited interferer channel estimation for $M = 1$

is

$$\mathbf{R}_{\text{DF,L}} = N_0\mathbf{I} + \mathbf{p}\mathbf{p}^H \tag{8.34}$$

where $\mathbf{p} = [\sqrt{P_I}\|x_0\|^{-\alpha/2} l_{0,x_0}, \sqrt{P_I}\|x_1\|^{-\alpha/2} l_{1,x_1}]^T$, x_0 and x_1 are the locations of the closest interferers in Phase 1 and Phase 2, respectively, and l_{0,x_0} and l_{1,x_1} are the fading coefficient of the channels from the closest interferers to the destination in Phase 1 and Phase 2, respectively.

The resulting SINR of limited interferer channel estimation is

$$\gamma_{\text{DF,L}} = \frac{\mathbf{g}^H \mathbf{R}_{\text{DF,L}}^{-1}\mathbf{g}}{\mathbf{g}^H \mathbf{R}_{\text{DF,L}}^{-1}\mathbf{R}_{\text{DF,MR}}\mathbf{R}_{\text{DF, L}}^{-1}\mathbf{g}} \tag{8.35}$$

where $\mathbf{R}_{\text{DF,MR}}$ is given in (8.14). Eq. (8.35) is very difficult to analyze in the exact form. Hence, a close approximation to $\gamma_{\text{DF,L}}$ for $M = 1$ is proposed as follows,

$$\gamma_{\text{DF,L}} \approx \underbrace{\frac{P_{\text{S}} d_{\text{SD}}^{-\alpha}|g_0|^2}{N_0 + P_I \sum_{x\in\Phi_{\text{D}}} \|x\|^{-\alpha}|l_{0,x}|^2 + P_I\|x_1\|^{-\alpha}|l_{1,x_1}|^2}}_{T_1} + \underbrace{\frac{P_{\text{R}_1\text{D}} d_{\text{R}_1\text{D}}^{-\alpha}|g_1|^2}{N_0 + P_I \sum_{x\in\Phi_{\text{D}}\backslash x_1} \|x\|^{-\alpha}|l_{1,x}|^2}}_{T_2}. \tag{8.36}$$

Using the MGF approach employed earlier, the conditional cumulative density function (CDF) of T_1 is found as

$$F_{T_1|r_1}(\gamma) = 1 - \frac{\exp\left(-\frac{N_0\gamma}{P_{\text{S}} d_{\text{SD}}^{-\alpha}} - \lambda_{\text{D}}\Delta\left(\frac{\gamma P_I}{P_{\text{S}} d_{\text{SD}}^{-\alpha}}\right)^{\delta}\right)}{\left(\frac{P_I r_1^{-\alpha}\gamma}{P_{\text{S}} d_{\text{SD}}^{-\alpha}} + 1\right)} \tag{8.37}$$

where $r_1 = \|x_1\|$.

Based on the Slivnyak's Theorem [14], $\Phi_{\text{D}}\backslash x_1$ is also a homogeneous PPP with density λ_{D}. Following [34, eq. (3)] and using the integral identity [31, eq. (6.455.2)], the CDF of T_2 is can be found as

$$F_{T_2|r_1}(\gamma) = 1 - \exp\left(-\frac{N_0\gamma}{P_{\text{R}} d_{\text{RD}}^{-\alpha}} + \lambda_D\pi r_1^2 + \frac{\lambda_D \pi r_1^2 {}_2F_1\left(1, 1; 1 - \frac{2}{\alpha}; \frac{\frac{P_I r_1^{-\alpha}\gamma}{P_{\text{S}} d_{\text{SD}}^{-\alpha}}}{\left(\frac{P_I r_1^{-\alpha}\gamma}{P_{\text{S}} d_{\text{SD}}^{-\alpha}} + 1\right)}\right)}{\left(\frac{P_I r_1^{-\alpha}\gamma}{P_{\text{S}} d_{\text{SD}}^{-\alpha}} + 1\right)}\right). \tag{8.38}$$

Using (8.36), (8.37) and (8.38), an approximation for the conditional outage probability of the OC receiver with limited interferer estimation for $M = 1$ can be given as

$$\mathbb{P}_{\text{DF,L}}|(|C| = 1) \approx \int_0^{\infty} \int_0^{\gamma_{T,L}} F_{T_1|r_1}(\gamma_{T,L} - T_2) f_{T_2|r_1}(\gamma) d\gamma f_{r_1}(r) dr \tag{8.39}$$

where $\gamma_{T,L} = \gamma_{\text{min}}^2 + 2\gamma_{\text{min}}$ for $M = 1$ and the PDF of the distance to the closest interferer $f_{r_1}(r)$ is [35]

$$f_{r_1}(r) = 2\pi\lambda_{\text{D}} r \exp(-\lambda_{\text{D}} \pi r^2). \tag{8.40}$$

Hence, the end-to-end outage probability for $M = 1$ is

$$\mathbb{P}_{\text{DF,L}} = \mathbb{P}_{\text{R}} P_0 + (1 - \mathbb{P}_{\text{R}}) \mathbb{P}_{\text{DF,L}}|(|C| = 1) \tag{8.41}$$

where P_0 is found in (8.19).

