

Cooperative Relaying with Multi-Antenna System in Fading Channel



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Cooperative Relaying with Multi-Antenna System in Fading Channel

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Statement

I do hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the Department of Electronics and Electrical Engineering, Indian Institute of Technology Guwahati, under the supervision of Dr. Ratnajit Bhattacharjee, Department of Electronics and Electrical Engineering, Indian Institute of Technology Guwahati.

In keeping with the general practice of reporting scientific observations, due acknowledgement has been made wherever the work described is based on the findings of other investigators.

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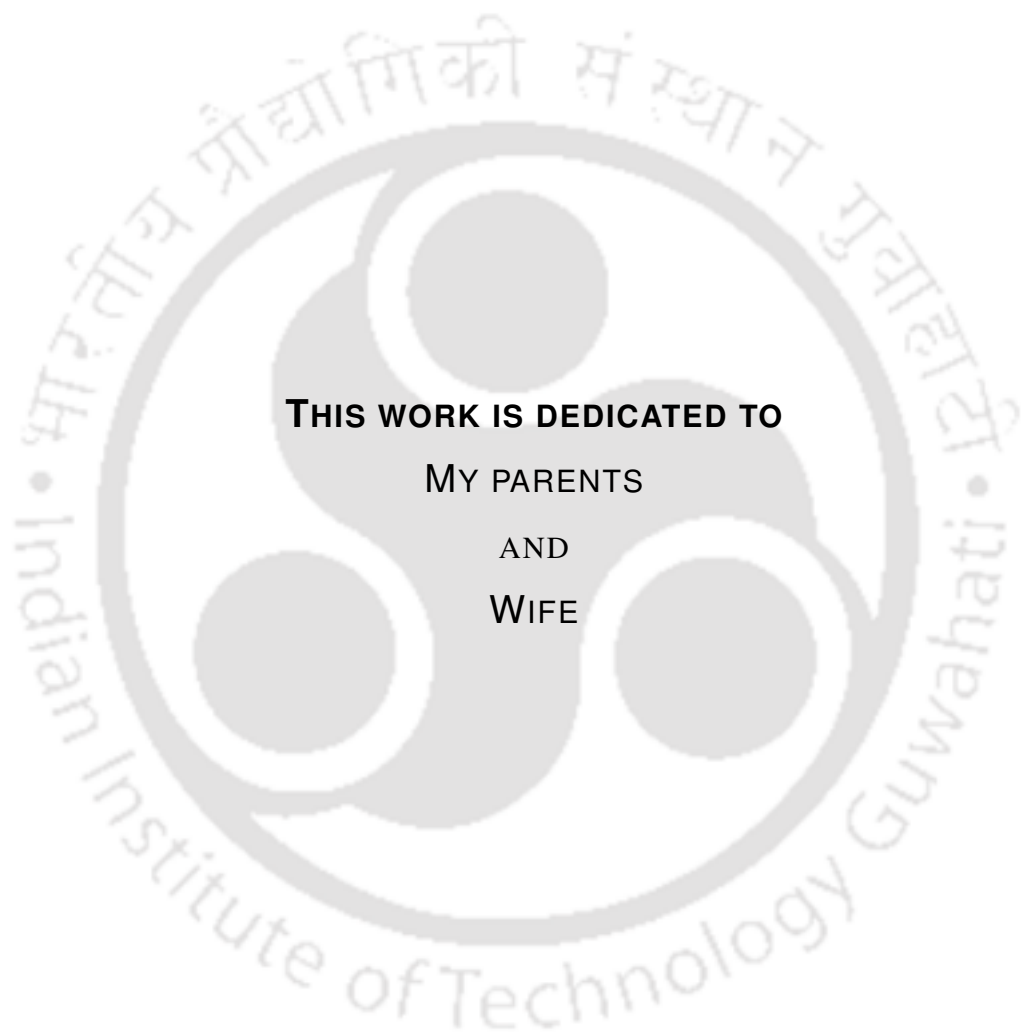
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Certificate

This is to certify that the thesis entitled “**Cooperative Relaying with Multi-Antenna System in Fading Channel**”, submitted by Himanshu Katiyar, a research scholar in the *Department of Electronics and Electrical Engineering*, *Indian Institute of Technology Guwahati*, for the award of the degree of **Doctor of Philosophy**, is a record of an original research work carried out by him under my supervision and guidance. The thesis has fulfilled all requirements as per the regulations of the Institute and in my opinion has reached the standard needed for submission. The results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

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THIS WORK IS DEDICATED TO

MY PARENTS

AND

WIFE

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(Himanshu Katiyar)

Abstract

In this thesis, performance of cooperative relaying with multi-antenna system in Rayleigh/Nakagami- m fading channels has been investigated. The relay is assumed to operate in adaptive decode and forward mode and perform threshold based decoding. Installation of multiple receiving antennas on infrastructure based fixed relay is feasible thereby increasing the probability of relay participation and hence diversity order may be increased for systems which contain such relays. Such systems in different configurations have been analyzed in various path-loss conditions, severity of fading, relay placement at different locations and antennas installed on it. It has been found that for some locations of relay placement, performance of system depends only marginally on the number of antennas installed on relay and combining schemes at relay and destination. System performance can be improved significantly by appropriately positioning the relay. For such positioning, system performance depends to a considerable extent on number of antennas on the relay and the combining schemes at relay and destination. Performance of a system in which two cooperative single antenna user nodes communicate with multi-antenna destination has been analyzed and compared with the performance of a conventional single input multiple output (SIMO) system. System performance has been analyzed in various path-loss conditions, severity of fading and different number of antennas installed on destination. At higher path-loss condition, communication through intermediate relay node has been found to be superior to SIMO system because relay intermediately boost the signal. In such scenario, performance of cooperative relay network is equivalent or may even outperform SIMO system of same diversity order. Due to half duplex nature of relay operation, spectral efficiency suffers with the increase in number of relays. Opportunistic relaying with multiple relays addresses this issue and the same has been studied in this thesis. However, in such system model, a lot of control signal exchange may be required if channel is rapidly changing which reduces the actual throughput. Cooperative relay system in which signals received from all potential relays are coherently combined at the destination has also been studied. In this case, less number of relay cooperation is better at lower SNR because most of time relay will not decode the message and unnecessary wastage of spectrum efficiency will take place. At higher SNR, more number of relay assisted transmission is superior because probability of relay participation increases. The investigations reported in this thesis are expected to be useful in design of cooperative relaying schemes with multi-antenna systems.

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Nomenclature

<i>AWGN</i>	Additive White Gaussian Noise
<i>BER</i>	Bit Error Rate
<i>CDF</i>	Cumulative Distribution Function
<i>CSI</i>	Channel State Information
<i>MGF</i>	Moment Generating Function
<i>MIMO</i>	Multiple Input Multiple Output
<i>M – PSK</i>	Multiple Phase-Shift-Keying
<i>MRC</i>	Maximum Ratio Combining
<i>PDF</i>	Probability Density Function
<i>RV</i>	Random Variable
<i>SC</i>	Selection Combining
<i>SER</i>	Symbol Error Rate
<i>SIMO</i>	Single Input Multiple Output
<i>SNR</i>	Signal to Noise Ratio

Mathematical Notations

s	Source
r	Relay
d	Destination
srd	Source→Relay→Destination Link
λ_{ij}	Inverse of transmitted SNR from node i
ψ	Path-loss exponent
n	Number of antenna elements
m_{ij}	Severity of fading parameter between node i and j
ρ	Exponential power correlation coefficient
P_e	Average error probability
$I_\nu(\cdot)$	ν^{th} order modified Bessel functions of the first kind
${}_2F_1(\cdot, \cdot; \cdot; \cdot)$	Gaussian hypergeometric function
$\Gamma(\cdot, \cdot)$	Upper incomplete gamma function
$\Gamma(\cdot)$	Gamma function
$\binom{a}{b}$	$\frac{a!}{b!(a-b)!}$

List of Publications

Publications in Journals:

- Himanshu Katiyar and R. Bhattacharjee, "Outage Performance of Multi-antenna Relay Cooperation in Absence of Direct Link," *IEEE Communications Letters*, vol. 15, pp. 398-400, no. 4, Apr. 2011.
- Himanshu Katiyar and R. Bhattacharjee, "Performance of Two-Hop Regenerative Relay Network under Correlated Nakagami- m Fading at Multi-antenna Relay," *IEEE Communications Letters*, vol. 13, pp. 820-822, no. 10, Nov. 2009.
- Himanshu Katiyar and R. Bhattacharjee, "Outage Performance of Two-hop Multi-antenna Cooperative relaying in Rayleigh Fading Channel," *IET Electronics Letters*, vol. 45, no. 17, pp. 881-883, Aug. 2009.
- Himanshu Katiyar and R. Bhattacharjee, "Average Capacity and SNR analysis of Multi-antenna Regenerative Cooperative Relay in Rayleigh Fading Channel," Accepted for publication in *IET Communications*.
- Himanshu Katiyar and R. Bhattacharjee, "Performance of MRC combining Multi-antenna Cooperative Relay network," *Elsevier's Int. J. Electron. Commun. (AEUe)* vol. 64, issue 10, pp. 988-991, Oct. 2010.
- Himanshu Katiyar and R. Bhattacharjee, "On the Performance of Decode-and-Forward Relaying with Multi-Antenna Destination," *Elsevier's Int. J. Electron. Commun. (AEUe) (in press)*, doi:10.1016/j.aeue.2011.04.007.
- Himanshu Katiyar and R. Bhattacharjee, "Power Allocation Strategies for Non-Regenerative Relay Network in Nakagami- m Fading Channel," *IETE Journal of Research*, vol. 55, issue 5, pp. 205-211, Sep-Oct 2009.

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- Himanshu Katiyar and R. Bhattacharjee, “Outage Performance of Dual-hop Opportunistic Relaying Compared to a Single-hop SIMO under Rayleigh Fading,” In Proceeding, *NCC 2010*, IIT Madras, Chennai, India, Jan. 29-31, 2010.
- Himanshu Katiyar, R. Jana and R. Bhattacharjee, “Performance Analysis of Two-Hop Regenerative Relay Network with Generalized Selection Combining at Multi-antenna Relay,” In Proceeding, *IEEE INDICON 2010*, Jadavpur University, Kolkata, India, Dec. 17-19, 2010.
- Himanshu Katiyar and R. Bhattacharjee, “Average Error Rate of Multi-antenna Decode and Forward Cooperative Relay Network,” In Proceeding, *IEEE INDICON 2009*, DAIICT Ahmedabad, India, Dec. 18-20, 2009.
- Himanshu Katiyar and R. Bhattacharjee, “Performance of Two-hop Decode-Forward Multi-antenna Cooperative relaying in Nakagami- n Fading Channel,” In Proceeding, *IEEE INDICON 2009*, DAIICT Ahmedabad, India, Dec. 18-20, 2009.
- Himanshu Katiyar and R. Bhattacharjee, “*BER* Performance of Regenerative Multi-antenna Cooperative Relay network in Rayleigh Fading Channel,” In Proceeding, *UKIWCWS 2009*, IIT Delhi, India, Dec. 11-12, 2009.
- Himanshu Katiyar and R. Bhattacharjee, “Performance of Regenerative Relay Network Operating in Uplink of Multi-Antenna Base Station under Rayleigh Fading Channel,” In Proceeding, *IEEE TENCON 2009*, Singapore, Nov. 23-26, 2009.
- Himanshu Katiyar and R. Bhattacharjee, “Performance of Regenerative Relaying at Uplink of Multi-Antenna Access Point in Nakagami- m Fading,” In Proceeding, *NCC 2009*, IIT Guwahati, India, Jan. 16-18, 2009.
- Himanshu Katiyar and R. Bhattacharjee, “Adaptive Power Allocation for Repetition Based Cooperative Relay in Nakagami- m Fading Channel,” In Proceeding, *IEEE TENCON 2008*, Hyderabad, Nov. 19-21, 2008.

Chapter 1

Introduction

The field of high data rate, spectrally efficient, and reliable wireless communications is currently receiving much attention. High data rate wireless communication services are to deal with the problems of power and bandwidth restriction and operate over a harsh multi-path fading channel. It was found that multiple-input multiple-output (MIMO) systems, whereby multiple antennas are employed at both the transmitter and receiver, offer large gain in capacity [Gol05]. For the last two decades, researchers are working on various aspects of MIMO systems. From the implementation point of view, there are still difficulties in accommodating multiple antennas in many types of wireless terminals and therefore the benefits promised by MIMO are yet to be fully exploited. A new technique called cooperative relaying [NHH04], in which spatially distributed nodes cooperate to improve the quality of communication between two nodes, is emerging as a topic of increasing interest. Cooperative relaying creates a virtual MIMO system by using the relay as both transmitter as well as receiver. The message received at the destination through direct path is buffered and subsequently combined with the signal received through relay path. Diversity gain thus can be obtained, even though the destination is a single antenna terminal. Such technology has potential for applications in sensor network, ad-hoc network and cellular network. In high path-loss scenarios, which occur in dense urban conditions, relay based communication have been found to perform better than direct transmission because it intermediately boost the signal strength and provide protection against multi-path fading [LK08]. The idea of cooperative relaying is different from the traditional relaying and other techniques (such as fixed mobile coverage, in-building solutions, repetition of transmission in code division multiple access (CDMA) by multiple transmitters etc.) used for high path-loss conditions. Cooperative relaying relies on exploiting the broadcast nature of wireless channels through user terminal/infrastructure relay cooperation and it tries to increase the diversity at the destination node. It is a well known fact that under fading conditions, the bit/symbol error rate can

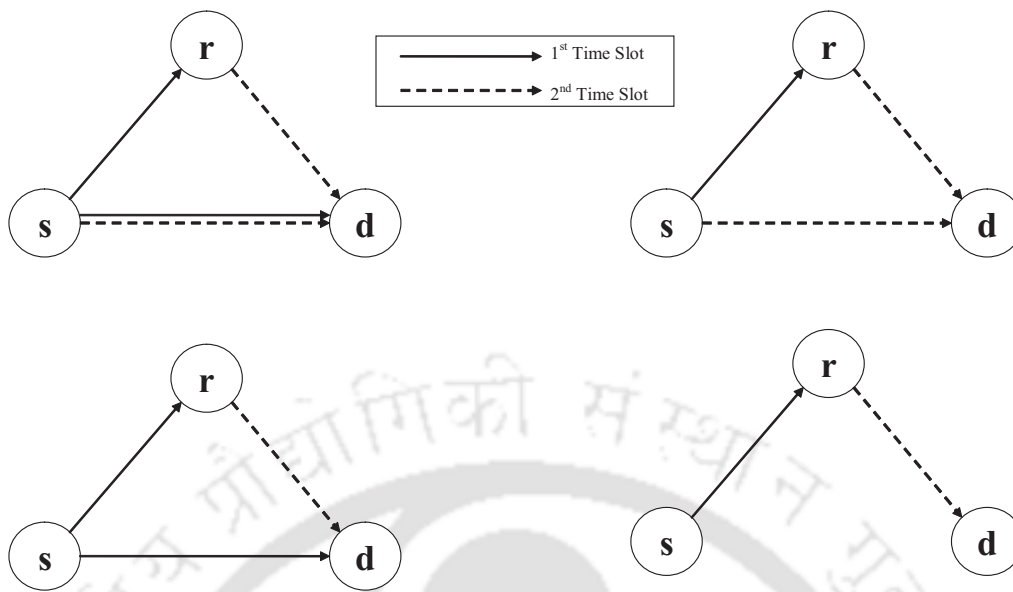


Figure 1.1: Two hop and three terminals cooperative relay network in different modes of operation [NBK04].

be improved considerably by increasing the diversity gain as compared to boosting of received signal to noise ratio (SNR). In a network environment cooperative relaying can provide extension of range and better coverage in shadow zones. New type of spatial diversity achieved by mobile terminals have been proposed in [SEA03a] and implementation issues have been discuss in [SEA03b]. Cooperative relay network have wide scope of application in cognitive radio networks, where efficient utilization of the radio spectrum is achieved by distributed radio sensing [ZBL09], [SGBNS07]. Fig. 1.1 shows the four different time slot based approaches for the cooperation between source (s), relay (r) and destination (d).

1.1 Previous Work

Cooperative relaying is a effective technique to combat multipath fading, improve system capacity and enhance the coverage. This section provides a literature survey on the various aspects of cooperative relaying. Initially capacity analysis of Gaussian relay channel was comprehensively studied in [CG79]. For network scenario capacity has been analyzed in [GK00]. Coding strategies that exploit node cooperation has been developed in [KGG05] for relay networks. Parallel relaying in ad hoc

networks with space-time modulation is presented in [HCM]. In [HZF05], various relaying strategies for wireless networks have been studied. End-to-end error and outage performance of non-regenerative relay network have been presented in [HA03a]. Here, all nodes are equipped with single antenna which operates in Nakagami- m fading channel. Approximate error rate and outage have been analyzed in [IA07b] for Nakagami- m fading channel with the help of numerical evaluation technique. Outage probability of multi-hop amplify and forward relay systems have been analyzed in [CK10]. In [IA07a], closed form expressions of average bit error rate, amount of fading and outage probability have been derived for Rayleigh-fading channel, when relay works in non-regenerative mode and destination performs equal gain combining. The moments-generating function, probability density function and cumulative distribution function of an arbitrary cascaded Nakagami distributed channel are derived in closed form in [KSM07]. In [KTM⁺05] and [KTM06], closed-form expressions are derived for the moment generating function, the probability density function, and the cumulative distribution function of the product of rational powers of statistically independent Gamma RVs. Here outage probability and the average bit-error probability for phase and frequency-modulated signals are also studied. Exact symbol error probability expression for spatially distributed and arbitrary number of amplifying relays in a Rayleigh-fading environment has been derived in [AK04]. In [RCG05] and [RCG04], general expression of symbol error rate has been derived for arbitrary number of cooperating branches, arbitrary number of cooperating hops per branch, and various channel fading models. In [ZAL06], authors derive expression of symbol error rate when selected relays with high contribution are allowed to participate in communication. An amplify-and-forward relay network have been studied in [KK08a], where a source communicates with the user having best channel conditions through an intermediate relay that caters to multiple users. Probability density function and the cumulative density function of the SNR received at the best user in Rayleigh fading channels are also derived. Spatial reuse of relay time-slot in interference limited channel has been analyzed in [AV08] for amplify and forward cooperative relaying. Performance of non-regenerative cooperative relay system with selection combining at the destination over independent and nonidentical Nakagami- m fading channels has been studied in [TKMS06]. Here, closed form expressions for outage probability, cumulative distribution function and the probability density function of received SNR have been presented. In [HA03b], authors have analyzed the end-to-end outage probability of multi-hop wireless communication systems with non-regenerative relays over Nakagami- m fading channels. Collaboration in shadow-fading and multi-user cooperative diversity is discussed in [EAK02] and [EK01]. Distributed Space-time coding in cooperative diversity system is discussed in [AK03], [ALK06] [AK06] and [ALK03]. In [EGA03],

authors have proposed a novel space-time filtering approach that achieves the optimal tradeoff between diversity advantage and receiver complexity. They have also compared this approach with existing space-time coding approach. Various low complexity protocols which exploit space diversity through wireless relay terminals have been developed in [LTW04]. In [LW03], Laneman et al. have developed and analyzed distributed space-time coded cooperative diversity protocols for improving spectral efficiency. In [BH06], closed form expression for outage probability in dissimilar Rayleigh fading is presented. Approximate analysis of outage probability of selection cooperation for all SNR levels and arbitrary channel distributions is given in [BA07]. Outage and diversity multiplexing tradeoff have been analyzed in [LK10] for bidirectional communication protocols based on decode and forward Relaying. In [SSA06], outage behavior of cooperative relay network in Nakagami- m fading channel has been discussed and closed form expression of outage probability for Rayleigh fading channel has been established. Error performance has been analyzed in [AY06], when cooperative relay system operates in asymmetric channels. In [CV08], outage performance of MIMO relay channel has been investigated, when source and relay use same orthogonal space time block code. Probability of SNR gain achieved by dual-hop relay over the single-hop SISO in Rayleigh fading channel have been discussed in [LK08]. Average bit error rate for multi-hop Decode-and-Forward relay network in fading channel has been investigated in [MMJV⁺10]. For opportunistic relay network, closed form expression of outage probability and average capacity have been derived in [IA10], when relays operate in adaptive decode and forward mode. In [QJC⁺04], power allocation schemes for regenerative mode of operation for both conventional and cooperative relaying have been presented. Various power allocation schemes for regenerative and non-regenerative relaying in cellular scenario have been investigated in [JCYP04]. In [KA10], authors investigate the problems of optimal relay assignment and power allocation at the relays for maximizing the sum rate of relay aided cellular network. In [SMY10], closed-form expressions for the overall throughput and energy consumption for opportunistic relay network have been derived. Selection cooperation in network scenario has been discussed in [BA08], where multiple sources transmit their message and support each other to forward signals to their respective destinations. End-to-end error performance of selection cooperation has been discussed in [AFYP]. Closed form expressions of outage probability and channel capacity with tight approximation over a sufficiently wide range of SNR is presented in [AFY⁺09]. In [SS08], authors analyzed the various cooperative protocol for decode and forward relay network. Error performance of distributed space time coding for cooperative relay network has been analyzed in [MTH04]. A closed-form expressions for outage probability of single antenna relay network is analyzed in [RWWH09], where some of the practical issues like fre-

quency reuse and signal leakage between the relay transmitter and receiver has also been addressed. Installation of multiple receiving antennas on relay (Infrastructure based fixed relay) increases the probability of relay participation, hence diversity order may increased. Such relay are in close proximity of power supply, so they donot have limited energy constraints like mobile relays. However, they may have limited power constraint due to power amplifier design issues. In [TK08], optimum power allocation for multi-antenna relay network at the expense of increased computational complexity have been presented. Expression of approximate bit error rate for such system has been established in [AY07].

1.2 Diversity Combining Strategies

In a wireless environment, the signals get faded due to the presence of multi-path. Spatial diversity is as effective method of combating multi-path. Diversify is achieved through use of arrays or cooperative relaying. The multiple copies of signals received through different diversity paths are appropriately combined at the receiver. Hence, a brief description of the combining strategies have been presented here:

- **Selection combining (SC):**In selection combining, diversity branch with the highest SNR of individual component is choosen at receiver and co-phasing is not required.
- **Switch and stay combining (SSC):** Switch and stay combining is a simplified form of selection combining. In this scheme, the receiver selects another branch only if SNR of the current branch falls below the required threshold.
- **Maximum-ratio combining:** This is the most complex scheme in which all available paths are optimally combined at the receiver. This scheme requires scaling and co-phasing of individual paths. For MRC, SNR of individual paths may be below the desired threshold but the combined SNR may be above the threshold. A variant of MRC is called EGC where the weights of individual paths have equal magnitude.
- **Generalized selection combining:** In this scheme, receiver optimally combines only those paths whose channel SNR are above a particular threshold. Performance and complexity of this combining scheme is in between of selection combining and maximum-ratio combining.



Figure 1.2: Serial relay transmission topology.

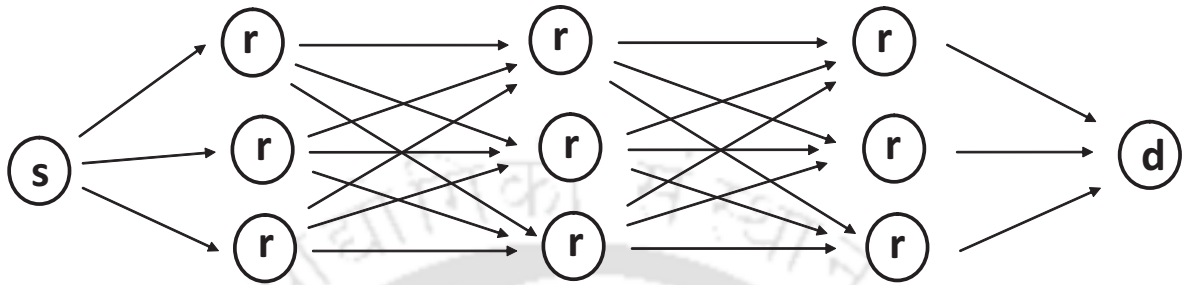


Figure 1.3: Parallel relay transmission topology.

1.3 Relaying Protocols

Cooperative communication exploits the broadcast nature of the wireless medium and allows terminals to jointly transmit information through relaying. Such intermediate relay terminals may process the signals as follows:

- **Fixed Protocols:** Such protocols can be further classified as
 - **Amplify and Forward (AF):** This is an analog scheme, which works in non-regenerative mode. In this scheme, a relay receives the signal, amplifies it and then retransmits it in the next phase. Operation in this mode puts less processing burden on the relay, so it causes much smaller delay, and hence is often preferred for delay sensitive traffic such as voice and live video. Noise amplification is a major issue for such schemes.
 - **Decode and Forward (DF):** This is a digital scheme, which works in regenerative mode. In this scheme relay receive the signal, decode it and after encoding retransmit it in the next time-slot. Noise does not prorogate to next stage but error may propagate. Processing time is high, so it is not suitable for delay sensitive traffic.
 - **Decode and Re-encode (DR):** In this protocol, codeword used to encode the message at relay may different from the source. Therefore, additional redundancy can be achieved at destination since it receives two copies of the same message encoded with different code-words.

- **Adaptive Protocols:** Fixed protocols suffers from noise/error propagation, which limits the performance of relay based system. Cooperative relay system can adapt their transmission format according to channel condition between source and relay. In the time-slot reserved for relay, relay node can process the signal received from source if received SNR at relay is more than particular value else the relay remains silent. For the case when relay remains silent in its allocated time-slot, source may retransmit the signal to destination or can choose more powerful codes for combat fading.
- **Incremental Protocols:** In fixed and adaptive protocol, spectrum efficiency of the system suffers because all the time source/relay has to repeat the message. Incremental protocols can dramatically improve the spectrum efficiency of relay based system. For incorporating incremental protocol, source requires limited feedback from destination. This can be done by broadcasting single bit information, which indicates the success or failure of direct transmission. If destination gives positive feedback, channel is suitable for direct transmission. The relay does not participates and spectrum efficiency of such mode becomes R . For the case when channel is not suitable for direct transmission, destination can not decode the message transmitted from source, it broadcasts a negative feedback which ensures the participation of relay. Now system spectrum efficiency reduced to $R/2$ and destination try to decode the message by combining the signal received via direct path and relay path.

1.4 Relay Transmission Topology

- **Serial Relay Transmission:** Serial relay transmission is used for long distance communication and range-extension in shadowy region. It provides power gain. In this topology signal propagates from one relay to another relay and the channels of neighboring hop are orthogonal to avoid any interference. Fig. 1.2 shows the serial relay transmission topology.
- **Parallel Relay Transmission:** The serial relay transmission suffers from multi-path fading. For outdoors and non-line of sight communication, signal wavelength may be large and installation of multiple antennas are not possible. To increase the robustness against multi-path fading, parallel relay transmission can be used. In this topology, signal propagate through multiple relay path in same hop and destination combine the signals received with the help of various combining schemes. It provides power gain and diversity gain simultaneously. Fig. 1.3 shows the parallel

relay transmission topology.

1.5 Applications

This section highlights some of the areas where the cooperative relaying strategies can be applied.

- **Virtual antenna array:** The field of high-data-rate, spectrally efficient and reliable wireless communication is currently receiving much attention. It is well known that the use of multiple-input multiple-output (MIMO) antennas, improves the diversity gain of wireless systems. However, multi-antenna techniques is not attractive for tiny wireless nodes due to limited hardware and signal processing capability. Diversity can be achieved through user cooperation, whereby mobile users share their physical resources to create a virtual array, which removes the burden of multiple antennas on wireless terminals.
- **Wireless Ad-hoc network:** Ad hoc network is an autonomous and self organizing network without any centralized controller or pre-established infrastructure. In this network randomly distributed nodes forms a temporary functional network and support seamless leaving or joining of nodes. Such network has been successfully deployed for military communication and have lot of potential for civilian applications include commercial and educational use, disaster management, road vehicle network etc.
- **Wireless sensor network:** Cooperative relaying can be used to reduced the energy consumption in sensor nodes, hence lifetime of sensor network increases. Due to nature of wireless medium, communication through weaker channels requires huge energy as compared to relatively stronger channels. Careful incorporation of relay cooperation into routing process can selects better communication links and precious battery power can be saved.
- **Cooperative sensing for cognitive radio:** In cognitive radio system, unlicensed secondary users can use the resources which is licensed for primary users. When primary users want to use their licensed resources, secondary users has to vacant these resources. Hence secondary users has to constantly sense the channel for detecting the presence of primary user. It is very challenging to sense the activity of spatially distributed primary users in wireless channel. Spatially distributed nodes can improve the channel sensing reliability by sharing the information and reduce the probability of false alarming [PL07].

1.6 Motivation of the Present Work

Mobile and wireless communication have seen tremendous growth in the recent years. Although as per the present scenario voice oriented services are dominant, next generation systems would mainly provide data-oriented services and applications [SD08]. Many future services will require to provide higher data rate with lower error probability, so more efficient radio access technologies will be needed. MIMO technique can be used to provide such high data rates, but it is not always possible to install multiple antennas on wireless nodes. Relay cooperation is emerging as a topic of interest among research groups and industrial players. For example, a project named WINNER (wireless world initiative new radio) is in operation for enhancing the performance of mobile communication systems with the help of relay based deployment. As stated earlier, cooperative relaying is a transmission technique, where multiple relay terminals, forward the copies of transmitted information to the destination so that each copy experiences different channel fading, thereby increasing the diversity order. In fixed transmission protocol, relay always process the received signals. Relay can amplify and forward (AF) the received signal or decodes and forwards (DF) the received signal. In AF mode, noise propagation is a major issue. Relay in DF mode does not propagate noise to next stage but it suffers from the error propagation, hence limits the performance of system. Adaptive DF transmission protocol performs threshold based decoding at relay, which avoids the error propagation to next stage. Relay operating in this mode remain silent if received SNR is below a particular threshold. In a dense urban environment, cooperative communication is possible with the help of tiny wireless single antenna user terminals. Cooperation in this form is known as user cooperation, here user terminals not only transmit their own data but also relay other users data by sharing its battery power and bandwidth. Single antenna relay node can not actively participate if channel condition from source is not good, so diversity order of the system reduces. Installation of multiple receiving antennas on relay is possible in case of infrastructure based fixed relay, which increases the probability of relay participation. Such type of relays are in close proximity of power, so they do not have limitations in terms of operational life time as well as signal processing capabilities. Cooperative communication is an emerging concept and there are several issues which require investigation and proper understanding. In this thesis work, we are exploring the communication model supported by both infrastructure based multi-antenna fixed relay as well as single antenna tiny wireless relay. Mode of operation has been considered to be adaptive DF.

1.7 Thesis Contributions

In this thesis work, we investigate the performance of relay based systems where either the relay or the destination is equipped with multiple receiving antennas. The different configurations of cooperative relay networks which have been investigated in this thesis are shown in Fig. 1.4(a)-1.4(f). It is assumed that the relay operate in adaptive DF mode and the destination receives the signals from source/relay in orthogonal time-slots.

For the two hop cooperative relaying shown in Fig. 1.4(a), the following analysis have been carried out.

- Considering Rayleigh fading channel, closed form expressions of outage probability, average error rate, end-to-end average received SNR and average capacity have been derived for all four combinations i.e. MRC at relay and MRC at destination, MRC at relay and SC at destination, SC at relay and MRC at destination, SC at relay and SC at destination.
- Closed form expressions of outage probability and average error rate for different operating modes has been derived. Here the relay performs MRC combining of signals in Rayleigh fading channel. Performance of various modes are also compared.
- Considering Nakagami- m fading channel with integer value of m , closed form expressions of outage probability, average error rate and throughput have been derived for all four combinations i.e. MRC at relay and MRC at destination, MRC at relay and SC at destination, SC at relay and MRC at destination, SC at relay and SC at destination.
- Closed form expressions of outage probability and average error rate has also been derived for MRC combining at relay and destination for exponentially correlated Nakagami- m fading at the relay and uncorrelated Nakagami- m fading at the destination. Analytical expressions have been derived for integral values of m .

Performance of this system has been analyzed in different path-loss conditions, severity of fading, correlation among antenna elements, location of relay with respect to the source and number of antennas installed on the relay. It has been found that for some specific relay locations, the system performance depends only marginally on the number of antennas installed on relay and combining schemes at relay and destination. Relay placement at a particular location gives best performance. In the vicinity of such

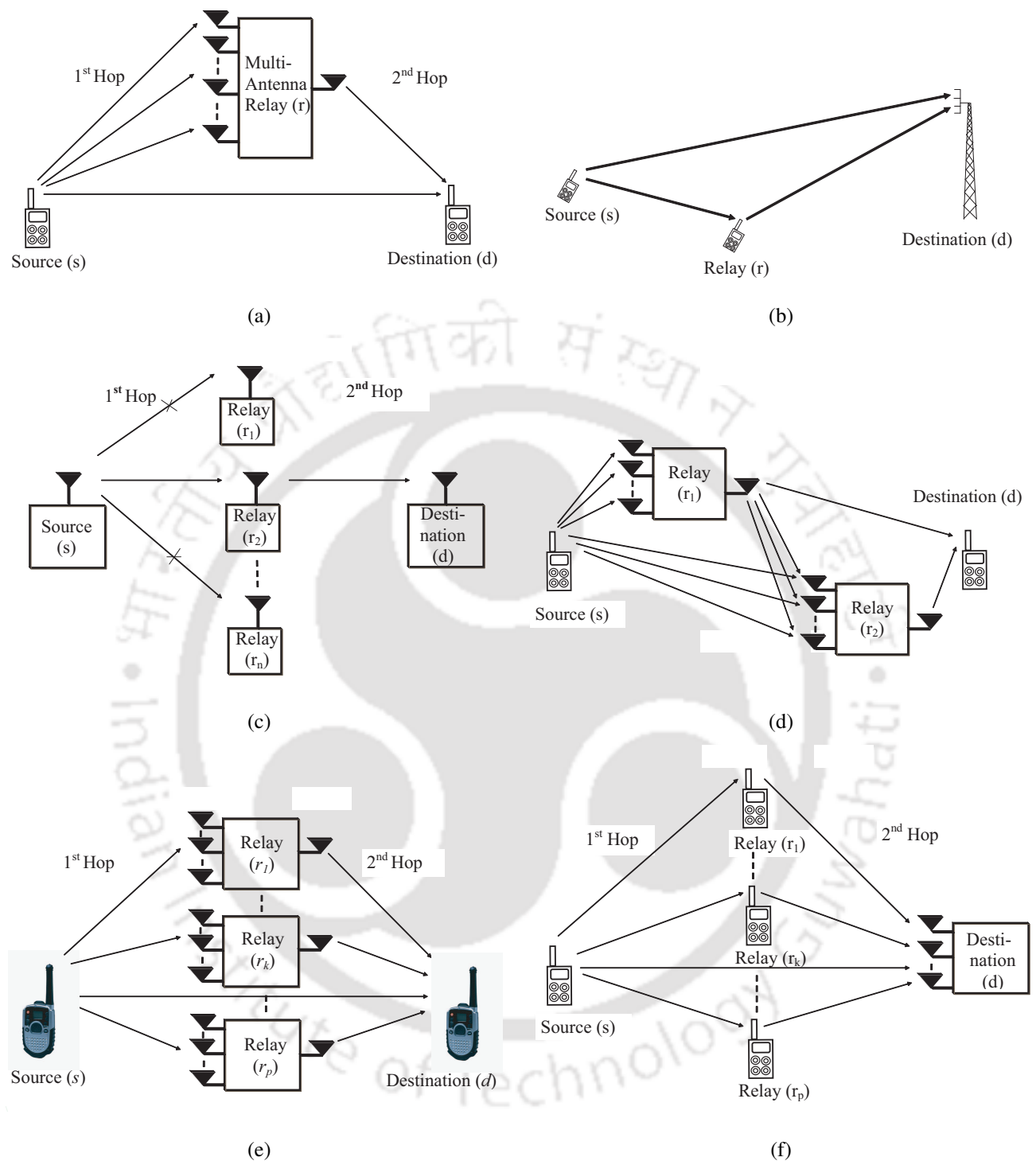


Figure 1.4: Cooperative relay network with various configurations (a) two-hop cooperative relaying with multi-antenna relay system, (b) two-hop cooperative relay communicating with multi-antenna base station, (c) single antenna dual-hop opportunistic relaying in absence of direct path, (d) multi-antenna cooperative relaying with the help of two relay in absence of direct path, (e) two-hop system in which communication between single antenna source and destination is supported by multi-antenna relays, (f) two-hop system in which single antenna source, relays communicating with multi-antenna destination,

location, system performance highly depends on number of antennas on relay and combining schemes at relay and destination.

In the system model shown in Fig. 1.4(b), single antenna source and relay communicate with multi-antenna destination. For such a system, following analysis have been performed.

- Considering Nakagami- m fading channel with integer value of m , closed form expressions of outage probability, average error rate, end-to-end average received SNR and average capacity have been derived. Here, severity of fading parameter m at relay and destination are considered to be non-identical.
- Considering Nakagami- m fading channel with non-integer value of m , closed form expressions of outage probability, average error rate and end-to-end average received SNR have been derived. Here, severity of fading parameter m at all nodes are considered to be identical.

System performance has been analyzed in various path-loss condition, various severity of fading and different number of antennas installed on destination. Performance of such relay based system has been compared with conventional SIMO system. It is found that, cooperative relaying can out perform conventional SIMO system depending on path-loss conditions, number of antenna elements on destination and SNR conditions. For same performance level, in some specific conditions, cooperative relaying can be used to reduce the burden of large antenna array on base station.

Communication between source and destination supported by multiple relays have also been studied. The scenario is shown in Fig. 1.4(c). All the nodes are equipped with single antennas. For such a network, closed form expression of outage probability has been derived for dual-hop opportunistic relaying in Rayleigh fading channel. The outage performance of such system has been analyzed in various path-loss conditions and relay placement at various locations. Performance of such system has been compared with single-hop SIMO.

Cooperative relaying with the help of two multi-antenna relays in absence of direct path has been studied. For the system model shown in Fig. 1.4(d), considering Rayleigh fading channel, closed form expression of outage probability has been derived.

In the two-hop cooperative relaying shown in Fig. 1.4(e), communication between single antenna source and destination is supported by multi-antenna relays. Destination selects one of the best signal received via direct path and various relay path. For the system under consideration, closed-form expression of outage probability has been derived, for dual-hop selection combining when the relays operate in Rayleigh fading channel.

Closed-form expressions of outage probability, average error rate, end-to-end average received SNR and average capacity have been derived for the system model shown in Fig. 1.4(f), where the communication between single antenna source and multi-antenna destination is supported by multiple single-antenna relays. Destination is assumed to perform MRC combining of signals received from direct path and different relay paths in symmetric Rayleigh fading channel. Effect of number of supporting relays and antennas installed on destination in various path-loss conditions is also analyzed. In case of lower SNR condition, support of large number of relays degrades system performance because most of relays could not decode the message. In this case, majority of relays cannot actively participate and spectrum efficiency suffers. However, in higher SNR condition, participation of relay terminals increases hence system performance improves.

1.8 Thesis Organization

The thesis is organized in 6 chapters. Chapter 1 gives an overview of relay based communication systems, related issues, previous work and problem definition. Chapter 2 and chapter 3 analyze multi-antenna relay based system in Rayleigh and Nakagami- m fading channels, respectively. Here, relay and destination may perform either maximum ratio combining or selection combining of the signals. Comparative performance of all four possible combinations has been analyzed for different relay locations, number of antennas on the relay, transmission rate, correlation among antenna elements and fading conditions. In chapter 4, a system model in which communication between source and multi-antenna destination is supported by single antenna regenerative relay has been analyzed in Nakagami- m fading channel. Comparative performance of such system with conventional SIMO system, in various severity of fading, different path-loss conditions and different number of antenna elements on destination, have been studied. Chapter 5 analyzes the performance of a system in which communication between source and relay is supported by multiple relay in Rayleigh fading channel. Performance of a system in which selection combining multi-antenna relays communicating with single antenna source and destination has also been discussed. Here, destination performs selection combining of the signal received through direct path and various relay paths. A system in which single antenna source and relays communicate with multi-antenna destination has been considered next. Multi-antenna destination coherently combine the signal through direct and through various relay path. Effect of number of supporting relay and antennas installed on destination in various path-loss conditions is also analyzed. Chapter 6 summarizes the main results and also presents the future research directions.

