RELAY SELECTION AND POWER ALLOCATION IN WIRELESS COOPERATIVE NETWORKS

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

ELECTRONICS AND COMMUNICATION ENGINEERING
(With Specialization in Communication Systems)

By

KAMAL GUPTA

DEPARTMENT OF ELECTRONICS AND COMPUTER ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)

JUNE, 2011

CANDIDATE'S DECLARATION

I hereby declare that the work, which is presented in this dissertation report entitled, **"RELAY SELECTION AND POWER ALLOCATION IN WIRELESS COOPERATIVE NETWORKS"** towards the partial fulfillment of the requirements for the award of the degree of **Master of Technology** with specialization in **Communication Systems**, submitted in the Department of Electronics and Computer Engineering, Indian Institute of Technology Roorkee, Roorkee (India) is an authentic record of my own work carried out during the period from July 2010 to June 2011, under the guidance of **Mr. S. Chakravorty, Assistant Professor, Department of Electronics and Computer Engineering, Indian Institute of Technology Roorkee.**

I have not submitted the matter embodied in this dissertation for the award of any other degree.

Kamal Gupta.

Date: 30 June, 2011

Place: Roorkee

KAMAL GUPTA

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

S. Chakravorty

Date: 30 June, 2011

Place: Roorkee

Mr. S. Chakravorty,
Asst.Professor, E&C Department,
IIT Roorkee,
Roorkee – 247 667 (India).

ACKNOWLEDGEMENTS

I would like to extend gratitude to my guide, **Mr. S. Chakravorty** for his intellectual guidance, attention and constant encouragement that inspired me throughout my dissertation work. I am greatly indebted to him for teaching me the sweetness of self learning. Also his critical arguments in correcting the thesis made me to read in between the lines.

I would also like to thank the Lab staff of Signal Processing Lab, Department of Electronics and Communication Engineering, IIT Roorkee for providing necessary facilities.

I gratefully acknowledge my sincere thanks to my family members for their inspirational impetus and moral support during course of this work.

I thank to all my friends, who have graciously applied themselves to the task of helping me with morale support and valuable suggestions. Finally, I would like to extend my gratitude to all those persons who directly or indirectly contributed towards this work.

KAMAL GUPTA

ABSTRACT

Cooperative communication aims to achieve spatial diversity gain through cooperation of user terminals in transmission without requiring multiple antennas on the same node. It employs one or more terminals as relays in the neighborhood of the transmitter and the receiver, which collaborate in the transmission and serve as a virtual Multiple Input Multiple Output (MIMO) antenna array. Allowing cooperation in wireless communication introduces new problems related to resource allocation (like power, bandwidth) and relay selection. Relay selection is vital for reaping the performance benefits of cooperative communication.

Relay selection is capable of extracting diversity with higher bandwidth efficiency as compared to distributed space-time coding. Relay selection mechanism may be centralized or distributed. A centralized mechanism employs a controlling unit which collects and utilizes the required channel information to select relays to each source-destination pair. In contrast to centralized relay selection, in a distributed mechanism, each node individually determines whether to cooperate or not based on the information exchange that occurs between nodes.

In many relay selection schemes, the current observed channel condition is used to make the relay-selection decision for the subsequent frame. Since, the data rate is high (hundreds of kbits/s), the duration of a data block is smaller than the coherence time. When data transmission takes place, consecutive blocks of data experience approximately the same channel condition. To take the advantage of channel memory, the channel is approximated by means of a Markov model. We proposed a relay selection method using finite state Markov model for Rayleigh fading channel. It is aimed at achieving diversity gain and reducing signaling overheads. Further, Optimal Power Allocation (OPA) is applied along with the proposed relay selection method. It provides improvement in symbol error rate performance as expected.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1
INTRODUCTION

Modern communication systems are an important part of our day to day life. Especially, wireless communication systems such as mobile phone, wireless local area network (WLAN), Bluetooth, etc., provide the freedom for users to roam and to communicate from anywhere at any time. The next generation broadband wireless communication systems are expected to provide wireless multimedia services such as high-speed Internet access, multimedia message services (MMS) and mobile computing. There is a need for high-speed, reliable and cost-effective transmission solutions. The wireless communication system designers face a number of challenges which include the limited availability of the radio frequency spectrum and time-varying wireless channel environment.