8.6 Numerical Results

In this section, the outage probability results obtained using numerical integration are compared with the simulation results. The source node is assumed to be a macro base station and the interferers are assumed to predominantly consist of pico/femto base stations and relay nodes. The transmit power ratios $\frac{P_{\text{S}}}{P_{\text{R}}} = 23$ dB and $\frac{P_I}{P_{\text{R}}} = 0$ dB, which complies with the 3GPP LTE-Advanced specifications [13]. Hence, the transmit powers of the interferers are scaled with the source and the relay powers. The noise floor is assumed to be 1 pW. The source-destination, source-relay and relay-destination distances are 400 m, 300 m and 100 m, respectively. Unless specified otherwise, $\lambda_{\text{R}} = \lambda_{\text{D}} = 10^{-5}$. Simulation results are averaged over 10^4 interferer location configurations and up to 10^4 channel realizations for each interferer location configuration. The SINR threshold for outage, $\gamma_{\text{min}} = 0$ dB, which corresponds to $R_{\text{min}} = 1$ bps.

In Figs. 8.2 and 8.3, the outage performance results with interference-limited relay nodes and destination node are shown for $\alpha = 3$ and $\alpha = 4$, respectively. At higher signal-to-noise ratio (SNR) values, performance gains can be achieved using more relay nodes, due to the array gain of multi-relay transmission. However, at lower SNR values, increasing of M degrades the performance since the capacity reduces with the increase of M. Furthermore, the performance advantages of using more relays diminish with the increase of M due the interference correlation between different relay nodes. As expected, outage performance degrades with the increase of the path loss exponent. It can be seen that the diversity gains of OC degrade in the presence of interference at the relay nodes, since the interference at the relays is not suppressed.

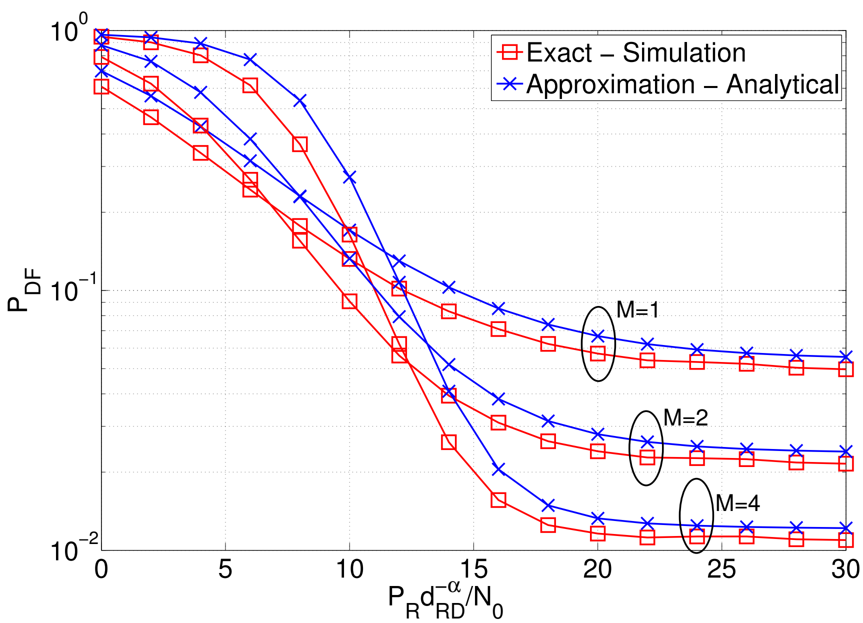

Figure 8.2: The outage performance vs. the average SNR of the $\mathrm{R}_i - \mathrm{D}$ link for DF relaying with interference-limited relay nodes and interference-limited destination node with $M = 1, 2, 4$ and $\alpha = 3$.

The degradation of outage performance due to the interference correlation at the relays is shown in Fig. 8.4. The interference correlation at the relays, which is a result of the modeling of the interferer distribution at different relays by the same homogeneous PPP, results in significant performance losses. Furthermore, compared to independent interferer signals, the performance gains achieved by increasing of M degrades.

The outage performance of DF relaying against the variation of λ_{R} and λ_{D} are