Chapter 2

Performance of Multi-antenna Relay Network in Rayleigh Fading Channel

Spatial diversity has been widely exploited in wireless systems to combat multi-path fading. Cooperative relaying, is a technique in which, multiple nodes share their antennas and create virtual antenna array [LTW04]. Such scheme is able to introduce diversity into the system with the help of supporting relay nodes, which re-transmit the information to the destination after some delay. Spectrum efficiency of such system suffers due to half-duplex operation of wireless relay [CKK10]. In [LW03], Laneman developed and analyzed distributed space-time coded cooperative diversity protocols for improving spectral efficiency. In [BH06], closed form expression for outage probability in dissimilar Rayleigh fading has been presented. Approximate analysis of outage probability of selection cooperation for all SNR levels and arbitrary channel distributions has been given in [BA07]. Selection cooperation in network scenario has been discussed in [BA08], where multiple sources transmit their messages and support each other to forward signals to their respective destinations. Recently, use of multi-antenna relay nodes (infrastructure based fixed relay) in a cooperative network has been proposed and a probability density function (PDF) based approach for calculating approximate bit error rate of infrastructure based fixed relay with multiple receiving antennas and single transmit antenna has been presented in [AY07]. This paper considers the channels between source - relay and relay - destination to be symmetric Nakagami- m fading type. Relays are assumed to operate in regenerative mode and perform maximum ratio combining or selection combining of received signal before decoding. After decoding, relays forward the signal and destination perform maximum ratio combining of signals received via direct path and relay path.

In this chapter, we analyze a three node system, which is the basic building block of cooperative

relay network. Source and destination are tiny wireless terminals and equipped with single antenna. The relay is an infrastructure based fixed node which operates in adaptive decode and forward mode. Single antenna relay node can not actively participate if channel condition from source to relay is not good, so diversity order of the system gets reduced. Installation of multiple receiving antennas are possible in infrastructure based relay, which increases the probability of relay participation. In order to keep the signal processing operations low at the destination, single transmitting antenna has been used at the relay. In section 2.1, closed form expressions of outage probability, average error probability, average received SNR and average capacity have been derived, for a system model shown in Fig. 2.1. In type-1 operation, source transmits signal to relay and destination in the first time slot. Relay receives the signal through multiple links and if the SNR is above a specified threshold it decodes and re-transmits the signal to the destination in the second time slot. For obtaining analytical results, an ideal threshold based decoding has been assumed for the success/failure of a transmission from the relay. When the received SNR exceeds a threshold, the message is correctly decoded, otherwise, it has uncorrectable errors [SV06]. Destination can process the two copies of signal received via direct path and via relay path. In section 2.2, analytical expressions of outage probability and average error probability have been derived for the type-2 and type-3 operation. The system model of type-2 operation same as type-1 operation. Only difference is that source always re-transmit the signal in second time slot. Details of such type of operation is given in [NBK04]. In type-3 operation, source only re-transmit the signal in second time slot, if relay is not transmitting. System model for two hop cooperative relay network with type-2 and type-3 operations is shown in Fig. 2.7. Some of the results obtained here for type-2 and type-3 operation are also compared with type-1 operation. Throughout this chapter, channel is assumed to be Rayleigh faded with no direct or line of sight (LOS) component. The signals received at the multiple antennas of the array at the relay are assumed to be independent and identically distributed but the signal received by destination via two different paths are independent and non-identically distributed. Such an assumption is justified because relay antennas are located at in the close proximity of each other, so there is high probability that channel seen by these relay antennas are identical. Destination receives the signals from source and relay, which are located at different places, hence non-identical fading is assumed at destination. Performance of such system, has been evaluated including the effects of relay placement, number of antennas installed on relay node and different path-loss conditions. Some of our works have been reported and published in open literature. In [KB09c] and [KB09a], outage probability and bit error rate of two-hop multi-antenna relay based system is analyzed in Rayleigh fading channel for the case when relay performs SC of signals and destination performs MRC of signals respectively.

Closed form expressions of outage probability and bit error rate for BPSK are derived in [KB10b], for the case when communication between source and destination is supported by multi-antenna relay, and both relay and destination perform MRC of signals in a Rayleigh fading channel. In [KB09b], closed form expressions of bit error rate have been established for two-hop multi-antenna cooperative relay network in Rayleigh fading channel. Here, destination performs selection combining of signals received from source, relay and relay performs selection or MRC of signals.

2.1 Multi-antenna Relay System with type-1 operation

In system model shown in Fig. 2.1, source broadcasts the message to the relay and the destination in the first time slot. Relay receives the signal and either coherently combines the signal from multiple links or selects one of the best links. A relay operating in regenerative mode decodes the message, if SNR is above a particular threshold and re-transmits to the destination in next time slot. Single antenna destination, may coherently combine both copies of received signals or it may select the best received copy. Coherent combination of signal (i.e. MRC) requires regular estimation of exact channel state information (CSI), which increases receiver complexity. Alternately, selection of best link (i.e. SC), requires only SNR measurements, hence reduces receiver complexity and power consumption but this comes at the expense of performance loss since the signal power in all the available links are not fully exploited. Based on the performance/complexity trade-off between MRC and SC, one can choose any one of the combining schemes according to the system requirement. The possible combinations of type-1 operation is shown in Table-2.1. Here, it is assumed that s is only busy for first time-slot and remains silent in second time-slot. Such system model is beneficial for the case when s has limited battery power or fading does not independently changes from first time-slot to second time-slot.

Table 2.1: Representation of combining Schemes at r and d

$r(\downarrow)\backslash d(\rightarrow)$	MRC	SC
MRC	$MRC - MRC$	$MRC - SC$
SC	$SC - MRC$	$SC - SC$

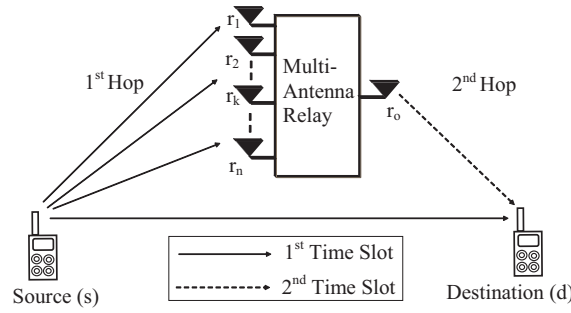


Figure 2.1: Two hop cooperative relay network with type-1 operation.

2.1.1 System Model

The system considered here consists of a multi-antenna relay (r), placed between source (s) and destination (d). Relay node is assumed to be equipped with one transmitting antenna and n receiving antennas¹. Due to half-duplex nature of relay, the source transmits to the relay and destination in first hop (i.e. $s \rightarrow r$ and $s \rightarrow d$). A multi-antenna relay receives signal from the source through multiple links and either coherently combines them or selects the best link. If received signal is above the threshold of the decoder (active mode), the message is assumed to be decoded and re-transmitted to the destination (i.e. $r \rightarrow d$). If this condition is not fulfilled (inactive mode), only direct path is used. Signals received via direct path and via relay path are then either coherently combined or best one of them is selected by destination. In our system model it is assumed that equal power is allocated to s , r , identical noise power at r and d as well as channel parameters are available at the receiver. Fading envelop is Rayleigh distributed so received SNR is exponentially distributed, hence PDF of received SNR between $s \rightarrow d$ or $r \rightarrow d$, can be written as [YA05]

$$f_{\gamma_{ij}}(\gamma) = \lambda_{ij} \exp(-\lambda_{ij}\gamma), \quad (2.1.1)$$

where, $i \in \{s, r_o\}$, $j \in \{d\}$, $\lambda_{ij} = (2l_{ij}/l_{sd})^\psi / \omega$, ψ is path loss exponent, l_{ij} represents distance between node i and j , which is normalized by reference distance $l_{sd}/2$, γ is running variable of received SNR, ω is the SNR at reference point. In this system model independent and identically distributed (i.i.d.) fading between $s \rightarrow r$ (i.e. $\forall \lambda_{sr_k} = \bar{\lambda}_{sr}$) has been assumed. So PDF of received SNR at r can

¹In this chapter, symbol r_o represents transmitting antenna of r and r_k represents the k^{th} receiving antenna of r .

be written as [YA05] and [KK08b, Eq.(6)]

$$f_{\gamma_{sr}}(\gamma) = \begin{cases} \frac{\bar{\lambda}_{sr}^n \gamma^{n-1} \exp(-\bar{\lambda}_{sr}\gamma)}{(n-1)!} & \text{for MRC} \\ \frac{n\bar{\lambda}_{sr} \exp(-\bar{\lambda}_{sr}\gamma)}{[1-\exp(-\bar{\lambda}_{sr}\gamma)]^{1-n}} & \text{for SC.} \end{cases} \quad (2.1.2)$$

Average received SNR at d due to $s \rightarrow d$, $r \rightarrow d$ transmissions will be $\varpi_{sd} (=1/\lambda_{sd})$ & $\varpi_{rd} (=1/\lambda_{rd})$, respectively. Due to $s \rightarrow r$ transmission, average received SNR at r after SC will be $\varpi_{sr}^{SC} \left(= 1/\bar{\lambda}_{sr} \sum_{k=1}^n 1/k \right)$ [KM99, Eq.(8)] and average received SNR at r after MRC will be $\varpi_{sr}^{MRC} (= n/\bar{\lambda}_{sr})$ [KM99, Eq.(9)]. In first hop, if the channel condition between $s \rightarrow r$ link (after coherent addition in case of MRC or selection of best link for SC) is above a given threshold, then relay decodes the message received from the source. In this condition, mutual information (I), transmitted by the source is greater than target data rate R (spectral efficiency) [LW03]:

$$I = \begin{cases} \frac{1}{2} \log_2 \left[1 + \sum_{k=1}^n \gamma_{sr_k} \right] > R & \text{for MRC} \\ \frac{1}{2} \log_2 [1 + \max(\gamma_{sr_k})] > R & \text{for SC} \end{cases} \quad (2.1.3)$$

In equation (2.1.3), logarithm has been multiplied with $1/2$ because such system operates in two time-slots and utilize only $1/2$ part of channel.

Probability of relay in inactive mode

Probability that the relay is in inactive mode is given by²

$$P[I \leq R] = \begin{cases} P \left[\sum_{k=1}^n \gamma_{sr_k} \leq \chi \right] & \text{for MRC} \\ P [\max(\gamma_{sr_k}) \leq \chi] & \text{for SC,} \end{cases} \quad (2.1.4)$$

here $\chi = 2^{2R} - 1$ is the threshold. In our system model we assume a scenario of independent and identically distributed (i.i.d.) fading between $s \rightarrow r$ (i.e. $\forall \lambda_{sr_k} = \bar{\lambda}_{sr}$). So, (2.1.4) can be evaluated with the help of (2.1.2) and [GR07, Eq.(3.381.1)]

$$P[I \leq R] = \begin{cases} \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} & \text{for MRC} \\ [1 - \exp(-\bar{\lambda}_{sr}\chi)]^n & \text{for SC,} \end{cases} \quad (2.1.5)$$

here $\Gamma(\cdot, \cdot)$ is upper incomplete gamma function [GR07, Eq.(8.350.1)]. Probability that relay in active mode

$$P[I > R] = 1 - P[I \leq R]. \quad (2.1.6)$$

²For avoiding the error propagation from the relays, relay decode the message if received instantaneous SNR at relay is above the threshold or the decoded data block always passes the CRC test [AY06].

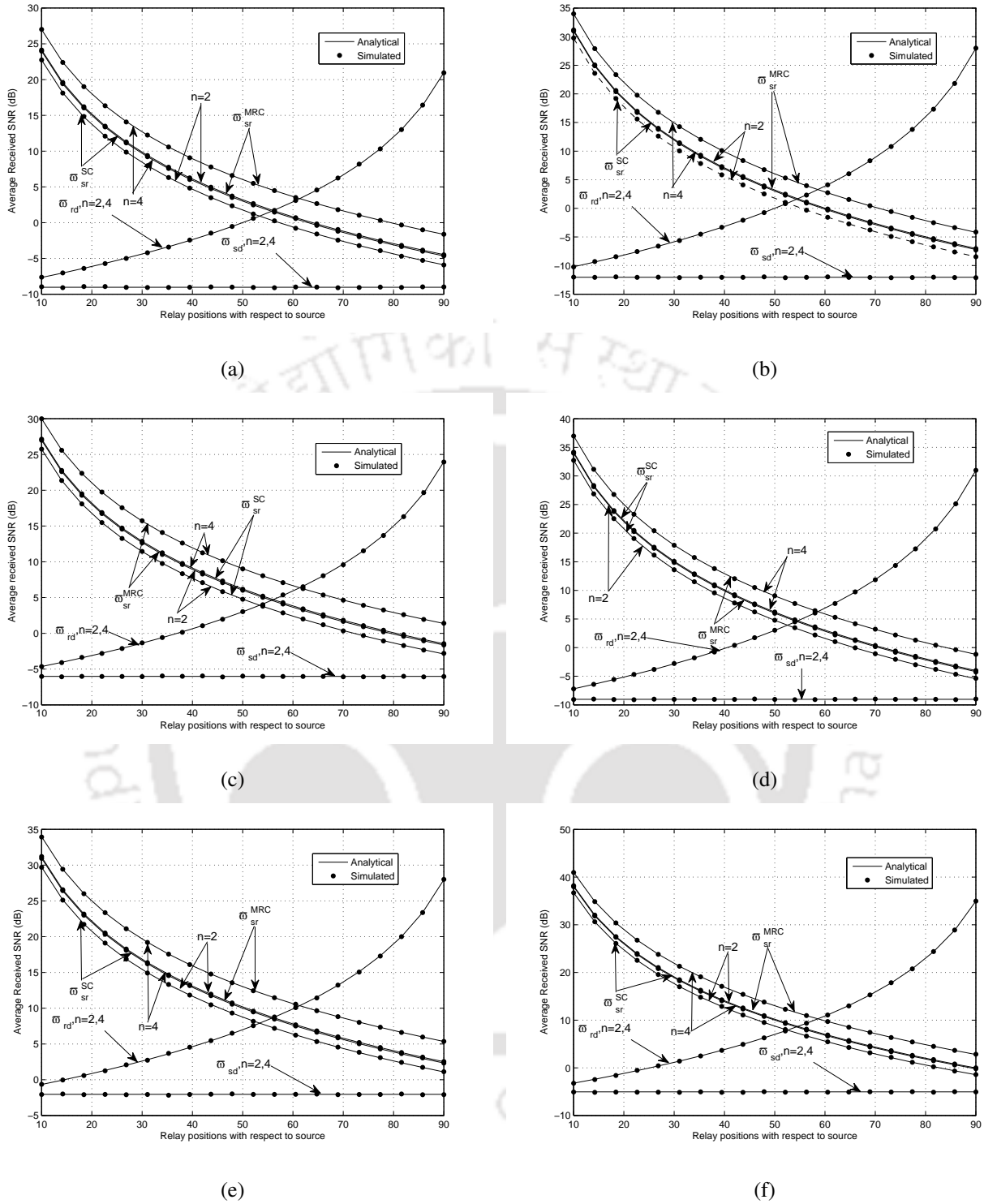


Figure 2.2: Average received SNR of ϖ_{sr}^{MRC} , ϖ_{sr}^{SC} , ϖ_{sd} and ϖ_{rd} for (a) $\psi = 3, \omega = 0dB$, (b) $\psi = 4, \omega = 0dB$, (c) $\psi = 3, \omega = 3dB$, (d) $\psi = 4, \omega = 3dB$, (e) $\psi = 3, \omega = 7dB$, (f) $\psi = 4, \omega = 7dB$, when r placed at various locations between s and d .

PDF of received SNR based on link condition

Let, random variable Θ models the received SNR at d via relay link. So, the conditional PDF of received SNR, when r is not active

where $\delta(\cdot)$ is the dirac delta function. For the case when the relay is active, conditional PDF of received SNR is given as

$$f_{\Theta|I>R}(\theta) = \lambda_{r_{od}} \exp(-\lambda_{r_{od}}\theta). \quad (2.1.8)$$

PDF of received SNR, when d performs MRC

From the theorem on total probability, PDF of received SNR can be written as

$$f_{\Theta}^{srd}(\theta) = f_{\Theta|I\leq R}(\theta) P[I \leq R] + f_{\Theta|I>R}(\theta) P[I > R]. \quad (2.1.9)$$

The MGF³ of $f_{\Theta}^{srd}(\theta)$, through relay link is given by

$$M_{srd}(s) = P[I \leq R] + P[I > R] \frac{\lambda_{r_{od}}}{s + \lambda_{r_{od}}}. \quad (2.1.10)$$

When channels between $s \rightarrow r \rightarrow d$ and $s \rightarrow d$ are independent, MGF of equivalent link is given by

$$M_T(s) = M_{srd}(s)M_{sd}(s), \quad (2.1.11)$$

where, $M_{sd}(s) = \lambda_{sd}/(s + \lambda_{sd})$ is MGF of direct link. From (2.1.11), PDF of total received SNR at d can be calculated, by taking inverse Laplace transform of $M_T(s)$

$$f_{\Theta}^{(1)}(\theta) = P[I \leq R] \lambda_{sd} \exp(-\lambda_{sd}\theta) + P[I > R] \left(\frac{\lambda_{r_{od}}\lambda_{sd}}{\lambda_{r_{od}} - \lambda_{sd}} \right) \{ \exp(-\lambda_{sd}\theta) - \exp(-\lambda_{r_{od}}\theta) \} \quad (2.1.12)$$

PDF of received SNR, when d performs SC

The MGF of $f_{sd}(\gamma)$ (direct link) can be written as

$$M_{sd}(s) = \frac{\lambda_{sd}}{s + \lambda_{sd}}. \quad (2.1.13)$$

From (2.1.13), CDF of received SNR through direct link can be calculated by taking inverse Laplace transform of $M_{sd}(s)/s$

$$F_{\gamma_{sd}}(\gamma) = 1 - \exp(-\lambda_{sd}\gamma), \quad (2.1.14)$$

From (2.1.10), CDF of received SNR through relay link can be calculated by taking inverse Laplace transform of $M_{srd}(s)/s$ i.e.

$$F_{\gamma_{srd}}(\gamma) = P[I \leq R] + P[I > R] [1 - \exp(-\lambda_{r_{od}}\gamma)]. \quad (2.1.15)$$

³MGF = $\int_0^{\infty} f_{\Theta}^{srd}(\theta) \exp(-s\theta) d\theta$

For the case, when channels between $s \rightarrow r \rightarrow d$ and $s \rightarrow d$ are assumed to be independent and d selects the best path, then PDF of total received SNR at d can be written as

$$\begin{aligned} f_{\Theta}^{(2)}(\theta) &= \frac{d}{d\theta} \{F_{\gamma_{sd}}(\theta) \times F_{\gamma_{srd}}(\theta)\} \\ &= P[I \leq R] \lambda_{sd} \exp(-\lambda_{sd}\theta) + P[I > R] \\ &\quad \times [\lambda_{sd} \exp(-\lambda_{sd}\theta) + \lambda_{r_{od}} \exp(-\lambda_{r_{od}}\theta)] \\ &\quad - (\lambda_{sd} + \lambda_{r_{od}}) \exp\{-(\lambda_{sd} + \lambda_{r_{od}})\theta\} \end{aligned} \quad (2.1.16)$$

2.1.2 Performance Analysis

In this section, closed form expressions are provided for the following performance parameters:

Outage Probability (P_{out})

Outage occurs when received SNR falls below a certain specified threshold. Here, for the given threshold χ , outage probability can be calculated as follows [SA05, Eq.(1.4)]

$$P_{out} = \int_0^{\chi} f_{\Theta_T}(\theta) d\theta, \quad (2.1.17)$$

here $f_{\Theta_T}(\theta) \in \{f_{\Theta}^{(1)}(\theta), f_{\Theta}^{(2)}(\theta)\}$.

Average error probability (P_e) for MPSK signals

Wireless channel suffers from additive channel noise and multi-path fading, so bit/symbol error occurs in transmission. Average error probability is the expectation of this error, which is defined as [SA05, Eq.(5.1)]

$$P_e = \int_0^{\infty} Q(\sqrt{c\theta}) f_{\Theta_T}(\theta) d\theta, \quad (2.1.18)$$

where $Q(\cdot)$ is Gaussian Q-function, $c = 2 \sin^2(\pi/M)$ for M-PSK signal.

Average received SNR ($\bar{\gamma}$)

Average received SNR is the statistical average of instantaneous received SNR over the SNR distribution of fading channel. It can be evaluated as [SA05, Eq.(1.1)]

$$\bar{\gamma} = \int_0^{\infty} \theta f_{\Theta_T}(\theta) d\theta. \quad (2.1.19)$$

Average capacity (C)

Average (Shannon or Ergodic) capacity [Sha98] provides the maximum limit of data transfer over wireless channel. In fading channel, it (in terms of bit per second per Hertz) can be defined as [Gol05, Eq.(4.4)]

$$C = \int_0^{\infty} \log_2(1 + \theta) f_{\Theta_T}(\theta) d\theta \quad (2.1.20)$$

2.1.3 MRC-MRC based system

Outage probability ($P_{out}^{MRC-MRC}$)

Outage Probability can be calculated with the help of (2.1.5), (2.1.6), (2.1.12), (2.1.17) and [GR07, Eq.(3.381.1)]

$$P_{out}^{MRC-MRC} = \{1 - \exp(-\lambda_{sd}\chi)\} \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} + \left[1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!}\right] \times \left[1 + \frac{1}{\lambda_{sd} - \lambda_{r_{od}}} \{\lambda_{r_{od}} \exp(-\lambda_{sd}\chi) - \lambda_{sd} \exp(-\lambda_{r_{od}}\chi)\}\right] \quad (2.1.21)$$

here $\chi = 2^{2R} - 1$. Details for deriving outage probability expression is given in section A.3.

Average error probability ($P_e^{MRC-MRC}$) for MPSK signals

Average error probability, for this case can be evaluated with the help of (2.1.5), (2.1.6), (2.1.12), (2.1.18) and [EM95, Eq.(A8)]

$$P_e^{MRC-MRC} = \lambda_{sd} \mu(\lambda_{sd}, 1) \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} + \left\{1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!}\right\} \times \frac{\lambda_{sd} \lambda_{r_{od}}}{\lambda_{r_{od}} - \lambda_{sd}} \{\mu(\lambda_{sd}, 1) - \mu(\lambda_{r_{od}}, 1)\} \quad (2.1.22)$$

where, $\mu\{x, y\} = \frac{\Gamma(y)}{x^y} \left\{ \sqrt{\frac{c}{2x+c}} \frac{(2x+c)^{-y} \Gamma(y+0.5)}{2\sqrt{\pi} \Gamma(y+1) (2x)^{-y}} \right\} {}_2F_1(1, y+0.5; y+1; \frac{2x}{2x+c})$, ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ is Gauss hypergeometric function [GR07, Eq.(9.100)]. Details for deriving error expression is given in section A.1 and A.3.

End-to-end average received SNR ($\bar{\gamma}^{MRC-MRC}$)

For relay case, average received SNR can be evaluated by modifying (2.1.19) i.e.

$$\bar{\gamma} = \frac{1}{2} \int_0^{\infty} \theta f_{\Theta}^{(1)}(\theta) d\theta. \quad (2.1.23)$$

In (2.1.23), we use an additional multiplier 1/2 because average received SNR at multi-antenna destination, received in two time-slot. So, (2.1.23) can be represent in closed form with the help of (2.1.5), (2.1.6), (2.1.12) and [GR07, Eq.(3.326.2)]

$$\bar{\gamma}^{MRC-MRC} = \frac{1}{2} \left[\frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{\lambda_{sd}(n-1)!} + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \left\{ \frac{\lambda_{rod} + \lambda_{sd}}{\lambda_{rod}\lambda_{sd}} \right\} \right] \quad (2.1.24)$$

Details for deriving average received SNR expression is given in section A.3.

Average capacity ($C^{MRC-MRC}$)

For relay case, average capacity can be evaluated by modifying (2.1.20) i.e.

$$C = \frac{1}{2} \int_0^{\infty} \log_2(1 + \theta) f_{\Theta}^{(1)}(\theta) d\theta. \quad (2.1.25)$$

In (2.1.25), a multiplier 1/2 is introduced because signal is received at destination in two time-slot. So, (2.1.25) can be represented in closed form with the help of (2.1.5), (2.1.6), (2.1.12) and [GR07, Eq.(4.337.2)]

$$C^{MRC-MRC} = \frac{-1}{2 \log_e 2} \left[\frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \exp(\lambda_{sd}) Ei(-\lambda_{sd}) + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \times \left(\frac{\lambda_{rod}\lambda_{sd}}{\lambda_{rod} - \lambda_{sd}} \right) \left\{ \frac{\exp(\lambda_{sd}) Ei(-\lambda_{sd})}{\lambda_{sd}} - \frac{\exp(\lambda_{rod}) Ei(-\lambda_{rod})}{\lambda_{rod}} \right\} \right] \quad (2.1.26)$$

here $Ei(\cdot)$ is exponential integral [GR07, Eq.(8.211.1)]. Details for deriving capacity expression is given in section A.3.

2.1.4 SC-MRC based system

Performance parameters for this case can be easily derived with the help of methodology given in section A.3.

Outage Probability (P_{out}^{SC-MRC})

Outage Probability can be calculated with the help of (2.1.5), (2.1.6), (2.1.17) and [GR07, Eq.(3.381.1)]

$$P_{out}^{SC-MRC} = \{1 - \exp(-\lambda_{sd}\chi)\} \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n + [1 - \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n] \times \left[1 + \frac{1}{\lambda_{sd} - \lambda_{rod}} \{ \lambda_{rod} \exp(-\lambda_{sd}\chi) - \lambda_{sd} \exp(-\lambda_{rod}\chi) \} \right] \quad (2.1.27)$$

Average error probability (P_e^{SC-MRC}) for MPSK signals

Average error probability, for this case can be evaluated with the help of (2.1.5), (2.1.6), (2.1.18) and [EM95, Eq.(A8)]

$$P_e^{SC-MRC} = \lambda_{sd} \mu(\lambda_{sd}, 1) \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n + [1 - \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n] \times \frac{\lambda_{sd} \lambda_{rod}}{\lambda_{rod} - \lambda_{sd}} \{ \mu(\lambda_{sd}, 1) - \mu(\lambda_{rod}, 1) \} \quad (2.1.28)$$

End-to-end average received SNR ($\bar{\gamma}^{SC-MRC}$)

Average received SNR can be calculated with the help of (2.1.5), (2.1.6), (2.1.12), (2.1.23) and [GR07, Eq.(3.326.2)]

$$\bar{\gamma}^{SC-MRC} = \frac{1}{2} \left[\frac{[1 - \exp(-\bar{\lambda}_{sr}\chi)]^n}{\lambda_{sd}} + \{1 - [1 - \exp(-\bar{\lambda}_{sr}\chi)]^n\} \left(\frac{\lambda_{rod} + \lambda_{sd}}{\lambda_{rod} \lambda_{sd}} \right) \right] \quad (2.1.29)$$

Average capacity (C^{SC-MRC})

Average capacity can be calculated with the help of (2.1.5), (2.1.6), (2.1.12), (2.1.25) and [GR07, Eq.(4.337.2)]

$$C^{SC-MRC} = \frac{-1}{2 \log_e 2} \left[\{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n \exp(\lambda_{sd}) Ei(-\lambda_{sd}) + [1 - \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n] \times \left(\frac{\lambda_{rod} \lambda_{sd}}{\lambda_{rod} - \lambda_{sd}} \right) \left\{ \frac{\exp(\lambda_{sd}) Ei(-\lambda_{sd})}{\lambda_{sd}} - \frac{\exp(\lambda_{rod}) Ei(-\lambda_{rod})}{\lambda_{rod}} \right\} \right] \quad (2.1.30)$$

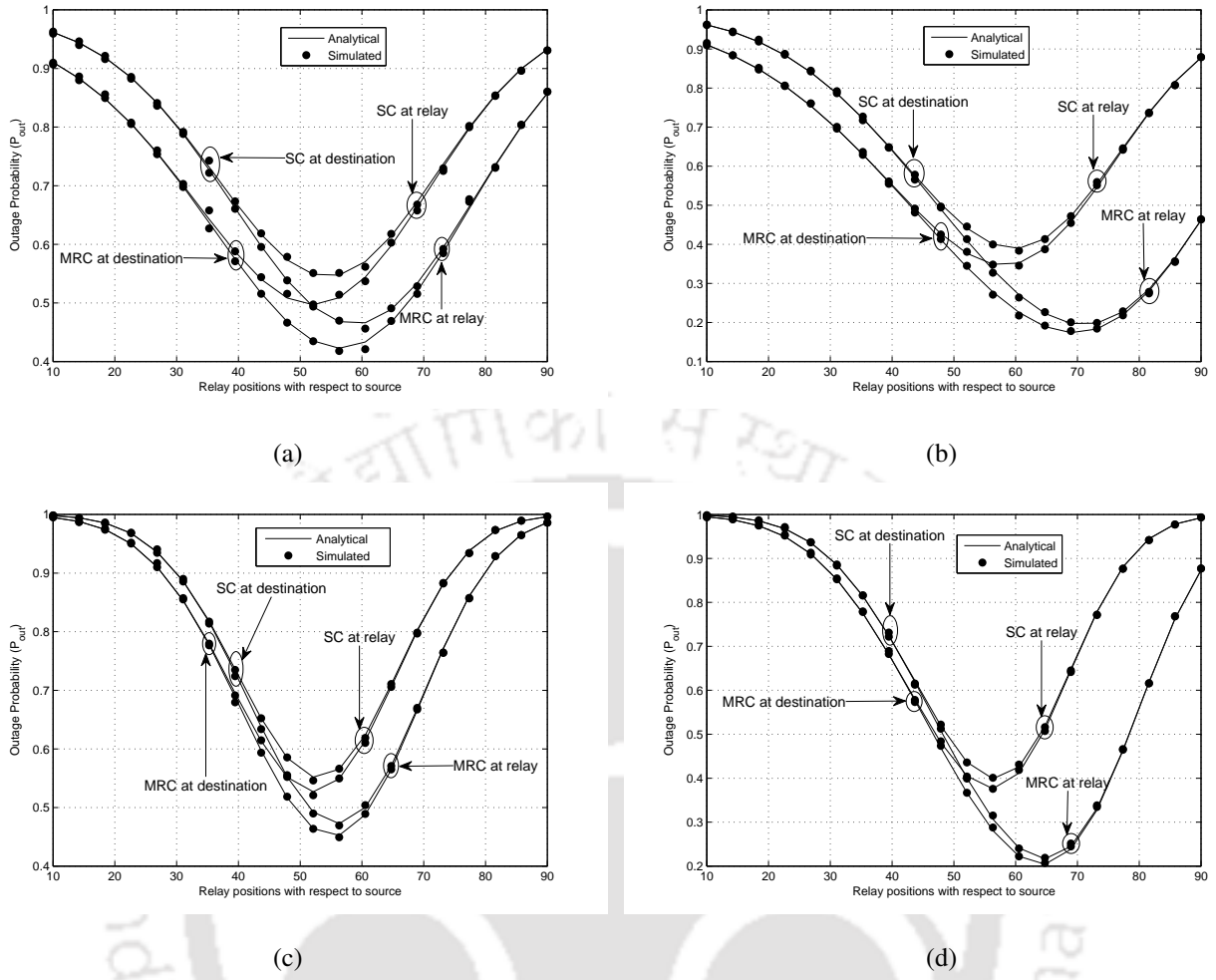


Figure 2.3: Outage Probability (at $\omega=7$ dB) of multi-antenna cooperative relay system (a) $n = 2, \psi = 3$, (b) $n = 4, \psi = 3$, (c) $n = 2, \psi = 4$, (d) $n = 4, \psi = 4$, when r placed at various locations between s and d .

2.1.5 MRC-SC based system

Outage Probability (P_{out}^{MRC-SC})

Outage Probability can be calculated with the help of (2.1.5), (2.1.6), (2.1.16), (2.1.17) and [GR07, Eq.(3.381.1)]

$$P_{out}^{MRC-SC} = \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \{1 - \exp(-\lambda_{sd}\chi)\} + \left[1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!}\right] \times [1 - \exp(-\lambda_{sd}\chi) - \exp(-\lambda_{r_o d}\chi) + \exp\{-(\lambda_{sd} + \lambda_{r_o d})\chi\}] \quad (2.1.31)$$

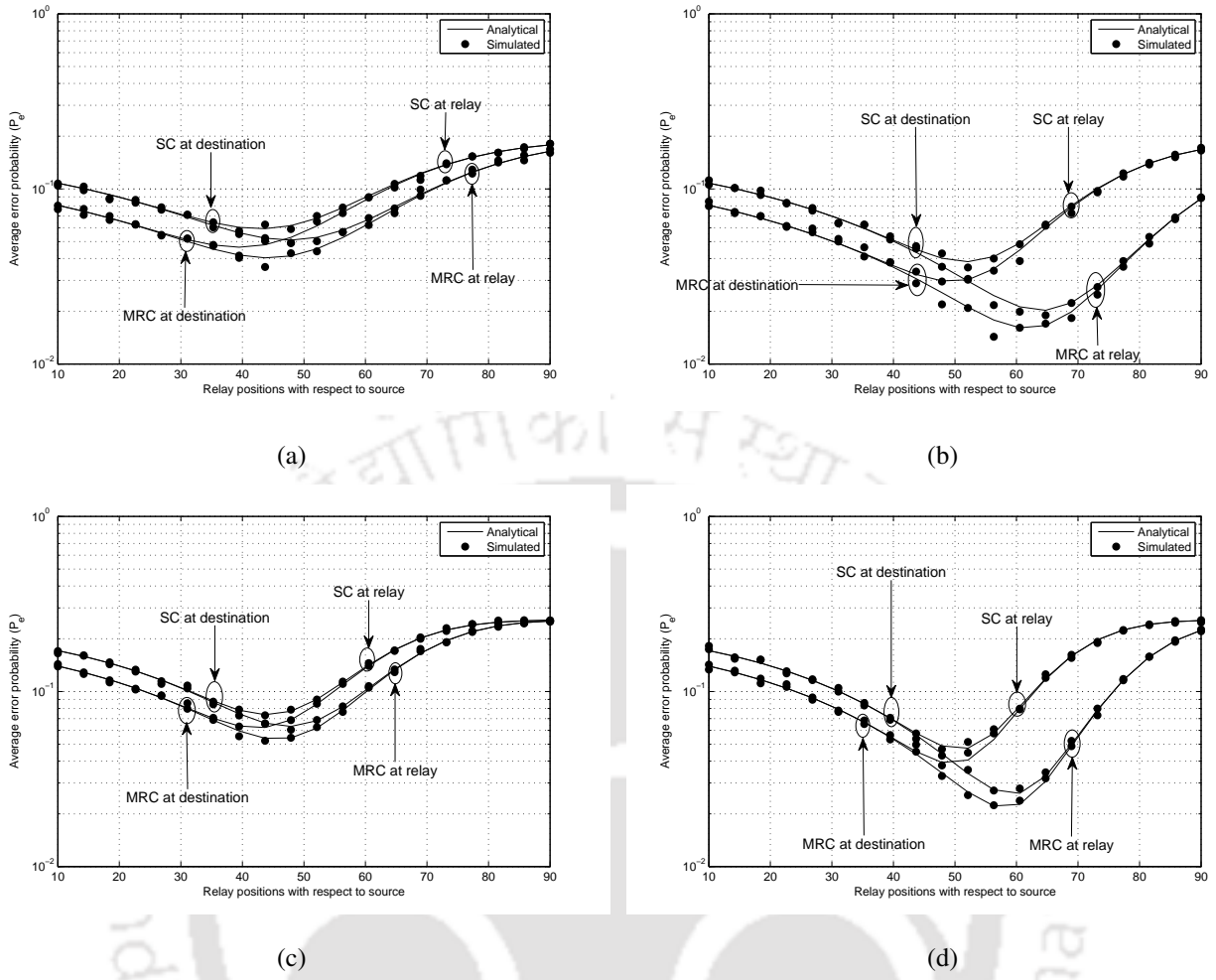


Figure 2.4: Average error probability (at $\omega=7$ dB) of multi-antenna cooperative relay system (a) $n = 2$, $\psi = 3$, (b) $n = 4$, $\psi = 3$, (c) $n = 2$, $\psi = 4$, (d) $n = 4$, $\psi = 4$, when r placed at various locations between s and d .

Average error probability (P_e^{MRC-SC}) for MPSK signals

Average error probability, for this case can be evaluated with the help of (2.1.5), (2.1.6), (2.1.16), (2.1.18) and [EM95, Eq.(A8)]

$$\begin{aligned}
 P_e^{MRC-SC} = & \lambda_{sd} \mu(\lambda_{sd}, 1) \frac{\Gamma(n, \bar{\lambda}_{sr} \chi)}{(n-1)!} + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr} \chi)}{(n-1)!} \right\} \{ \lambda_{sd} \mu(\lambda_{sd}, 1) \\
 & + \lambda_{r_o d} \mu(\lambda_{r_o d}, 1) - (\lambda_{sd} + \lambda_{r_o d}) \mu(\lambda_{sd} + \lambda_{r_o d}, 1) \}
 \end{aligned} \quad (2.1.32)$$

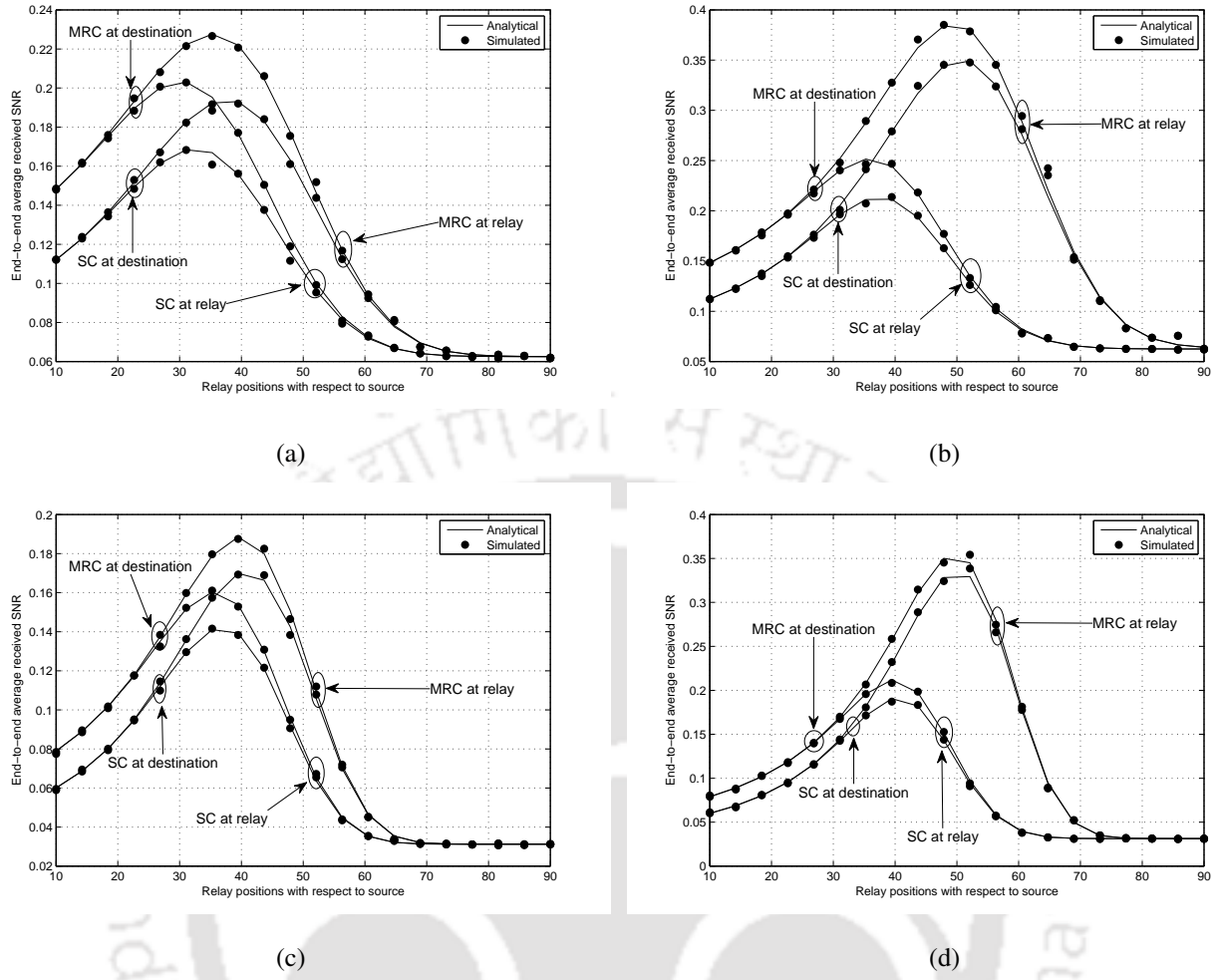


Figure 2.5: End-to-end average received SNR (at $\omega=0$ dB) of multi-antenna cooperative relay system (a) $n = 2$, $\psi = 3$, (b) $n = 4$, $\psi = 3$, (c) $n = 2$, $\psi = 4$, (d) $n = 4$, $\psi = 4$, when r placed at various locations between s and d .