The signals arriving at the receiver through different paths interfere with each other. The signal attenuation and interference can be due to path loss and fading. Fading can be mitigated by the exploitation of diversity [1] with complicated signal processing. Diversity techniques are based on transmitting several replicas of the same information bearing signal to the receiver over independent fading channels so that the channel effects can be averaged out. Temporal diversity, frequency diversity and space diversity are three main techniques that are widely used in wireless communication systems. Space or multi-antenna diversity technique is gaining importance as it can be easily combined with the other two forms of diversity. By deploying multiple transmit and receive antennas, which are separated by a few wavelengths (3λ to 10λ) to create independent fading, spatial diversity can be achieved. Depending on whether multiple antennas are used for transmission or reception, diversity is classified as transmit antenna diversity and receive antenna diversity. In receive antenna diversity schemes, multiple receive antennas are deployed at the receiver to receive multiple copies of the transmitted signal and combine them to mitigate the channel fading. This scheme has been incorporated with 2G mobile communication systems such as GSM and IS-136. Multiple-Input Multiple-Output (MIMO) is an advanced technology which can provide spatial diversity and significant improvement in link reliability through the use of multiple antennas at the transmitter and receiver side. MIMO systems can provide spatial multiplexing gain and diversity gain with a trade-off between them. Deployment of MIMO techniques is not always feasible mainly due to size, cost factor or power constraints of devices used in cellular as well as in wireless sensor and ad-hoc networks. An approach to utilize the advantages of spatial diversity without using multiple antennas is cooperative diversity, also known as cooperative communications [2]. Technological advances in communication hardware allow more complicated signal processing and coding techniques at mobile users and make the vision of cooperative communications a reality. In wireless networks, direct transmission between distant terminals is very expensive in terms of transmitted power required for reliable communication. Use of high power at the transmitting nodes reduces the network lifetime and causes interference to nearby nodes also. Hence in cellular networks, connectivity is provided between mobiles with the help of base stations [3].

1.1 Cooperative Diversity

The basic idea is that some nodes that overheard the information transmitted from the source node assist the source node by transmitting the received information to the destination node. Since the destination node receives multiple independently faded copies of the transmitted information from the source node and the relay node, cooperative diversity is achieved. Cooperative communication techniques take advantage of the broadcast nature of wireless transmission. The cooperating nodes share their antennas and other resources to create a virtual antenna array. Relaying can be implemented using an amplify-and-forward, decode-and-forward or coded cooperation scheme. For cooperative diversity transmission, the medium-access control protocol manages orthogonal relaying to ensure that terminals satisfy the half-duplex constraint and do not transmit and receive simultaneously on the same subchannel.

In repetition-based cooperative diversity, relays either amplify what they receive or fully decode and repeat the source signal. In order for the destination to combine these signals and achieve diversity gains, the repetitions must occur on orthogonal subchannels [4]. In space-time coded cooperative diversity, relays utilize a suitable space-time code and therefore can transmit simultaneously on the same subchannel.

Cooperative diversity protocols include fixed relaying, selection relaying and incremental relaying. For fixed relaying, the relays are allowed to either amplify their received signal or to decode, re-encode and retransmit the messages. Selection relaying builds upon fixed relaying by allowing transmitting terminals to select a suitable cooperative action based upon the measured SNR between them. Incremental relaying improves upon the spectral efficiency of both fixed and selection relaying by exploiting limited feedback from the destination and relaying only when necessary [4].