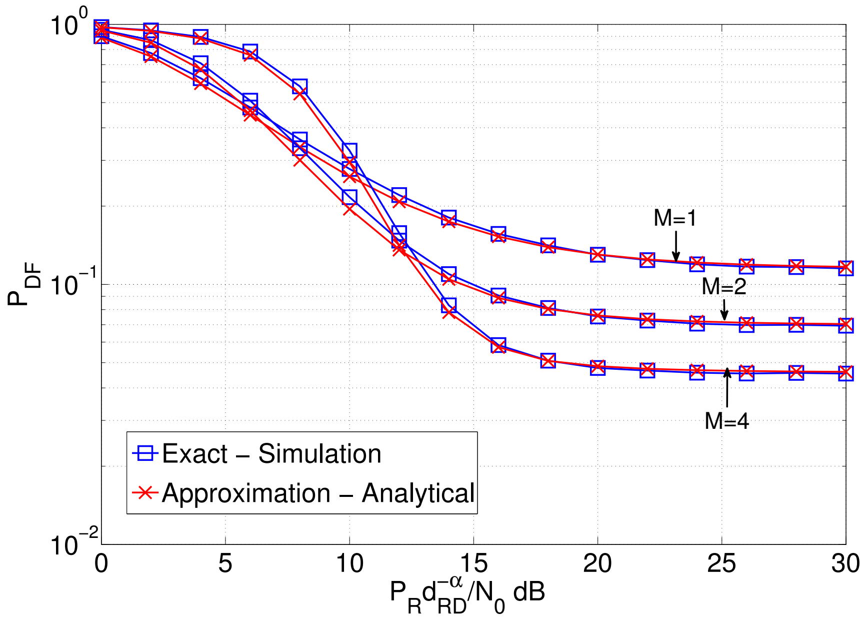

Figure 8.3: The outage performance vs. the average SNR of the $R_i - D$ link for DF relaying with interference-limited relay nodes and interference-limited destination node with $M = 1, 2, 4$ and $\alpha = 4$.

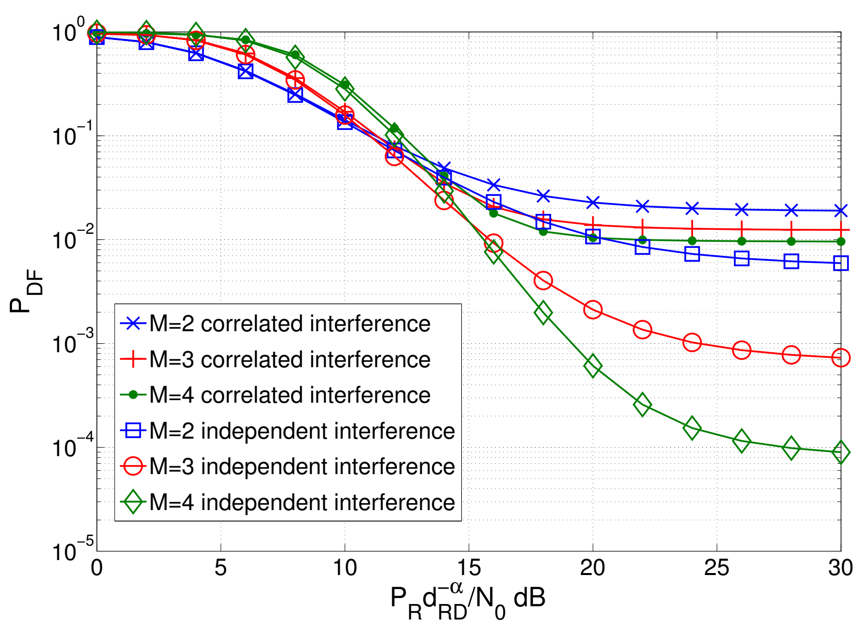

Figure 8.4: The degradation of outage performance due to correlation between the interference at the relays for DF relaying with multi-relay transmission with $M = 2, 3, 4$ and $\alpha = 3$.

shown in Fig. 8.5 and in Fig. 8.6, respectively, for $\frac{P_{\mathrm{R}} d_{\mathrm{RD}}^{-\alpha}}{N_0} = 20$ dB. As λ_R increases, the outage probability converges to the outage probability of the direct communication. Furthermore, by increasing λ_{D}, the outage probability can be increased up to an upper bound. Using (8.17) and (8.23), it can be proved that this upper bound is equal to

$$\lim_{\lambda_D \to \infty} \mathbb{P}_{\text{DF,MR}} = \sum_{q=1}^{M} \sum_{\substack{\forall C \subset \Omega, \\ |C| = q, \\ C \neq \emptyset}} \Psi_{\mathrm{R}_C} P_{\text{assym}} \tag{8.42a}$$

where P_{assym} is found from (8.20) as

$$P_{\text{assym}} = \lim_{\lambda_D \to \infty} \mathbb{P}_{\text{DF,MR}} | (|C| = q) = 1 - \mathcal{I}_1. \tag{8.42b}$$