Average received SNR ($\bar{\gamma}^{MRC-SC}$)

Average received SNR can be evaluated by modifying (2.1.19) i.e.

$$\bar{\gamma} = \frac{1}{2} \int_0^\infty \theta f_\Theta^{(2)}(\theta) d\theta, \quad (2.1.33)$$

so, (2.1.33) can be represented in closed form with the help of (2.1.5), (2.1.6), (2.1.16) and [GR07, Eq.(3.326.2)]

$$\bar{\gamma}^{MRC-SC} = \frac{1}{2} \left[\frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{\lambda_{sd} (n-1)!} + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \left(\frac{1}{\lambda_{sd}} + \frac{1}{\lambda_{r_o d}} + \frac{1}{\lambda_{sd} + \lambda_{r_o d}} \right) \right] \quad (2.1.34)$$

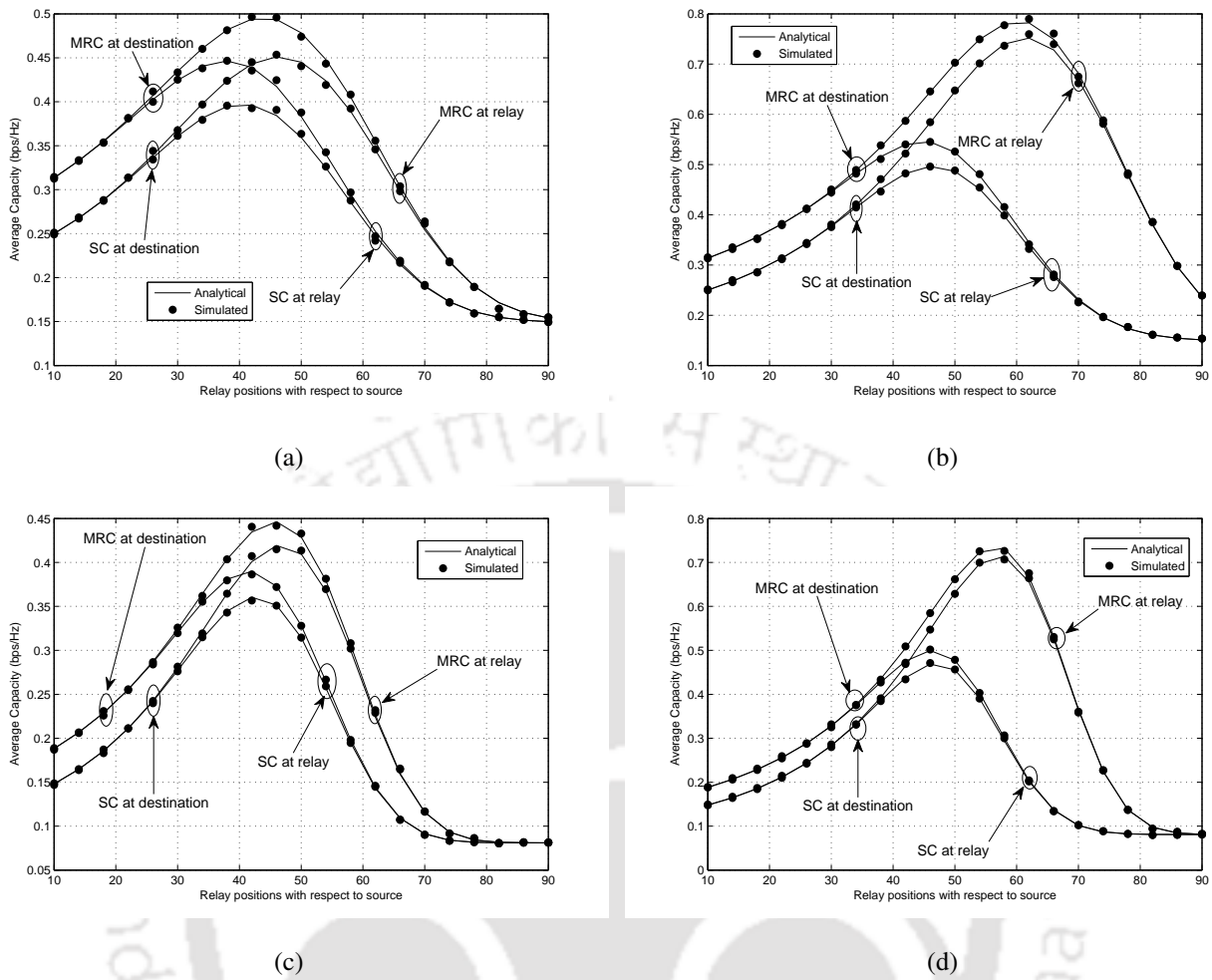


Figure 2.6: Average capacity (at $\omega=3$ dB) of multi-antenna cooperative relay system (a) $n = 2, \psi = 3$, (b) $n = 4, \psi = 3$, (c) $n = 2, \psi = 4$, (d) $n = 4, \psi = 4$, when r placed at various locations between s and d .

Average capacity (C^{MRC-SC})

Average capacity for this case can be calculated by modifying (2.1.20) i.e.

$$C = \frac{1}{2} \int_0^\infty \log_2(1 + \theta) f_\Theta^{(2)}(\theta) d\theta. \tag{2.1.35}$$

So, (2.1.35) can be represented in closed form with the help of (2.1.5), (2.1.6), (2.1.16) and [GR07, Eq.(4.337.2)]

$$C^{MRC-SC} = \frac{-1}{2 \log_e 2} \left[\frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \exp(\lambda_{sd}) Ei(-\lambda_{sd}) \right. \\ \left. + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \exp(\lambda_{sd}) Ei(-\lambda_{sd}) + \exp(\lambda_{r_{od}}) \right. \\ \left. \times Ei(-\lambda_{r_{od}}) - \exp(\lambda_{sd} + \lambda_{r_{od}}) Ei(-\lambda_{sd} - \lambda_{r_{od}}) \right] \quad (2.1.36)$$

2.1.6 SC-SC based system

Outage Probability (P_{out}^{SC-SC})

Outage Probability can be calculated with the help of (2.1.5), (2.1.6), (2.1.16), (2.1.17) and [GR07, Eq.(3.381.1)]

$$P_{out}^{SC-SC} = \{1 - \exp(-\lambda_{sd}\chi)\} \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n + [1 - \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n] \\ \times [1 - \exp(-\lambda_{sd}\chi) - \exp(-\lambda_{r_{od}}\chi) + \exp\{-(\lambda_{sd} + \lambda_{r_{od}})\chi\}] \quad (2.1.37)$$

Average error probability (P_e^{SC-SC}) for MPSK signals

Average error probability, for this case can be evaluated with the help of (2.1.5), (2.1.6), (2.1.16), (2.1.18) and [EM95, Eq.(A8)]

$$P_e^{SC-SC} = \lambda_{sd}\mu(\lambda_{sd}, 1) \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n + [1 - \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n] \\ \times \{\lambda_{sd}\mu(\lambda_{sd}, 1) + \lambda_{r_{od}}\mu(\lambda_{r_{od}}, 1) - (\lambda_{sd} + \lambda_{r_{od}})\mu(\lambda_{sd} + \lambda_{r_{od}}, 1)\} \quad (2.1.38)$$

Average received SNR ($\bar{\gamma}^{SC-SC}$)

Average received SNR can be calculated with the help of (2.1.5), (2.1.6), (2.1.16), (2.1.33) and [GR07, Eq.(3.326.2)]

$$\begin{aligned} \bar{\gamma}^{SC-SC} = & \frac{1}{2} \left[\frac{[1 - \exp(-\bar{\lambda}_{sr}\chi)]^n}{\lambda_{sd}} + \{1 - [1 - \exp(-\bar{\lambda}_{sr}\chi)]^n\} \right. \\ & \left. \times \left(\frac{1}{\lambda_{sd}} + \frac{1}{\lambda_{r,d}} + \frac{1}{\lambda_{sd} + \lambda_{r,d}} \right) \right] \end{aligned} \quad (2.1.39)$$

Average capacity (C^{SC-SC})

Average capacity can be calculated with the help of (2.1.5), (2.1.6), (2.1.16), (2.1.35) and [GR07, Eq.(4.337.2)]

$$\begin{aligned} C^{SC-SC} = & \frac{-1}{2 \log_e 2} \left[\{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n \exp(\lambda_{sd}) Ei(-\lambda_{sd}) \right. \\ & + [1 - \{1 - \exp(-\bar{\lambda}_{sr}\chi)\}^n] \{ \exp(\lambda_{sd}) Ei(-\lambda_{sd}) + \exp(\lambda_{r,d}) \\ & \left. \times Ei(-\lambda_{r,d}) - \exp(\lambda_{sd} + \lambda_{r,d}) Ei(-\lambda_{sd} - \lambda_{r,d}) \} \right] \end{aligned} \quad (2.1.40)$$

2.2 Multi-antenna Relay System with type-2 and type-3 operation

In this section, a system model shown in Fig. 2.7 have been analyzed for type-2 and type-3 operation described earlier. Closed form expressions of outage probability and average error rate have been derived. In first time slot, source transmit signal to relay and destination. Relay receive the signal through multiple link and performs MRC of signal. If received SNR at relay is above a particular threshold, relay re-transmit the signal in second time-slot. In type-2 operation, source also re-transmits the signal in second time slot but in type-3 operation, source re-transmits the signal only if relay has not participated. Destination coherently combine the signal received through direct path and through relay path. System operating in type-2 operation, consumes more battery power from source but exploits extra diversity path. Type-2 operation may be used when there is no limitation of transmitted power imposed by transmitter circuitry of source or energy constraint at source is not an important issue. Type-3 operation is useful for the case when all the transmitters are supported by limited power battery (in case of wireless sensor network) or system operates in un-licensed band (limitation on total transmitted

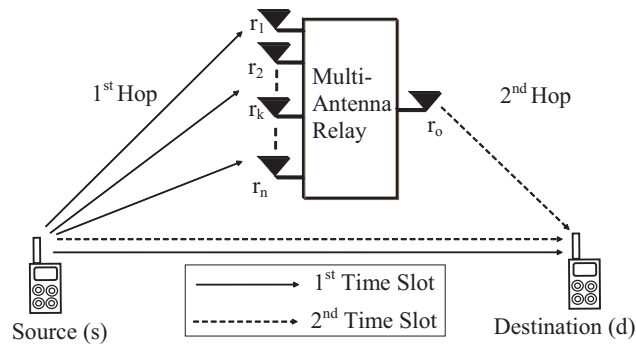


Figure 2.7: Two hop cooperative relay network with type-2 and type-3 operation.

power). Some of the results obtained in this section for type-2 and type-3 operation are also compared with the results of type-1 operation described in section 2.1.

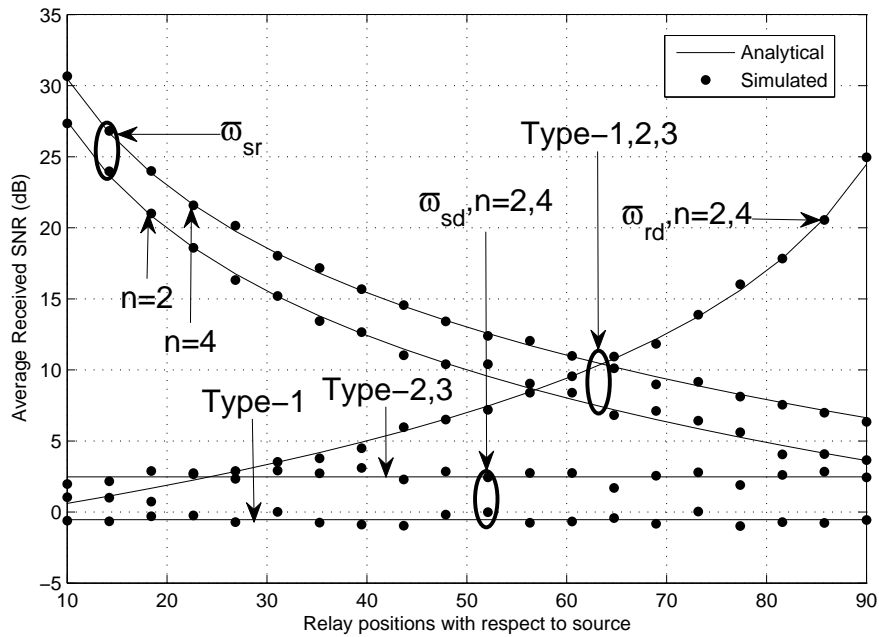


Figure 2.8: Average received SNR of ω_{sr} , ω_{sd} and ω_{rd} for type-1, 2, 3 operations, when r is placed at various locations between s and d .

2.2.1 System Model

In the system model shown in Fig. 2.7, s and d are equipped with single antenna but r has multiple receiving antennas and single transmitting antenna. s transmits signal to r and d in first time-slot. r

receives signals through multiple links and perform MRC. If received SNR is above the threshold of the decoder, the message is decoded and retransmitted to the destination (i.e. $r \rightarrow d$) in the second time-slot. For the case when fading changes independently from one time-slot to another time-slot, s can re-transmit the signal along with r in second time-slot (i.e. $s \rightarrow d$ and $r \rightarrow d$). Signals received via direct paths in first, second time-slots (i.e. $s \rightarrow d$) and via relay path (i.e. $r \rightarrow d$) in second time-slot are coherently combined at d . This can be done with the help of distributed space time coding, which is originally proposed in [NBK04] and presented as Protocol-I in the same paper. In the case of type-3 operation, s transmits to the r and d in first time-slot (i.e. $s \rightarrow r$ and $s \rightarrow d$). If r is able to decoded the message, signal is re-transmitted by r in the second time-slot else s again transmit the message. Such decision mechanism can be executed with the help of appropriate handshaking signals. In this chapter, fading envelop is assumed to be Rayleigh distributed, so the PDF of received SNR (γ_{ij}) when j^{th} node perform MRC of signals transmitted from i^{th} node [YA05]

$$f_{\gamma_{ij}}(\gamma) = \frac{\lambda_{ij}^n \gamma^{n-1}}{(n-1)!} \exp(-\lambda_{ij}\gamma), \quad (2.2.1)$$

here $i \in \{s, r_o\}$, $j \in \{r, d\}$, $\lambda_{ij} = (2\ell_{ij}/\ell_{sd})^\psi / \omega$, ψ is path loss exponent, ℓ_{ij} represents distance between node i and j , which is normalized by reference distance $\ell_{sd}/2$, ω is SNR at reference point. In this system model, independent and identically distributed (i.i.d.) fading between $s \rightarrow r$ (i.e. $\forall \lambda_{sr_k} = \bar{\lambda}_{sr}$) have been assumed. Average received SNR at r due to $s \rightarrow r$ transmission will be $\varpi_{sr} (= n/\bar{\lambda}_{sr})$ [KM99, Eq.(9)]. Similarly, average received SNR at d due to $r \rightarrow d$ transmissions will be $\varpi_{rd} (= 1/\lambda_{r_o d})$. In type-1 operation, s transmit only in first time-slot, so average received SNR at d due to $s \rightarrow d$ transmissions will be $\varpi_{sd} (= 1/\lambda_{sd})$. However, in type-2 and type-3 operation s may transmit in first and second time-slots, hence average received SNR at d for such cases due to $s \rightarrow d$ transmissions will be $\varpi_{sd} (= 2/\lambda_{sd})$. In first hop, if the received SNR at r_k after MRC is above the threshold, relay decodes the message received from the source. In this condition, mutual information (I), transmitted by the source is grater than target data rate R (spectral efficiency) [LW03]:

$$I = \frac{1}{2} \log_2 \left(1 + \sum_{k=1}^n \gamma_{sr_k} \right) > R. \quad (2.2.2)$$

When r is inactive, SNR received at d due to the transmission from r can be modeled by RV $\gamma_{r_o d}^{inactive}$ and its PDF is given as

$$f_{\gamma_{r_o d}^{inactive}}(\theta) = \delta(\theta), \quad (2.2.3)$$

where $\delta(\bullet)$ is dirac delta function. Similarly, PDF of RV $\gamma_{sd}^{inactive}$ models the received SNR at d due to the transmission from s when s is inactive

$$f_{\gamma_{sd}^{inactive}}(\theta) = \delta(\theta). \quad (2.2.4)$$

In case r is active, SNR received at d due to the transmission from r can be modeled by RV γ_{rod}^{active} and its PDF is given as

$$f_{\gamma_{rod}^{active}}(\theta) = f_{\gamma_{rod}}(\theta) = \lambda_{rod} \exp(-\lambda_{rod}\theta). \quad (2.2.5)$$

Similarly, PDF of RV γ_{sd}^{active} models the received SNR at d due to the transmission from s when s is active, and the same can be modeled as

$$f_{\gamma_{sd}^{active}}(\theta) = f_{\gamma_{sd}}(\theta) = \lambda_{sd} \exp(-\lambda_{sd}\theta). \quad (2.2.6)$$

2.2.2 Mathematical Analysis

In this section, we first outline the steps involved in finding out the PDF of total received SNR based on the link conditions. With the pdf of received SNR known, outage probability and average error rate expressions are derived. System model for type-1 operation is considered once again here along with type-2 and type-3 operation.

Probability of relay transmission

Probability of relay transmission (active mode) is given by

$$P[I > R] = P\left[\sum_{k=1}^n \gamma_{sr_k} > \chi\right] = 1 - \int_0^{\chi} f_{sr}(\gamma) d\gamma, \quad (2.2.7)$$

here $\chi = 2^{2R} - 1$ is the threshold. So, (2.2.7) can be written as

$$P[I > R] = 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!}. \quad (2.2.8)$$

Probability that relay will not transmit (inactive mode)

$$P[I \leq R] = 1 - P[I > R]. \quad (2.2.9)$$

PDF of received SNR based on link condition

Let, random variable Θ models the received SNR at d in second time-slot. In type-1 operation, s never transmit the signal in second time. However, in type-2 operation, s always re-transmit the

signal in second time also but in type-3 operation, s re-transmit the signal when r is not active. So, the conditional PDF of RV Θ when r is not active

$$f_{\Theta|I \leq R}(\theta) = \begin{cases} f_{\gamma_{rod}^{inactive} + \gamma_{sd}^{inactive}}(\theta) & \text{type} - 1 \\ f_{\gamma_{rod}^{inactive} + \gamma_{sd}^{active}}(\theta) & \text{type} - 2, 3 \end{cases} \quad (2.2.10)$$

For the case when r is active, s retransmit the signal in type-2 operation but s remain silent in type-3 operation. So, the conditional PDF of RV Θ can be given as

$$f_{\Theta|I > R}(\theta) = \begin{cases} f_{\gamma_{rod}^{active} + \gamma_{sd}^{inactive}}(\theta) & \text{type} - 1 \\ f_{\gamma_{rod}^{active} + \gamma_{sd}^{active}}(\theta) & \text{type} - 2 \\ f_{\gamma_{rod}^{active} + \gamma_{sd}^{inactive}}(\theta) & \text{type} - 3 \end{cases} \quad (2.2.11)$$

Combined PDF of received SNR

In first time-slot, d receives the signal through direct link only. So, PDF of received SNR in first time-slot can be calculated with the help of (2.2.1)

$$f_{\Theta}^{(1)}(\theta) = f_{\gamma_{sd}}(\theta) = \lambda_{sd} \exp(-\lambda_{sd}\theta). \quad (2.2.12)$$

MGF⁴ of received SNR in first time-slot can be calculated with the help of (2.2.12)

$$M_1(s) = \left\{ \frac{\lambda_{sd}}{s + \lambda_{sd}} \right\}. \quad (2.2.13)$$

From the theorem on total probability, PDF of received SNR in second time-slot can be written as

$$f_{\Theta}^{(2)}(\theta) = f_{\Theta|I \leq R}(\theta) P[I \leq R] + f_{\Theta|I > R}(\theta) P[I > R]. \quad (2.2.14)$$

For type-1 operation, MGF of received SNR in second time-slot can be written as

$$M_2^{type-1}(s) = P[I \leq R] + P[I > R] \left\{ \frac{\lambda_{rod}}{s + \lambda_{rod}} \right\}. \quad (2.2.15)$$

For the case of type-2 operation, MGF of received SNR in second time-slot is given as

$$M_2^{type-2}(s) = P[I \leq R] \left\{ \frac{\lambda_{sd}}{s + \lambda_{sd}} \right\} + P[I > R] \left\{ \frac{\lambda_{rod}}{s + \lambda_{rod}} \right\} \left\{ \frac{\lambda_{sd}}{s + \lambda_{sd}} \right\}. \quad (2.2.16)$$

In case of type-3 operation, MGF of received SNR in second time-slot can be written as

$$M_2^{type-3}(s) = P[I \leq R] \left\{ \frac{\lambda_{sd}}{s + \lambda_{sd}} \right\} + P[I > R] \left\{ \frac{\lambda_{rod}}{s + \lambda_{rod}} \right\}. \quad (2.2.17)$$

⁴MGF = $\int_0^{\infty} f_{\Theta}^{(1)}(\theta) \exp(-s\theta) d\theta$

When the links are independent in first and second time-slot, MGF of equivalent link is given by

$$M_T(s) = M_2(s)M_1(s), \quad (2.2.18)$$

here, $M_2(s) \in \{M_2^{type-1}(s), M_2^{type-2}(s), M_2^{type-3}(s)\}$. For type-1 operation, PDF of total received SNR at d can be calculated, by taking inverse Laplace transform of $M_T(s)$

$$\begin{aligned} f_{\Theta}^{type-1}(\theta) &= P[I \leq R] \lambda_{sd} \exp(-\lambda_{sd}\theta) + P[I > R] \left(\frac{\lambda_{rod}\lambda_{sd}}{\lambda_{rod} - \lambda_{sd}} \right) \\ &\quad \times \{ \exp(-\lambda_{sd}\theta) - \exp(-\lambda_{rod}\theta) \}. \end{aligned} \quad (2.2.19)$$

Similarly for type-2 operation, PDF of total received SNR at d can be given as

$$\begin{aligned} f_{\Theta}^{type-2}(\theta) &= \theta \lambda_{sd}^2 \exp(-\lambda_{sd}\theta) P[I \leq R] + \frac{\lambda_{rod}\lambda_{sd}^2 P[I > R]}{(\lambda_{rod} - \lambda_{sd})^2} \\ &\quad \times [\exp(-\lambda_{rod}\theta) + \{ (\lambda_{rod} - \lambda_{sd})\theta - 1 \} \exp(-\lambda_{sd}\theta)]. \end{aligned} \quad (2.2.20)$$

In type-3 operation, PDF of total received SNR at d can be written as

$$\begin{aligned} f_{\Theta}^{type-3}(\theta) &= \theta \lambda_{sd}^2 \exp(-\lambda_{sd}\theta) P[I \leq R] + \frac{\lambda_{rod}\lambda_{sd} P[I > R]}{\lambda_{sd} - \lambda_{rod}} \\ &\quad \times \{ \exp(-\lambda_{rod}\theta) - \exp(-\lambda_{sd}\theta) \}. \end{aligned} \quad (2.2.21)$$

Outage Probability (P_{out})

Outage occurs when received SNR falls below a certain specified threshold. Here, for the given threshold χ , outage probability can be calculated as follows [SA05, Eq.(1.4)]

$$P_{out} = \int_0^{\chi} f_{\Theta_T}(\theta) d\theta, \quad (2.2.22)$$

here, $f_{\Theta_T}(\theta) \in \{f_{\Theta}^{type-1}(\theta), f_{\Theta}^{type-2}(\theta), f_{\Theta}^{type-3}(\theta)\}$. For type-1 operation, outage probability can be calculated with the help of (2.2.8), (2.2.9), (2.2.20), (2.2.22) and [GR07, Eq.(3.381.1)]

$$\begin{aligned} P_{out}^{type-1} &= \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \{1 - \exp(-\lambda_{sd}\chi)\} + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \\ &\quad \times \left[1 + \frac{1}{\lambda_{sd} - \lambda_{rod}} \{ \lambda_{rod} \exp(-\lambda_{sd}\chi) - \lambda_{sd} \exp(-\lambda_{rod}\chi) \} \right]. \end{aligned} \quad (2.2.23)$$

Expression derived in (2.2.23) is same as the expression derived in (2.1.21). For type-2 operation, outage probability can be calculated with the help of (2.2.8), (2.2.9), (2.2.20), (2.2.22) and [GR07,

Eq.(3.381.1)]

$$\begin{aligned}
P_{out}^{type-2} &= \left\{ \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \{1 - \exp(-\lambda_{sd}\chi) - \lambda_{sd}\chi \exp(-\lambda_{sd}\chi)\} \\
&+ \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \left[1 - \frac{\lambda_{sd}^2}{(\lambda_{r_{od}} - \lambda_{sd})^2} \exp(-\lambda_{r_{od}}\chi) \right. \\
&\quad \left. - \lambda_{r_{od}}\lambda_{sd}^2 \exp(-\lambda_{sd}\chi) \left\{ \frac{\chi}{\lambda_{sd}(\lambda_{r_{od}} - \lambda_{sd})} + \frac{\lambda_{r_{od}} - 2\lambda_{sd}}{\lambda_{sd}^2(\lambda_{r_{od}} - \lambda_{sd})^2} \right\} \right]. \quad (2.2.24)
\end{aligned}$$

Similarly, for type-3 operation, outage probability can be calculated with the help of (2.2.8), (2.2.9), (2.2.21), (2.2.22) and [GR07, Eq.(3.381.1)]

$$\begin{aligned}
P_{out}^{type-3} &= \left\{ \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \{1 - \exp(-\lambda_{sd}\chi) - \lambda_{sd}\chi \exp(-\lambda_{sd}\chi)\} \quad (2.2.25) \\
&+ \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \left[\frac{\lambda_{sd} \{1 - \exp(-\lambda_{r_{od}}\chi)\} - \lambda_{r_{od}} \{1 - \exp(-\lambda_{sd}\chi)\}}{\lambda_{sd} - \lambda_{r_{od}}} \right].
\end{aligned}$$

Average error probability (P_e)

Average error probability is a standard performance measure of diversity systems operating over fading channels. Average error rate for M-PSK modulated signal is define as [SA05, Eq.(5.1)]

$$P_e = \int_0^\infty Q(\sqrt{c\theta}) f_{\Theta_T}(\theta) d\theta, \quad (2.2.26)$$

here $c = 2 \sin^2(\pi/M)$. For type-1 operation, average error probability can be evaluated with the help of (2.2.20), (2.2.26) and [EM95, Eq.(A8)]

$$\begin{aligned}
P_e^{type-1} &= \lambda_{sd}\mu(\lambda_{sd}, 1) \left\{ \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \\
&\quad \times \frac{\lambda_{sd}\lambda_{r_{od}}}{\lambda_{r_{od}} - \lambda_{sd}} \{ \mu(\lambda_{sd}, 1) - \mu(\lambda_{r_{od}}, 1) \}, \quad (2.2.27)
\end{aligned}$$

where, $\mu\{x, y\} = \frac{\Gamma(y)}{x^y} \left\{ \sqrt{\frac{c}{2x+c}} \frac{(2x+c)^{-y} \Gamma(y+0.5)}{2\sqrt{\pi} \Gamma(y+1) (2x)^{-y}} \right\} {}_2F_1(1, y+0.5; y+1; \frac{2x}{2x+c})$, ${}_2F_1(\bullet, \bullet; \bullet; \bullet)$ is Gauss hypergeometric function [GR07, Eq.(9.100)]. Expression derived in (2.2.27) is same as the expression derived in (2.1.22). For type-2 operation, average error probability can be evaluated with the help of (2.2.20), (2.2.26) and [EM95, Eq.(A8)]

$$\begin{aligned}
P_e^{type-2} &= \lambda_{sd}^2 \mu(\lambda_{sd}, 2) \left\{ \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} + \frac{\lambda_{r_{od}}\lambda_{sd}^2}{(\lambda_{r_{od}} - \lambda_{sd})^2} \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \\
&\quad \times [\mu(\lambda_{r_{od}}, 1) + \{(\lambda_{r_{od}} - \lambda_{sd}) \mu(\lambda_{sd}, 2) - \mu(\lambda_{sd}, 1)\}]. \quad (2.2.28)
\end{aligned}$$

Similarly, for type-3 operation, average error probability can be evaluated with the help of (2.2.21), (2.2.26) and [EM95, Eq.(A8)]

$$P_e^{type-3} = \lambda_{sd}^2 \mu(\lambda_{sd}, 2) \left\{ \frac{\Gamma(n, \bar{\lambda}_{sr} \chi)}{(n-1)!} \right\} + \frac{\lambda_{rod} \lambda_{sd}}{\lambda_{sd} - \lambda_{rod}} \times \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr} \chi)}{(n-1)!} \right\} \{ \mu(\lambda_{rod}, 1) - \mu(\lambda_{sd}, 1) \}. \quad (2.2.29)$$

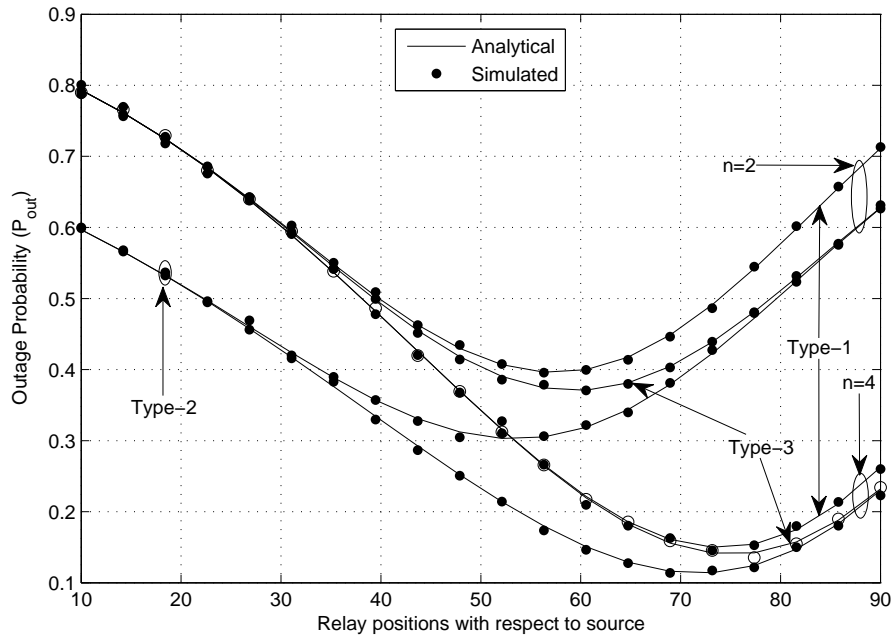


Figure 2.9: Outage probability ($\psi = 2.5$) at d for multi-antenna cooperative relay network.

2.3 Numerical Results and Discussions

For evaluating the performance of multi-antenna relay system under some specific conditions, s & d have been assumed to be located at $(0,0)$ and $(0,100)$, respectively. Relay r is assumed to be located on the line joining s and d and its position is varied over the range 10 to 90. Spectral efficiency (R) is assumed to be unity. Average received SNR at various nodes have been plotted in Fig. 2.2, for the case of type-1 operation. In Fig. 2.3, Fig. 2.4, Fig. 2.5, Fig. 2.6, outage probability, average error rate, average received SNR and average capacity have been plotted for all possible combinations given in table-2.1 and different values of n and ψ , respectively. Average received SNR at various nodes have

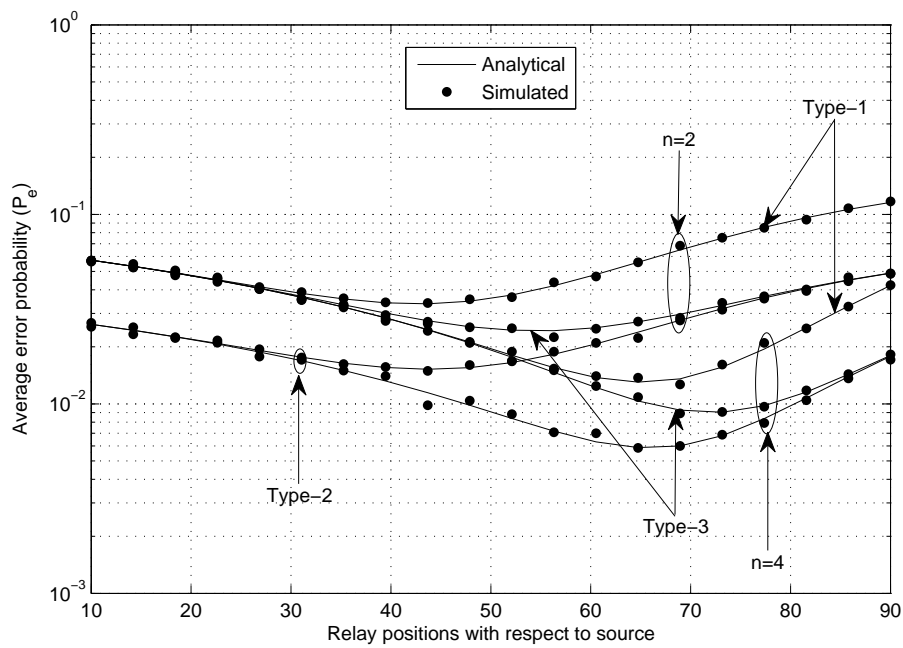


Figure 2.10: Average error rate ($\psi = 2.5$) at d for multi-antenna cooperative relay network.

been plotted in Fig. 2.8, for the cases of type-1, 2, 3 operations. Comparative outage probability and average error rate for various types of operation and various values of n have been plotted in Fig. 2.9 and Fig. 2.10, respectively.

It is observed that, when r is placed near s , overall performance is largely decided by the combining schemes that has been employed at the d , as for this condition both SC and MRC are equally effective in decoding the signal at r . This is due to fact that, most of time received SNR at r through MRC/SC is higher than particular threshold, so r can perform decode and forward operation and d with MRC gives better result than d with SC. When r is near d , the choice of combining scheme at d is less important as compared to choice of combining scheme at r . This is due to the fact that r with MRC has higher probability to perform decode and forward operation and d has better probability to perform MRC/SC of the received signals. With increment of n , optimum performance (minimum outage, minimum average error rate, maximum average received SNR, maximum capacity) of such system is obtained when r is moved towards d because probability of decoding the message by r , increases with n , so r can be placed far away from s . Performance curves for type-1 and type-3 operation, overlaps for various values of n , when r is placed near s because average received SNR at r is sufficiently high and most of the time message is decoded by r . So, s does not re-transmit the message in second time-slot

and type-3 operation reduces to type-1 operation. As location of r moves towards d , r receives poor SNR and fails to decode the message for most of the time. In this case, performance of type-3 operation is near to type-2 operation because most of time s has to re-transmit the message in second time-slot.

2.4 Conclusion

In this chapter, a three node relay network with relay node carrying multiple receiving antennas has been investigated for three different types of operation. Analytical expressions of outage probability, average error rate, average received SNR and average capacity of cooperative relay network for various combining schemes in type-1 operation, have been derived. For type-2 and type-3 operation, analytical expressions of outage probability and average error rate have been derived. Monte Carlo simulation (running simulator freely with 10^4 samples) has been carried out and the analytical results are found to match the simulation results. For simulation, random variables of received SNR has been generated with the help of [WHT04, Eq.(7.41)]. It is seen that installation of more number of receiving antennas on relay improves its participation, hence system performance improves. In such case, relay can be placed towards destination for further improving the system performance. It is also observed that, when relay is placed near the source, type-2 operation outperforms type-1 and type-3 operation but the performance of type-3 operation is equivalent to type-1 operation. When relay is placed near the destination, performance of type-3 operation is near to type-2 operation. Result shows that, number of antennas on the relay, its location, combining schemes at relay/destination and type of operation plays vital role on system performance.

Chapter 3

Performance of Multi-antenna Relay Network in Nakagami- m Fading Channel

3.1 Introduction

Performance of cooperative relay schemes employing infrastructure based fixed relays having multiple antennas in Nakagami- m fading channel, have been investigated in this chapter. Works presented in chapter 2 (section 2.1) for type-1 operation has been extended here. This type of operation provides cooperative diversity gain without any complicated coordination among source and relay, hence does not suffer from synchronization problem. Nakagami- m fading is a parameter based distribution which gives the best fit to landmobile and indoor mobile multi-path propagation, as well as scintillating ionospheric radio links. Parameter m of Nakagami- m fading channel models the wide range of multi-path distribution. For $m = 1/2$, it includes the one-sided Gaussian distribution. Rayleigh distribution becomes a special case and can be modeled by taking $m=1$. When $m \rightarrow \infty$ Nakagami- m fading channel converges to an AWGN channel. For $m = (1 + n^2)^2 / (1 + 2n^2)$, we get the Nakagami- n (Rice) fading model while by taking $m = (1 + q^2)^2 / (2(1 + 2q^4))$, the channel is made to behave more like a Nakagami- q (Hoyt) channel [SA05].

This chapter presents comparative outage probability (P_{out}), average error rate (P_e) and throughput (ζ) analysis for a multi-antenna regenerative relay network in which relay and destination may perform, MRC or SC of signal. Thus, there are four combinations of combining schemes possible, which are shown in Table-2.1. Closed form expressions of outage probability, average error rate and throughput, for all four combinations are derived. Non-identical fading channels have been assumed for source-destination and relay-destination pairs but identical fading channels have been considered

between source and relay. Outage and average error rate have also been investigated for the case when the receiving antenna elements in the relay experience identical but exponentially correlated fading. Analytical formulations have been carried out with integer values of m which represents severity of fading. Performance of such system, has been evaluated including the effects of relay placement, number of antennas installed on relay node, correlation among antenna elements, different transmission rate and various fading conditions. Parts of this work have been reported and published in open literature. In [KB09e], closed form expressions for outage probability and average error rate have been derived, when multi-antenna cooperative relay network operates in correlated Nakagami- m fading channel and both the relay and destination perform MRC combining of signals.