1.1.1 Advantages of Cooperative Diversity

Cooperative diversity mitigate not only the effects of short term fading but also the effects of long term fading, i.e., shadowing, by selecting the relay node which does not experience shadowing. It has the potential to be successfully used in cellular networks and wireless ad-hoc networks. It provides high data rate and decreased sensitivity to channel variations. The increased data rate with cooperation means now the nodes need to use less total power to achieve a certain rate as compared to no cooperation. This feature can thus be used to increase the battery life of the nodes particularly in wireless sensor networks. The gain achieved through cooperation can also be used to increase the cell coverage in cellular networks [5].

1.1.2 Relay Selection

In contrast to the conventional forms of employing space diversity with multiple antenna arrays located at the single terminal, a lot of work has been done on the problem of creating and exploiting space diversity using a set of distributed antennas located at multiple nodes. In amplify and forward algorithm and decode and forward algorithm, full spatial diversity can be achieved by allowing all the relays to cooperate in the transmission between a pair of terminals at the cost of bandwidth efficiency. Another approach can be the use of space-time codes. It allows all the relays to transmit on the same channel [4]. The number of participating antennas in cooperative diversity schemes is random and therefore space – time coding which is generally designed for fixed number of antennas needs to be modified each time the number of antennas changes. Also tight synchronization is required at block and symbol level to implement this protocol. These requirements demand modifications to the layers of communication stack up to the routing layer which has been built according to point–to–point communication.

The benefits of cooperative diversity can be achieved with comparatively less overhead if appropriate relays are selected to cooperate with the source. All the nodes in the network need not to participate in the cooperation process. Selecting a best relay is important to get the benefits of cooperation. It makes cooperation practical by reducing the synchronization required among many cooperating relays. Selection cooperation outperforms Distributed Space Time Coding (DSTC) scheme in terms of outage probability due to the more efficient use of power. In DSTC scheme each relay shares its power between all source nodes while in selection cooperation scheme a relay uses its power among the nodes that have selected that node as a relay [6]. In a multi-user scenario, relay selection scheme determines how relays are assigned, how it is determined which users cooperate with each other, and how often relays are assigned. In systems such as cellular networks in which users communicate with a base station, centralized relay selection mechanism is used. It means that a central base station collects and utilizes the required information that can be channel information or geographical location to select one or more relays to each source-destination pair. Systems such as ad–hoc networks which do not have centralized controlling unit, employ distributed relay selection protocol. The distributed algorithm limits communication overhead and calculation complexity compared to the centralized algorithm but the latter provides good performance. The number of relay nodes to be selected to cooperate with the source node is important for the relay node selection algorithm. This number determines the performance of the system in terms of complexity, overheads, hardware requirement and cooperative gain.

Most of the models that have been used for evaluating the performance of data block transmissions over the wireless channel assume that the block transmissions are independent and identically distributed (i.i.d.). To eliminate channel memory, techniques like interleaving were developed. For high data rates, the fading process can be considered to be slowly varying particularly at the carrier frequency (900-1800 MHz) and for vehicular speeds (13-27 m/s). Therefore, the dependence between transmissions of consecutive blocks of data cannot be neglected and hence the assumption that the success or failure of the reception of data blocks at the destination node is an iid process is not realistic [7]. The advantage of the channel memory can be exploited by the Markov modeling of the fading channel. Depending upon the nature of fading (fast or slow), the number of states in the model can be decided. A Finite state Markov model is widely used to approximate a channel with memory including Rayleigh, Ricean and Nakagami fading channels. Most of the relay selection schemes proposed in literature [6], [24]-[29], [33] use present channel conditions to select the relay for the next frame. Use of Markov model in the relay selection process reduces the complexity and overheads and thus helps in saving power.