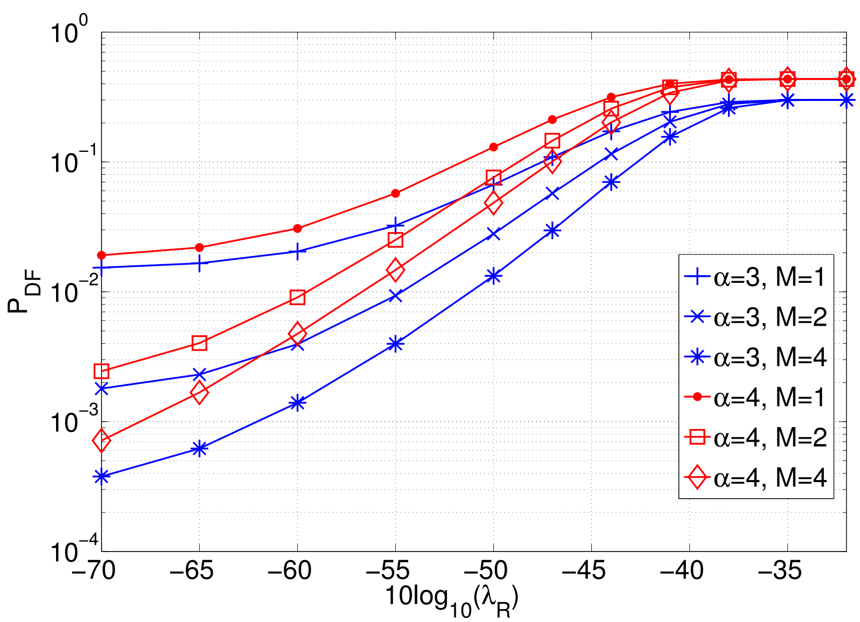

Figure 8.5: The outage performance with the variation of λ_R with $\lambda_{\mathrm{D}} = 10^{-5}$ and $\frac{P_{\mathrm{R}} d_{\mathrm{RD}}^{-\alpha}}{N_0} = 20$ dB.

The performances of multi-relay transmission and relay selection are compared in Fig. 8.7 for DF relaying. It is evident that relay selection outperforms multi-relay transmission in low-to-medium SNR values since relay selection achieves a

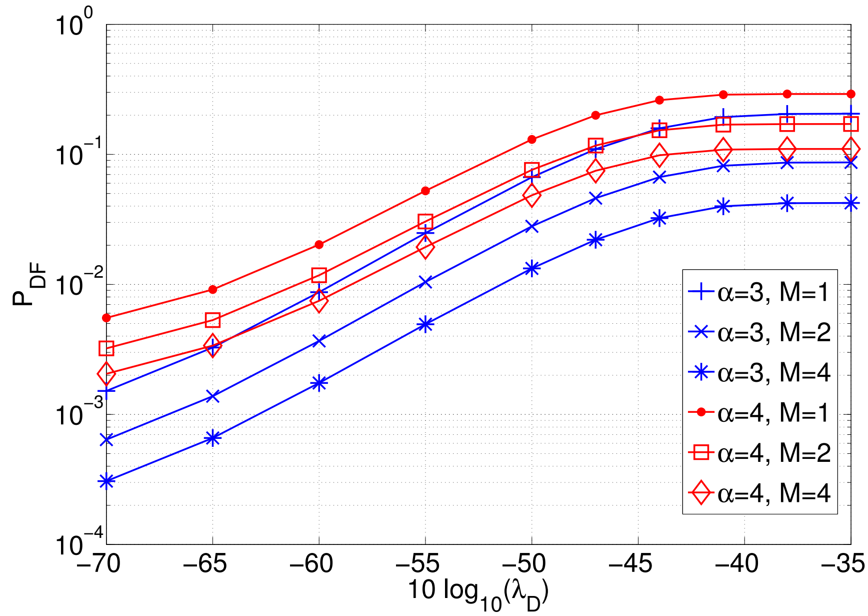

Figure 8.6: The outage performance with the variation of λ_{D} with $\lambda_{\mathrm{R}} = 10^{-5}$ and $\frac{P_{\mathrm{R}} d_{\mathrm{RD}}^{-\alpha}}{N_0} = 20$ dB.

better capacity than multi-relay transmission for $M > 1$. Furthermore, with relay selection, the destination has to estimate CSI of its interferers in only two time slots, compared to $K + 1$ time slots in multi-relay transmission. Consequently, relay selection is preferred over multi-relay transmission in Phase 2.

In Fig. 8.8, the outage performance results for AF relaying with noise-limited relays and interference-limited destination are given for $\alpha = 3$. Accordingly, diversity gains are achieved when the relays are noise limited. However, diversity gain is not derived analytically, since the outage probability expression involves a single numerical integration. Furthermore, it is evident that for low-to-medium SNR values, having $M > 2$ degrades the outage probability, due to the degradation of the capacity in multi-relay transmission. Moreover, the proposed approximation for OC in AF relaying is also tight with the gap between the simulation and analytical results always under 1 dB.

The performances of multi-relay transmission and best-relay transmission are compared in Fig. 8.9 for AF relaying with $\alpha = 3$ and both techniques achieve the same diversity gains. However, similar to DF relaying, relay selection outperforms