3.2 Channel Modeling

As shown in Fig. 2.1, the regenerative cooperative relay network considered here consists of multi-antenna relay (r), placed between source (s) and destination (d). Relay node is assumed to be equipped with one transmitting antenna and n receiving antennas¹. Due to half-duplex nature of relay, the source transmits to the relay and destination in first hop (i.e. $s \rightarrow r$ and $s \rightarrow d$). The multi-antenna relay receives signal from the source through multiple links and it either coherently combines them or selects the best link. If received signal is above the threshold of the decoder, the message is decoded and retransmitted to the destination (i.e. $r \rightarrow d$). If this condition is not fulfilled, only direct path is used. Signals received via direct path and via relay path are either coherently combined or best one of them is selected by d . Here, SNR (γ_{ij}) gamma distributed [SA05, Eq.(2.21)]

$$f_{\gamma_{ij}}(\gamma) = \frac{\lambda_{ij}^{m_{ij}} m_{ij}^{m_{ij}}}{\Gamma(m_{ij})} \gamma^{m_{ij}-1} \exp(-\lambda_{ij} m_{ij} \gamma), \quad (3.2.1)$$

where, $i \in \{s, r_o\}$, $j \in \{r_k, d\}$, $\lambda_{ij} = (2l_{ij}/l_{sd})^\psi / \omega$, ψ is path loss exponent, l_{ij} represents distance between node i and j , which is normalized by reference distance $l_{sd}/2$, ω is the SNR at reference point, m_{ij} is severity of fading parameter. In this chapter, independent and identically distributed (i.i.d.) fading between $s \rightarrow r$ (i.e. $\forall \lambda_{sr_k} = \bar{\lambda}_{sr}$ and $\forall m_{sr_k} = m_{sr}$) have been considered. So the PDF of received SNR at r when it is equipped with n antennas and perform MRC [YA05]

$$f_{\gamma_{sr}}^{mrc}(\gamma) = \frac{(\bar{\lambda}_{sr} m_{sr})^{nm_{sr}}}{\Gamma(nm_{sr})} \gamma^{nm_{sr}-1} \exp(-\bar{\lambda}_{sr} m_{sr} \gamma). \quad (3.2.2)$$

¹As defined earlier, symbol r_o represents transmitting antenna of r and r_k represents the k^{th} receiving antenna of r .

In case when r perform SC, PDF of received SNR at r can be calculated with the help of [KK08b, Eq.(6)]

$$f_{\gamma_{sr}}^{sc}(\gamma) = \frac{n\bar{\lambda}_{sr}^{m_{sr}} m_{sr}^{m_{sr}}}{\Gamma(m_{sr})} \gamma^{m_{sr}-1} \exp(-\bar{\lambda}_{sr} m_{sr} \gamma) \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \gamma)}{\Gamma(m_{sr})} \right\}^{n-1}. \quad (3.2.3)$$

For the case when antenna elements of relay experience identical but exponentially correlated fading and performs MRC, PDF of received SNR (γ_{sr}) at r can be given as [SA05, Eq.(9.215)]

$$f_{\gamma_{sr}}^{corr-mrc}(\gamma) = \frac{\gamma^{m_{sr}n^2/r_\rho-1} \exp\left(-\frac{m_{sr}\bar{\lambda}_{sr}n}{r_\rho}\gamma\right)}{\Gamma\left(\frac{m_{sr}n^2}{r_\rho}\right) \left(\frac{r_\rho}{m_{sr}\bar{\lambda}_{sr}n}\right)^{(m_{sr}n^2/r_\rho)}}, \quad (3.2.4)$$

here $r_\rho = n + \frac{2\sqrt{\rho}}{1-\sqrt{\rho}} \left(n - \frac{1-\rho^{n/2}}{1-\sqrt{\rho}}\right)$, ρ is exponential power correlation coefficient. In first hop, if channel condition between $s \rightarrow r$ link (after coherent addition in case of MRC or selection of best link for SC) is above the particular threshold, then relay is assumed to decode the message received from the source. In this condition, mutual information (I), transmitted by the source is greater than target data rate R (spectral efficiency) [LW03]:

$$I = \begin{cases} \frac{1}{2} \log_2 \left[1 + \sum_{k=1}^n \gamma_{sr_k} \right] > R & \text{for MRC} \\ \frac{1}{2} \log_2 [1 + \max(\gamma_{sr_k})] > R & \text{for SC.} \end{cases} \quad (3.2.5)$$

In equation (3.2.5), logarithm is multiplied with 1/2 because such system operates in two time-slots and utilize only 1/2 part of channel.

3.2.1 Probability of relay in inactive mode

Probability that the relay would not transmit (inactive mode) is given by

$$P[I \leq R] = \begin{cases} P \left[\sum_{k=1}^n \gamma_{sr_k} \leq \chi \right] & \text{For MRC} \\ P [\max(\gamma_{sr_k}) \leq \chi] & \text{For SC,} \end{cases} \quad (3.2.6)$$

where $\chi = 2^{2R} - 1$ is the threshold. So, (3.2.6) can be evaluated with the help of (3.2.2), (3.2.3) and [GR07, Eq.(3.381.1)]

$$P[I \leq R] = \begin{cases} \frac{\Gamma(nm_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(nm_{sr})} & \text{For MRC} \\ \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \right\}^n & \text{For SC} \end{cases} \quad (3.2.7)$$

where $\Gamma(\cdot, \cdot)$, $\Gamma(\cdot)$ are upper incomplete gamma function [GR07, Eq.(8.350.1)] and gamma function [GR07, Eq.(8.310.1)] respectively. In case antenna elements of relay are effected with identical but

exponentially correlated fading and perform MRC, the probability that the relay would not transmit (inactive mode), can be evaluated from (3.2.4)

$$P [I \leq R] = \int_0^{\chi} f_{\gamma_{sr}}^{corr-mrc}(\gamma) d\gamma, \quad (3.2.8)$$

Evaluation of (3.2.8) can be carried out with the help of [GR07, Eq.(3.381.1)]

$$P [I \leq R] = \frac{\Gamma(m_{sr}n^2/r_\rho, m_{sr}n\bar{\lambda}_{sr}\chi/r_\rho)}{\Gamma(m_{sr}n^2/r_\rho)}, \quad (3.2.9)$$

Probability that relay would transmit (active mode)

$$P [I > R] = 1 - P [I \leq R]. \quad (3.2.10)$$

3.2.2 PDF of received SNR based on link condition

Let, random variable Θ models the received SNR at d via $s \rightarrow r \rightarrow d$ link, which take-care the fading on both side of relay link. When relay is inactive, then conditional PDF of RV Θ is given as

$$f_{\Theta|I \leq R}(\theta) = \delta(\theta). \quad (3.2.11)$$

For the case when the relay is active, conditional PDF of RV Θ can be written as

$$f_{\Theta|I > R}(\theta) = \frac{\lambda_{r_{od}}^{m_{r_{od}}} m_{r_{od}}^{m_{r_{od}}}}{\Gamma(m_{r_{od}})} \theta^{m_{r_{od}}-1} \exp(-\lambda_{r_{od}} m_{r_{od}} \theta). \quad (3.2.12)$$

3.2.3 PDF of total received SNR

From the theorem on total probability, PDF of received SNR through relay link can be expressed as

$$f_{\Theta}^{srd}(\theta) = f_{\Theta|I \leq R}(\theta) P [I \leq R] + f_{\Theta|I > R}(\theta) P [I > R]. \quad (3.2.13)$$

The MGF² of $f_{\Theta}^{srd}(\theta)$, through relay link can be written as

$$M_{srd}(s) = P [I \leq R] + P [I > R] \left(\frac{\lambda_{r_{od}} m_{r_{od}}}{s + \lambda_{r_{od}} m_{r_{od}}} \right)^{m_{r_{od}}}. \quad (3.2.14)$$

Similarly, MGF of direct link can be given as

$$M_{sd}(s) = \left(\frac{\lambda_{sd} m_{sd}}{s + \lambda_{sd} m_{sd}} \right)^{m_{sd}}. \quad (3.2.15)$$

²MGF = $\int_0^{\infty} f_{\Theta}^{srd}(\theta) \exp(-s\theta) d\theta$

MRC at Destination

For the case, when channels between $s \rightarrow r \rightarrow d$ and $s \rightarrow d$ are assumed to be independent, MGF of equivalent link is given by

$$M_T(s) = M_{srd}(s)M_{sd}(s), \quad (3.2.16)$$

$M_T(s)$ can be simplified as [GR07, Eq.(2.102)]

$$M_T(s) = P[I \leq R] \left(\frac{m_{sd}\lambda_{sd}}{s+m_{sd}\lambda_{sd}} \right)^{m_{sd}} + P[I > R] \times \left[\sum_{\alpha=1}^{m_{sd}} \frac{A_\alpha}{(s+m_{sd}\lambda_{sd})^\alpha} + \sum_{\beta=1}^{m_{r_0d}} \frac{B_\beta}{(s+m_{r_0d}\lambda_{r_0d})^\beta} \right], \quad (3.2.17)$$

where $A_{m_{sd}-k+1} = \frac{\psi_A^{(k-1)}(-m_{sd}\lambda_{sd})}{(k-1)!}$, $\psi_A(s) = \frac{(m_{sd}\lambda_{sd})^{m_{sd}}(m_{r_0d}\lambda_{r_0d})^{m_{r_0d}}}{(s+m_{r_0d}\lambda_{r_0d})^{m_{r_0d}}}$, $B_{m_{r_0d}-k+1} = \frac{\psi_B^{(k-1)}(-m_{r_0d}\lambda_{r_0d})}{(k-1)!}$, $\psi_B(s) = \frac{(m_{sd}\lambda_{sd})^{m_{sd}}(m_{r_0d}\lambda_{r_0d})^{m_{r_0d}}}{(s+m_{sd}\lambda_{sd})^{m_{sd}}}$. Details for partial fraction of the expression is given in section A.2.

Similarly $M_T(s)/s$ can be simplified as [GR07, Eq.(2.102)]

$$\frac{M_T(s)}{s} = P[I \leq R] \left[\frac{1}{s} + \sum_{\alpha=1}^{m_{sd}} \frac{C_\alpha}{(s+\lambda_{sd}m_{sd})^\alpha} \right] + P[I > R] \times \left[\frac{1}{s} + \sum_{\alpha=1}^{m_{sd}} \frac{D_\alpha}{(s+\lambda_{sd}m_{sd})^\alpha} + \sum_{\beta=1}^{m_{r_0d}} \frac{E_\beta}{(s+\lambda_{r_0d}m_{r_0d})^\beta} \right] \quad (3.2.18)$$

here $C_{m_{sd}-k+1} = \frac{\psi_C^{(k-1)}(-\lambda_{sd}m_{sd})}{(k-1)!} (\lambda_{sd}m_{sd})^{m_{sd}}$, $\psi_C(s) = \frac{1}{s}$, $D_{m_{sd}-k+1} = \frac{\psi_D^{(k-1)}(-\lambda_{sd}m_{sd})}{(k-1)!} \times (\lambda_{sd}m_{sd})^{m_{sd}} (\lambda_{r_0d}m_{r_0d})^{m_{r_0d}}$, $\psi_D(s) = \frac{1}{s(s+\lambda_{r_0d}m_{r_0d})^{m_{r_0d}}}$, $E_{m_{r_0d}-k+1} = \frac{\psi_E^{(k-1)}(-\lambda_{r_0d}m_{r_0d})}{(k-1)!} \times (\lambda_{sd}m_{sd})^{m_{sd}} (\lambda_{r_0d}m_{r_0d})^{m_{r_0d}}$, $\psi_E(s) = \frac{1}{s(s+\lambda_{sd}m_{sd})^{m_{sd}}}$. From (3.2.17), PDF of received SNR at d can be calculated, by taking inverse Laplace transform of $M_T(s)$ i.e.

$$f_\Theta^{(1)}(\theta) = \frac{(m_{sd}\lambda_{sd})^{m_{sd}} P[I \leq R]}{\Gamma(m_{sd})} \theta^{m_{sd}-1} \exp(-m_{sd}\lambda_{sd}\theta) + P[I > R] \left[\sum_{\alpha=1}^{m_{sd}} \frac{A_\alpha \theta^{\alpha-1}}{(\alpha-1)!} \exp(-m_{sd}\lambda_{sd}\theta) + \sum_{\beta=1}^{m_{r_0d}} \frac{B_\beta \theta^{\beta-1}}{(\beta-1)!} \exp(-m_{r_0d}\lambda_{r_0d}\theta) \right] \quad (3.2.19)$$

SC at Destination

CDF of received SNR through direct link can be calculated from (3.2.1), [GR07, Eq.(3.381.1)], [GR07, Eq.(8.352.1)]

$$F_{sd}(\gamma) = 1 - \exp(-m_{sd}\lambda_{sd}\gamma) \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd}\lambda_{sd}\gamma)^\alpha}{\alpha!}. \quad (3.2.20)$$

Similarly, CDF of received SNR through relay link can be calculated from (3.2.13)

$$F_{srd}(\gamma) = P[I \leq R] + P[I > R] \times \left[1 - \exp(-m_{rod}\lambda_{rod}\gamma) \sum_{\beta=0}^{m_{rod}-1} \frac{(m_{rod}\lambda_{rod}\gamma)^\beta}{\beta!} \right] \quad (3.2.21)$$

So, CDF of total received SNR can be given as

$$F(\gamma) = F_{sd}(\gamma) F_{srd}(\gamma). \quad (3.2.22)$$

From (3.2.20),(3.2.21) and (3.2.22), CDF of total received SNR can be simplified as

$$\begin{aligned} F(\gamma) = & P[I \leq R] \left[1 - \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd}\lambda_{sd})^\alpha}{\alpha!} \gamma^\alpha \exp(-m_{sd}\lambda_{sd}\gamma) \right] \\ & + P[I > R] \left[1 - \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd}\lambda_{sd})^\alpha}{\alpha!} \gamma^\alpha \exp(-m_{sd}\lambda_{sd}\gamma) \right. \\ & \left. - \sum_{\beta=0}^{m_{rod}-1} \frac{(m_{rod}\lambda_{rod})^\beta}{\beta!} \gamma^\beta \exp(-m_{rod}\lambda_{rod}\gamma) \right. \\ & \left. + \sum_{\alpha=0}^{m_{sd}-1} \sum_{\beta=0}^{m_{rod}-1} \frac{(m_{sd}\lambda_{sd})^\alpha (m_{rod}\lambda_{rod})^\beta}{\alpha!\beta!} \right. \\ & \left. \times \gamma^{\alpha+\beta} \exp\{-(m_{sd}\lambda_{sd} + m_{rod}\lambda_{rod})\gamma\} \right] \quad (3.2.23) \end{aligned}$$

Differentiating (3.2.23) with respect to γ gives PDF of total received SNR at d

$$\begin{aligned} f_{\Theta}^{(2)}(\gamma) = & P[I \leq R] \left[(-1) \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd}\lambda_{sd})^\alpha}{\alpha!} \xi(m_{sd}\lambda_{sd}, \alpha) \right] + P[I > R] \\ & \times \left[(-1) \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd}\lambda_{sd})^\alpha}{\alpha!} \xi(m_{sd}\lambda_{sd}, \alpha) + (-1) \sum_{\beta=0}^{m_{rod}-1} \frac{(m_{rod}\lambda_{rod})^\beta}{\beta!} \xi(m_{rod}\lambda_{rod}, \beta) \right. \\ & \left. + \sum_{\alpha=0}^{m_{sd}-1} \sum_{\beta=0}^{m_{rod}-1} \frac{(m_{sd}\lambda_{sd})^\alpha (m_{rod}\lambda_{rod})^\beta}{\alpha!\beta!} \xi\{(m_{sd}\lambda_{sd} + m_{rod}\lambda_{rod}), \alpha + \beta\} \right] \quad (3.2.24) \end{aligned}$$

where $\xi(a, b) = b\gamma^{b-1} \exp(-a\gamma) - a\gamma^b \exp(-a\gamma)$.

3.3 System Performance

The performance of such system has been evaluated on the basis of outage probability, average error rate and throughput.

3.3.1 MRC-MRC Based System

Outage Probability ($P_{out}^{MRC-MRC}$)

Outage occurs when received SNR, falls below a certain specified threshold. Outage probability, can be given as [SA05, Eq.(1.4)]

$$P_{out} = \int_0^\chi f_\Theta^{(1)}(\theta) d\theta, \quad (3.3.1)$$

so, outage probability can be calculated with the help of (3.2.19), (3.3.1) and [GR07, Eq.(3.381.1)]

$$\begin{aligned} P_{out}^{MRC-MRC} &= \frac{\Gamma(nm_{sr}, \bar{\lambda}_{sr}m_{sr}\chi) \Gamma(m_{sd}, m_{sd}\lambda_{sd}\chi)}{\Gamma(nm_{sr}) \Gamma(m_{sd})} \\ &+ \left\{ 1 - \frac{\Gamma(nm_{sr}, \bar{\lambda}_{sr}m_{sr}\chi)}{\Gamma(nm_{sr})} \right\} \left[\sum_{\alpha=1}^{m_{sd}} \frac{A_\alpha \Gamma(\alpha, m_{sd}\lambda_{sd}\chi)}{(\alpha-1)! (m_{sd}\lambda_{sd})^\alpha} \right. \\ &\left. + \sum_{\beta=1}^{m_{rod}} \frac{B_\beta \Gamma(\beta, m_{rod}\lambda_{rod}\chi)}{(\beta-1)! (m_{rod}\lambda_{rod})^\beta} \right] \end{aligned} \quad (3.3.2)$$

Alternatively from (3.2.18), outage probability can also be found out, by taking inverse Laplace transform of $M_T(s)/s$, evaluated at χ [KB09e, Eq.(12)]

$$\begin{aligned} P_{out}^{MRC-MRC} &= P[I \leq R] \left[1 + \sum_{\alpha=1}^{m_{sd}} \frac{C_\alpha \chi^{\alpha-1}}{(\alpha-1)!} \exp(-\lambda_{sd}m_{sd}\chi) \right] + P[I > R] \\ &\times \left[1 + \sum_{\alpha=1}^{m_{sd}} \frac{D_\alpha \chi^{\alpha-1}}{(\alpha-1)!} \exp(-\lambda_{sd}m_{sd}\chi) + \sum_{\beta=1}^{m_{rod}} \frac{E_\beta \chi^{\beta-1}}{(\beta-1)!} \exp(-\lambda_{rod}m_{rod}\chi) \right] \end{aligned} \quad (3.3.3)$$

Average error rate ($P_e^{MRC-MRC}$)

Average error rate is a standard performance measure of diversity systems operating over fading channels. For M -PSK modulated signal average error rate can be define as [SA05, Eq.(5.1)]

$$P_e = \int_0^\infty Q(\sqrt{c\theta}) f_\Theta^{(1)}(\theta) d\theta, \quad (3.3.4)$$

where, $c = 2 \sin^2(\pi/M)$. Average error rate from (3.3.4), can be evaluated from (3.2.19) and [EM95, Eq.(A8)]

$$P_e^{MRC-MRC} = \frac{\Gamma(nm_{sr}, \bar{\lambda}_{sr}m_{sr}\chi) (m_{sd}\lambda_{sd})^{m_{sd}}}{\Gamma(nm_{sr}) \Gamma(m_{sd})} \mu\{m_{sd}\lambda_{sd}, m_{sd}\} + \left\{ 1 - \frac{\Gamma(nm_{sr}, \bar{\lambda}_{sr}m_{sr}\chi)}{\Gamma(nm_{sr})} \right\} \left[\sum_{\alpha=1}^{m_{sd}} \frac{A_\alpha \mu\{m_{sd}\lambda_{sd}, \alpha\}}{(\alpha-1)!} + \sum_{\beta=1}^{m_{rod}} \frac{B_\alpha \mu\{m_{rod}\lambda_{rod}, \beta\}}{(\beta-1)!} \right] \quad (3.3.5)$$

here $\mu\{x, y\} = \frac{\Gamma(y)}{x^y} \left\{ \sqrt{\frac{c-(2x+c)^{-y}\Gamma(y+0.5)}{2x+c}} \frac{1}{2\sqrt{\pi}\Gamma(y+1)(2x)^{-y}} \right\} {}_2F_1(1, y+0.5; y+1; \frac{2x}{2x+c})$, ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ is Gauss hypergeometric function [GR07, Eq.(9.100)]. Average error rate for M-PSK modulated signal can also be defined as [AG99, Eq.(20)]

$$P_e^{MRC-MRC} = \frac{1}{\pi} \int_0^{(M-1)\pi/M} M_T \left(\frac{a}{2 \sin^2(\theta)} \right) d\theta, \quad (3.3.6)$$

here, a depends on the modulation scheme [SA05, Sec.(9.2.3)]. So, average error rate can be evaluated from (3.2.17) and [KB09e, Eq.(14)]

$$P_e^{MRC-MRC} = P[I \leq R] \Psi \left(m_{sd}, \frac{1}{\lambda_{sd}m_{sd}} \right) + P[I > R] \left[\sum_{\alpha=1}^{m_{sd}} \frac{A_\alpha}{(\lambda_{sd}m_{sd})^\alpha} \times \Psi \left(\alpha, \frac{1}{\lambda_{sd}m_{sd}} \right) + \sum_{\alpha=1}^{m_{rod}} \frac{B_\alpha}{(\lambda_{rod}m_{rod})^\alpha} \Psi \left(\alpha, \frac{1}{\lambda_{rod}m_{rod}} \right) \right] \quad (3.3.7)$$

where, $\Psi(\cdot, \cdot)$ is error rate of various modulation schemes in standard fading channels, for BPSK $a = 2 \sin^2(\pi/M)$, $M=2$, $\Psi(\nu, c) = \{\xi(c)\}^\nu \sum_{k=0}^{\nu-1} \binom{\nu-1+k}{k} \{1-\xi(c)\}^k$ [AG99, Eq.(64)], $\xi(c) = \frac{1}{2} \left(1 - \sqrt{\frac{c}{1+c}} \right)$.

Throughput ($\zeta^{MRC-MRC}$)

The throughput of the system can be calculated from (3.3.2) and [AV08, Eq.(26)]

$$\zeta^{MRC-MRC} = \frac{R}{2} (1 - P_{out}^{MRC-MRC}). \quad (3.3.8)$$

3.3.2 SC-MRC Based System

Outage Probability (P_{out}^{SC-MRC})

Similarly, outage probability for this case can be derived with the help of (3.2.7) and (3.3.1)

$$\begin{aligned}
 P_{out}^{SC-MRC} = & \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \right\}^n \frac{\Gamma(m_{sd}, m_{sd} \lambda_{sd} \chi)}{\Gamma(m_{sd})} \\
 & + \left[1 - \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \right\}^n \right] \left[\sum_{\alpha=1}^{m_{sd}} \frac{A_{\alpha} \Gamma(\alpha, m_{sd} \lambda_{sd} \chi)}{(\alpha-1)! (m_{sd} \lambda_{sd})^{\alpha}} \right. \\
 & \left. + \sum_{\beta=1}^{m_{rod}} \frac{B_{\beta} \Gamma(\beta, m_{rod} \lambda_{rod} \chi)}{(\beta-1)! (m_{rod} \lambda_{rod})^{\beta}} \right]
 \end{aligned} \tag{3.3.9}$$

Average error rate (P_e^{SC-MRC})

Average error rate for this case can be calculated with the help of (3.2.7) and (3.3.4)

$$\begin{aligned}
 P_e^{SC-MRC} = & \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \right\}^n \frac{(m_{sd} \lambda_{sd})^{m_{sd}}}{\Gamma(m_{sd})} \mu \{m_{sd} \lambda_{sd}, m_{sd}\} \\
 & + \left[1 - \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \right\}^n \right] \left[\sum_{\alpha=1}^{m_{sd}} \frac{A_{\alpha} \mu \{m_{sd} \lambda_{sd}, \alpha\}}{(\alpha-1)!} \right. \\
 & \left. + \sum_{\beta=1}^{m_{rod}} \frac{B_{\beta} \mu \{m_{rod} \lambda_{rod}, \beta\}}{(\beta-1)!} \right]
 \end{aligned} \tag{3.3.10}$$

Throughput (ζ^{SC-MRC})

Throughput of such system can be calculated as

$$\zeta^{SC-MRC} = \frac{R}{2} (1 - P_{out}^{SC-MRC}) . \tag{3.3.11}$$

3.3.3 MRC-SC Based System

Outage Probability (P_{out}^{MRC-SC})

Outage probability at χ can be calculated with the help of (3.2.7) and (3.2.23)

$$\begin{aligned}
P_{out}^{MRC-SC} &= F(\chi) \\
&= \frac{\Gamma(nm_{sr}, \bar{\lambda}_{sr}m_{sr}\chi)}{\Gamma(nm_{sr})} \left[1 - \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd}\lambda_{sd})^\alpha}{\alpha!} \chi^\alpha \exp(-m_{sd}\lambda_{sd}\chi) \right] \\
&\quad + \left\{ 1 - \frac{\Gamma(nm_{sr}, \bar{\lambda}_{sr}m_{sr}\chi)}{\Gamma(nm_{sr})} \right\} \left[1 - \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd}\lambda_{sd})^\alpha}{\alpha!} \chi^\alpha \exp(-m_{sd}\lambda_{sd}\chi) \right. \\
&\quad \left. - \sum_{\beta=0}^{m_{r_{od}}-1} \frac{(m_{r_{od}}\lambda_{r_{od}})^\beta}{\beta!} \chi^\beta \exp(-m_{r_{od}}\lambda_{r_{od}}\chi) \right. \\
&\quad \left. + \sum_{\alpha=0}^{m_{sd}-1} \sum_{\beta=0}^{m_{r_{od}}-1} \frac{(m_{sd}\lambda_{sd})^\alpha (m_{r_{od}}\lambda_{r_{od}})^\beta}{\alpha!\beta!} \chi^{\alpha+\beta} \exp\{-(m_{sd}\lambda_{sd} + m_{r_{od}}\lambda_{r_{od}})\chi\} \right]. \tag{3.3.12}
\end{aligned}$$

Average error rate (P_e^{MRC-SC})

Average error rate for this case can be given as

$$P_e = \int_0^\infty Q(\sqrt{c\theta}) f_\Theta^{(2)}(\theta) d\theta, \tag{3.3.13}$$

so (3.3.13) can be given in closed form

$$\begin{aligned}
P_e^{MRC-SC} &= \frac{\Gamma(nm_{sr}, \bar{\lambda}_{sr}m_{sr}\chi)}{\Gamma(nm_{sr})} \left[(-1) \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd}\lambda_{sd})^\alpha}{\alpha!} \varphi(m_{sd}\lambda_{sd}, \alpha) \right] \\
&\quad + \left\{ 1 - \frac{\Gamma(nm_{sr}, \bar{\lambda}_{sr}m_{sr}\chi)}{\Gamma(nm_{sr})} \right\} \left[(-1) \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd}\lambda_{sd})^\alpha}{\alpha!} \varphi(m_{sd}\lambda_{sd}, \alpha) \right. \\
&\quad \left. + (-1) \sum_{\beta=0}^{m_{r_{od}}-1} \frac{(m_{r_{od}}\lambda_{r_{od}})^\beta}{\beta!} \varphi(m_{r_{od}}\lambda_{r_{od}}, \beta) + \sum_{\alpha=0}^{m_{sd}-1} \sum_{\beta=0}^{m_{r_{od}}-1} \frac{(m_{sd}\lambda_{sd})^\alpha (m_{r_{od}}\lambda_{r_{od}})^\beta}{\alpha!\beta!} \right. \\
&\quad \left. \times \varphi\{(m_{sd}\lambda_{sd} + m_{r_{od}}\lambda_{r_{od}}), \alpha + \beta\} \right], \tag{3.3.14}
\end{aligned}$$

here $\varphi(a, b) = b\mu(a, b) - a\mu(a, b + 1)$.

Throughput (ζ^{MRC-SC})

Throughput for this case can be written as

$$\zeta^{MRC-SC} = \frac{R}{2} (1 - P_{out}^{MRC-SC}). \tag{3.3.15}$$

3.3.4 SC-SC Based System

Outage Probability (P_{out}^{SC-SC})

Outage probability of such system can be calculated with the help of (3.2.7) and (3.2.23)

$$\begin{aligned}
P_{out}^{SC-SC} &= F(\chi) \\
&= \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \right\}^n \times \left[1 - \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd} \lambda_{sd})^\alpha}{\alpha!} \chi^\alpha \exp(-m_{sd} \lambda_{sd} \chi) \right] \\
&\quad + \left[1 - \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \right\}^n \right] \left[1 - \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd} \lambda_{sd})^\alpha}{\alpha!} \chi^\alpha \exp(-m_{sd} \lambda_{sd} \chi) \right] \\
&\quad - \sum_{\beta=0}^{m_{rod}-1} \frac{(m_{rod} \lambda_{rod})^\beta}{\beta!} \chi^\beta \exp(-m_{rod} \lambda_{rod} \chi) + \sum_{\alpha=0}^{m_{sd}-1} \sum_{\beta=0}^{m_{rod}-1} \frac{(m_{sd} \lambda_{sd})^\alpha (m_{rod} \lambda_{rod})^\beta}{\alpha! \beta!} \chi^{\alpha+\beta} \\
&\quad \times \exp\{-(m_{sd} \lambda_{sd} + m_{rod} \lambda_{rod}) \chi\}. \tag{3.3.16}
\end{aligned}$$

Average error rate (P_e^{SC-SC})

Average error rate can be given in close form as below (3.2.7) and (3.3.13)

$$\begin{aligned}
P_e^{SC-SC} &= \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \right\}^n \left\{ (-1) \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd} \lambda_{sd})^\alpha}{\alpha!} \varphi(m_{sd} \lambda_{sd}, \alpha) \right\} \\
&\quad + \left[1 - \left\{ \frac{\Gamma(m_{sr}, \bar{\lambda}_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \right\}^n \right] \left[(-1) \sum_{\alpha=0}^{m_{sd}-1} \frac{(m_{sd} \lambda_{sd})^\alpha}{\alpha!} \varphi(m_{sd} \lambda_{sd}, \alpha) \right] \\
&\quad + (-1) \sum_{\beta=0}^{m_{rod}-1} \frac{(m_{rod} \lambda_{rod})^\beta}{\beta!} \varphi(m_{rod} \lambda_{rod}, \beta) + \sum_{\alpha=0}^{m_{sd}-1} \sum_{\beta=0}^{m_{rod}-1} \frac{(m_{sd} \lambda_{sd})^\alpha (m_{rod} \lambda_{rod})^\beta}{\alpha! \beta!} \\
&\quad \times \varphi\{(m_{sd} \lambda_{sd} + m_{rod} \lambda_{rod}), \alpha + \beta\}. \tag{3.3.17}
\end{aligned}$$

Throughput (ζ^{SC-SC})

Throughput of such system can be calculated as

$$\zeta^{SC-SC} = \frac{R}{2} (1 - P_{out}^{SC-SC}). \tag{3.3.18}$$

3.4 Numerical Results and Discussions

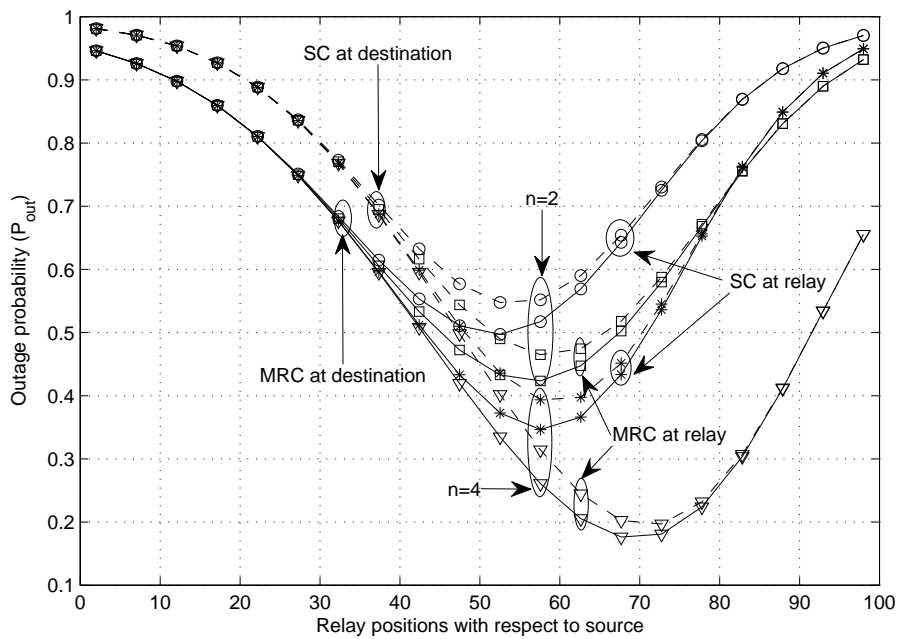
In evaluating the performance of the system, s & d have been assumed to be located at $(0,0)$ and $(0,100)$, respectively. R and ω are assumed to be 1 and 7 dB, respectively. Path loss exponent (ψ) between $s \rightarrow r$, $s \rightarrow d$ and $r \rightarrow d$ is taken to be 3. Outage probability and average error rate has been computed when r is placed on the line which joins s , d and the distance of r from s has been varied from 2 to 98. In Fig. 3.1(a) and Fig. 3.1(b), outage performance of this network are plotted for $m=1$ and 3, respectively. Similarly, average error rate for BPSK signals are plotted in Fig. 3.2(a) and Fig. 3.2(b) for $m=1$ and 3, respectively. It is observed that, when r is placed near s , overall performance is largely decided by the combining schemes that has been employed at the d , as for this condition both SC and MRC are equally effective in decoding the signal at the r . This is due to fact that, most of time received SNR at r through MRC/SC is higher than particular threshold, so r can perform decode and forward operation and d with MRC gives better result than d with SC. When r is near the d , choice of combining scheme at the d is less important as compared to choice of combining scheme at the r . This is due to the fact that r with MRC has higher probability to perform decode and forward operation and d has better probability to perform MRC/SC of signal (i.e. higher diversity order). With increment of n , optimum performance (minimum outage probability and average error rate) of such system gets shifted towards d because probability of decoding the message by r , increases with n , so r can be placed much far away from s . In Fig. 3.3 and Fig. 3.4, outage performance and error performance have been plotted for the case when relay is effected with identical but exponentially correlated fading, respectively. It is seen that effect of correlation among antenna element is more pronounced when relay is placed near the middle of s - d link. Throughput is modeled using (3.3.8), (3.3.11), (3.3.15) and (3.3.18). For determining the throughput, r is placed in between s - d link. In Fig. 3.5(a) and Fig. 3.5(b), throughput is plotted for various values of R , n and m . Here, one can observed that system operating with $MRC - MRC$ and $SC - SC$ gives upper and lower bound of throughput, respectively. At lower rate of transmission (i.e. R), threshold level ($\chi = 2^{2R} - 1$) for decoding at r would be low, so most of time received SNR at r after MRC/SC scheme is above the threshold level. In this case, system performance would be largely decided by combining scheme at d and MRC at d gives higher throughput. However, higher rate of transmission, increases decoding threshold level at r , so MRC at r have higher probability to perform decode and forward operation. In this case combining scheme at d is less important and throughput is largely depend on combining scheme at r .

It may be worthwhile to mention that in the previous chapter, we studied the multi-antenna relay

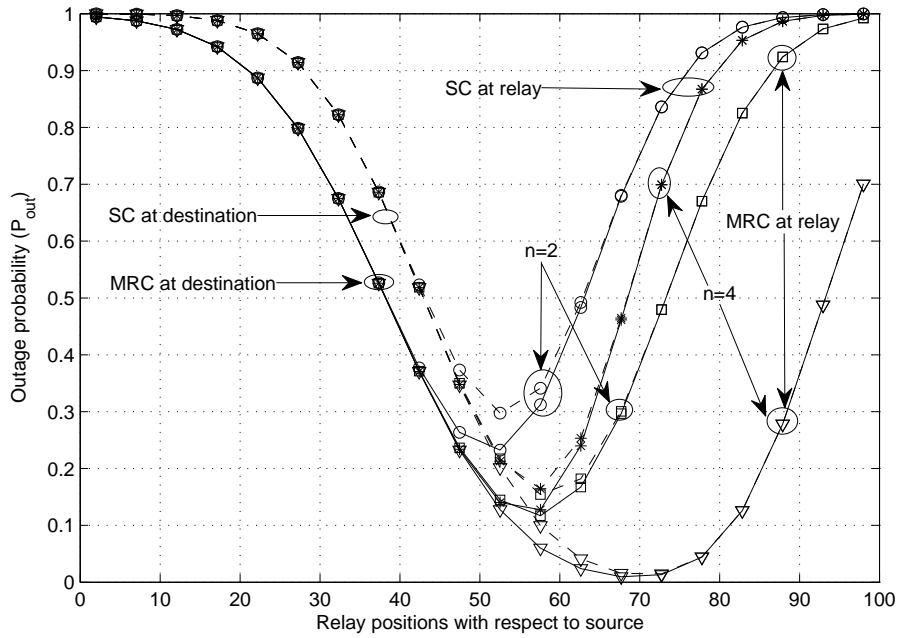
based system in Rayleigh fading channel and derived expressions for outage probability, average error rate, average received SNR and average capacity. Beside it we studied comparative performance of various types (type-1, type-2 and type-3) of operation of relay based system. In this chapter, we have considered more general channel (i.e. Nakagami- m) and studied only the type-1 operation. A special case when multi-antenna relay is effected with correlated fading is also considered. In this chapter we have derived the expressions for outage probability, average error rate and throughput. In this chapter, plots for various performance parameters have been plotted for $m=1$ also. Such plots match exactly with the corresponding plots in chapter 2. For example Fig. 3.1(a) matches with Fig. 2.3(a), Fig. 2.3(b). Similarly Fig. 3.2(a) matches with Fig. 2.4(a), Fig. 2.4(b). Throughput is considered in chapter 3 and plotted for the case of $m=1$ (i.e. Fig. 3.5) also, so the results given in this chapter for the throughput is directly applicable in chapter 2.

3.5 Conclusion

Analytical expressions of outage probability, average error rate and throughput, for multi-antenna cooperative relay network have been derived for integer value of m . It is seen that installation of more number of receiving antennas on relay improves its participation, hence system performance improves. In such case, relay can be placed towards destination for further improving the system performance. Severity of fading reduces with increasing value of m , hence system performance improves. In case relay antennas are effected with correlated fading then it is difficult to exploit spatial diversity effectively and hence system performance suffers. Data transmission rate and combining schemes at relay/destination also plays vital role on the system performance.