1.2 Statement of the Problem

Cooperative Diversity is one of the promising techniques for dealing with channel fading. This dissertation is aimed at achieving cooperative diversity through relay selection. The main objectives of this dissertation are as follows:

- Review of single relay selection and multiple relay selection schemes and the advantages and limitations of these schemes.
- Implementation of relay selection algorithm selecting a relay on the basis of instantaneous Signal-to-Noise Ratio (SNR) in decode-and-forward network and evaluating the performance in terms of Symbol Error Rate (SER). Comparison of the SER performance using Equal Power Allocation (EPA) strategy and Optimum Power Allocation (OPA) strategy has been done through simulations.
- Implementation of relay selection algorithm in decode-and-forward network using finite state Markov model of Rayleigh fading channel and evaluating the performance in terms of SER. Comparison of the SER performance using EPA strategy and OPA strategy has been done through simulations.

1.3 Organization of the Report

The dissertation has been organized in six chapters, including this introductory chapter.

Chapter2 introduces the concept of cooperative communication. It describes different relaying strategies and signaling techniques used for cooperative communication. *Chapter 3* introduces Markov chain concept and describes Markov modeling of the Rayleigh fading channel. It also includes the simulation results of two-state, three-state and eleven-state Markov model. *Chapter 4* describes different relay selection schemes that can be used in the wireless network depending upon the requirements and the constraints of the network. It shows the evaluation standards of the relay selection algorithms and the problems or challenges to be faced when applying these algorithms in the network. *Chapter 5* presents system description and includes simulation results and discussion on these results. The dissertation concludes with *Chapter 6* which also contains some suggestions for future work.

Chapter 2
COOPERATIVE COMMUNICATION

Cooperative communication refers to the sharing of resources and the realization of distributed protocols among multiple nodes in a network. Today, it is a very active research area with promising developments. Cooperation among peer nodes have been considered in the 1980's under the title of packet radio networks [8]. Since the 1990's, spread of highly capable mobile devices brought the attention back into peer cooperation and it appeared as an active research area.

2.1 Overview of Cooperative Communication

Cooperation is mainly applied in wireless infrastructural networks and wireless ad-hoc networks. The main characteristics of ad hoc networks are self-configuration and autonomous operation without relying on any infrastructure. One of the main focuses of research on ad hoc networks has been mobility and dynamic topologies. Besides the uncertainty of link qualities due to wireless fading, nodes can join and leave a network and the topology of the network changes over time. Some new classes of networks such as wireless sensor networks share some of the characteristics of ad hoc networks. Research on wireless sensor networks is becoming popular due to the advances in low-power RF and microelectronics. The advances in microelectronics enabled large scale deployment of small-size and low-cost sensors. Wireless sensor networks are used in wide range of applications such as security, habitat monitoring, and remote diagnostics and patient care. Typically, a low-cost sensor is constrained to work and last with limited energy resources. This limits the computation and communication capabilities of wireless sensor nodes.

The idea of cooperation has found its use in infrastructure based wireless networks also. Conventionally, infrastructure based networks follow a single hop cellular architecture, in which users and the base stations communicate directly. The main challenge in today's wireless broadband networks is to support high rate data communication with continuous coverage at a reduced cost. Despite continuous work and research in wireless communication to overcome these challenges, we are not fully successful. The scarcity of wireless spectrum encouraged the allocation of high frequency bands but in this band power attenuation with distance is more severe. This factor significantly decreases the coverage of a base station. Fast decay of power with distance suggests that both the capacity and the coverage of networks can be improved by increasing the density of base stations. However, this approach (sometimes called deploying microcells) adds to the already high infrastructure and deployment costs. As a result, we face a situation in which the wireless systems can achieve any two, but not all three, of high capacity, high coverage and low cost. Integrating cooperative communication to cellular networks emerged as a viable solution to mitigate this problem. Although wireless relays use additional radio resources, they have lower cost compared to base stations since high capacity wired connection to the backbone is not required. Multihop relaying is already part of the standards currently being developed for wireless broadband systems such as 802.16j and 802.16m, which is an indication of growing consensus on the effectiveness of cooperative communication. The conventional and simplest form of cooperation is multihop relaying, in which data is delivered to its destination through relay nodes forming a multihop path.