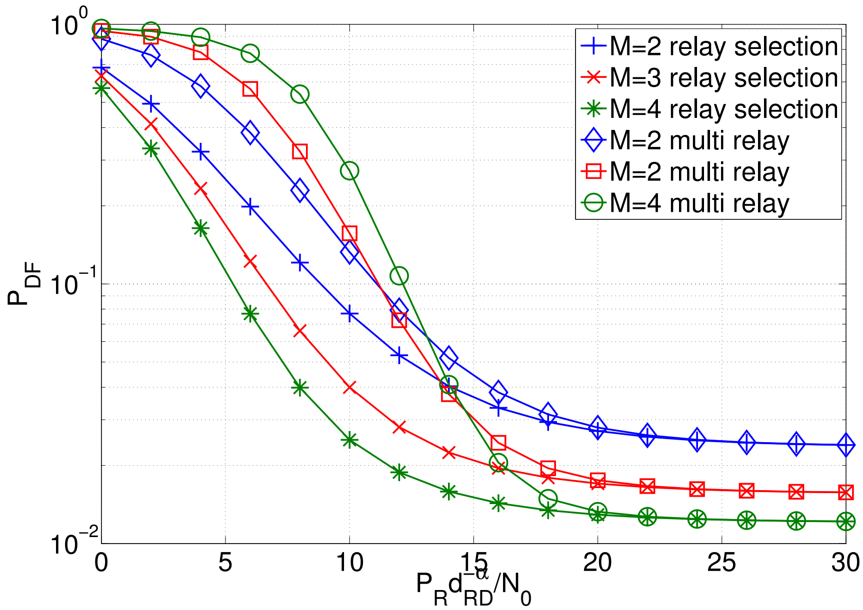

Figure 8.7: Performance comparison of multi-relay transmission and relay selection for DF relaying with $M = 2, 3, 4$ and $\alpha = 3$.

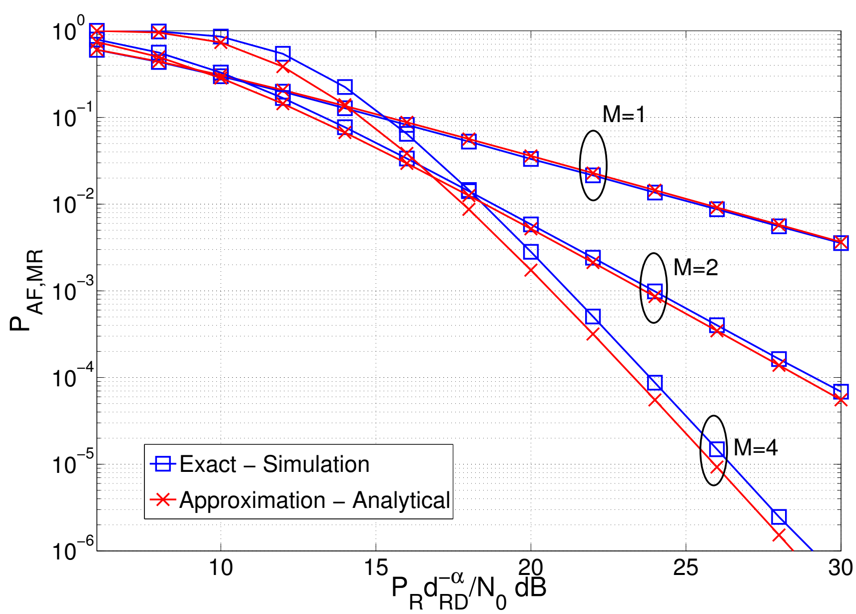

Figure 8.8: The outage performance vs. the average SNR of the $\mathrm{R}_i - D$ link for AF relaying with noise-limited relays and interference-limited destination with $M = 1, 2, 4$ and $\alpha = 3$.

multi-relay transmission. The performance gap between multi-relay transmission and relay selection is wider in AF relaying since AF relaying with multi-relay transmission uses all M relay nodes in phase 2, further degrading the capacity. Hence, relay selection is the more suitable transmission technique for both relaying protocols, in terms of the outage performance.

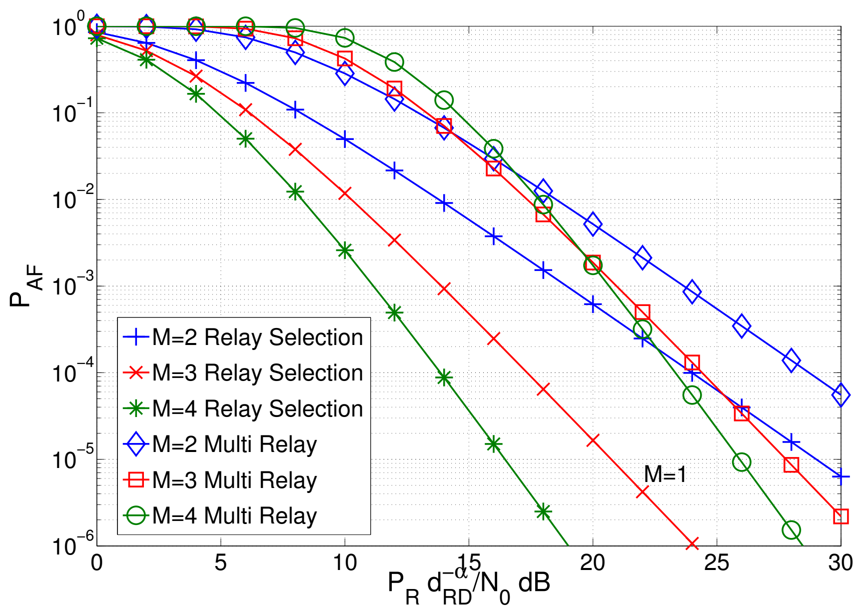

Figure 8.9: Performance comparison of multi-relay transmission and relay selection for AF relaying with $M = 2, 3, 4$ and $\alpha = 3$.