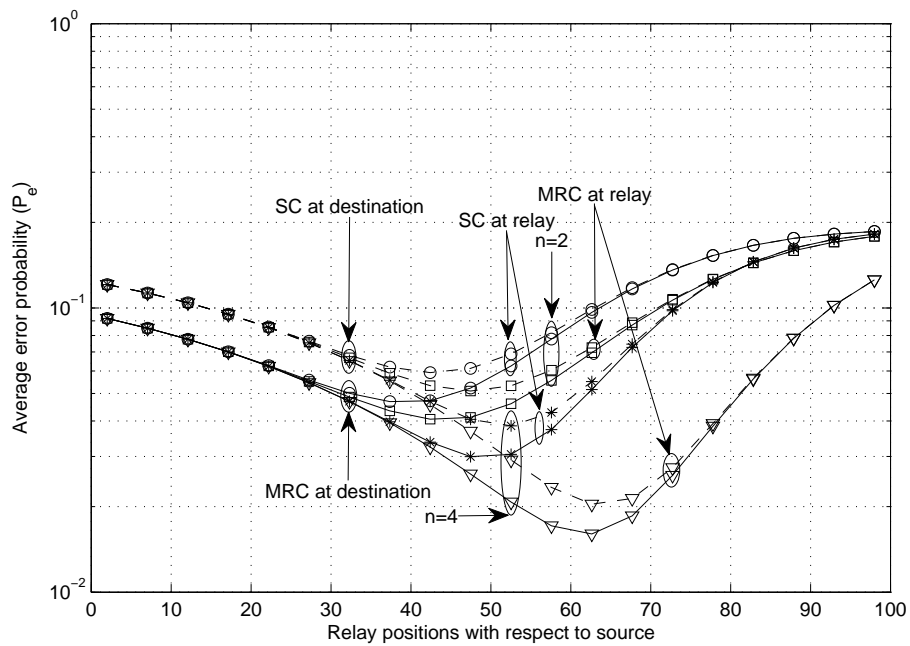


(a)

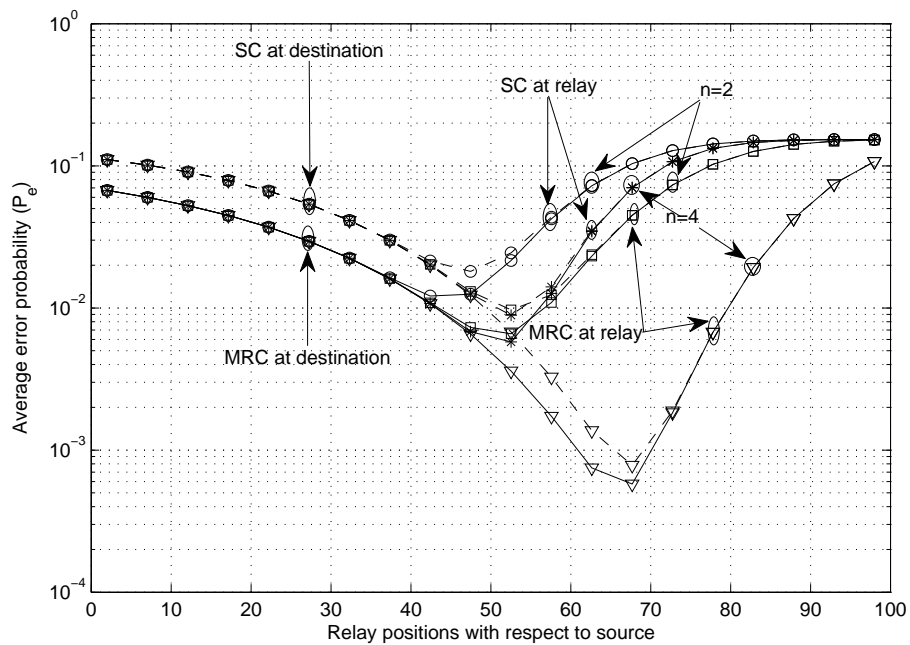


(b)

Figure 3.1: Outage Probability (at $R = 1$) of multi-antenna cooperative relay system (a) $m_{sr}=m_{r_o_d}=m_{sd}=1$, (b) $m_{sr}=m_{r_o_d}=m_{sd}=3$, when r placed at various locations between s and d .



(a)



(b)

Figure 3.2: Average error rate (at $R = 1$) of multi-antenna cooperative relay system (a) $m_{sr}=m_{r,d}=m_{sd}=1$, (b) $m_{sr}=m_{r,d}=m_{sd}=3$, when r placed at various locations between s and d .

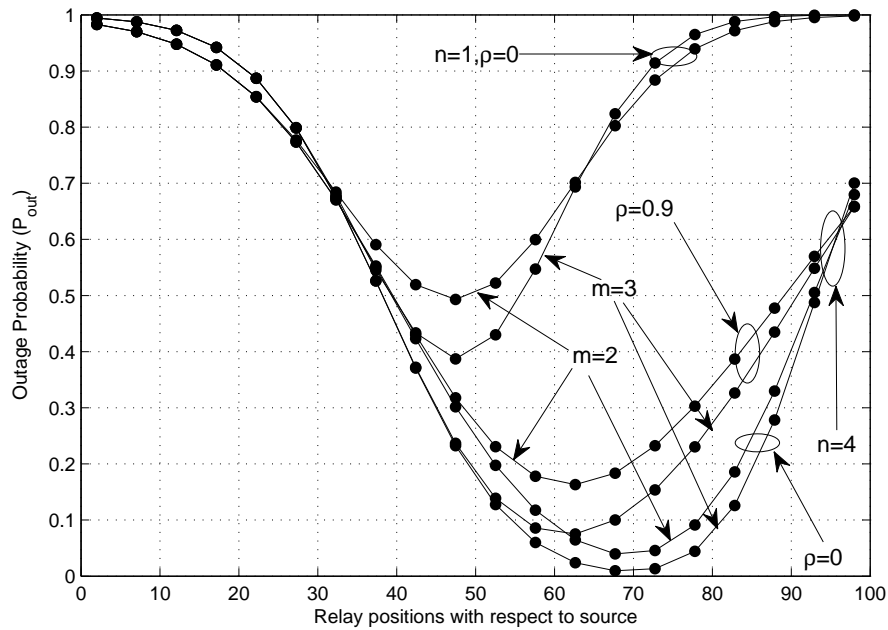


Figure 3.3: Outage performance of multi-antenna relay network ($m=m_{sr}=m_{rd}=m_{sd}$, $R = 1$), when r is effected with correlated fading and r, d perform MRC of signal.

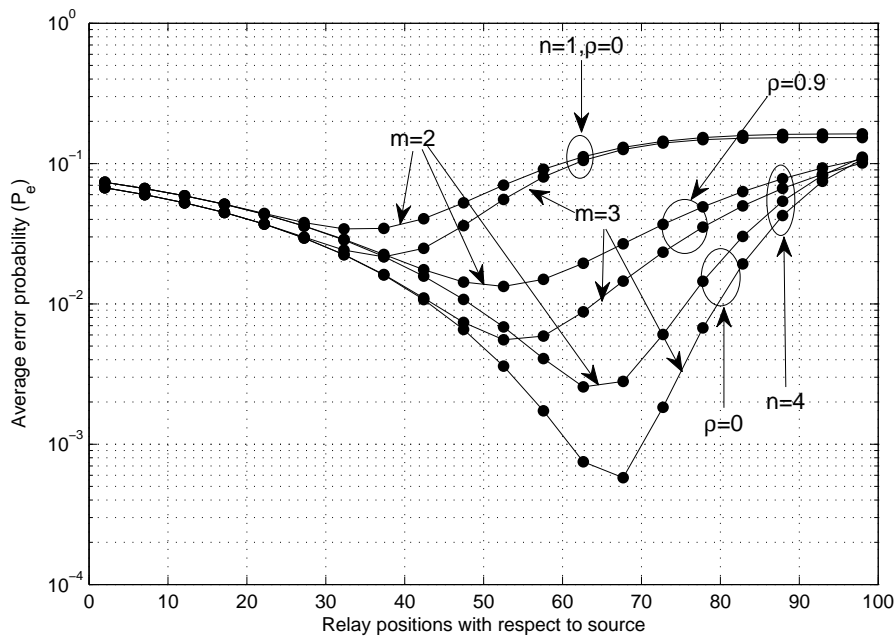
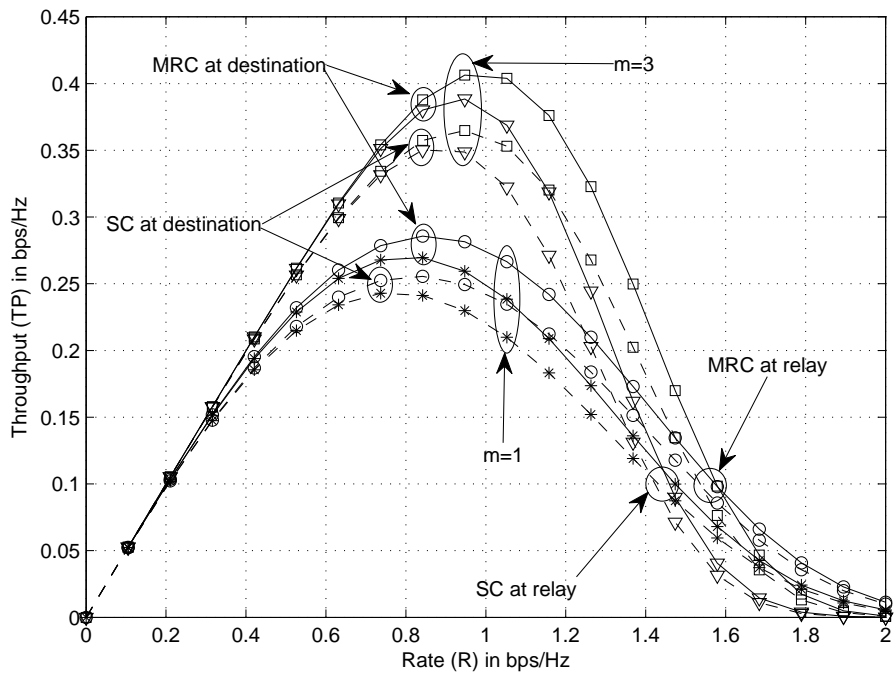
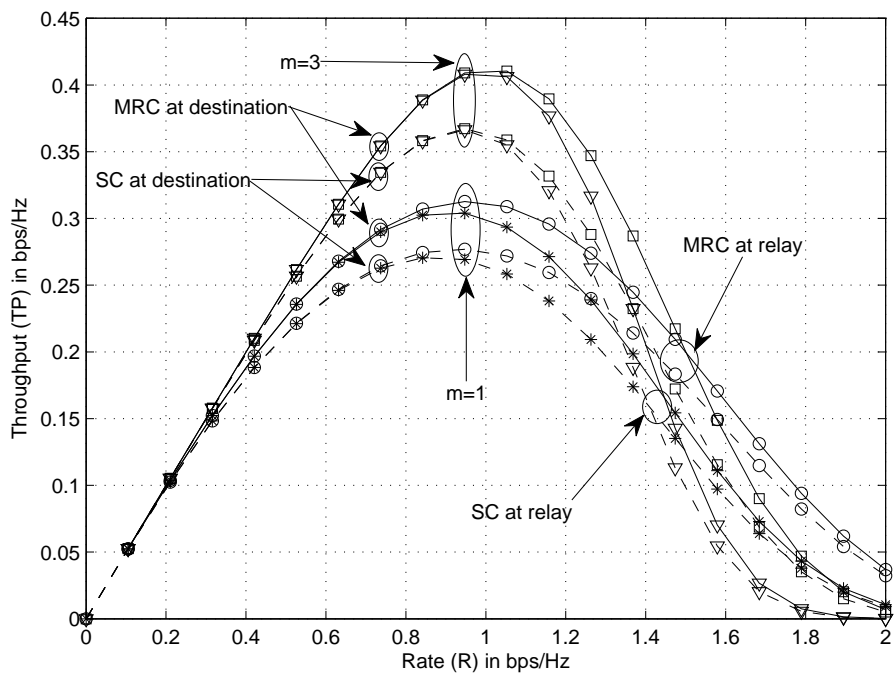


Figure 3.4: Average error rate of multi-antenna relay network ($m=m_{sr}=m_{rd}=m_{sd}$, $R = 1$), when r is effected with correlated fading and r, d perform MRC of signal.



(a)



(b)

Figure 3.5: Throughput of multi-antenna relay network (a) $n = 2$, (b) $n = 4$, at various R .

Chapter 4

Performance of Cooperative Relay Network Operating in Uplink of Multi-Antenna Base Station

4.1 Introduction

Communication through intermediate relay node, splits the channel between source and destination into two possibly shorter links, which improves the link quality as well as combat with harsh multi-path fading. In highly dense urban environment, cooperative diversity can be achieved with the help of user terminals [SEA03a]. These terminals are tiny wireless node, hence installation of multiple antennas are not possible. However, installation of multiple antennas at the base station is feasible. A cooperative relay network in which single antenna source and relay communicate with multi-antenna destination has been analyzed in this chapter. Similar type of structure is also investigated in [ZGL10], here authors investigate the effect of imperfect channel state information on the achievable diversity gain. Such system operate here in type-1 operation, which is given in chapter 2 (section 2.1). Closed form expressions of outage probability, average symbol error rate, average received SNR and channel capacity have been derived for such system model in Nakagami- m fading channel. Simplified expressions for this system model in Rayleigh fading channel are also presented. Comparative performance of such system with conventional SIMO (single input multiple output) system, in various severity of fading, different path-loss conditions and different number of antenna elements on destination, have also been studied. Some of the work presented here have been reported and published in open literature. In [KB09d], analytical expressions for outage probability, symbol error rate and end-to-end average received SNR

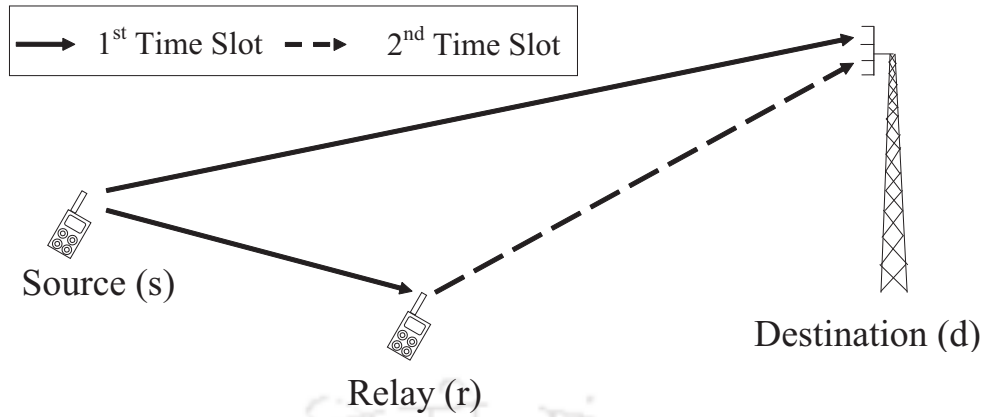


Figure 4.1: Two-hop cooperative relay communicating with multi-antenna base station.

are established in terms of infinite series, here such system operate in Rayleigh fading channel.

4.2 System Model

As shown in Fig. 4.1, communication between source (s) and destination (d) takes place with the help of supporting relay (r). Terminals s and r have single antenna but the terminal d have multiple antennas. Due to half-duplex nature of r , s transmits to the r and d in the first hop (i.e. $s \rightarrow r$ and $s \rightarrow d$). If received SNR at r is above the particular threshold (active mode), the message is decoded and retransmitted to the d in the next time slot (i.e. $r \rightarrow d$). Signal received via direct path and via relay path are coherently combined at d . If the received SNR at r is below the required threshold (inactive mode), then r remains silent and d receives the signal only through direct path. In this system model, channels between $s \rightarrow d$ and $r \rightarrow d$ are assumed to be independent and non-identical, because d is receiving the signal from transmitting nodes, located at different locations. However, signals received at d are identical, if they are coming from same place (i.e. from s or r). Here, received SNR at r (γ_{sr}) is gamma distributed, so PDF can be written as [SA05, Eq.(2.21)]

$$f_{\gamma_{sr}}(\gamma) = \frac{\lambda_{sr}^{m_{sr}} m_{sr}^{m_{sr}}}{\Gamma(m_{sr})} \gamma^{m_{sr}-1} \exp(-\lambda_{sr} m_{sr} \gamma) \quad (4.2.1)$$

$\lambda_{sr} = (2\ell_{sr}/\ell_{sd})^\psi / \omega$, ψ is path loss exponent, ω is the SNR at reference point, ℓ_{sr} represents distance between node s and r , which has been normalized here by half the distance between s and d (i.e. $\ell_{sd}/2$). Destination is equipped with multi-antenna array and performs MRC combining, so PDF of received SNR at d can be written as [YA05]

$$f_{\gamma_{ij}}(\gamma) = \frac{(\lambda_{ij} m_{ij})^{nm_{ij}}}{\Gamma(nm_{ij})} \gamma^{nm_{ij}-1} \exp(-\lambda_{ij} m_{ij} \gamma) \quad (4.2.2)$$

where $i \in \{s, r\}$, $j \in \{d\}$, n is the number of antennas at d , $\lambda_{ij} = (2l_{ij}/l_{sd})^\psi / \omega$, l_{ij} represents distance between node i and j .

4.3 Mathematical Analysis

Probability of relay transmission

Probability of relay in active mode can be given as

$$P[I > R] = P[\gamma_{sr} > \chi] = 1 - \int_0^\chi f_{sr}(\gamma) d\gamma, \quad (4.3.1)$$

where $\chi = 2^{2R} - 1$ is the threshold. Substituting (4.2.1) in (4.3.1) and solving integral the following expression is obtained

$$P[I > R] = 1 - \frac{\Gamma(m_{sr}, \lambda_{sr} m_{sr} \chi)}{\Gamma(m_{sr})} \quad (4.3.2)$$

Probability of relay being in inactive mode is given by

$$P[I \leq R] = 1 - P[I > R]. \quad (4.3.3)$$

PDF of received SNR based on link condition

Let, random variable Θ models the received SNR at d via $s \rightarrow r \rightarrow d$ link, which take-care the fading on both side of relay link. When the relay is inactive, conditional PDF of received SNR is given by

$$f_{\Theta|I \leq R}(\theta) = \delta(\theta). \quad (4.3.4)$$

For the case when relay is active, conditional PDF of received SNR can be written as

$$f_{\Theta|I > R}(\theta) = \frac{\lambda_{rd}^{nm_{rd}} m_{rd}^{nm_{rd}}}{\Gamma(nm_{rd})} \theta^{nm_{rd}-1} \exp(-\lambda_{rd} m_{rd} \theta) \quad (4.3.5)$$

PDF of total received SNR

The PDF of the received SNR can be expressed as [BH06]

$$f_{\Theta}^{srd}(\theta) = f_{\Theta|I \leq R}(\theta) P[I \leq R] + f_{\Theta|I > R}(\theta) P[I > R]. \quad (4.3.6)$$

The MGF¹ of $f_{\Theta}^{srd}(\theta)$, through relay link can be written as

$$M_{srd}(s) = P[I \leq R] + P[I > R] \left(\frac{m_{rd} \lambda_{rd}}{s + m_{rd} \lambda_{rd}} \right)^{nm_{rd}} \quad (4.3.7)$$

¹MGF = $\int_0^\infty f_{\Theta}^{srd}(\theta) \exp(-s\theta) d\theta$

On assuming the channels between $s \rightarrow r \rightarrow d$ and $s \rightarrow d$ are independent, MGF of equivalent link can be written as

$$M_T(s) = M_{srd}(s)M_{sd}(s), \quad (4.3.8)$$

where $M_{sd}(s) = \{m_{sd}\lambda_{sd}/(s + m_{sd}\lambda_{sd})\}^{nm_{sd}}$ is MGF of direct link. For the case when m_{sd}, m_{rd} are assumed to be integer then MGF of total received SNR can be simplified as

$$M_T(s) = P[I \leq R] \left(\frac{m_{sd}\lambda_{sd}}{s + m_{sd}\lambda_{sd}} \right)^{nm_{sd}} + P[I > R] \times \left[\sum_{\alpha=1}^{nm_{sd}} \frac{A_\alpha}{(s + m_{sd}\lambda_{sd})^\alpha} + \sum_{\alpha=1}^{nm_{rd}} \frac{B_\alpha}{(s + m_{rd}\lambda_{rd})^\alpha} \right] \quad (4.3.9)$$

here $A_{nm_{sd}-\alpha+1} = \frac{\psi_A^{(\alpha-1)}(-m_{sd}\lambda_{sd})}{(\alpha-1)!}$, $\psi_A(s) = \frac{(m_{sd}\lambda_{sd})^{nm_{sd}}(m_{rd}\lambda_{rd})^{nm_{rd}}}{(s+m_{rd}\lambda_{rd})^{nm_{rd}}}$, $B_{nm_{rd}-\alpha+1} = \frac{\psi_B^{(\alpha-1)}(-m_{rd}\lambda_{rd})}{(\alpha-1)!}$, $\psi_B(s) = \frac{(m_{sd}\lambda_{sd})^{nm_{sd}}(m_{rd}\lambda_{rd})^{nm_{rd}}}{(s+m_{sd}\lambda_{sd})^{nm_{sd}}}$. PDF of the received SNR at d can be calculated, by taking inverse Laplace transform of $M_T(s)$, using [GR07, Eq.(2.102)]

$$f_{\Theta_T}(\theta) = \frac{(m_{sd}\lambda_{sd})^{nm_{sd}} P[I \leq R]}{\Gamma(nm_{sd})} \theta^{nm_{sd}-1} \exp(-m_{sd}\lambda_{sd}\theta) + P[I > R] \left[\sum_{\alpha=1}^{nm_{sd}} \frac{A_\alpha \theta^{\alpha-1}}{(\alpha-1)!} \exp(-m_{sd}\lambda_{sd}\theta) + \sum_{\beta=1}^{nm_{rd}} \frac{B_\beta \theta^{\beta-1}}{(\beta-1)!} \exp(-m_{rd}\lambda_{rd}\theta) \right] \quad (4.3.10)$$

For the case when severity of fading parameter is non-integer but identical between $s-d, r-d$ link (i.e. $m_{sd}=m_{rd}=m$), PDF of received SNR can be calculated with the help of (4.3.8), [Pou99, Table(2.3.141)]

$$f_{\Theta_T}(\theta) = \frac{(m\lambda_{sd})^{nm} P[I \leq R]}{\Gamma(nm)} \theta^{nm-1} \exp(-m\lambda_{sd}\theta) + P[I > R] \frac{(m^2\lambda_{sd}\lambda_{rd})^{nm} \sqrt{\pi}\theta^{nm-0.5}}{\Gamma(nm) \{m(\lambda_{sd} - \lambda_{rd})\}^{nm-0.5}} \times \exp\left(-\frac{m(\lambda_{sd} + \lambda_{rd})}{2}\theta\right) I_{nm-0.5}\left\{\frac{m(\lambda_{sd} - \lambda_{rd})}{2}\theta\right\} \quad (4.3.11)$$

where $I_\nu(\cdot)$ is ν^{th} order modified Bessel functions of the first kind. Simplification of (4.3.11) can be done with the help of [GR07, Eq.(8.445)]

$$f_{\Theta_T}(\theta) = \frac{(m\lambda_{sd})^{nm} P[I \leq R]}{\Gamma(nm)} \theta^{nm-1} \exp(-m\lambda_{sd}\theta) + P[I > R] \frac{(m^2\lambda_{sd}\lambda_{rd})^{nm} \sqrt{\pi}}{\Gamma(nm)} \\ \times \sum_{\alpha=0}^{\infty} \frac{\{m(\lambda_{sd} - \lambda_{rd})\}^{2\alpha} \theta^{2\alpha+2nm-1} \exp\left\{-\frac{m(\lambda_{sd}+\lambda_{rd})}{2}\theta\right\}}{4^{2\alpha+nm-0.5} \alpha! \Gamma(\alpha + nm + 0.5)} \quad (4.3.12)$$

Outage Probability

Outage probability (P_{out}), can be evaluated as [SA05, Eq.(1.4)]

$$P_{out} = \int_0^\chi f_{\Theta_T}(\theta) d\theta, \quad (4.3.13)$$

here, χ is the threshold. Expression for P_{out} can be established with the help of (4.3.10), (4.3.13) and [GR07, Eq.(3.381.1)]

$$P_{out} = P[I \leq R] \frac{\Gamma(nm_{sd}, m_{sd}\lambda_{sd}\chi)}{\Gamma(nm_{sd})} + P[I > R] \\ \times \left\{ \sum_{\alpha=1}^{nm_{sd}} \frac{A_\alpha \Gamma(\alpha, m_{sd}\lambda_{sd}\chi)}{(m_{sd}\lambda_{sd})^\alpha (\alpha-1)!} + \sum_{\beta=1}^{nm_{rd}} \frac{B_\beta \Gamma(\beta, m_{rd}\lambda_{rd}\chi)}{(m_{rd}\lambda_{rd})^\beta (\beta-1)!} \right\} \quad (4.3.14)$$

where, $\Gamma(\cdot, \cdot)$ is upper incomplete gamma function [GR07, Eq.(8.350.1)]. In case of Rayleigh fading channel, (4.3.14) can be simplified as

$$P_{out} = P[I \leq R] \frac{\Gamma(n, \lambda_{sd}\chi)}{(n-1)!} + P[I > R] \\ \times \left[\sum_{\alpha=1}^n \frac{A_\alpha \Gamma(\alpha, \lambda_{sd}\chi)}{\lambda_{sd}^\alpha (\alpha-1)!} + \sum_{\beta=1}^n \frac{B_\beta \Gamma(\beta, \lambda_{rd}\chi)}{\lambda_{rd}^\beta (\beta-1)!} \right] \quad (4.3.15)$$

For non-integer but identical severity of fading parameter, P_{out} can be evaluated from (4.3.12), (4.3.13) and [GR07, Eq.(3.381.1)]

$$P_{out} = P[I \leq R] \frac{\Gamma(nm, \lambda_{sd}m\chi)}{\Gamma(nm)} + P[I > R] \frac{(m^2\lambda_{sd}\lambda_{rd})^{nm} \sqrt{\pi}}{\Gamma(nm)} \\ \times \sum_{\alpha=0}^{\infty} \frac{\{m(\lambda_{sd} - \lambda_{rd})\}^{2\alpha} \Gamma(2\alpha + 2nm, m(\lambda_{sd} + \lambda_{rd})\chi/2)}{2^{2\alpha-1} \alpha! \Gamma(\alpha + nm + 0.5) \{m(\lambda_{sd} + \lambda_{rd})\}^{2\alpha+2nm}} \quad (4.3.16)$$

For Rayleigh fading channel, (4.3.16) can be expressed as

$$P_{out} = P[I \leq R] \frac{\Gamma(n, \lambda_{sd}\chi)}{(n-1)!} + P[I > R] \frac{(\lambda_{sd}\lambda_{rd})^n \sqrt{\pi}}{(n-1)!} \\ \times \sum_{\alpha=0}^{\infty} \frac{(\lambda_{sd} - \lambda_{rd})^{2\alpha} \Gamma(2\alpha + 2n, (\lambda_{sd} + \lambda_{rd})\chi/2)}{2^{2\alpha-1}\alpha! \Gamma(\alpha + n + 0.5) (\lambda_{sd} + \lambda_{rd})^{2\alpha+2n}} \quad (4.3.17)$$

For the case when s communicates with d directly (i.e. SIMO), P_{out} can be evaluated with the help of (4.2.2), (4.3.13) and [GR07, Eq.(3.381.1)]

$$P_{out} = \frac{\Gamma(nm_{sd}, m_{sd}\lambda_{sd}\chi_{SIMO})}{\Gamma(nm_{sd})}, \quad (4.3.18)$$

Here, SIMO operates in single time-slot, so the threshold value χ for this case is taken as χ_{SIMO} .

Average Symbol Error Rate

Average SEr for M-PSK modulated signal is define as [SA05, Eq.(5.1)]

$$SEr = \int_0^{\infty} Q(\sqrt{c\theta}) f_{\Theta_T}(\theta) d\theta, \quad (4.3.19)$$

where, $c = 2 \sin^2(\pi/M)$. Average SEr from (4.3.19), can be evaluated as [EM95, Eq.(A8)]

$$SEr = P[I \leq R] \frac{\mu(m_{sd}\lambda_{sd}, nm_{sd})}{\Gamma(nm_{sd})} (m_{sd}\lambda_{sd})^{nm_{sd}} + P[I > R] \\ \times \left\{ \sum_{\alpha=1}^{nm_{sd}} \frac{A_{\alpha} \mu(m_{sd}\lambda_{sd}, \alpha)}{(\alpha-1)!} + \sum_{\beta=1}^{nm_{rd}} \frac{B_{\beta} \mu(m_{rd}\lambda_{rd}, \beta)}{(\beta-1)!} \right\} \quad (4.3.20)$$

where $\mu\{x, y\} = \frac{\Gamma(y)}{x^y} \left\{ \sqrt{\frac{c}{2x+c}} \frac{(2x+c)^{-y} \Gamma(y+0.5)}{2\sqrt{\pi} \Gamma(y+1) (2x)^{-y}} \right\} {}_2F_1(1, y+0.5; y+1; \frac{2x}{2x+c})$, ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ is Gauss hypergeometric function [GR07, eq.(9.100)]. In case of Rayleigh fading channel, (4.3.20) can be expressed as

$$SEr = \frac{P[I \leq R]}{(n-1)!} \lambda_{sd}^n \mu\{\lambda_{sd}, n\} + P[I > R] \\ \times \left[\sum_{\alpha=1}^n \frac{A_{\alpha} \mu\{\lambda_{sd}, \alpha\}}{(\alpha-1)!} + \sum_{\beta=1}^n \frac{B_{\beta} \mu\{\lambda_{rd}, \beta\}}{(\beta-1)!} \right] \quad (4.3.21)$$

For non-integer but identical severity of fading parameter, $SE R$ can be evaluated from (4.3.12), (4.3.19) and [GR07, Eq.(3.381.1)]

$$SE R = P [I \leq R] \frac{(m\lambda_{sd})^{nm}}{\Gamma (nm)} \mu (m\lambda_{sd}, nm) + P [I > R] \frac{(m^2\lambda_{sd}\lambda_{rd})^{nm} \sqrt{\pi}}{\Gamma (nm)} \\ \times \sum_{\alpha=0}^{\infty} \frac{\{m(\lambda_{sd} - \lambda_{rd})\}^{2\alpha} \mu (m(\lambda_{sd} + \lambda_{rd})/2, 2\alpha + 2nm)}{4^{2\alpha+nm-0.5} \alpha! \Gamma (\alpha + nm + 0.5)} \quad (4.3.22)$$

For Rayleigh fading channel, (4.3.22) can be written as

$$SE R = P [I \leq R] \frac{\lambda_{sd}^n \mu \{\lambda_{sd}, n\}}{(n-1)!} + P [I > R] \frac{(\lambda_{sd}\lambda_{rd})^n \sqrt{\pi}}{(n-1)!} \\ \times \sum_{\alpha=0}^{\infty} \frac{(\lambda_{sd} - \lambda_{rd})^{2\alpha} \mu \{(\lambda_{sd} + \lambda_{rd})/2, 2\alpha + 2n\}}{4^{2\alpha+n-0.5} \alpha! \Gamma (\alpha + n + 0.5)} \quad (4.3.23)$$

In case of SIMO, average $SE R$ can be evaluated from (4.2.2), (4.3.19) and [EM95, Eq.(A8)]

$$SE R = \frac{\mu (m_{sd}\lambda_{sd}, nm_{sd})}{\Gamma (nm_{sd})} (m_{sd}\lambda_{sd})^{nm_{sd}} \quad (4.3.24)$$

Average received SNR

Average received SNR ($\bar{\gamma}$), can be evaluated as [SA05, Eq.(1.1)]

$$\bar{\gamma} = \frac{1}{2} \int_0^{\infty} \theta f_{\Theta_T} (\theta) d\theta. \quad (4.3.25)$$

In (4.3.25), the factor 1/2 is used, because average received SNR at multi-antenna destination is received in two time-slots. For integer but non-identical severity of fading parameter, $\bar{\gamma}$ can be evaluated from (4.3.10), (4.3.25) and [GR07, Eq.(3.326.2)]

$$\bar{\gamma} = \frac{1}{2} \left[\frac{n}{\lambda_{sd}} P [I \leq R] + P [I > R] \left\{ \sum_{\alpha=1}^{nm_{sd}} \frac{\alpha A_{\alpha}}{(m_{sd}\lambda_{sd})^{\alpha+1}} + \sum_{\beta=1}^{nm_{rd}} \frac{\beta B_{\beta}}{(m_{rd}\lambda_{rd})^{\beta+1}} \right\} \right] \quad (4.3.26)$$

In case of Rayleigh fading channel, (4.3.26) can be simplified as

$$\bar{\gamma} = \frac{1}{2} \left[\frac{n}{\lambda_{sd}} P [I \leq R] + P [I > R] \left\{ \sum_{\alpha=1}^n \frac{\alpha A_{\alpha}}{(\lambda_{sd})^{\alpha+1}} + \sum_{\beta=1}^n \frac{\beta B_{\beta}}{(\lambda_{rd})^{\beta+1}} \right\} \right] \quad (4.3.27)$$

For non-integer but identical severity of fading parameter, $\bar{\gamma}$ can be evaluated from (4.3.12), (4.3.25) and [GR07, Eq.(3.326.2)]

$$\bar{\gamma} = \frac{1}{2} \left[\frac{n}{\lambda_{sd}} P [I \leq R] + P [I > R] \frac{(m^2\lambda_{sd}\lambda_{rd})^{nm} \sqrt{\pi}}{m(2nm+1)\Gamma (nm)} \right. \\ \left. \times \sum_{\alpha=0}^{\infty} \frac{\Gamma (2\alpha + 2nm + 1) (\lambda_{sd} - \lambda_{rd})^{2\alpha} 2^{(2-2\alpha)}}{\Gamma (\alpha + nm + 0.5) (\lambda_{sd} + \lambda_{rd})^{(2\alpha+2nm+1)} \alpha!} \right] \quad (4.3.28)$$

For Rayleigh fading channel, (4.3.28) reduces to

$$\begin{aligned} \bar{\gamma} &= \frac{1}{2} \left[\frac{n}{\lambda_{sd}} P[I \leq R] + P[I > R] \frac{(\lambda_{sd}\lambda_{rd})^n \sqrt{\pi}}{(n-1)!} \right. \\ &\quad \left. \times \sum_{\alpha=0}^{\infty} \frac{\Gamma(2\alpha + 2n + 1) (\lambda_{sd} - \lambda_{rd})^{2\alpha} 2^{(2-2\alpha)}}{\Gamma(\alpha + n + 0.5) (\lambda_{sd} + \lambda_{rd})^{(2\alpha+2n+1)} \alpha!} \right] \end{aligned} \quad (4.3.29)$$

In case of SIMO, $\bar{\gamma}$ can be evaluated with the help of (4.2.2), (4.3.25) and [GR07, Eq.(3.326.2)]

$$\bar{\gamma} = \frac{n}{\lambda_{sd}}. \quad (4.3.30)$$

Average Capacity

Average capacity is define as [SA05, eq.(5.1)]

$$C = \frac{1}{2} \int_0^{\infty} \log_2(1 + \gamma) f_{\Theta_T}(\gamma) d\gamma \quad (4.3.31)$$

Average capacity from (4.3.31), can be evaluated with the help of (4.3.10) and [GR07, Eq.(4.337.5)]

$$\begin{aligned} C &= \frac{1}{2} \left[\frac{(m_{sd}\lambda_{sd})^{nm_{sd}}}{\Gamma(nm_{sd})} \Omega(m_{sd}\lambda_{sd}, nm_{sd}) P[I \leq R] + P[I > R] \right. \\ &\quad \left. \times \left\{ \sum_{\alpha=1}^{nm_{sd}} \frac{A_{\alpha} \Omega(m_{sd}\lambda_{sd}, \alpha)}{(\alpha-1)!} + \sum_{\beta=1}^{nm_{rd}} \frac{B_{\beta} \Omega(m_{rd}\lambda_{rd}, \beta)}{(\beta-1)!} \right\} \right] \end{aligned} \quad (4.3.32)$$

Here, $\Omega(\alpha, \beta) = \frac{(\beta-1)!}{\alpha^{\beta} \log_e 2} \sum_{\mu=0}^{\beta-1} \frac{1}{(\beta-\mu-1)!} \left[(-1)^{\beta-\mu-2} \alpha^{\beta-\mu-1} \exp(\alpha) Ei(-\alpha) + \sum_{\nu=1}^{\beta-\mu-1} (\nu-1)! (-\alpha)^{\beta-\mu-\nu-1} \right]$, $Ei(\cdot)$ is exponential integral [GR07, Eq.(27.5.3)]. In case of Rayleigh fading channel, (4.3.32) reduces to

$$\begin{aligned} C &= \frac{1}{2} \left[\frac{\lambda_{sd}^n}{(n-1)!} \Omega(\lambda_{sd}, n) P[I \leq R] + P[I > R] \right. \\ &\quad \left. \times \left\{ \sum_{\alpha=1}^n \frac{A_{\alpha} \Omega(\lambda_{sd}, \alpha)}{(\alpha-1)!} + \sum_{\beta=1}^n \frac{B_{\beta} \Omega(\lambda_{rd}, \beta)}{(\beta-1)!} \right\} \right] \end{aligned} \quad (4.3.33)$$

For integer and identical severity of fading parameter, average capacity can be evaluated with the help of (4.3.12) and [GR07, Eq.(4.337.5)]

$$\begin{aligned} C &= \frac{1}{2} \left[P[I \leq R] \frac{(m\lambda_{sd})^{nm}}{\Gamma(nm)} \Omega(m\lambda_{sd}, nm) + P[I > R] \frac{(m^2\lambda_{sd}\lambda_{rd})^{nm} \sqrt{\pi}}{\Gamma(nm)} \right. \\ &\quad \left. \times \sum_{\alpha=0}^{\infty} \frac{\{m(\lambda_{sd} - \lambda_{rd})\}^{2\alpha} \Omega\{m(\lambda_{sd} + \lambda_{rd})/2, 2\alpha + 2nm\}}{4^{2\alpha+nm-0.5} \alpha! \Gamma(\alpha + nm + 0.5)} \right] \end{aligned} \quad (4.3.34)$$

For Rayleigh fading channel, (4.3.34) can be simplified as

$$C = \frac{1}{2} \left[P[I \leq R] \frac{(\lambda_{sd})^n}{\Gamma(n)} \Omega(\lambda_{sd}, n) + P[I > R] \frac{(\lambda_{sd}\lambda_{rd})^n \sqrt{\pi}}{\Gamma(n)} \right. \\ \left. \times \sum_{\alpha=0}^{\infty} \frac{(\lambda_{sd} - \lambda_{rd})^{2\alpha} \Omega\{(\lambda_{sd} + \lambda_{rd})/2, 2\alpha + 2n\}}{4^{2\alpha+n-0.5} \alpha! \Gamma(\alpha + n + 0.5)} \right] \quad (4.3.35)$$

In case of SIMO, average capacity is define as [SA05, eq.(5.1)]

$$C = \int_0^{\infty} \log_2(1 + \gamma) f_{\gamma_{sd}}(\gamma) d\gamma \quad (4.3.36)$$

Average capacity from (4.3.36), can be evaluated with the help of (4.2.2) and [GR07, Eq.(4.337.5)]

$$C = \frac{(m_{sd}\lambda_{sd})^{nm_{sd}}}{\Gamma(nm_{sd})} \Omega(m_{sd}\lambda_{sd}, nm_{sd}) \quad (4.3.37)$$

4.4 Numerical Results and Discussion

In evaluating the performance of the system, asymmetrical channel conditions (i.e. $\lambda_{sr}=\lambda_{rd}\neq\lambda_{sd}$) have been considered, here r is placed between s and d . The threshold values of cooperative relaying and conventional SIMO system are $\chi = 2^{2R} - 1$ and $\chi_{SIMO} = 2^R - 1$, respectively and R is the spectral efficiency in bps/Hz. Value of R is assumed to be unity for numerical evaluation. For various SNRs, outage probability for integer value of m and non-integer value of m can be calculated from (4.3.14) and (4.3.16), respectively. SER for integer value of m and non-integer value of m are calculated from (4.3.20) and (4.3.22), respectively. Similarly, average received SNR for integer value of m and non-integer value of m can be calculated from (4.3.26) and (4.3.28), respectively. Average channel capacity for only integer value of m is calculated from (4.3.32) or (4.3.34). It has been found that numerical values of the expressions converge up to fourth place of decimal digit in maximum forty iterations (i.e. $\alpha=40$). Plots of these performance parameter expressions in terms of infinite series for non-integer values of m matches with its counterpart in terms of partial fraction for integer values of m . In Fig. 4.2, Fig. 4.3 and Fig. 4.4, the outage performance has been plotted for various values of n , m and ψ . Due to wastage of one time slot in cooperative relay network, spectrum efficiency of this system is just half of SIMO system. So for faithful comparison, performance of BPSK for SIMO has been compared with the performance of QPSK for cooperative relay network and plotted in Fig. 4.5,

Fig. 4.6 and Fig. 4.7. Average received SNR has been plotted in Fig. 4.8, Fig. 4.9 and Fig. 4.10. Similarly, average capacity of such system has been plotted in Fig. 4.11, Fig. 4.12 and Fig. 4.13. It is observed that direct transmission is better at lower SNR because most of time relay will not decode the message (i.e. relay will not participate) and unnecessary wastage of spectrum efficiency will take place. At higher SNR, relay assisted transmission is better than direct transmission as probability of participation of relay increases. SNR corresponding to intersection point of direct transmission curve and curve for transmission through relay increases with increase in antenna elements at destination. This is due to fact that slope of these performance curve increases and advantage of cooperation will be visible at much higher SNR. It is worthwhile to mention here that at higher SNR, logarithm term in capacity expression of relay based system will increase marginally compared to the capacity expression of SIMO system but capacity for relay system become half due to multiplication factor of $1/2$. Hence capacity plots for SIMO system again outperform relay based system. At higher path-loss condition, communication through intermediate relay node is superior to lower path-loss condition because signals are intermediately boosted up. In such scenario, performance of cooperative relaying is equivalent or may outperform SIMO system of same diversity order. From Fig. 4.6, it can be seen that at high path-loss conditions and above 16dB SNR, SE_R performance of cooperative relaying for QPSK with two antennas at destination becomes better than that of SIMO with BPSK and having four antennas at the destination. Similar type of observations can be made for the case of outage, average received SNR and capacity plots.