The impact of limited estimation of the noise-plus-interference correlation matrix on the performance of OC in DF relaying is shown in Fig. 8.10. The approximation for the outage probability with the limited estimation of the NICM is only derived for $M = 1$. It is assumed that the relays are noise-limited since the main objective is to evaluate the impact of the limited estimation of the NICM. Accordingly, diversity gains are reduced to zero and the performance degradation at medium-to-high SNRs can be clearly identified. At low SNR values, noise is more dominant than the interference since the interferer powers are scaled with the source and the relay powers. Hence, the performance loss due to the limited estimation of the NICM is minimal at low SNRs. Moreover, unlike in the case of perfect estimation of the NICM, the outage performance degrades with the increase of M over the complete SNR range. Hence, the array gain of OC with multi-relay transmission is degraded by the limited estimation of the NICM. Furthermore, OC with limited estimation of the NICM outperforms MRC. Hence, performance gains can be achieved using OC with a minimal additional overhead.

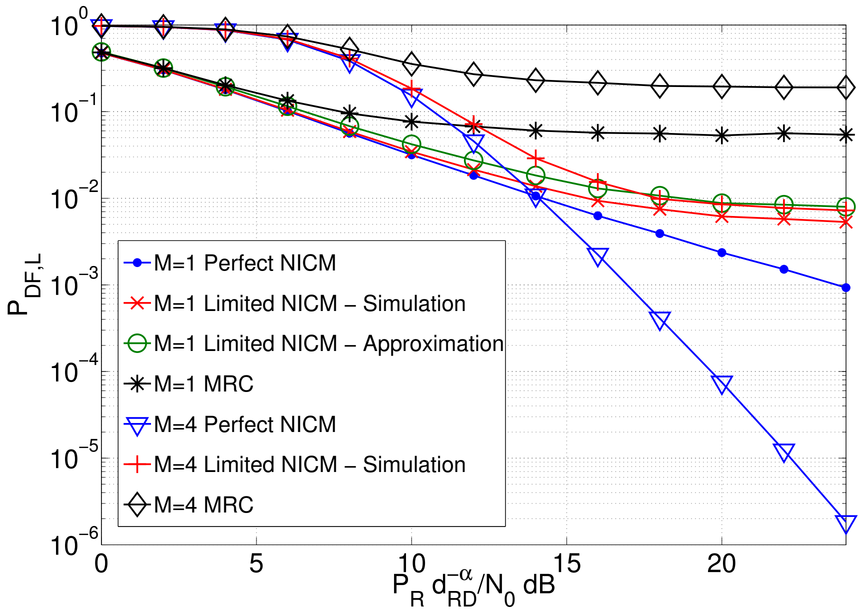

Figure 8.10: The impact of limited estimation of the NICM on the performance of OC in DF relaying for $M = 1$ and 4 with $\alpha = 3$.

8.7 Conclusion

In this chapter, the performance of optimum combining in DF and AF cooperative relaying with multi-relay transmission and relay selection were analyzed in the presence of Poisson fields of interferers at the relays and the destination. Close approximations for the outage probabilities of each relay protocol were derived for the case with perfect estimation of the noise-plus-interference correlation matrix (NICM) at the destination. Relay selection outperforms multi-relay transmission in terms of the outage performance and overhead consumed in both relay protocols. Furthermore, the performance of DF relaying was investigated for the case with limited estimation of the NICM, where the destination only estimates the CSI of the closest interferer. Diversity gains are not achieved with the limited estimation of the NICM. However, OC with limited interferer channel estimation still outperforms MRC.

8.A The Derivation of (8.10)

$$
\begin{aligned}
&\Psi_{\mathrm{R}_C} = \\
&= \mathcal{P}\left(|h_1|^2 > \frac{\gamma_{\min} Z_{\mathrm{R}_1}}{P_{\mathrm{S}} d_{\mathrm{SR}_1}^{-\alpha}}, \ldots, |h_K|^2 > \frac{\gamma_{\min} Z_{\mathrm{R}_K}}{P_{\mathrm{S}} d_{\mathrm{SR}_K}^{-\alpha}}, |h_{K+1}|^2 < \frac{\gamma_{\min} Z_{\mathrm{R}_{K+1}}}{P_{\mathrm{S}} d_{\mathrm{SR}_{K+1}}^{-\alpha}}, \ldots, |h_M|^2 < \frac{\gamma_{\min} Z_{\mathrm{R}_M}}{P_{\mathrm{S}} d_{\mathrm{SR}_M}^{-\alpha}}\right) \\
&\overset{(a)}{=} \mathbb{E}\left[\prod_{k=1}^{K} \exp\left(-\frac{\gamma_{\min} Z_{\mathrm{R}_k}}{P_{\mathrm{S}} d_{\mathrm{SR}_K}^{-\alpha}}\right) \prod_{k=K+1}^{M}\left(1 - \exp\left(-\frac{\gamma_{\min} Z_{\mathrm{R}_K}}{P_{\mathrm{S}} d_{\mathrm{SR}_k}^{-\alpha}}\right)\right)\right] \\
&\overset{(b)}{=} \sum_{j=1}^{2^{M-K}} (-1)^{\sum_{t=1}^{M-K} \tau_{j,t}} \mathbb{E}\left[\exp\left(-\sum_{k=1}^{K} \frac{\gamma_{\min} Z_{\mathrm{R}_k}}{P_{\mathrm{S}} d_{\mathrm{SR}_k}^{-\alpha}} - \sum_{k=K+1}^{M} \frac{\gamma_{\min} Z_{\mathrm{R}_k} \tau_{j,k-K}}{P_{\mathrm{S}} d_{\mathrm{SR}_k}^{-\alpha}}\right)\right] \\
&\overset{(c)}{=} \sum_{j=1}^{2^{M-K}} (-1)^{\sum_{t=1}^{M-K} \tau_{j,t}} \mathbb{E}_{\Phi_{\mathrm{R}}}\left[\prod_{x \in \Phi_{\mathrm{R}}} \prod_{k=1}^{K} \frac{1}{\left(1 + \frac{\gamma_{\min} P_I \|x\|^{-\alpha}}{P_{\mathrm{S}} d_{\mathrm{SR}_k}^{-\alpha}}\right)} \prod_{k=K+1}^{M} \frac{1}{\left(1 + \frac{\gamma_{\min} P_I \|x\|^{-\alpha} \tau_{j,k-K}}{P_{\mathrm{S}} d_{\mathrm{SR}_k}^{-\alpha}}\right)}\right] \\
&\overset{(d)}{=} \sum_{j=1}^{2^{M-K}} (-1)^{\sum_{t=1}^{M-K} \tau_{j,t}} \exp\left(-\lambda_{\mathrm{R}} \int_{\mathbb{R}^2} \left(1 - \prod_{k=1}^{K} \frac{1}{\left(1 + \frac{\gamma_{\min} P_I \|x\|^{-\alpha}}{P_{\mathrm{S}} d_{\mathrm{SR}_k}^{-\alpha}}\right)}\right.\right. \\
&\qquad\qquad\qquad \left.\left. \times \prod_{k=K+1}^{M} \frac{1}{\left(1 + \frac{\gamma_{\min} P_I \|x\|^{-\alpha} \tau_{j,k-K}}{P_{\mathrm{S}} d_{\mathrm{SR}_k}^{-\alpha}}\right)}\right) dx\right)
\end{aligned}
\tag{8.43}
$$

where (a) follows from the independence of the fading coefficients of the source-relay channels, (b) is obtained by expanding the second product term in (a), (c) follows from the independence of the fading coefficients of the interferer channels in $Z_{\mathrm{R}_k} = P_I \sum_{x \in \Phi_{\mathrm{R}}} \|x\|^{-\alpha} |f_{k,x}|^2$, and (d) follows from the probability generating functional (PGFL) for a homogenous PPP [16, eq. (A.3)]. Eq. (8.10) can be obtained by a simple variable change.

8.B The Derivation of $\mathcal{I}_2$ in (8.20)

Considering only the interference component and with $\theta = \frac{P_I(\gamma_{T_{\text{DF,MR}}} - y)}{P_{\text{S}} d_{\text{SD}}^{-\alpha}}$,

$$\begin{aligned}
&\mathbb{E}_{\Phi_{\text{D}}}\left[\exp\left(-\theta Z_T\right)|Y_1\right] \\
&= \mathbb{E}_{\Phi_{\text{D}}}\left[\exp\left(-\theta \sum_{k=0}^{K} \sum_{x\in\Phi_{\text{D}}} \|x\|^{-\alpha}|l_{k,x}|^2\right)\right] \\
&= \mathbb{E}_{\Phi_{\text{D}}}\left[\prod_{k=0}^{K} \prod_{x\in\Phi_{\text{D}}} \exp\left(-\theta\|x\|^{-\alpha}|l_{k,x}|^2\right)\right] \\
&\overset{(a)}{=} \mathbb{E}_{\Phi_{\text{D}}}\left[\prod_{x\in\Phi_{\text{D}}} \frac{1}{\left(\theta\|x\|^{-\alpha}+1\right)^{K+1}}\right] \\
&\overset{(b)}{=} \exp\left(-\lambda_{\text{D}} \int_{\mathbb{R}^2} \left(1 - \frac{1}{\left(\theta\|x\|^{-\alpha}+1\right)^{K+1}}\right) dx\right)
\end{aligned} \tag{8.44}$$

where (a) is obtained by the fact that $|l_{k,x}|^2$ are IID unit exponential random variables and (b) follows from the PGFL of a homogeneous PPP. By following the steps in [36] and by averaging (8.44) over the PDF of Y_1, $\mathcal{I}_2$ in (8.22) can be obtained.