4.5 Conclusion

In this chapter, the outage probability, SE_R , average received SNR and average capacity of cooperative relay network having a multi-antenna base station have been with a conventional SIMO system. Analytical expressions for each case have been derived. It is seen that, superior performance of cooperative relaying over conventional SIMO system depends on path-loss conditions, number of antenna elements on destination and SNR conditions. For same performance level in some specific conditions, cooperative relaying can be used to reduce the burden of large antenna array on base. Cooperative relaying may outperform conventional SIMO system in higher path-loss condition.

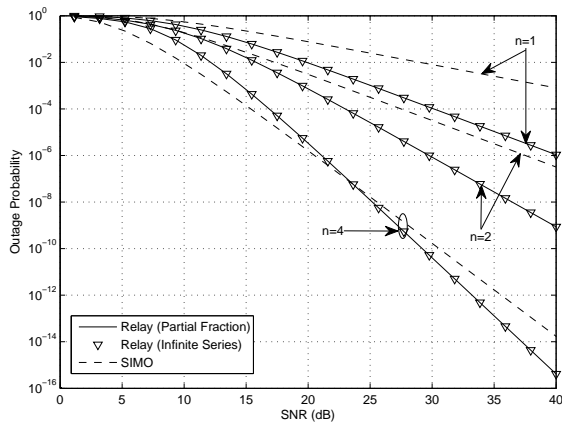


Figure 4.2: Outage performance ($m = 1, \psi = 3$) of cooperative relay network communicating with multi-antenna base station.

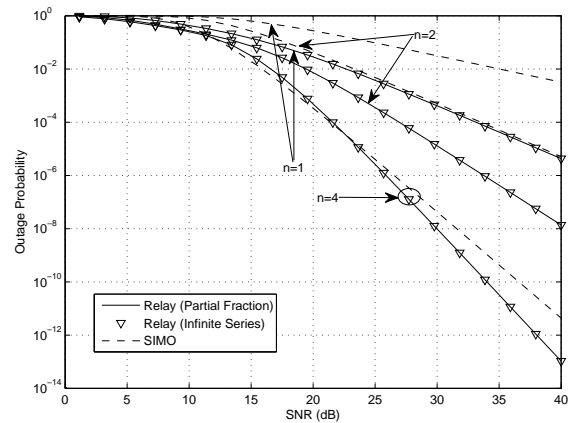


Figure 4.3: Outage performance ($m = 1, \psi = 5$) of cooperative relay network communicating with multi-antenna base station.

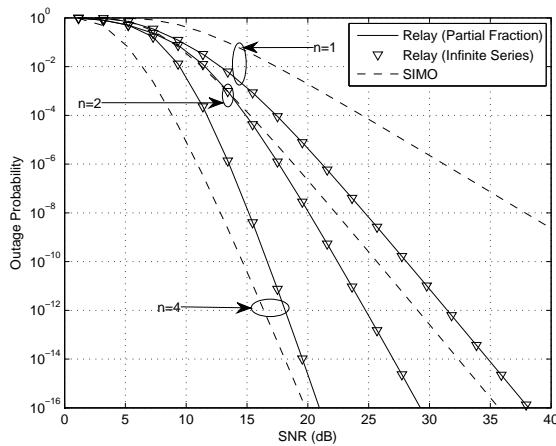


Figure 4.4: Outage performance ($m = 3, \psi = 3$) of cooperative relay network communicating with multi-antenna base station.

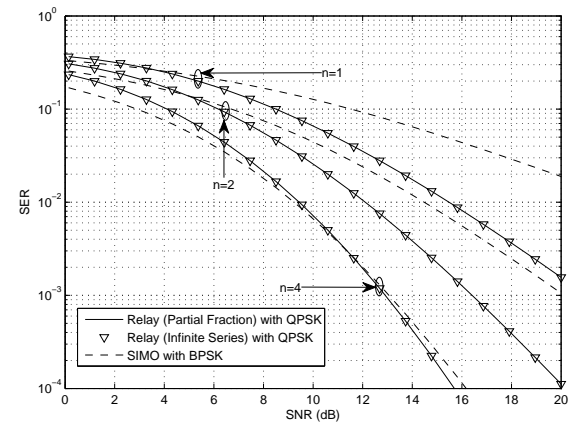


Figure 4.5: SER performance ($m = 1, \psi = 3$) of cooperative relay network communicating with multi-antenna base station.

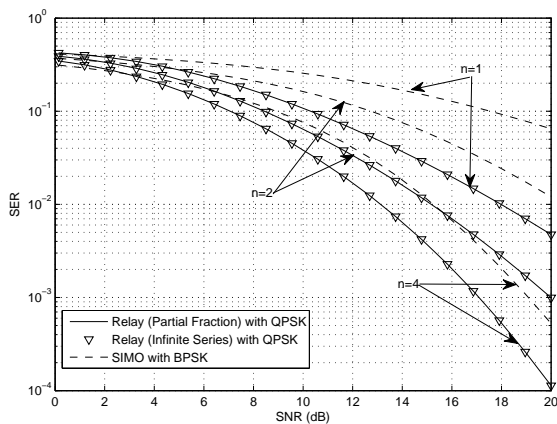


Figure 4.6: SER performance ($m = 1, \psi = 5$) of cooperative relay network communicating with multi-antenna base station.

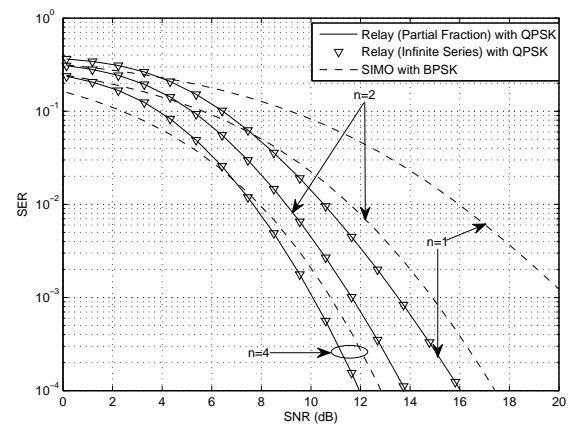


Figure 4.7: SER performance ($m = 3, \psi = 3$) of cooperative relay network communicating with multi-antenna base station.

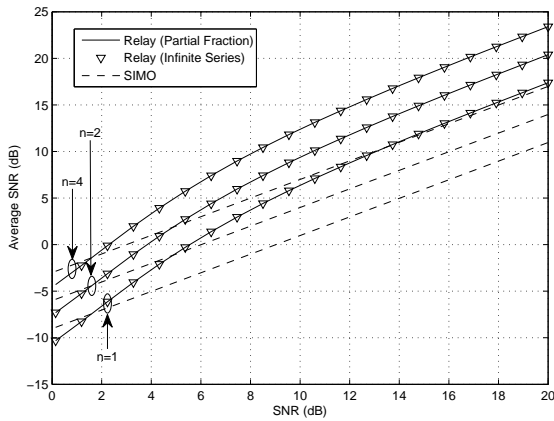


Figure 4.8: End-to-end average received SNR ($m = 1, \psi = 3$) of cooperative relay network communicating with multi-antenna base station.

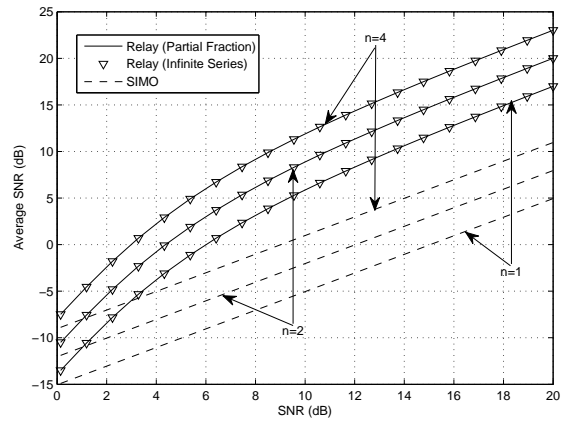


Figure 4.9: End-to-end average received SNR ($m = 1, \psi = 5$) of cooperative relay network communicating with multi-antenna base station.

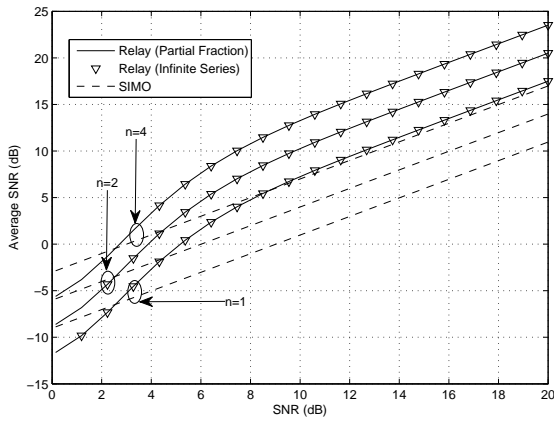


Figure 4.10: End-to-end average received SNR ($m = 3, \psi = 3$) of cooperative relay network communicating with multi-antenna base station.

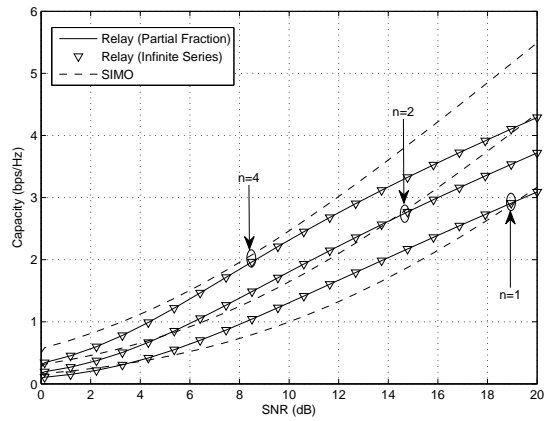


Figure 4.11: Average Capacity ($m = 1, \psi = 3$) of cooperative relay network communicating with multi-antenna base station.

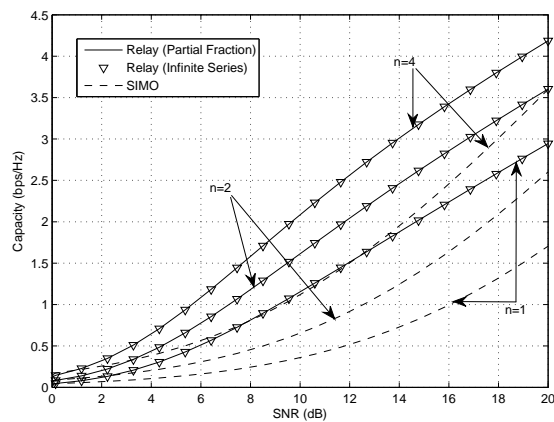


Figure 4.12: Average Capacity ($m = 1, \psi = 5$) of cooperative relay network communicating with multi-antenna base station.

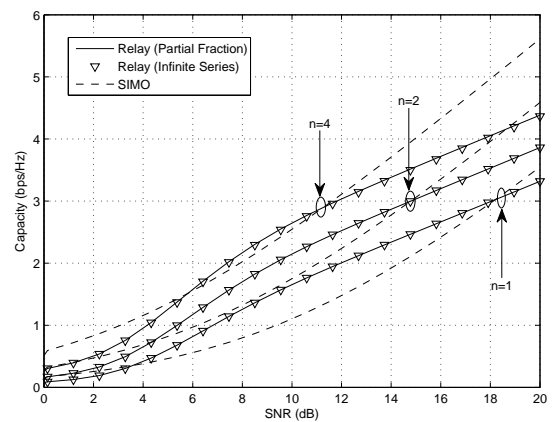


Figure 4.13: Average Capacity ($m = 3, \psi = 3$) of cooperative relay network communicating with multi-antenna base station.

Chapter 5

Performance of Cooperative Relay Network Supported by Multiple Relay

5.1 Introduction

Previous chapters dealt with a system model in which communication between source and destination is supported by a single relay. In this chapter we consider system models having more than one relays. Use of more than one relays does not always ensure higher diversity order and all the available relays need not participate all the time. Opportunistic relaying is a technique where only one relay having best channel condition is allowed to cooperate. However, global knowledge of all relay channel conditions is difficult to obtain, so some sub-optimum techniques are proposed in [BA08]. Distributed space-time coding can also improve the spectral efficiency but the same is difficult to implement in real scenario because prior knowledge of number of relay is necessary before encoding [LW03]. Besides this, a lot of control signal exchanges are required for relay synchronization, which may reduce actual throughput. In this chapter, all analysis have been carried out considering Rayleigh fading channel.

In section 5.2, a dual hop relay system has been analyzed in which multiple relays receive the signal from source and one of the relays which decode the message successfully as well as has best relay to destination channel condition, transmits in the second hop. An analytical expression for outage probability of dual-hop cooperative relay system has been derived and its performance has been compared with a SIMO system have the number antennas same as the number of supporting relays. In order to have fair comparison with SIMO system, the signal received in the first time slot is not buffered and combined with the signal received via relay in second time slot. Next in section 5.3, outage performance of infrastructure based multi-antenna relay network in absence of direct link has been

investigated. A closed form expression of outage probability has been derived, when the cooperating relays and destination performs MRC of signals. The effect of relay antennas and relay placement on the system performance has also been studied. In section 5.4, a system model in which communication between single antenna source and destination supported by multiple relays and each relay is equipped with single transmitting antenna and multiple receiving antennas has been considered. In this case, multiple relays receive the signal from source through multiple antennas and perform SC. One of the relays which decodes the message successfully and have best relay to destination channel condition, transmits in second slot. Destination performs SC on the signal received through direct path and through relay path. Closed form expression for outage probability has been derived in this section and plotted for various number of relays, various number of antenna installed on these relays in various SNRs conditions. In section 5.5, the effect of number of supporting relays and antennas installed on destination has been investigated. Here, destination perform MRC of the signal received through direct path and through various relay paths. Closed form expressions for outage probability, symbol error rate, average received SNR and average capacity have been derived in this section. It has been found that at lower SNR, performance of such system does not improve by increasing the number of supporting relays. However, at higher SNR system performance improves with increment of supporting relay, due to higher diversity order and higher probability of participation. Some of the work have been reported and published in open literature. In [KB10a], closed form expression of outage probability for opportunistic relay network has been derived.

5.2 Performance of Single antenna Relaying with SC

5.2.1 Opportunistic Relay Network

As shown in Fig. 5.1(a), opportunistic relay network consists of n relays ($\{r_k\}_{k=1}^n$), placed between source (s) and destination (d). Due to half-duplex nature of relay, s transmits to all n relays (i.e. $r_1, r_2 \cdots r_k \cdots r_n$) in first time-slot and one of the relay, which decodes the message successfully and have best $r_k \rightarrow d$ channel condition, transmits to the d in second time-slot. Direct link available between source and destination has not been taken into consideration. PDF of received SNR (γ_{ij}) is taken to be exponentially distributed (as the channel is rayleigh fading type), which can be written as [SA05, Eq.(2.7)]

$$f_{\gamma_{ij}}(\gamma) = \lambda_{ij} \exp(-\lambda_{ij}\gamma), \quad (5.2.1)$$

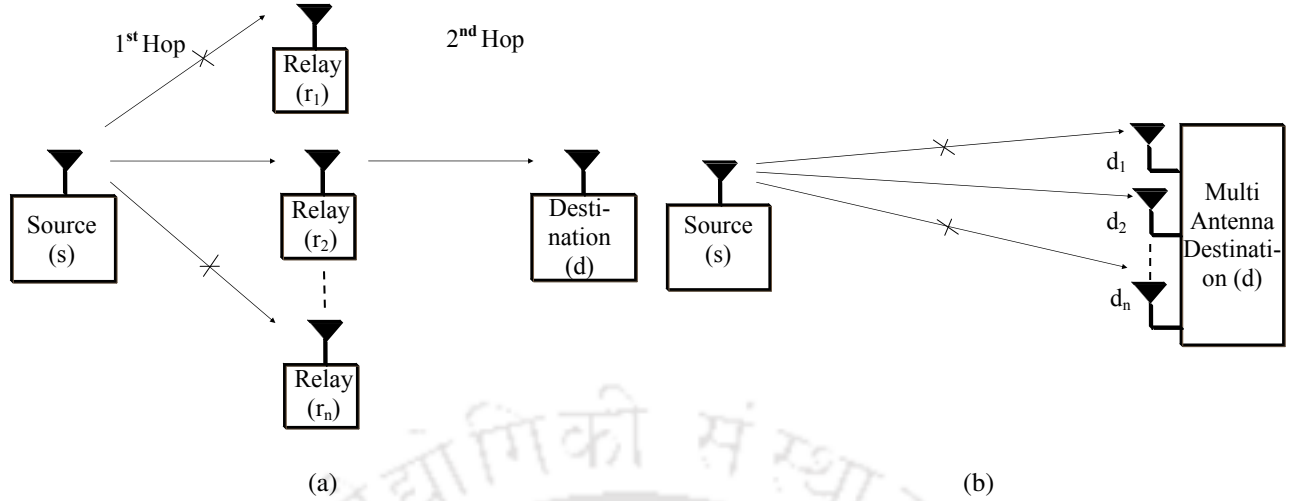


Figure 5.1: (a) Dual-hop opportunistic relaying and (b) single-hop SIMO.

Here $i \in \{s, r_k\}$, $j \in \{r_k, d\}$, parameter $\lambda_{ij} = (2l_{ij}/l_{sd})^\psi / \omega$, l_{ij} represents distance between node i and j , which is normalized by $l_{sd}/2$, ψ is path loss exponent, ω is SNR at reference point. In this system model relays are not communicating to each other (i.e. $\{i, j\} \notin \{r_k\}$ at same time). Random variable γ_{ij} (mean $1/\lambda_{ij}$ and variance $1/\lambda_{ij}^2$) captures the effect of long-term and short term fading. The source distributes its message to all relays in first time slot. Those relays whose channel condition from the source are good, can decode the message successfully. Such relays are member of decoding set and represented here as potential relays. Any relay is member of the decoding set $D(s)$, if mutual information between $s \rightarrow r_k$ (i.e. I_{sr_k}) is more than target data rate R (spectral efficiency) [ZAL05]:

$$I_{sr_k} = \frac{1}{2} \log_2 (1 + \gamma_{sr_k}) > R \quad (5.2.2)$$

In equation (5.2.2), multiplication factor $1/2$ is used because such system operates in two time-slots and utilizes only $1/2$ part of channel. One of the potential relay having best relay to destination channel condition, forwards the message to destination in second time slot. Hence, end-to-end mutual information transmits in this scheme is given by

$$I_{sd} = \frac{1}{2} \log_2 \{1 + \max(\gamma_{r_k d})\} \quad \forall r_k \in D(s) \quad (5.2.3)$$

The outage probability is mathematically defined as $P_{out} = P[I_{sd} \leq R]$.

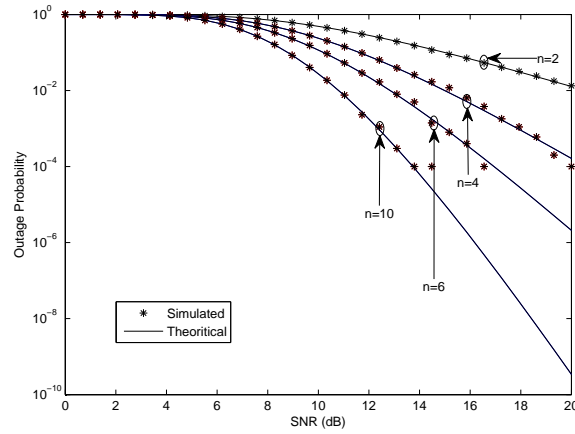


Figure 5.2: Outage probability of opportunistic relay network.

Decoding Set Probability

Assuming that a relay is capable of deciding whether transmitted data has been decoded correctly or not, probability of a relay being a member of the decoding set is given by

$$P[r_k \in D(s)] = P[\gamma_{sr_k} > \chi] \quad (5.2.4)$$

Here $\chi = 2^{2R} - 1$. So, (5.2.4) can be written as

$$P[r_k \in D(s)] = 1 - \int_0^\chi f_{\gamma_{sr_k}}(\gamma) d\gamma = \exp(-\lambda_{sr_k} \chi) \quad (5.2.5)$$

Moreover, since each potential relay makes its decision independently, probability of choosing any decoding set can be expressed as

$$P[D(s)] = \prod_{r_k \in D(s)} P[r_k \in D(s)] \prod_{r_k \notin D(s)} (1 - P[r_k \in D(s)]). \quad (5.2.6)$$

In case of identically distributed Rayleigh fading (i.e. $\lambda_{sr_1}, \lambda_{sr_2} \cdots \lambda_{sr_n} = \lambda_{sr}$) between $s \rightarrow r_k$, (5.2.6) can be simplified as

$$P[D(s)] = \binom{n}{\varphi} \{\exp(-\lambda_{sr} \chi)\}^\varphi \{1 - \exp(-\lambda_{sr} \chi)\}^{n-\varphi}, \quad (5.2.7)$$

here, φ is cardinality of decoding set $D(s)$ (i.e. $\varphi = |D(s)|$).

Conditional Outage Probability

Relay $r_k \in D(s)$, with best channel condition between $r_k \rightarrow d$, is allowed to transmit in the next time slot. So, conditional outage probability $P[I_{sd} \leq R | D(s)]$ is defined as

$$P[I_{sd} \leq R | D(s)] = \prod_{\varphi} \{1 - \exp(-\lambda_{r_k d} \chi)\} \quad (5.2.8)$$

Under the assumption that the channel between $r_k \rightarrow d$ are i.i.d. (i.e. $\lambda_{r_1 d}, \lambda_{r_2 d} \cdots \lambda_{r_n d} = \lambda_{rd}$), we can simplify (5.2.8) as given below

$$P[I_{sd} \leq R | D(s)] = \{1 - \exp(-\lambda_{rd} \chi)\}^{\varphi} \quad (5.2.9)$$

Total Outage Probability

From total probability law, P_{out} for the regenerative scheme can be expressed as [BA08, Eq.(15)]

$$P_{out}^{relay} = \sum_{D(s)} P[D(s)] P[I_{sd} \leq R | D(s)] \quad (5.2.10)$$

Here, summation is over all the possible decoding set $D(s)$. Outage probability can be calculated by substituting (5.2.6) and (5.2.8) into (5.2.10). Calculation of outage probability given in (5.2.10) is difficult when the channels are assumed to be asymmetric. Under assumption of symmetric channel between $s \rightarrow r_k$ and $r_k \rightarrow d$, (5.2.10) can be simplify with the help of (5.2.7) and (5.2.9)

$$P_{out}^{relay} = \sum_{\varphi=0}^n \binom{n}{\varphi} \{\exp(-\lambda_{sr} \chi)\}^{\varphi} \{1 - \exp(-\lambda_{sr} \chi)\}^{n-\varphi} \{1 - \exp(-\lambda_{rd} \chi)\}^{\varphi} \quad (5.2.11)$$

5.2.2 SIMO System

The system model for SIMO is shown in Fig. 5.1(b), here source (s) equipped with single antenna and transmits message to destination (d), which is equipped with n antennas ($d_1, d_2 \cdots d_k \cdots d_n$). This system works on the principle of selection diversity and choose k^{th} antenna with best channel condition. Probability of channel SNR between $s \rightarrow d_k$, is below a certain threshold χ_{SIMO}

$$P[\gamma_{sd_k} \leq \chi_{SIMO}] = \int_0^{\chi_{SIMO}} f_{\gamma_{sd_k}}(\gamma) d\gamma = 1 - \exp(-\lambda_{sd_k} \chi_{SIMO}) \quad (5.2.12)$$

here, $\chi_{SIMO} = 2^R - 1$. Outage probability of selection diversity for this case

$$P_{out}^{SIMO} = \prod_{k=1}^n \{1 - \exp(-\lambda_{sd_k} \chi_{SIMO})\} \quad (5.2.13)$$

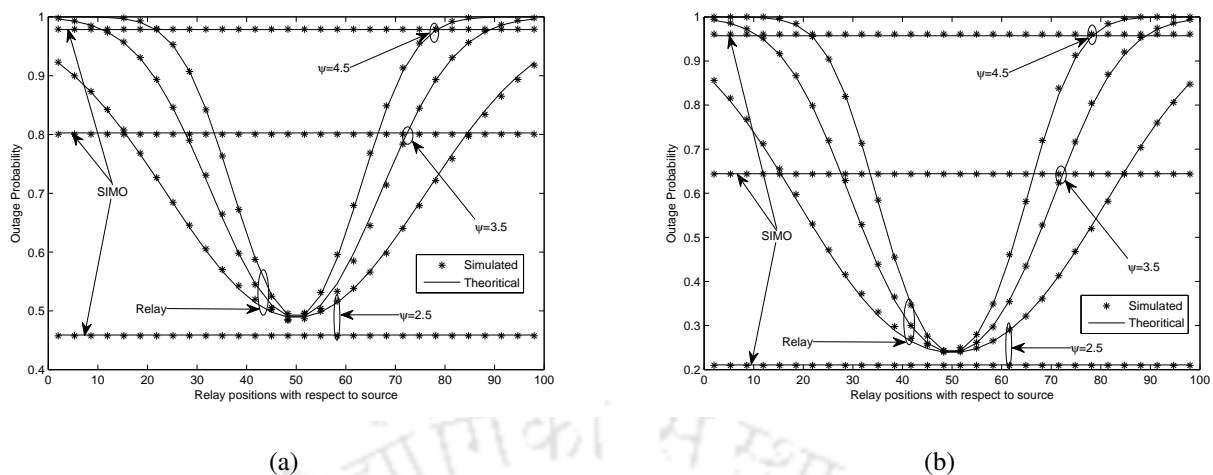


Figure 5.3: Outage probability of single antenna relay network (a) $n=2$, (b) $n=4$, when r placed at various locations between s and d .

Under the assumption that the Rayleigh fading from $s \rightarrow d_k$ are i.i.d. (i.e. $\lambda_{sd_1}, \lambda_{sd_2} \cdots \lambda_{sd_n} = \lambda_{sd}$), we can simplify (5.2.13) as given below

$$P_{out}^{SIMO} = \{1 - \exp(-\lambda_{sd}\chi_{SIMO})\}^n \quad (5.2.14)$$

5.2.3 Numerical Results and Discussion

This section presents the comparison of outage performance of single-hop SIMO system with that of dual-hop opportunistic relaying. s and d are assumed to be located at $(0,0)$ and $(0,100)$ respectively. Outage probability expression is established in (5.2.11), which is plotted in Fig. 5.2, for various values of n . Here, ψ is taken to be 3 and relays are assumed to be placed at middle point of s and d . Next relays are placed at different locations, which ranges from 2 to 98 from s . ψ for s to r , s to d and r to d links ranges from 2.5 to 4.5. Outage probability have been plotted in Fig. 5.3(a) and Fig. 5.3(b) for two and four relay network, respectively. It has been found that the relays placed near the source receive higher SNR, hence they have higher probability of being selected as potential relay but signals suffers in next-hop due to higher path-loss. Similarly, when relays are placed near d , signals received at d does not suffers due to path-loss but number of potential relays are less. Outage probability of such network can be minimized when relays are placed at the middle of s - d link.

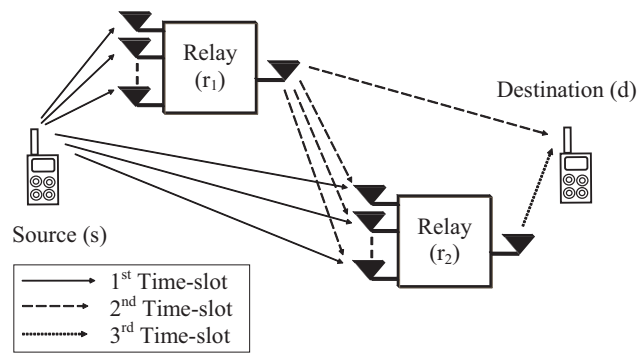


Figure 5.4: Two-hop multi-antenna cooperative relaying in absence of direct link between s and d .

5.3 Multi-antenna Relay Cooperation in Absence of Direct Link

This section reports the outage performance of a system in which communication between source and destination are supported by two multi-antenna relays. Source and destination are single-antenna tiny wireless nodes and have limited signal processing capability. Hardware complexity for the relays are not an important issue because they are infrastructure type fixed nodes. Relays operate here in adaptive decode forward mode hence remain silent if received SNR is below a particular threshold. In our system model, only signals received through relays are combined, the signal received by destination directly from the source is assumed to be too weak to make any contribution. Single transmitting antennas at the relays and destination node together form a MISO system when buffering is employed at the destination. Spectrum efficiency of relay based system suffers because relays operate in half-duplex mode [ZAL05], hence communication with support of large number of relays is not recommended. For avoiding any synchronization problem between nodes, channels are assumed to be orthogonal in time. Fading channel between different pair of nodes (i.e. source-relay, relay-relay and relay-destination) have been considered to be non-identical in statistical parameters, whereas identical fading parameters are assumed for the channels seen by antenna elements of relays. Such an assumption has been made because of the fact that receiving antennas on the relays are in close proximity of each other and are likely to experience identically distributed fading. Link performance has been evaluated with varying number of antennas installed on relays and its placement at various locations in Rayleigh fading channel.

5.3.1 System Model

As shown in Fig. 5.4, a system model has been analyzed in which communication between source (s) and destination (d) is supported by two multi-antenna relays (r_1, r_2). Here, r_1, r_2 are assumed to be equipped with m, n receiving antennas, respectively and one transmitting antenna each. Due to half-duplex nature of relays, s transmits to r_1 and r_2 in first time-slot (i.e. $s \rightarrow r_1$ and $s \rightarrow r_2$). Relay r_1 receives the signal from s through multiple links and performs MRC. If received SNR is above the threshold of the decoder, the message is decoded by r_1 and retransmitted to r_2 and d (i.e. $r_1 \rightarrow r_2$ and $r_1 \rightarrow d$) in the second time slot. In case the received SNR at r_1 is below the threshold, r_1 will remain silent in second time slot. Through multiple receiving antennas, relay r_2 receives the signal from s and r_1 in first and second time slots, respectively. After coherent combination, if received SNR is above a threshold, r_2 retransmit the signal to d in third time slot. In this work, fading envelop is assumed to be Rayleigh distributed, so the PDF of received SNR (γ_{ij}) when j^{th} node perform MRC of signals transmitted from i^{th} node [YA05]

$$f_{\gamma_{ij}}(\gamma_{ij}) = \frac{\lambda_{ij}^\eta \gamma_{ij}^{\eta-1}}{(\eta-1)!} \exp(-\lambda_{ij} \gamma_{ij}), \quad (5.3.1)$$

here $i \in \{s, r_1, r_2\}$, $j \in \{r_1, r_2, d\}$, $\lambda_{ij} = (2\ell_{ij}/\ell_{sd})^\psi / \omega$, ψ is path loss exponent, ℓ_{ij} represents distance between node i and j , which is normalized by reference distance $\ell_{sd}/2$, ω is SNR at reference point. Value of η will be $m, n, 1$, if j is assigned to r_1, r_2, d , respectively. Since relays operates in half-duplex mode they cannot transmit and receive the signal simultaneously. Relays r_1 and r_2 decode the message if the receive SNR is above the particular threshold. In this condition, mutual information (I) should be grater than target data rate R (spectral efficiency) [ZAL05]:

$$I = \frac{1}{3} \log_2(1 + SNR) > R. \quad (5.3.2)$$

In equation (5.3.2), we multiply logarithm with $1/3$ because such system operates in three time-slots and utilize only $1/3$ part of channel.

5.3.2 Mathematical Analysis

In this section, we first outline the steps involved in finding out the PDF of total received SNR based on the link conditions. With the PDF of received SNR known, outage probability expression has been derived next.

Probability of relay r_1 remaining inactive

Relay r_1 will not transmit (inactive mode), if maximum possible transmitted information between $s \rightarrow r_1$ (i.e. I_{sr_1}) is less than R , so its probability can be modeled as

$$P [r_1^{inactive}] = P [I_{sr_1} \leq R] = P [\gamma_{sr_1} \leq \chi], \quad (5.3.3)$$

here, $\chi = 2^{3R} - 1$ is the threshold. So, (5.3.3) can be written as [GR07, Eq.(3.381.1)]

$$P [r_1^{inactive}] = \frac{\Gamma(m, \lambda_{sr_1} \chi)}{(m-1)!}. \quad (5.3.4)$$

Probability that relay will transmit (active mode) can be given as

$$P [r_1^{active}] = 1 - P [r_1^{inactive}]. \quad (5.3.5)$$

Probability of relay r_2 remaining inactive

If r_1 is inactive then conditional probability of maximum possible transmitted information between $s \rightarrow r_2$ (i.e. I_{sr_2}) is less than R is given as [GR07, Eq.(3.381.1)]

$$\begin{aligned} P [I_{sr_2} \leq R | r_1^{inactive}] &= P [\gamma_{sr_2} \leq \chi] \\ &= \frac{\Gamma(n, \lambda_{sr_2} \chi)}{(n-1)!}. \end{aligned} \quad (5.3.6)$$

For the case when r_1 is in active mode, r_2 will coherently combined the signal received from s and r_1 . In such scenario, r_2 is in inactive mode, if maximum possible transmitted information between $s \rightarrow r_2$ and $r_1 \rightarrow r_2$ (i.e. $I_{sr_2} + I_{r_1 r_2}$) is less than R . Conditional probability that r_2 will not decode the message can be calculated with the help of (5.3.1) and [GR07, Eq.(2.102)]

$$\begin{aligned} &P [I_{sr_2} + I_{r_1 r_2} \leq R | r_1^{active}] \\ &= P [\gamma_{sr_2} + \gamma_{r_1 r_2} \leq \chi] \\ &= \sum_{\alpha=1}^n \frac{A_{\alpha} \Gamma(\alpha, \lambda_{sr_2} \chi)}{\lambda_{sr_2}^{\alpha} (\alpha-1)!} + \sum_{\alpha=1}^n \frac{B_{\alpha} \Gamma(\alpha, \lambda_{r_1 r_2} \chi)}{\lambda_{r_1 r_2}^{\alpha} (\alpha-1)!}, \end{aligned} \quad (5.3.7)$$

here $A_{\mu-\kappa+1} = \frac{\psi_A^{(\kappa-1)}(-\lambda_{sr_2})}{(\kappa-1)!} (\lambda_{sr_2})^{\mu} (\lambda_{r_1 r_2})^{\mu}$, $B_{\mu-\kappa+1} = \frac{\psi_B^{(\kappa-1)}(-\lambda_{r_1 r_2})}{(\kappa-1)!} (\lambda_{sr_2})^{\mu} (\lambda_{r_1 r_2})^{\mu}$, $\psi_A(s) = \frac{1}{(s+\lambda_{r_1 r_2})^{\mu}}$ and $\psi_B(s) = \frac{1}{(s+\lambda_{sr_2})^{\mu}}$.

From the theorem of total probability, probability that r_2 will not transmit (inactive mode) can be written as

$$\begin{aligned} P [r_2^{inactive}] &= P [I_{sr_2} \leq R | r_1^{inactive}] P [r_1^{inactive}] \\ &\quad + P [I_{sr_2} + I_{r_1 r_2} \leq R | r_1^{active}] P [r_1^{active}]. \end{aligned} \quad (5.3.8)$$

Probability that relay will transmit (active mode)

$$P [r_2^{active}] = 1 - P [r_2^{inactive}]. \quad (5.3.9)$$

PDF of received SNR based on link condition

Let random variable Θ models the received SNR at d . In case r_1 and r_2 are inactive, the conditional PDF of RV Θ can be written as

$$f_{\Theta|r_1^{inactive}, r_2^{inactive}}(\theta) = \delta(\theta), \quad (5.3.10)$$

where $\delta(\bullet)$ is dirac delta function. When r_1 is active but r_2 is inactive, the conditional PDF is given by

$$f_{\Theta|r_1^{active}, r_2^{inactive}}(\theta) = \lambda_{r_1 d} \exp(-\lambda_{r_1 d} \theta). \quad (5.3.11)$$

For the case when r_1 is inactive but r_2 is active, the conditional PDF is given by

$$f_{\Theta|r_1^{inactive}, r_2^{active}}(\theta) = \lambda_{r_2 d} \exp(-\lambda_{r_2 d} \theta). \quad (5.3.12)$$

When both r_1 and r_2 are active, the conditional PDF is given by

$$f_{\Theta|r_1^{active}, r_2^{active}}(\theta) = \frac{\lambda_{r_1 d} \lambda_{r_2 d}}{\lambda_{r_2 d} - \lambda_{r_1 d}} \times \{\exp(-\lambda_{r_1 d} \theta) - \exp(-\lambda_{r_2 d} \theta)\}. \quad (5.3.13)$$

End-to-end PDF of received SNR

From the theorem on total probability, end-to-end PDF of received SNR can be written as

$$\begin{aligned} f_{\Theta_T}(\theta) = & P [r_1^{inactive}, r_2^{inactive}] f_{\Theta|r_1^{inactive}, r_2^{inactive}}(\theta) \\ & + P [r_1^{active}, r_2^{inactive}] f_{\Theta|r_1^{active}, r_2^{inactive}}(\theta) \\ & + P [r_1^{inactive}, r_2^{active}] f_{\Theta|r_1^{inactive}, r_2^{active}}(\theta) \\ & + P [r_1^{active}, r_2^{active}] f_{\Theta|r_1^{active}, r_2^{active}}(\theta). \end{aligned} \quad (5.3.14)$$

In (5.3.14), r_1 and r_2 experience independent fading, so the event of relay participation will be independent

$$\left. \begin{aligned} P [r_1^{inactive}, r_2^{inactive}] &= P [r_1^{inactive}] P [r_2^{inactive}] \\ P [r_1^{active}, r_2^{inactive}] &= P [r_1^{active}] P [r_2^{inactive}] \\ P [r_1^{inactive}, r_2^{active}] &= P [r_1^{inactive}] P [r_2^{active}] \\ P [r_1^{active}, r_2^{active}] &= P [r_1^{active}] P [r_2^{active}]. \end{aligned} \right\} \quad (5.3.15)$$

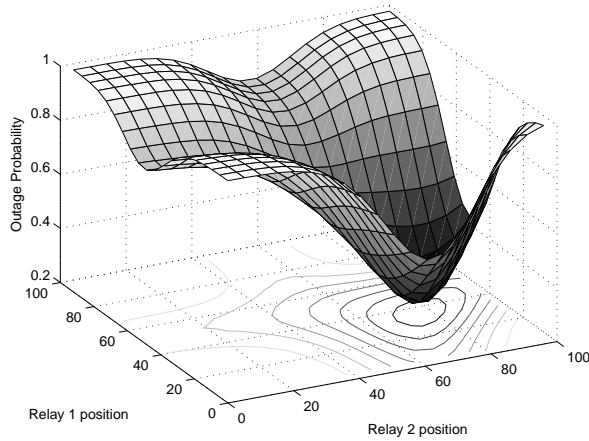


Figure 5.5: Outage probability at d for multi-antenna cooperative relay network for $n = 2$.