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Chapter 9

Conclusions

The concluding remarks of the thesis and the future research directions based on this thesis are presented in Sections 9.1 and 9.2, respectively.

9.1 Concluding Remarks

The main focus of this thesis was co-channel interference (CCI) cancellation in cooperative relay networks using optimum combining. The main contributions and the insights of each chapter can be summarized as follows.

- The performance of optimum combining (OC) in decode-and-forward (DF) relaying in the presence of CCI at the destination node was studied in Chapter 3. The probability density function of signal-to-interference-plus-noise-ratio (SINR) and the outage probability were derived in exact form for $N_I \leq M + 1$, where N_I is the number of interferers and M is the number of relay nodes. Furthermore, a close approximation for the average symbol error rate was derived. The results suggest that OC achieves a diversity gain of M, which is a significant gain over conventional maximal-ratio combining (MRC).

- In Chapter 4, the performance of OC in DF relaying was studied for Nakagami-m fading when CCI present at both the relay nodes and the destination node. The outage probability was derived in closed-form. It was shown that OC cannot be used to achieve diversity gains if CCI present at the relays since single-antenna relays with CCI act as a bottleneck for end-to-end performance improvement.

- The impact of imperfect channel estimations on the performance of OC in DF relaying was analyzed in Chapter 5. The outage probability was derived when the desired channels are corrupted with a Gaussian error and it was proven that the diversity gains are lost if the error variance does not change with the source and the relay powers. Furthermore, it was shown that, if the destination node estimates only the variance of interferer channel state information (CSI) instead of instantaneous interferer CSI, no performance loss is observed. This is a remarkable outcome as it reduces the channel estimation overhead associated with OC significantly.

- The performance of OC with joint relay and antenna selection was studied in Chapter 6 for a relay network with multiple-antenna relay nodes with CCI present at both the relays and the destination. The exact outage probability was derived as a single integral and an approximation was derived in closed-form. It was shown that OC with joint relay and antenna selection achieves positive diversity gains if $n > 0$, where n is the number of relay nodes having $N_i < T_i$, and N_i and T_i are the number of interferers and the number of antennas at relay i, respectively. Furthermore, the diversity gain increases with the increase of n. Hence, this analysis provides a solution for the issue raised in Chapter 5.

- The performance of OC in amplify-and-forward relaying was analyzed in Chapter 7. Two types relaying schemes were considered: all-relay transmission and best-relay transmission. Approximate outage probabilities and the diversity gains of both schemes were derived. Both relay schemes achieve a diversity gain of M when CCI present only at the destination. Furthermore, best-relay transmission maximizes the capacity as it consumes only two time slots for a single communication. Moreover, the outage performance of best-relay transmission was studied when CCI present at both the relay nodes and the destination node, and the diversity gain degrades to zero in the presence of CCI at the relays.

- In Chapter 8, the performance of OC in DF and AF relaying was analyzed in the presence of a homogeneous Poisson field of interferers. Approximations for the outage probabilities of each relay protocol were derived for both multi-relay transmission and relay selection. OC achieves positive diversity gains provided that the relays are noise-limited and the destination node perfectly estimates the noise-plus-interference correlation matrix (NICM). Moreover, relay selection outperforms multi-relay transmission in both relay protocols. Furthermore, the impact of the limited estimation of the NICM on the outage performance was studied for DF relaying, where the destination only estimates the channel state information of the closest interferer, using a close approximation for the SINR expression. Significant performance gains can be achieved using OC with limited estimation of NICM

Consequently, in the presence of co-channel interference, significant performance gains can be achieved using optimum combining and cooperative relaying in single-antenna receivers in a range of system and channel models. Furthermore, channel estimation overhead of these techniques can be significantly reduced with a minimum loss of performance.

9.2 Future Research Directions

Some research avenues, which will improve the contributions of this thesis can be presented as follows.

Interference cancellation in heterogeneous (multi-tier) cellular networks

Although the interferer distribution was assumed to be random in Chapter 8, the analysis was confined to single-tier networks. Here, the tier represents the transmit power level of each base station. Fourth-generation wireless networks are heterogeneous in nature, where macro, pico and femto are examples of different tiers of base stations found. Typically, the node distribution in each tier is described by a spatial point process and a cell association policy is used to decide the base station to be connected [1]. The analysis of this thesis has to be be extended from single-tier to multi-tier networks to understand the viability of interference cancellation in heterogeneous networks.

Using non-homogeneous point processes to model the interference

In the scope of the thesis, the interferer distribution in the random interferer model is described by a homogeneous Poisson point process. However, homogeneous Poisson point processes may be inadequate to model interferer distribution in practical wireless networks due to the reasons discussed in Section 2.2. Instead, binomial point process, Poisson cluster process and Mattern point process have been proposed as appropriate point processes to model interferer distribution for different applications [2]. Extending the analysis in Chapter 8 of this thesis to these point processes is vital to understand the practical gains of the proposed techniques in ad hoc and heterogeneous wireless networks.

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