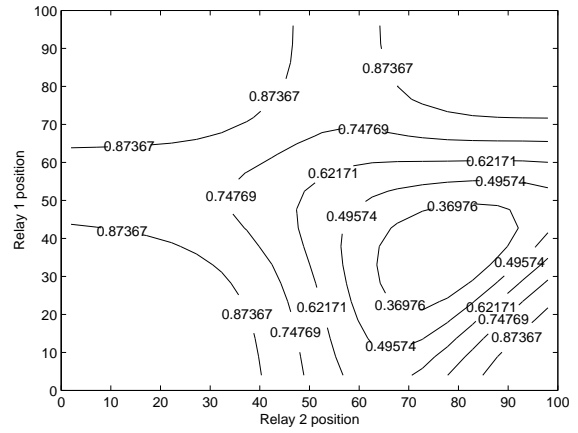


Figure 5.6: Contour plot for outage performance of multi-antenna cooperative relay network for $n = 2$.

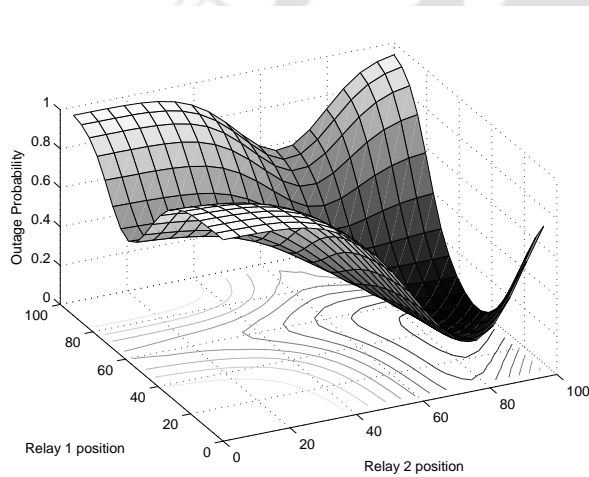


Figure 5.7: Outage probability at d for multi-antenna cooperative relay network for $n = 4$.

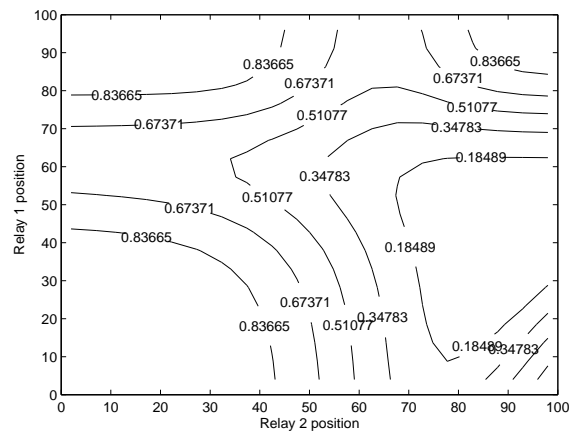


Figure 5.8: Contour plot for outage performance of multi-antenna cooperative relay network for $n = 4$.

Outage Probability (P_{out})

Outage occurs when received SNR falls below a certain specified threshold. Here, for the given threshold χ , we can calculate outage probability as follows [SA05, Eq.(1.4)]

$$P_{out} = \int_0^\chi f_{\Theta_T}(\theta) d\theta. \tag{5.3.16}$$

Outage Probability can be calculated with the help of (5.3.14), (5.3.15), (5.3.16) and [GR07, Eq.(3.381.1)]

$$\begin{aligned}
P_{out} = & P [r_1^{inactive}] P [r_2^{inactive}] + P [r_1^{active}] P [r_2^{inactive}] \{1 - \exp(-\lambda_{r_1 d} \chi)\} \\
& + P [r_1^{inactive}] P [r_2^{active}] \{1 - \exp(-\lambda_{r_2 d} \chi)\} + P [r_1^{active}] P [r_2^{active}] \\
& \times \left[1 + \frac{1}{\lambda_{r_1 d} - \lambda_{r_2 d}} \{ \lambda_{r_2 d} \exp(-\lambda_{r_1 d} \chi) - \lambda_{r_1 d} \exp(-\lambda_{r_2 d} \chi) \} \right] \quad (5.3.17)
\end{aligned}$$

5.3.3 Numerical Results and Discussion

For evaluating the performance of this system, the following scenario is considered: s and d have been assumed to be located at (0,0) and (0,100) respectively, while r_1 and r_2 are located at a distance (from s), which ranges from 2 to 98. R , ψ and ω are assumed to be 1, 3 and 7dB, respectively. For $m=n=2, 4$, outage performance have been plotted in Fig. 5.6 and Fig. 5.8, respectively. We observed that when r_1, r_2 are placed near s , most of the time message is decoded by r_1, r_2 . However, d receives signal of lower strengths from r_1, r_2 resulting in high outage and system performance suffers. As location of r_1, r_2 moves close to d , system performance again suffers as r_1, r_2 now receive poor signals. Therefore, most of the time r_1, r_2 will not participate and diversity order of the system reduces. Outage performance improves when r_1 and r_2 are away from both s and d . When r_1 is near s compared to r_2 superior performance is obtained as compared to the case r_1 is placed near d and r_2 is placed near s . This is due to fact that r_2 have higher diversity order compared to r_1 , so r_2 receives higher SNR and it can be placed much closer to d . Installation of more number of receiving antennas on r_1 and r_2 improves the relay participation, hence system performance improves. With increase of number of antennas, distances of r_1 and r_2 from s can be increased for improving system performance.

5.4 Performance of Multi-antenna Relaying employing SC

This section presents outage performance of cooperative relay system in which transmission is supported by multiple multi-antenna relays in asymmetric Rayleigh fading channel. Relays process the signals if received SNR is more than a particular threshold else they remain silent, hence error would not propagate to next stage. In first time-slot, message transmitted by source is decoded by each relay after performing SC of signals. Those relays which are able to decode the message successfully and have best channel with destination, are allowed to transmit in next time-slot. Destination performs SC of the message received through direct path and through relay path. SC at destination requires only

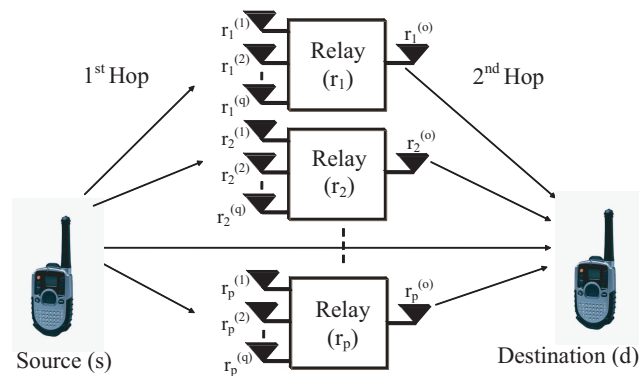


Figure 5.9: Two-hop multi-antenna relay system.

SNR measurements, which reduces receiver complexity. Here, required time-slots for p relay network is only two; hence spectrum efficiency does not suffer compared to a system model in which destination perform MRC. However, for incorporating such system, source should have knowledge of the channel between relays and destination for deciding best channel. This can be possible through some feedback mechanism which can increase control signal exchange and in rapidly changing environment it reduces the actual throughput.

5.4.1 System Modeling

As shown in Fig. 5.9, cooperative relay network have a single antenna source (s) and destination (d), communicating with the help of p relays ($r_1, r_2 \dots r_k \dots r_p$), here each relay equipped with q antennas¹. Due to half-duplex nature of r_k , s transmits to r_k (i.e. $s \rightarrow r_k$) and d (i.e. $s \rightarrow d$) in first time-slot. Any relay r_k which is equipped with multiple-antenna, first selects the link with best $s \rightarrow r_k^{(l)}$ channel condition. If it is grater than a particular threshold, then that relay r_k (potential relay) would be possible candidate for re-transmitting the signal. One of the potential relays having best channel condition to destination, allow to transmit in second time-slot. Destination receives the copy of direct path and through relay path, accepts only one of the best copy of signal. The system model presented here is similar to the system model analyzed in section 5.2, the difference is that relays have single antenna and direct link is not considered in section 5.2.

¹In this paper, symbol $r_k^{(l)}$ represents l^{th} receiving antenna of k^{th} relay and $r_k^{(o)}$ represents transmitting antenna of k^{th} relay.

5.4.2 Mathematical Analysis

In our system model we assume that the random variable (RV) of received SNR (γ_{ij}) is exponentially distributed. So, probability distribution function (PDF) can be written as

$$f_{\gamma_{ij}}(\gamma) = \lambda_{ij} \exp(-\lambda_{ij}\gamma) \quad (5.4.1)$$

Here $i \in \{s, r_k^{(o)}\}$, $j \in \{r_k^{(l)}, d\}$, $1/\lambda_{ij}$ is SNR.

Probability of transmission by k^{th} relay node

Probability of k^{th} relay transmission (active mode) is given by

$$P[I_{sr_k} > R] = P\left[\max(\gamma_{sr_k^{(l)}}) > \chi\right] = 1 - \prod_{l=1}^q \int_0^\chi f_{sr_k^{(l)}}(\gamma) d\gamma \quad (5.4.2)$$

Here $\chi = 2^{2R} - 1$, R is spectrum efficiency. So, we can write (5.4.2) as below

$$P[I_{sr_k} > R] = 1 - \prod_{l=1}^q \left\{1 - \exp\left(-\lambda_{sr_k^{(l)}}\chi\right)\right\} \quad (5.4.3)$$

Probability that the k^{th} relay does not transmit (inactive)

$$P[I_{sr_k} \leq R] = 1 - P[I_{sr_k} > R] \quad (5.4.4)$$

PDF of received SNR based on link condition

Let, RV Θ_k models the received SNR at d via k^{th} relay link, which take-care the fading on both side in k^{th} relay link. PDF of RV Θ_k , when k^{th} relay would not transmit

$$f_{\Theta_k|I_{sr_k} \leq R}(\theta) = \delta(\theta) \quad (5.4.5)$$

For the case when k^{th} relay will transmit, then conditional PDF is given as

$$f_{\Theta_k|I_{sr_k} > R}(\theta) = \lambda_{r_k^{(o)}d} \exp\left(-\lambda_{r_k^{(o)}d}\theta\right) \quad (5.4.6)$$

PDF of total received SNR

From theorem on total probability, PDF of received SNR through k^{th} relay link can be expressed as

$$f_{\Theta_k}(\theta) = f_{\Theta_k|I_{sr_k} \leq R}(\theta) P[I_{sr_k} \leq R] + f_{\Theta_k|I_{sr_k} > R}(\theta) P[I_{sr_k} > R] \quad (5.4.7)$$

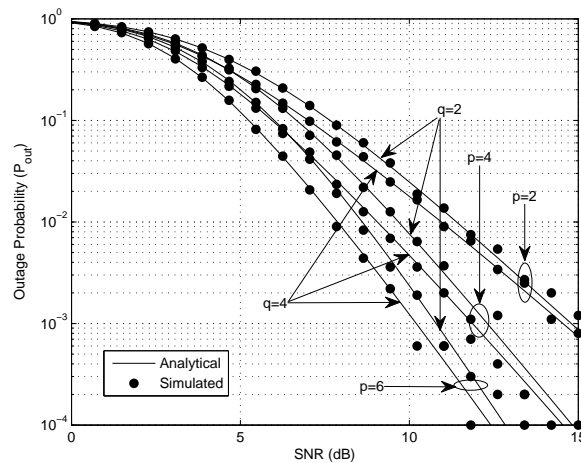


Figure 5.10: Outage performance of cooperative relay network.

Outage Probability

Outage occurs when received SNR, falls below a certain specified threshold (χ). Here, for this system model, P_{out} can be calculated as

$$P_{out} = \int_0^{\chi} f_{\gamma_{sd}}(\gamma) d\gamma \prod_{k=1}^p \int_0^{\chi} f_{\Theta_k}(\theta) d\theta \quad (5.4.8)$$

So, (5.4.8) can be simplify as

$$P_{out} = \{1 - \exp(-\lambda_{sd}\chi)\} \prod_{k=1}^p \prod_{l=1}^q \left\{1 - \exp\left(-\lambda_{sr_k^{(l)}}\chi\right)\right\} + \left[1 - \prod_{l=1}^q \left\{1 - \exp\left(-\lambda_{sr_k^{(l)}}\chi\right)\right\}\right] \left\{1 - \exp\left(-\lambda_{r_k^{(o)}d}\chi\right)\right\} \quad (5.4.9)$$

5.4.3 Numerical Results and Discussion

In evaluating the performance of the system, asymmetrical channel condition (i.e. $\lambda_{sr_k^{(l)}} \neq \lambda_{r_k^{(o)}d} \neq \lambda_{sd}$) has been assumed. Spectral efficiency R is assumed to be unity. For various SNRs, outage probability at destination is calculated using (5.4.9) and the same has been plotted in Fig. 5.10. It has been observed that performance of system improves with increase of supporting relays (i.e. p) and antenna installed on relays (i.e. q). This is due to fact that higher number of q improves the probability of relay participation and probability of better received SNR at d increases with increment of p . However, in such system model, a lot of control signal exchange may be required if channel is rapidly changing which reduces the actual throughput.

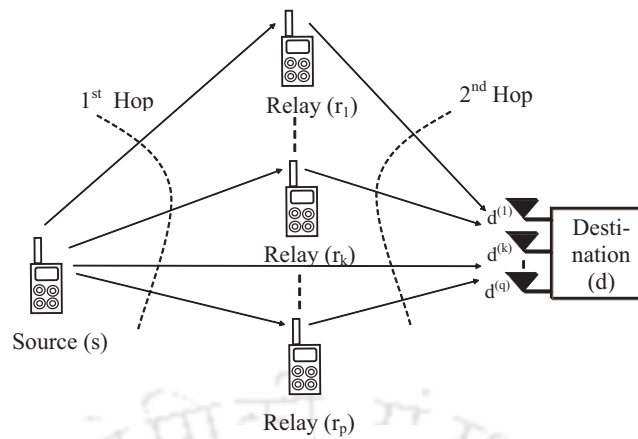


Figure 5.11: Two-hop system in which single antenna source, relay communicating with multi-antenna destination.

5.5 Performance of Relay Network employing MRC

This section presents outage probability, average error probability, average received SNR and channel capacity of a system in which single source and multiple cooperative relay terminals are communicating with a destination (base station). Here, source and relays are equipped with single antenna but destination is equipped with multiple antennas. Analytical expressions for each case have been derived for Rayleigh fading channel. Such system model is useful for the case of user cooperation where source and relays are tiny wireless user terminals and destination is a base station which is equipped with multiple antennas.

5.5.1 System Modeling

As shown in Fig. 5.11, communication between source (s) and destination (d) takes place with the help of p supporting relays (i.e. $r_1, r_2 \dots r_k \dots r_p$), which are located at middle. Each terminal s and r_k have single antenna but the terminal d have q antennas². To avoiding any synchronization problem between s and r_k , channels are assumed to be orthogonal in time which require $p+1$ time-slots for complete transmission. s transmits to each r_k and d in first time-slot. If received SNR at r_k is above a particular threshold (active mode), the message is assumed to be decoded without error and re-transmitted to the d in their respective time slots. Multi-antenna destination coherently combines all the copies of signal, received through direct path and various active relay paths. In this system

²In this section, r_k represents k^{th} relay and $d^{(k)}$ represents k^{th} antenna of d .

model, it is assumed that the signals received at d via various relay paths are identically distributed. Such assumption is made because all relays are located at same place (i.e. at middle of s , d) and relative distance among the relays are negligible compared to the distance between s , d . However, signals received at d through direct path is nonidentical to the various relay paths because transmitters s and r_k are located at different locations. In this section, we assumed that received SNR at r (γ_{sr_k}) is exponentially distributed, PDF of which can be given as [SA05, Eq.(2.21)]

$$f_{\gamma_{sr_k}}(\gamma) = \lambda_{sr_k} \exp(-\lambda_{sr_k} \gamma). \quad (5.5.1)$$

where $\lambda_{sr_k} = (2\ell_{sr_k}/\ell_{sd})^\psi / \omega$, ψ is path loss exponent, ω is the SNR at reference point, ℓ_{sr_k} represents distance between node s and r_k , which has been normalized here by half the distance between s and d (i.e. $\ell_{sd}/2$). Destination is equipped with multi-antenna array and performs MRC of identically distributed signals, so the PDF of received SNR at d can be written as [YA05]

$$f_{\gamma_{ij}}(\gamma) = \frac{\lambda_{ij}^n \gamma^{n-1}}{(n-1)!} \exp(-\lambda_{ij} \gamma), \quad (5.5.2)$$

where $i \in \{s, r_k\}$, $j \in \{d\}$, n is the number of antennas at d , $\lambda_{ij} = (2\ell_{ij}/\ell_{sd})^\psi / \omega$, ℓ_{ij} represents distance between node i and j . In first hop, if received SNR at any r_k is above the required threshold, then that relay decodes the message received from source. This condition, corresponds to mutual information (I_{sr_k}), transmitted by the source is more than target data rate R (spectral efficiency) [LW03]

$$I_{sr_k} = \frac{1}{p+1} \log_2(1 + \gamma_{sr_k}) > R \quad (5.5.3)$$

In equation (5.5.3), we multiply logarithm with $1/(p+1)$ because such system operates in $p+1$ time-slots and utilize only $1/(p+1)$ part of channel.

5.5.2 Channel Modeling

Probability of transmission by k^{th} relay node

Probability of k^{th} relay transmission (active mode) is given by [ZAL05]

$$\begin{aligned} P[I_{sr_k} > R] &= P[\gamma_{sr_k} > \chi] \\ &= 1 - \int_0^\chi f_{sr_k}(\gamma) d\gamma \\ &= \exp(-\lambda_{sr_k} \chi) \end{aligned} \quad (5.5.4)$$

Here χ is threshold value. Probability that the k^{th} relay does not transmit (inactive)

$$P [I_{sr_k} \leq R] = 1 - P [I_{sr_k} > R] \quad (5.5.5)$$

PDF of received SNR based on link condition

Let, random variable (RV) Θ_k models the received SNR at d via k^{th} relay link, which take-care of the fading on both side in k^{th} relay link. PDF of RV Θ_k , when k^{th} relay would not transmit

$$f_{\Theta_k|I_{sr_k} \leq R}(\theta) = \delta(\theta) \quad (5.5.6)$$

For the case when k^{th} relay would transmit, then conditional PDF of identically distributed channel between $r_k \rightarrow d$ (i.e. $\forall \lambda_{r_k d} = \lambda_{rd}$) is given as

$$f_{\Theta_k|I_{sr_k} > R}(\theta) = \frac{\lambda_{r_k d}^q \theta^{q-1}}{(q-1)!} \exp(-\lambda_{r_k d} \theta) \quad (5.5.7)$$

PDF of total received SNR

From theorem on total probability, PDF of received SNR through k^{th} relay link can be expressed as

$$f_{\Theta_k}(\theta) = f_{\Theta_k|I_{sr_k} \leq R}(\theta) P [I_{sr_k} \leq R] + f_{\Theta_k|I_{sr_k} > R}(\theta) P [I_{sr_k} > R] \quad (5.5.8)$$

MGF³ of $f_{\Theta_k}(\theta)$, through k^{th} relay link can be written as

$$M_k(s) = P [I_{sr_k} \leq R] + P [I_{sr_k} > R] \left(\frac{\lambda_{rd}}{s + \lambda_{rd}} \right)^q \quad (5.5.9)$$

If channels between $s \rightarrow d$ and $s \rightarrow r_k \rightarrow d$ are independent and non-identical then total MGF is given as

$$M_T(s) = M_{sd}(s) \prod_{k=1}^p M_k(s) \quad (5.5.10)$$

Here, $M_{sd}(s)$ is the MGF of direct link. For the case when $s \rightarrow d$ link is identically distributed (i.e. $\forall \lambda_{sd(l)} = \lambda_{sd}$), MGF of s - d link can be written as $M_{sd}(s) = \lambda_{sd}^q / (s + \lambda_{sd})^q$. For identical channel between $s \rightarrow r_k$ (i.e. $\forall \lambda_{sr_k} = \lambda_{sr}$ and $\forall M_k(s) = M_{sr_d}(s)$), total MGF can be simplified as

$$M_T(s) = M_{sd}(s) [M_{sr_d}(s)]^p \quad (5.5.11)$$

³ $M_k(s) = \int_0^\infty f_{\Theta_k}(\theta) \exp(-s\theta) d\theta$

So, $M_T(s)$ can be simplified using method of partial fractions [GR07, Eq.(2.102)]

$$\begin{aligned}
M_T(s) &= \{P[I \leq R]\}^p \left(\frac{\lambda_{sd}}{s + \lambda_{sd}} \right)^q \\
&+ \sum_{k=0}^{p-1} \binom{p}{k} \{P[I \leq R]\}^k \{P[I > R]\}^{(p-k)} \\
&\times \left[\sum_{\alpha=1}^q \frac{A_\alpha}{(s + \lambda_{sd})^\alpha} + \sum_{\beta=1}^{q(p-k)} \frac{B_\beta}{(s + \lambda_{rd})^\beta} \right]
\end{aligned} \tag{5.5.12}$$

Here $A_{n-k+1} = \frac{\psi_A^{(k-1)}(-\lambda_{sd})}{(k-1)!} (\lambda_{sd})^q (\lambda_{rd})^{q(p-k)}$, $\psi_A(s) = \frac{1}{(s+\lambda_{rd})^{q(p-k)}}$,
 $B_{n-k+1} = \frac{\psi_B^{(k-1)}(-\lambda_{rd})}{(k-1)!} (\lambda_{sd})^q (\lambda_{rd})^{q(p-k)}$, $\psi_B(s) = \frac{1}{(s+\lambda_{sd})^q}$. Expression for PDF of received SNR at d can be found out, by taking inverse Laplace transform of $M_T(s)$. So the PDF of end-to-end received SNR can be written as

$$\begin{aligned}
f_{\Theta_T}(\theta) &= \frac{\{P[I \leq R]\}^p}{(q-1)!} \lambda_{sd}^q \theta^{q-1} \exp(-\lambda_{sd}\theta) \\
&+ \sum_{k=0}^{p-1} \binom{p}{k} \{P[I \leq R]\}^k \{P[I > R]\}^{(p-k)} \\
&\times \left[\sum_{\alpha=1}^q \frac{A_\alpha \theta^{\alpha-1}}{(\alpha-1)!} \exp(-\lambda_{sd}\theta) + \sum_{\beta=1}^{q(p-k)} \frac{B_\beta \theta^{\beta-1}}{(\beta-1)!} \exp(-\lambda_{rd}\theta) \right]
\end{aligned} \tag{5.5.13}$$

5.5.3 System Performance

Outage Probability

Outage probability (P_{out}), can be evaluated as [SA05, Eq.(1.4)]

$$P_{out} = \int_0^\chi f_{\Theta_T}(\theta) d\theta, \tag{5.5.14}$$

so, P_{out} can be evaluated from (5.5.13), (5.5.14) and [GR07, Eq.(3.381.1)]

$$\begin{aligned}
P_{out} &= \{P[I \leq R]\}^p \frac{\Gamma(q, \lambda_{sd}\chi)}{(q-1)!} \\
&+ \sum_{k=0}^{p-1} \binom{p}{k} \{P[I \leq R]\}^k \{P[I > R]\}^{(p-k)} \\
&\times \left[\sum_{\alpha=1}^q \frac{A_\alpha \Gamma(\alpha, \lambda_{sd}\chi)}{\lambda_{sd}^\alpha (\alpha-1)!} + \sum_{\beta=1}^{q(p-k)} \frac{B_\beta \Gamma(\beta, \lambda_{rd}\chi)}{\lambda_{rd}^\beta (\beta-1)!} \right]
\end{aligned} \tag{5.5.15}$$

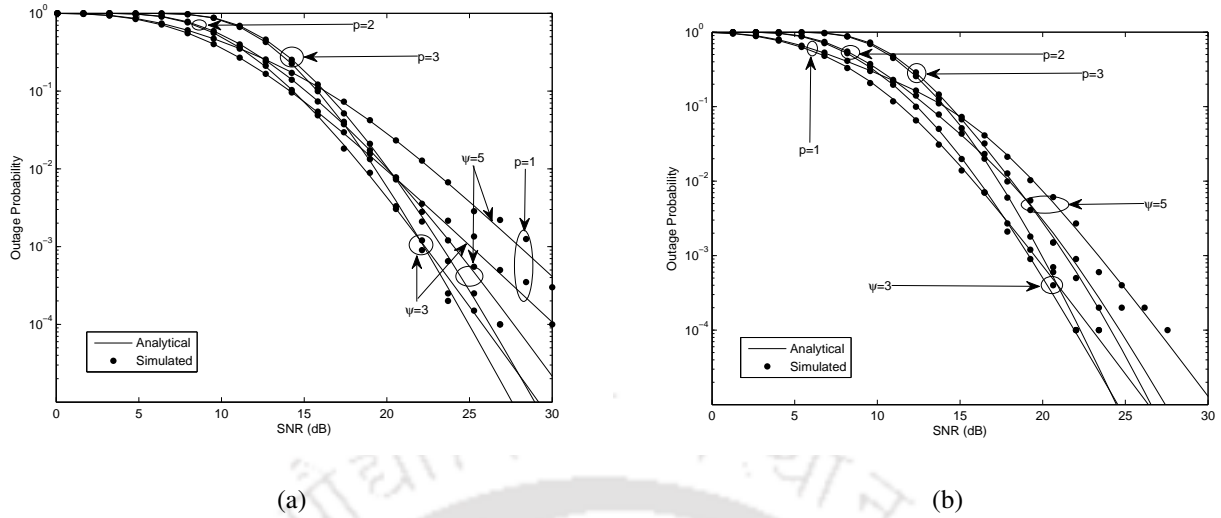


Figure 5.12: Outage probability of system (a) $q=1$, (b) $q=2$, at various SNR and relays placed at the middle of s and d .

where, $\Gamma(\cdot, \cdot)$ is upper incomplete gamma function [GR07, Eq.(8.350.1)].

Average Symbol Error Rate

Average SE_R for M-PSK modulated signal is define as [SA05, Eq.(5.1)]

$$SE_R = \int_0^\infty Q(\sqrt{c\theta}) f_{\Theta_T}(\theta) d\theta, \quad (5.5.16)$$

where, $c = 2 \sin^2(\pi/M)$. Average SE_R from (5.5.16), can be evaluated from (5.5.13) and proper substitution in [EM95, Eq.(A8)]

$$SE_R = \frac{\{P[I \leq R]\}^p}{(q-1)!} \lambda_{sd}^q \mu(\lambda_{sd}, q) + \sum_{k=0}^{p-1} \binom{p}{k} \{P[I \leq R]\}^k \{P[I > R]\}^{(p-k)} \times \left\{ \sum_{\alpha=1}^q \frac{A_\alpha \mu(\lambda_{sd}, \alpha)}{(\alpha-1)!} + \sum_{\beta=1}^{q(p-k)} \frac{B_\beta \mu(\lambda_{rd}, \beta)}{(\beta-1)!} \right\} \quad (5.5.17)$$

Average received SNR

Average received SNR ($\bar{\gamma}$), can be evaluated as [SA05, Eq.(1.1)]

$$\bar{\gamma} = \frac{1}{p+1} \int_0^\infty \theta f_{\Theta_T}(\theta) d\theta. \quad (5.5.18)$$

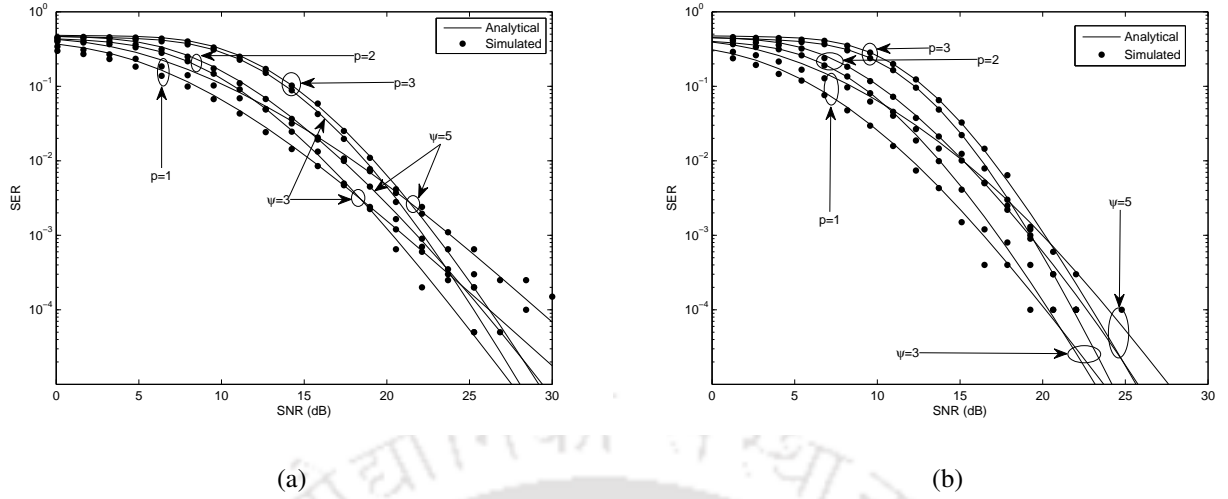


Figure 5.13: *SER* of system (a) $q=1$, (b) $q=2$, at various SNR and relays placed at the middle of s and d .

In (5.5.18), the factor $1/(p+1)$ has been used as signal is received at multi-antenna destination received in $(p+1)$ time-slots. End-to-end average SNR $\bar{\gamma}$ can be evaluated from (5.5.13), (5.5.18) and [GR07, Eq.(3.326.2)]

$$\bar{\gamma} = \frac{1}{1+p} \left[\{P[I \leq R]\}^p \frac{q}{\lambda_{sd}} \right. \quad (5.5.19)$$

$$\left. + \sum_{k=0}^{p-1} \binom{p}{k} \{P[I \leq R]\}^k \{P[I > R]\}^{(p-k)} \right]$$

$$\times \left[\sum_{\alpha=1}^q \frac{A_{\alpha} \alpha}{(\lambda_{sd})^{\alpha+1}} + \sum_{\beta=1}^{q(p-k)} \frac{B_{\beta} \beta}{(\lambda_{rd})^{\beta+1}} \right] \quad (5.5.20)$$

Average Capacity

Average capacity is defined as [SA05, Eq.(5.1)]

$$C = \frac{1}{p+1} \int_0^{\infty} \log_2(1+\theta) f_{\Theta_T}(\theta) d\theta \quad (5.5.21)$$

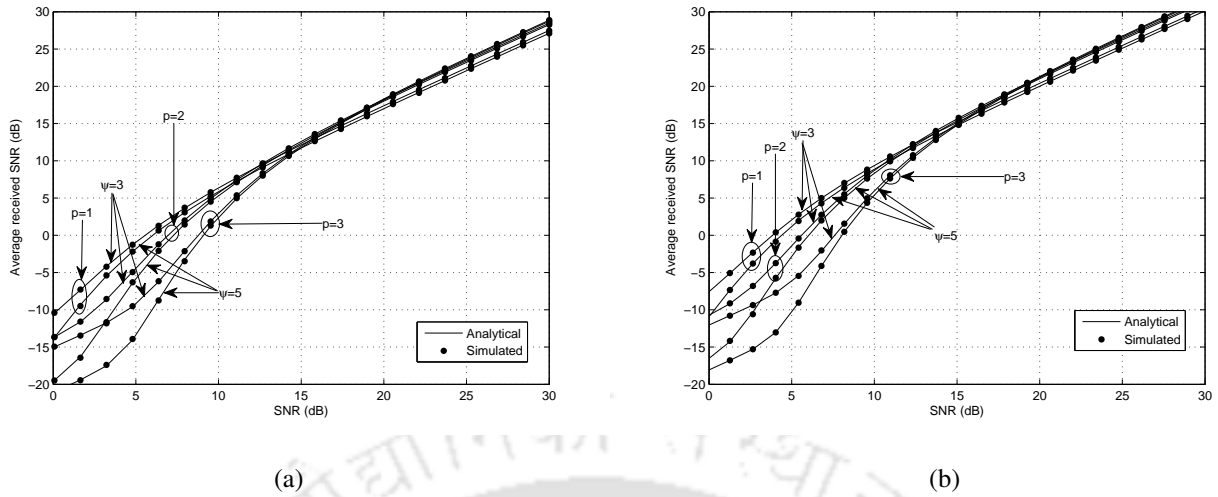


Figure 5.14: Average received SNR of system (a) $q=1$, (b) $q=2$, at various SNR and relays placed at the middle of s and d .

Average capacity from (5.5.21), can be evaluated with the help of (5.5.13) and proper substitution in [GR07, Eq.(4.337.5)]

$$\begin{aligned}
 C = & \frac{1}{1+p} \left[\frac{\{P[I \leq R]\}^p}{(q-1)!} \lambda_{sd}^q \Omega(\lambda_{sd}, q) \right. \\
 & + \sum_{k=0}^{p-1} \binom{p}{k} \{P[I \leq R]\}^k \{P[I > R]\}^{(p-k)} \\
 & \left. \times \left\{ \sum_{\alpha=1}^q \frac{A_{\alpha} \Omega(\lambda_{sd}, \alpha)}{(\alpha-1)!} + \sum_{\beta=1}^{q(p-k)} \frac{B_{\beta} \Omega(\lambda_{rd}, \beta)}{(\beta-1)!} \right\} \right]
 \end{aligned} \tag{5.5.22}$$

here, $\Omega(\alpha, \beta) = \frac{(\beta-1)!}{\alpha^{\beta} \log_e 2} \sum_{\mu=0}^{\beta-1} \frac{1}{(\beta-\mu-1)!} \left[(-1)^{\beta-\mu-2} \alpha^{\beta-\mu-1} \exp(\alpha) Ei(-\alpha) + \sum_{\nu=1}^{\beta-\mu-1} (\nu-1)! (-\alpha)^{\beta-\mu-\nu-1} \right]$, $Ei(\cdot)$ is exponential integral [GR07, Eq.(27.5.3)].

5.5.4 Numerical Results and Discussion

In evaluating the performance of the system, asymmetrical channel conditions have been assumed i.e. $\lambda_{sr} = \lambda_{rd} \neq \lambda_{sd}$, where r_k is placed between s & d . The threshold values of cooperative relaying is $\chi = 2^{(p+1)R} - 1$, here R is spectral efficiency in b/s/Hz. Value of R is assumed to be unity for numerical evaluation. Outage probability, SEr , average received SNR and average capacity have been plotted in Fig. 5.12, Fig. 5.13, Fig. 5.14 and Fig. 5.15 respectively, for various values of p , q , ψ and SNR (i.e. ω). Each cooperative relay utilizes one time slot out of $p+1$ time slots, hence spectrum efficiency of such system become $1/(p+1)$ part of available spectrum. So modulation parameter

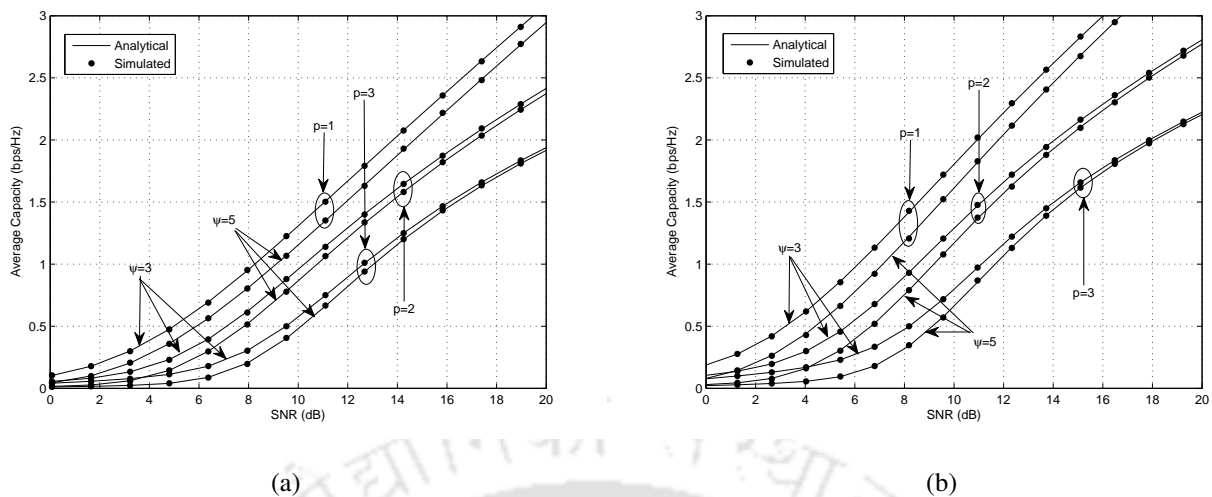


Figure 5.15: Average received SNR of system (a) $q=1$, (b) $q=2$, at various SNR and relays placed at the middle of s and d .

$M = p + 1$, has been chosen for faithful comparison between different numbers of cooperative relay nodes. We observed that less number of relay cooperation is better at lower SNR because most of time relay would not decode the message (i.e. relay would not participate) and unnecessary wastage of spectrum efficiency will take place. At higher SNR, more number of relay assisted transmission is superior because probability of relay participation increases. As can be seen from the Fig. 5.12 and Fig. 5.13, SNR corresponding to intersection points of the curves for lower and higher values of p increases with the increase in the number of antennas at the destination. This is due to fact that slope of these performance curves increases and advantage of cooperation will be visible at higher SNRs. More number of relay cooperation at higher path-loss condition is also found to perform better because signals are intermediately boosted up by the relay terminals.

5.6 Conclusion

In this chapter, performance of a system in which communication between source and destination is supported by multiple relay in Rayleigh fading channel has been analyzed. In section 5.2, closed-form expression of outage for dual-hop opportunistic relaying has been derived and the outage performance has been compared with that of a single-hop SIMO system. The results shows that performance of dual-hop opportunistic relay network may become inferior to conventional SIMO system, if the relays are placed near the source or the destination. Placement of relays at the middle of source and destination has been found to outperform conventional SIMO system in higher path-loss condition. Outage

performance of dual-hop opportunistic relay over single-hop SIMO further improves in higher path-loss condition. Next in section 5.3, outage performance of two relay cooperation in absence of direct path, has been investigated. Analytical expression of outage probability has been found. Results shows that number of antennas installed on relays and location of relays, play vital role on the system performance. It is seen that if one of the relay having lower order of diversity, placed near the middle of source-destination link and other relay having higher diversity order, placed near the destination gives better performance. Performance of this system can be improved by increasing number of antennas installed on relays. In this case, positioning of relays can be shifted towards destination for further improvement of system performance. In section 5.4, analytical expression for calculating end-to-end outage probability for multiple cooperative relay network employing multiple antenna relay, has been derived for the case when relay and destination perform SC of signals. Results show that, outage performance improves with increasing the number of relays and antennas installed on those relays. Next in section 5.5, outage probability, SER, average received SNR and average capacity of a system in which multiple cooperative relay terminals communicate with a multi-antenna base station have been analyzed. Analytical expressions for each case has been derived. It has been found that, performance of such cooperative relaying depends on path-loss conditions, number of cooperating relay terminals, number of antenna elements on destination and SNR conditions. Higher number of relay participation may deteriorate the system performance in lower SNR condition but performance improves in higher SNR condition. Monte Carlo simulation has been carried out and numerical evaluation of analytical expressions derived in this chapter are found to match with simulation results.

Chapter 6

Conclusions

As stated at the outset, the field of high-data-rate, spectrally efficient and reliable wireless communication is currently receiving much attention. Cooperative transmission is emerging as an effective technique for combating the effects of path loss, shadowing and multi-path fading. Cooperative relaying provides diversity gain, reduces outage and improves BER performance. In this thesis cooperative relaying with multi antenna infrastructure based relays has been investigated in detail. Use of multiple receiving antennas in a relay increases probability of relay participation when appropriate combining technique is used and such system has potential for improving the performances of existing as well as emerging wireless communication technologies involving communication between single antenna source and destination. Apart from multi antenna relays, in this thesis investigation has been carried out for systems involving multiple single antenna relays and effect of cooperative relaying on the performance of a multi antenna destination has been studied. The main contributions of the thesis are summarized in Section 6.1 and a few tracks for future research are outlined in Section 6.2.

6.1 Summary of Contributions

A major portion of this thesis is devoted in investigating the performance of cooperative relaying with multi-antenna relays in Rayleigh/Nakagami- m fading channels. Communication with the help of relay terminals can exploit spatial diversity, which improve the system performance in fading channel. Installation of multiple antennas at relay terminals is possible if they are infrastructure type, which further improve the system performance through increased relay participation. In such type of a system, a relay receives the signal from multiple antennas, decodes it and forwards to the next stage. Destination may perform various diversity combining schemes on the signal received via direct path and via relay

path. In chapter 2 and chapter 3, performance of such system have been analyzed in various path-loss condition, severity of fading, relay placement at different locations and different number of antennas installed on relay. It is found that for relay placement at some specific locations, the performance of system depends only marginally on number of antennas installed on the relay and the combining schemes used at relay and destination. System performance can be improved significantly by appropriately positioning the relay. For such positioning, system performance depends to a considerable extent on number of antennas on the relay and the combining schemes at relay and destination. Analytical expressions for various performance parameters for different combining schemes in Rayleigh and Nakagami- m fading channel have also been derived. Apart from the basic three node systems shown in Fig. 2.1 and Fig. 2.7, other multi-antenna relaying schemes have also been investigated in this thesis. In chapter 4, analysis has been carried out for a system model in which communication between source and multi-antenna destination is supported by a single-antenna regenerative relay in Nakagami- m fading channel. Comparative performance of such a system with conventional SIMO system, in various severity of fading, different path-loss condition and different number of antenna elements on destination, have been studied. At higher path-loss condition, communication through intermediate relay node has been found superior as compared to performance in lower path-loss condition because signals are intermediately boosted up. In such scenario, performance of cooperative relaying is equivalent or may outperform SIMO system of same diversity order. Communication between source and destination supported by multiple relays are studied in Chapter 5. Here, in section 5.2, outage performance of dual-hop opportunistic relaying has been compared with that of a single-hop SIMO system. The results shows that performance of dual-hop opportunistic relay network may become inferior to conventional SIMO system, if the relays are placed near the source or the destination. Cooperative scheme with relays placed at the middle of source and destination has been found to outperform conventional SIMO system. Outage performance of dual-hop opportunistic relay over single-hop SIMO improves further in high path-loss condition. Next in section 5.3, outage performance of two multi-antenna relay cooperation in absence of direct path, has been investigated. Results shows that number of antennas installed on relays and location of relays, plays vital role on the system performance. In section 5.4, system performance has been evaluated for the case when multiple multi-antenna relays support the communication between single antenna source and destination. Here, each relay and destination perform selection combining of signal. Analytical expressions have been derived for such a system and its performance has also been studied through simulation. In section 5.5, a system in which single antenna source and relays communicate with multi-antenna destination has been analyzed. Here, it is observed

that less number of relay cooperation is better at lower SNR because most of time relay will not decode the message (i.e. relay would not participate) and unnecessary wastage of spectrum efficiency will take place. At higher SNR, more number of relay assisted transmission is preferable because probability of relay participation increases.

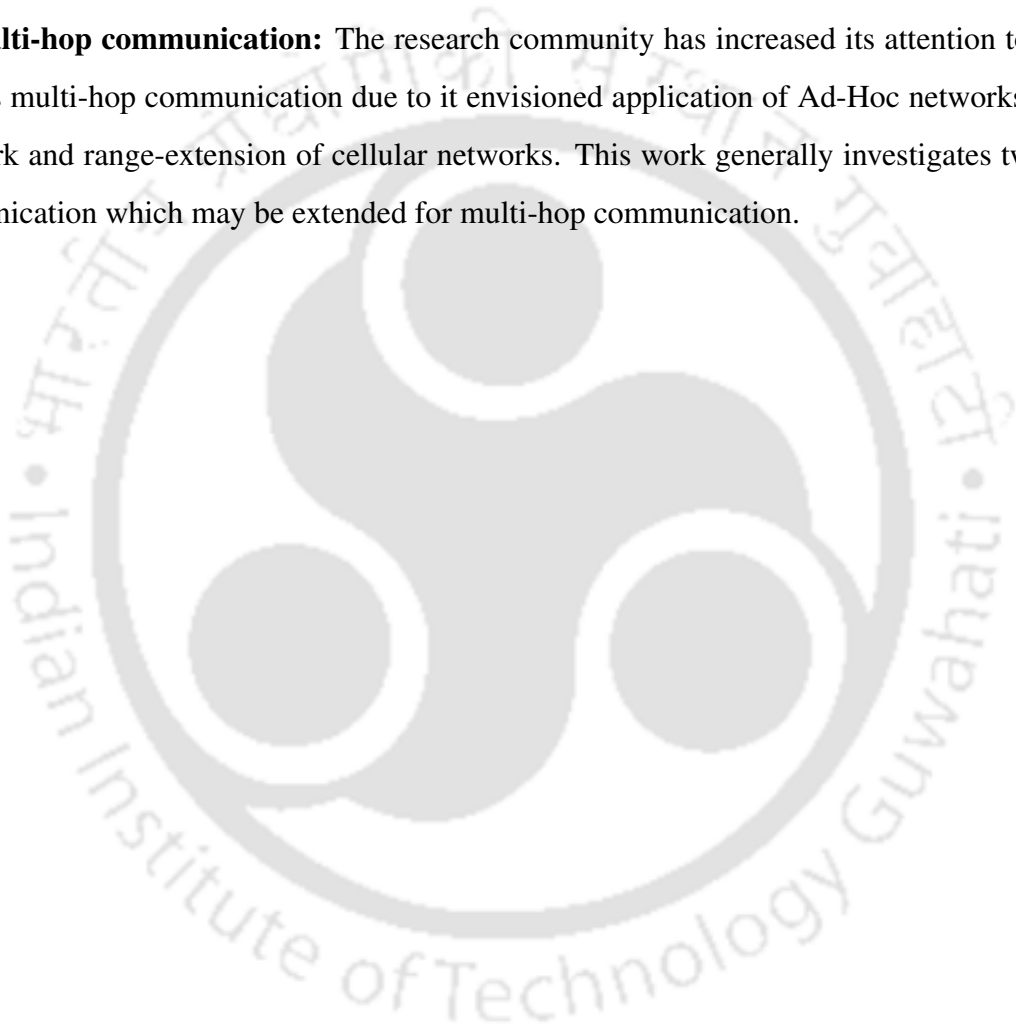
6.2 Tracks for Future Work

This thesis has investigated the performance of some of the basic multi-antenna cooperative relaying schemes. For practical implementation of such multi antenna cooperative relaying schemes in a network environment, it is necessary to investigate several other issues, some of which are briefly outlined below:

- **System modelling taking inference into consideration:** In network scenario, cooperative relay system can suffer from co-channel and adjacent channel interference in to consideration. Hence, effect of these interference need be addressed in future.
- **Power Optimization based on link condition:** Wireless nodes generally have limited battery power. If relay based systems have some feedback mechanism then power can be allocated based on link condition [CSY08]. Such dynamic allocation of power may save battery power or boost the data transfer rate and hence an important area to be investigated.
- **Full duplex operation of relays:** Relay operation in half-duplex mode creates system bandwidth expansion. Full-duplex relay operating in single frequency can solve this problem. Hence, further investigation is necessary for full-duplex relay operation.
- **Spectral efficiencies:** Orthogonal transmission from relays to receiver in different time slots effects the spectrum efficiency. Relays can interact with the receiver using orthogonal codes which avoid bandwidth expansion. Therefore, orthogonal code design for distributed relay nodes may be a possible extension of this work.
- **Complexity performance trade off:** Relays can process the signal in non-regenerative or regenerative mode depending on their functionality. Non-regenerative mode of operation puts less processing burden as compared to regenerative mode of operation, hence often preferred when complexity and/or latency are important issues. Scope exists in extending the present

work for non-regenerative mode of relay operation. Noise amplification is a major issue in non-regenerative mode of operation.

- **System performance in fast fading scenarios:** In this thesis slow fading environment has been considered, here channels are independently faded from one time-slot to other time-slot but remain stationary in a particular time-slot. Relay operation in fast fading environment will be possible extension of this work.
- **Multi-hop communication:** The research community has increased its attention towards wireless multi-hop communication due to it envisioned application of Ad-Hoc networks, sensor network and range-extension of cellular networks. This work generally investigates two-hop communication which may be extended for multi-hop communication.



Appendix A

Supplementary Materials

A.1 Error Expression

In the study of coherent reception of fading signals, the following integral frequently arises,

$$P = \frac{a^b}{\Gamma(b)} \int_0^\infty e^{-at} t^{b-1} Q(-\sqrt{ct}) dt, \quad (\text{A.1.1})$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-t^2/2} dt$, and a , b , and c are positive real numbers; noting that $Q(-x) = 1 - Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt$, P may be written as

$$P = \frac{a^b}{\Gamma(b)} \frac{1}{\sqrt{2\pi}} \int_0^\infty e^{-at} t^{b-1} \int_{\sqrt{ct}}^\infty e^{-u^2/2} du dt \quad (\text{A.1.2})$$

Note that the region of integration is the portion of the upper right quadrant above the curve $t = u^2/c$ (t is the horizontal axis, u the vertical axis). Changing the order of integration, (A.1.2) is written as

$$P = \frac{a^b}{\Gamma(b)} \frac{1}{\sqrt{2\pi}} \int_0^\infty e^{-u^2/2} \int_0^{u^2/c} e^{-at} t^{b-1} dt du \quad (\text{A.1.3})$$

Letting $x = at$ in the inner integral yields

$$P = \frac{1}{\Gamma(b)} \frac{1}{\sqrt{2\pi}} \int_0^\infty e^{-u^2/2} \int_0^{au^2/c} e^{-x} x^{b-1} dx du \quad (\text{A.1.4})$$

where the inner integral in (A.1.4) is now recognized as the incomplete Gamma function, which is expressible as a confluent hypergeometric function by the following identity

$$\int_0^z x^{b-1} e^{-x} dx = b^{-1} z^b e^{-z} {}_1F_1(1; b+1; z) \quad (\text{A.1.5})$$

Using (A.1.5) in (A.1.4) yields

$$P = \frac{(a/c)^b}{b\Gamma(b)} \frac{1}{\sqrt{2\pi}} \int_0^\infty u^{2b} e^{-\alpha u^2} {}_1F_1(1; b+1; au^2/c) du \quad (\text{A.1.6})$$

where $\alpha = a/c + 1/2$. Next, let $y = \alpha u^2$; then (A.1.6) becomes

$$P = \frac{(a/c)^2}{\Gamma(b+1)2\sqrt{2\pi}} \left(\frac{1}{\alpha}\right)^{b+1/2} \int_0^\infty y^{b-1/2} e^{-y} {}_1F_1\left(1; b+1; \frac{a}{\alpha c}y\right) dy \quad (\text{A.1.7})$$

The integral in (A.1.7) is integrable by the following formula, which is easily verified by integrating term by term the power series expansion of ${}_1F_1$,

$$\Gamma(\sigma) {}_2F_1(\sigma, p; q; w) = \int_0^\infty e^{-y} y^{\sigma-1} {}_1F_1(p; q; wy) dy \quad (\text{A.1.8})$$

Eq. (A.1.8) is valid whenever the LHS converges, a sufficient condition for which is $w < 1$. Using (A.1.8) in (A.1.7) yields

$$P = \sqrt{\frac{\gamma}{1+\gamma}} \frac{(1+\gamma)^{-b} \Gamma(b+\frac{1}{2})}{2\sqrt{\pi}\Gamma(b+1)} {}_2F_1\left(1, b+\frac{1}{2}; b+1; (1+\gamma)^{-1}\right) \quad (\text{A.1.9})$$

where $\gamma = c/(2a)$. Note that since a and c are both assumed positive, the argument of the hypergeometric function in (A.1.9), $(1+\gamma)^{-1}$, is less than one; hence (A.1.9) converges for all permissible values of a , b and c .

A.2 Rational Function

If a, b, c, \dots, m are roots of the equation $f(x)=0$ and if $\alpha, \beta, \gamma, \dots, \mu$ are their corresponding multiplicities, so that $f(x) = (x-a)^\alpha (x-b)^\beta \dots (x-m)^\mu$, then $\varphi(x)/f(x)$ can be decomposed into the following partial fractions:

$$\begin{aligned} \frac{\varphi(x)}{f(x)} &= \frac{A_\alpha}{(x-a)^\alpha} + \frac{A_{\alpha-1}}{(x-a)^{\alpha-1}} + \dots + \frac{A_1}{x-a} + \frac{B_\beta}{(x-b)^\beta} + \frac{B_{\beta-1}}{(x-b)^{\beta-1}} + \dots + \frac{B_1}{x-b} \\ &+ \frac{M_\mu}{(x-m)^\mu} + \frac{M_{\mu-1}}{(x-m)^{\mu-1}} + \dots + \frac{M_1}{x-m} \end{aligned}$$

where the numerators of the individual fractions are determined by the following formulas:

$$\begin{aligned} A_{\alpha-k+1} &= \frac{\psi_1^{(k-1)}(a)}{(k-1)!}, & B_{\beta-k+1} &= \frac{\psi_2^{(k-1)}(b)}{(k-1)!}, & \dots, & & M_{\mu-k+1} &= \frac{\psi_m^{(k-1)}(m)}{(k-1)!} \\ \psi_1(x) &= \frac{\varphi(x)(x-a)^\alpha}{f(x)}, & \psi_2(x) &= \frac{\varphi(x)(x-b)^\beta}{f(x)}, & \dots, & & \psi_m(x) &= \frac{\varphi(x)(x-m)^\mu}{f(x)} \end{aligned}$$

A.3 Derivation of Performance Parameters

From (2.1.12), end-to-end PDF of received SNR for MRC-MRC based system can be given as

$$f_\Theta^{(1)}(\theta) = P[I \leq R] \lambda_{sd} \exp(-\lambda_{sd}\theta) + P[I > R] \left(\frac{\lambda_{r_o d} \lambda_{sd}}{\lambda_{r_o d} - \lambda_{sd}} \right) \{ \exp(-\lambda_{sd}\theta) - \exp(-\lambda_{r_o d}\theta) \} \quad (\text{A.3.1})$$

here, $P[I \leq R] = \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!}$ and $P[I > R] = 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!}$. With the help of the PDF given in (A.3.1), various performance parameters can be derived as follows

Outage Probability

Outage probability can be calculated as follows [SA05, Eq.(1.4)]

$$P_{out}^{MRC-MRC} = \int_0^\chi f_\Theta^{(1)}(\theta) d\theta, \quad (\text{A.3.2})$$

$$P_{out}^{MRC-MRC} = P[I \leq R] \lambda_{sd} \int_0^\chi \exp(-\lambda_{sd}\theta) d\theta + P[I > R] \left(\frac{\lambda_{r_{od}}\lambda_{sd}}{\lambda_{r_{od}} - \lambda_{sd}} \right) \times \left\{ \int_0^\chi \exp(-\lambda_{sd}\theta) d\theta - \int_0^\chi \exp(-\lambda_{r_{od}}\theta) d\theta \right\}$$

here $\chi = 2^{2R} - 1$. After evaluating the integral, outage probability can be given as

$$P_{out}^{MRC-MRC} = \{1 - \exp(-\lambda_{sd}\chi)\} \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} + \left[1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right] \times \left[1 + \frac{1}{\lambda_{sd} - \lambda_{r_{od}}} \{ \lambda_{r_{od}} \exp(-\lambda_{sd}\chi) - \lambda_{sd} \exp(-\lambda_{r_{od}}\chi) \} \right]$$

Average error probability ($P_e^{MRC-MRC}$) for MPSK signals

$$P_e^{MRC-MRC} = \int_0^\infty Q(\sqrt{c\theta}) f_\Theta^{(1)}(\theta) d\theta, \quad (\text{A.3.3})$$

where $Q(\cdot)$ is Gaussian Q-function, $c = 2 \sin^2(\pi/M)$ for M-PSK signal. So, average error probability can be simplify with the help of (A.3.1), (A.3.3) and (A.1.9)

$$P_e^{MRC-MRC} = P[I \leq R] \lambda_{sd} \int_0^\infty Q(\sqrt{c\theta}) \exp(-\lambda_{sd}\theta) d\theta + P[I > R] \left(\frac{\lambda_{r_{od}}\lambda_{sd}}{\lambda_{r_{od}} - \lambda_{sd}} \right) \times \left\{ \int_0^\infty Q(\sqrt{c\theta}) \exp(-\lambda_{sd}\theta) d\theta - \int_0^\infty Q(\sqrt{c\theta}) \exp(-\lambda_{r_{od}}\theta) d\theta \right\}$$

After evaluating the integral, average error probability can be given as

$$P_e^{MRC-MRC} = \lambda_{sd} \mu(\lambda_{sd}, 1) \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \times \frac{\lambda_{sd}\lambda_{r_{od}}}{\lambda_{r_{od}} - \lambda_{sd}} \{ \mu(\lambda_{sd}, 1) - \mu(\lambda_{r_{od}}, 1) \}$$

where, $\mu\{x, y\} = \frac{\Gamma(y)}{x^y} \left\{ \sqrt{\frac{e}{2x+c}} \frac{(2x+c)^{-y} \Gamma(y+0.5)}{2\sqrt{\pi} \Gamma(y+1) (2x)^{-y}} \right\} {}_2F_1(1, y+0.5; y+1; \frac{2x}{2x+c})$, ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ is Gauss hypergeometric function [GR07, Eq.(9.100)].

End-to-end average received SNR ($\bar{\gamma}^{MRC-MRC}$)

Average received SNR can be evaluated by modifying (2.1.19) i.e.

$$\bar{\gamma} = \frac{1}{2} \int_0^{\infty} \theta f_{\Theta}^{(1)}(\theta) d\theta. \quad (\text{A.3.4})$$

So, (A.3.4) can be simplify with the help of (A.3.1) and [GR07, Eq.(3.326.2)]

$$\begin{aligned} \bar{\gamma}^{MRC-MRC} &= \frac{1}{2} \left[P[I \leq R] \lambda_{sd} \int_0^{\infty} \theta \exp(-\lambda_{sd}\theta) d\theta + P[I > R] \left(\frac{\lambda_{r_{od}}\lambda_{sd}}{\lambda_{r_{od}} - \lambda_{sd}} \right) \right. \\ &\quad \left. \times \left\{ \int_0^{\infty} \theta \exp(-\lambda_{sd}\theta) d\theta - \int_0^{\infty} \theta \exp(-\lambda_{r_{od}}\theta) d\theta \right\} \right] \end{aligned} \quad (\text{A.3.5})$$

After evaluating the integral, average received SNR can be given as

$$\bar{\gamma}^{MRC-MRC} = \frac{1}{2} \left[\frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{\lambda_{sd}(n-1)!} + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \left\{ \frac{\lambda_{r_{od}} + \lambda_{sd}}{\lambda_{r_{od}}\lambda_{sd}} \right\} \right] \quad (\text{A.3.6})$$

Average capacity ($C^{MRC-MRC}$)

Average capacity can be evaluated with the help of (2.1.20)

$$C = \frac{1}{2} \int_0^{\infty} \log_2(1 + \theta) f_{\Theta}^{(1)}(\theta) d\theta. \quad (\text{A.3.7})$$

So, (A.3.7) can be simplify with the help of (A.3.1) and [GR07, Eq.(4.337.2)]

$$\begin{aligned} C^{MRC-MRC} &= \frac{1}{2} \left[P[I \leq R] \lambda_{sd} \int_0^{\infty} \log_2(1 + \theta) \exp(-\lambda_{sd}\theta) d\theta + P[I > R] \left(\frac{\lambda_{r_{od}}\lambda_{sd}}{\lambda_{r_{od}} - \lambda_{sd}} \right) \right. \\ &\quad \times \left\{ \int_0^{\infty} \log_2(1 + \theta) \exp(-\lambda_{sd}\theta) d\theta \right. \\ &\quad \left. \left. - \int_0^{\infty} \log_2(1 + \theta) \exp(-\lambda_{r_{od}}\theta) d\theta \right\} \right] \end{aligned} \quad (\text{A.3.8})$$

After evaluating the integral, average capacity can be given as

$$\begin{aligned} C^{MRC-MRC} &= \frac{-1}{2 \log_e 2} \left[\frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \exp(\lambda_{sd}) Ei(-\lambda_{sd}) + \left\{ 1 - \frac{\Gamma(n, \bar{\lambda}_{sr}\chi)}{(n-1)!} \right\} \right. \\ &\quad \left. \times \left(\frac{\lambda_{r_{od}}\lambda_{sd}}{\lambda_{r_{od}} - \lambda_{sd}} \right) \left\{ \frac{\exp(\lambda_{sd}) Ei(-\lambda_{sd})}{\lambda_{sd}} - \frac{\exp(\lambda_{r_{od}}) Ei(-\lambda_{r_{od}})}{\lambda_{r_{od}}} \right\} \right] \end{aligned}$$

here $Ei(\cdot)$ is exponential integral [GR07, Eq.(8.211.1)].

Bibliography

- [AFY⁺09] A. Adinoyi, Yijia Fan, H. Yanikomeroglu, H. Poor, and F. Al-Shaalan. Performance of selection relaying and cooperative diversity. *IEEE Transactions on Wireless Communications*, 8(12):5790–5795, Dec. 2009.
- [AFYP] A. Adinoyi, Yijia Fan, H. Yanikomeroglu, and H.V. Poor. On the performance of selection relaying. In *Proc. of IEEE Vehicular Technology Conference*, pages 1–5, Sep. 2008.
- [AG99] M.-S. Alouini and A.J. Goldsmith. A unified approach for calculating error rates of linearly modulated signals over generalized fading channels. *IEEE Transactions on Communications*, 47(9):1324–1334, Sep 1999.
- [AK03] P.A. Anghel and M. Kaveh. Relay assisted uplink communication over frequency-selective channels. In *Proc. of SPAWC 2003*, pages 125 – 129, June 2003.
- [AK04] P.A. Anghel and M. Kaveh. Exact symbol error probability of a cooperative network in a rayleigh-fading environment. *IEEE Transactions on Wireless Communications*, 3(5):1416–1421, Sep. 2004.
- [AK06] P. Anghel and M. Kaveh. On the performance of distributed space-time coding systems with one and two non-regenerative relays. *IEEE Transactions on Wireless Communications*, 5(3):682–692, Mar. 2006.
- [ALK03] P.A. Anghel, G. Leus, and M. Kaveh. Multi-user space-time coding in cooperative networks. In *Proc. of ICASSP 03*, volume 4, June 2003.
- [ALK06] P. Anghel, G. Leus, and M. Kaveh. Distributed space-time cooperative systems with regenerative relays. *IEEE Transactions on Wireless Communications*, 5(11):3130–3141, Nov. 2006.

-
- [AV08] A. Agustin and J. Vidal. Amplify-and-forward cooperation under interference-limited spatial reuse of the relay slot. *IEEE Transactions on Wireless Communications*, 7(5):1952–1962, May 2008.
- [AY06] A. Adinoyi and H. Yanikomeroglu. On the performance of cooperative wireless fixed relays in asymmetric channels. In *Proc. of IEEE Global Telecommunications Conference*, pages 1–5, Dec., 2006.
- [AY07] Abdulkareem Adinoyi and Halim Yanikomeroglu. Cooperative relaying in multi-antenna fixed relay networks. *IEEE Transactions on Wireless Communications*, 6(2):533–544, Feb. 2007.
- [BA07] E. Beres and R. Adve. Outage probability of selection cooperation in the low to medium SNR regime. *IEEE Communications Letters*, 11(7):589–597, July 2007.
- [BA08] E. Beres and R. Adve. Selection cooperation in multi-source cooperative networks. *IEEE Transactions on Wireless Communications*, 7(1):118–127, Jan. 2008.
- [BH06] Norman C. Beaulieu and Jeremiah Hu. A closed-form expression for the outage probability of decode-and-forward relaying in dissimilar rayleigh fading channels. *IEEE Communications Letters*, 10(12):813–815, Dec. 2006.
- [CG79] T. Cover and A.E. Gamal. Capacity theorems for the relay channel. *IEEE Transactions on Information Theory*, 25(5):572–584, Sep. 1979.
- [CK10] C. Conne and Il-Min Kim. Outage probability of multi-hop amplify-and-forward relay systems. *IEEE Transactions on Wireless Communications*, 9(3):1139–1149, Mar. 2010.
- [CKK10] Wan Choi, Dong Kim, and Byoung-Hoon Kim. Adaptive multi-node incremental relaying for hybrid-arq in af relay networks. *Wireless Communications, IEEE Transactions on*, 9(2):505–511, Feb. 2010.
- [CSY08] Min Chen, S. Serbetli, and A. Yener. Distributed power allocation strategies for parallel relay networks. *IEEE Transactions on Wireless Communications*, 7(2):552–561, Feb. 2008.

- [CV08] B.K. Chalise and L. Vandendorpe. Outage probability analysis of a MIMO relay channel with orthogonal space-time block codes. *IEEE Communications Letters*, 12(4):280–282, April 2008.
- [EAK02] V. Emamian, P. Anghel, and M. Kaveh. Multi-user spatial diversity in a shadow-fading environment. In *Proc. of Vehicular Technology Conference, Vancouver, Canada*, volume 1, 2002.
- [EGA03] H. El Gamal and D. Aktas. Distributed space-time filtering for cooperative wireless networks. In *Proc. of IEEE Global Telecommunications Conference*, volume 4, pages 1826–1830, Dec. 2003.
- [EK01] V. Emamian and M. Kaveh. Combating shadowing effects for systems with transmitter diversity by using collaboration among mobile users. In *Proc. of Intern. Symp. on Commun., Taiwan,*, volume 9.4, page 105.1105.4, Nov. 2001.
- [EM95] T. Eng and L.B. Milstein. Coherent DS-CDMA performance in Nakagami multipath fading. *IEEE Transactions on Communications*, 43(234):1134–1143, Feb./Mar./Apr. 1995.
- [GK00] P. Gupta and P.R. Kumar. The capacity of wireless networks. *IEEE Transactions on Information Theory*, 46(2):388–404, Mar. 2000.
- [Gol05] Andrea Goldsmith. *Wireless communication*. Cambridge University Press, Cambridge University Press 40West 20th Street, NewYork, NY 10011-4211, USA, first edition, 2005.
- [GR07] I. S. Gradshteyn and I. M. Ryzhik. *Table of Integrals, Series and Products*. Academic Press Inc, 7th revised edition, 2007.
- [HA03a] M.O. Hasna and M.-S. Alouini. End-to-end performance of transmission systems with relays over rayleigh-fading channels. *IEEE Transactions on Wireless Communications*, 2(6):1126–1131, Nov. 2003.
- [HA03b] M.O. Hasna and M.-S. Alouini. Outage probability of multihop transmission over Nakagami fading channels. *IEEE Communications Letters*, 7(5):216–218, May 2003.
- [HCM] Yingbo Hua, Yu Chang, and Yan Mei. A networking perspective of mobile parallel relays. In *Proc. of IEEE Signal Processing Education Workshop*, pages 249–253, Aug. 2007.

- [HZF05] Patrick Herhold, Ernesto Zimmermann, and Gerhard Fettweis. Cooperative multi-hop transmission in wireless networks. *Computer Networks*, 49(3):299 – 324, 2005. Selected Papers from the European Wireless 2004 Conference.
- [IA07a] S. Ikki and M.H. Ahmed. Performance analysis of cooperative diversity using equal gain combining (EGC) technique over rayleigh fading channels. In *Proc. of IEEE International Conference on Communications*, pages 5336–5341, June 2007.
- [IA07b] S. Ikki and M.H. Ahmed. Performance analysis of cooperative diversity wireless networks over Nakagami-m fading channel. *IEEE Communications Letters*, 11(4):334–336, April 2007.
- [IA10] S.S. Ikki and M.H. Ahmed. Performance analysis of adaptive decode-and-forward cooperative diversity networks with best-relay selection. *IEEE Transactions on Communications*, 58(1):68 –72, Jan. 2010.
- [JCYP04] Zhang Jingmei, Shao Chunju, Wang Ying, and Zhang Ping. Performance of a two-hop cellular system with different power allocation schemes. In *Proc. of IEEE Vehicular Technology Conference*, volume 6, pages 4538–4542, Sep. 2004.
- [KA10] S. Kadloor and R. Adve. Relay selection and power allocation in cooperative cellular networks. *IEEE Transactions on Wireless Communications*, 9(5):1676–1685, May 2010.
- [KB09a] H. Katiyar and R. Bhattacharjee. Average error rate of multi-antenna decode and forward cooperative relay network. In *Proc. of IEEE INDICON 2009, DAICT Ahmedabad, India*, Dec. 18-20, 2009.
- [KB09b] H. Katiyar and R. Bhattacharjee. BER performance of regenerative multi-antenna cooperative relay network in Rayleigh fading channel. In *Proc. of UKIWCWS 2009, IIT Delhi, India*, Dec. 11-12, 2009.
- [KB09c] H. Katiyar and R. Bhattacharjee. Outage performance of two-hop multi-antenna cooperative relaying in Rayleigh fading channel. *IET Electronics Letters*, 45(17):881–883, Aug. 13, 2009.
- [KB09d] H. Katiyar and R. Bhattacharjee. Performance of regenerative relay network operating in

-
- uplink of multi-antenna base station under Rayleigh fading channel. In *Proc. of TENCON 2009, IEEE Region 10 Conference, Singapore*, pages 1–5, Nov. 23-26, 2009.
- [KB09e] H. Katiyar and R. Bhattacharjee. Performance of two-hop regenerative relay network under correlated Nakagami-m fading at multi-antenna relay. *IEEE Communications Letters*, 13(11):820–822, Nov. 2009.
- [KB10a] H. Katiyar and R. Bhattacharjee. Outage performance of dual-hop opportunistic relaying compared to a single-hop SIMO under Rayleigh fading. In *Proc. of NCC 2010, Chennai, India*, Jan. 29-31, 2010.
- [KB10b] H. Katiyar and R. Bhattacharjee. Performance of MRC combining multi-antenna cooperative relay network. *AEU (Elsevier) - International Journal of Electronics and Communications*, 64(10):988 – 991, 2010.
- [KGG05] G. Kramer, M. Gastpar, and P. Gupta. Cooperative strategies and capacity theorems for relay networks. *IEEE Transactions on Information Theory*, 51(9):3037–3063, Sep. 2005.
- [KK08a] Jung-Bin Kim and Dongwoo Kim. Comparison of two SNR-based feedback schemes in multiuser dual-hop amplify-and-forward relaying networks. *Communications Letters, IEEE*, 12(8):557–559, Aug. 2008.
- [KK08b] Jung-Bin Kim and Dongwoo Kim. Performance analysis for amplify-and-forward opportunistic relaying with quality based channel state reporting. In *Advanced Communication Technology, 2008. ICACT 2008. 10th International Conference on*, volume 1, pages 798–801, 17-20 2008.
- [KM99] Ning Kong and L.B. Milstein. Average SNR of a generalized diversity selection combining scheme. *IEEE Communications Letters*, 3(3):57–59, Mar. 1999.
- [KSM07] G.K. Karagiannidis, N.C. Sagias, and P.T. Mathiopoulos. N*Nakagami: A novel stochastic model for cascaded fading channels. *IEEE Transactions on Communications*, 55(8):1453–1458, Aug. 2007.
- [KTM⁺05] G.K. Karagiannidis, T.A. Tsiftsis, R.K. Mallik, N.C. Sagias, and S.A. Kotsopoulos. Closed-form bounds for multihop relayed communications in Nakagami-m fading. In

Proc. of IEEE International Conference on Communications, volume 4, pages 2362–2366, May 2005.

- [KTM06] G.K. Karagiannidis, T.A. Tsiftsis, and R.K. Mallik. Bounds for multihop relayed communications in Nakagami-m fading. *IEEE Transactions on Communications*, 54(1):18–22, Jan. 2006.
- [LK08] I.-H. Lee and Dongwoo Kim. Probability of SNR gain by dual-hop relaying over single-hop transmission in SISO rayleigh fading channels. *IEEE Communications Letters*, 12(10):734–736, Oct. 2008.
- [LK10] Peng Liu and Il-Min Kim. Performance analysis of bidirectional communication protocols based on decode-and-forward relaying. *IEEE Transactions on Communications*, 58(9):2683–2696, Sep. 2010.
- [LTW04] J.N. Laneman, D.N.C. Tse, and G.W. Wornell. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory*, 50(12):3062–3080, Dec. 2004.
- [LW03] J.N. Laneman and G.W. Wornell. Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks. *IEEE Transactions on Information Theory*, 49(10):2415–2425, Oct. 2003.
- [MMJV⁺10] E. Morgado, I. Mora-Jimenez, J.J. Vinagre, J. Ramos, and A.J. Caamano. End-to-End average BER in multihop wireless networks over fading channels. *IEEE Transactions on Wireless Communications*, 9(8):2478–2487, Aug. 2010.
- [MTH04] J. Mietzner, R. Thobaben, and P.A. Hoeher. Analysis of the expected error performance of cooperative wireless networks employing distributed space-time codes. In *Proc. of IEEE Global Telecommunications Conference*, volume 5, pages 2854–2858, Nov.-3 Dec. 2004.
- [NBK04] R.U. Nabar, H. Bolcskei, and F.W. Kneubuhler. Fading relay channels: performance limits and space-time signal design. *IEEE Journal on Selected Areas in Communications*, 22(6):1099–1109, Aug. 2004.

-
- [NHH04] A. Nosratinia, T.E. Hunter, and A. Hedayat. Cooperative communication in wireless networks. *IEEE Communications Magazine*, 42(10):74–80, Oct. 2004.
- [PL07] E. Peh and Ying-Chang Liang. Optimization for cooperative sensing in cognitive radio networks. In *Proc. of IEEE Wireless Communications and Networking Conference*, pages 27–32, Mar. 2007.
- [Pou99] A. D. Poularikas. *The Handbook of Formulas and Tables for Signal Processing*. CRC Press, 1999.
- [QJC⁺04] Zhang Qi, Zhang Jingmei, Shao Chunju, Wang Ying, Zhang Ping, and Hu Rong. Power allocation for regenerative relay channel with rayleigh fading. In *Proc. of IEEE Vehicular Technology Conference, 2004*, volume 2, pages 1167–1171, May 2004.
- [RCG04] A. Ribeiro, X. Cai, and G.B. Giannakis. Symbol error probabilities for general cooperative links. In *Proc. of IEEE International Conference on Communications*, volume 6, pages 3369–3373 Vol.6, June 2004.
- [RCG05] A. Ribeiro, Xiaodong Cai, and G.B. Giannakis. Symbol error probabilities for general cooperative links. *IEEE Transactions on Wireless Communications*, 4(3):1264–1273, May 2005.
- [RWWH09] T. Riihonen, S. Werner, R. Wichman, and J. Hamalainen. Outage probabilities in infrastructure-based single-frequency relay links. In *Proc. of IEEE Wireless Communications and Networking Conference*, pages 1–6, April 2009.
- [SA05] Marvin K. Simon and Mohamed-Slim Alouini. *Digital Communication over Fading Channels*. John Wiley and Sons, Inc., 111 River Street, Hoboken, NJ 07030, second edition, 2005.
- [SD08] D. Soldani and S. Dixit. Wireless relays for broadband access [radio communications series]. *Communications Magazine, IEEE*, 46(3):58–66, Mar. 2008.
- [SEA03a] A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity. part I. system description. *IEEE Transactions on Communications*, 51(11):1927–1938, Nov. 2003.

- [SEA03b] A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity. part II. implementation aspects and performance analysis. *IEEE Transactions on Communications*, 51(11):1939–1948, Nov. 2003.
- [SGBNS07] O. Simeone, J. Gambini, Y. Bar-Ness, and U. Spagnolini. Cooperation and cognitive radio. In *Proc. of IEEE International Conference on Communications*, pages 6511–6515, June 2007.
- [Sha98] C.E. Shannon. Communication in the presence of noise. *Proceedings of the IEEE*, 86(2):447–457, Feb. 1998.
- [SMY10] V. Shah, N.B. Mehta, and R. Yim. The relay selection and transmission trade-off in cooperative communication systems. *IEEE Transactions on Wireless Communications*, 9(8):2505–2515, Aug. 2010.
- [SS08] S. Savazzi and U. Spagnolini. Cooperative fading regions for decode and forward relaying. *IEEE Transactions on Information Theory*, 54(11):4908–4924, Nov. 2008.
- [SSA06] Himal A. Suraweera, Peter J. Smith, and Jean Armstrong. Outage probability of cooperative relay networks in Nakagami-m fading channels. *IEEE Communications Letters*, 10(12):834–836, Dec. 2006.
- [SV06] M.R. Souryal and B.R. Vojcic. Performance of amplify-and-forward and decode-and-forward relaying in rayleigh fading with turbo codes. In *Acoustics, Speech and Signal Processing, 2006. ICASSP 2006 Proceedings. 2006 IEEE International Conference on*, volume 4, pages IV–IV, 14-19 2006.
- [TK08] Arash Talebi and Witold A. Krzymien. Optimized power allocation for multiple-antenna multiple-relay cooperative communication system. In *Proc. of IEEE International Conference on Spread Spectrum Techniques and Applications*, pages 222–226, Aug. 2008.
- [TKMS06] A. T. Theodoros, G.K. Karagiannidis, P.T. Mathiopoulos, and Kotsopoulos S.A. Non-regenerative dual-hop cooperative links with selection diversity. *EURASIP Journal on Wireless Communications and Networking*, 2006(17862):1–8, 2006.
- [WHT04] Theodore S. Rappaport Kurt L. Kosbar William H. Tranter, K. Sam Shanmugan. *Principles of Communication Systems Simulation with Wireless Applications*. Prentice Hall,

Professional Technical Reference, Upper Saddle River, New Jersey 07458, first edition, 2004.

- [YA05] Hong-Chuan Yang and M. S. Alouini. MRC and GSC diversity combining with an output threshold. *IEEE Transactions on Vehicular Technology*, 54(3):1081–1090, May 2005.
- [ZAL05] Yi Zhao, R. Adve, and Teng Joon Lim. Outage probability at arbitrary SNR with cooperative diversity. *IEEE Communications Letters*, 9(8):700–702, Aug. 2005.
- [ZAL06] Yi Zhao, R. Adve, and Teng Joon Lim. Symbol error rate of selection amplify-and-forward relay systems. *IEEE Communications Letters*, 10(11):757–759, Nov. 2006.
- [ZBL09] Wei Zhang and K. Ben Letaief. Cooperative communications for cognitive radio networks. *Proceedings of the IEEE*, 97(5):878–893, May 2009.
- [ZGL10] Xiao Zhang, Yi Gong, and K. Letaief. On the diversity gain in cooperative relaying channels with imperfect CSIT. *IEEE Transactions on Communications*, 58(4):1273 – 1279, April 2010.