2.2 Preliminaries of Multihop Relaying

Relaying protocols can be classified into two according to the processing at the relay: Analog Relaying (AR) and Digital Relaying (DR). AR can be implemented in a very primitive way in which the relay functions as an active reflector. In DR, the relay performs detection of the incoming signal and regenerates a noise-free version of original signal. AR and DR incur different limitations in practice. In DR, the relay is required to first demodulate and detect the received signal, and then modulate and retransmit the regenerated signal. These operations require more processing and causes more latency than simple AR which does not require any of these.

The relay nodes can operate in full-duplex or half-duplex modes. In full-duplex mode the relay can transmit and receive at the same time on the same frequency band. To implement full-duplex operation, the relay can cancel its self - interference from the received signal.

However, in practice this approach may not be robust. Thus, relays are expected to operate in half-duplex mode only. The half-duplex constraint requires the use of orthogonal channels for transmission and reception. For instance, the relay can use different time slots to receive and transmit as shown in Figure 2.1. In the first time slot the source node transmits and the next relay node R_1 receives. In the second time slot, R_1 transmits the processed signal to the next relay. With this protocol, relaying can be easily integrated to wireless networks using time-division multiple

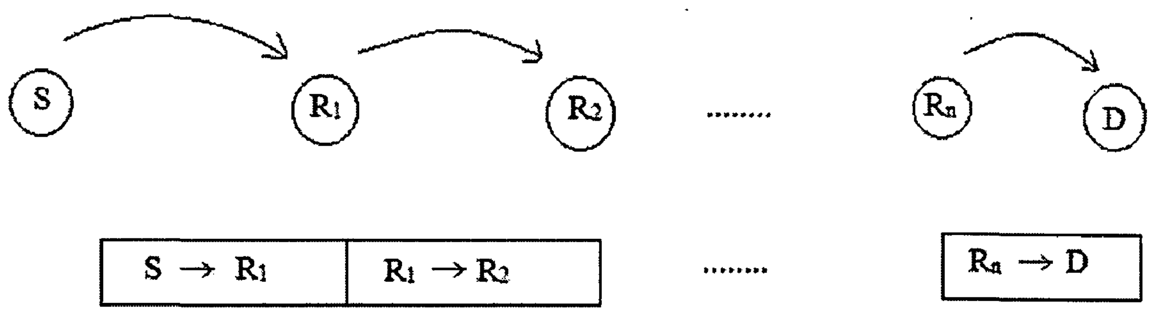

Figure 2.1: Multihop relaying and time – division protocol.

access. As the number of hops increases, the number of time slots allocated for delivering data from the source to the destination increases. To increase the spectral efficiency, spatial reuse can be allowed among the relay nodes.

2.3 Multiple Antennas and Cooperative Communication

Multihop relaying imposes a chain structure in which each node listens to one other node in the chain. It can be seen as the simplest form of cooperative communication. Consider the network in Figure 2.1 with n = 2 relays. Assume that the link from S to R_1 is error-free. Then, R_1 can act as a second transmit antenna for S. Similarly, if R_2 and D has an error free link, R_2 can serve as a receive antenna for D. Multi-antenna techniques can improve the performance of wireless links in terms of both capacity and reliability without additional bandwidth use. Multiple receive antennas provide the spatial receive diversity; whereas multiple transmit antennas can provide diversity through space-time coding [9]. Availability of multiple antennas both at the transmitter and receiver sides creates a MIMO link. In scattering rich environments, at high SNR, the information theoretic capacity of a MIMO link grows linearly with the number of transmit and receive antennas. For MIMO link, there is a fundamental trade-off between the two gains, diversity gain d and multiplexing gain r [10]. Similar to MIMO systems, cooperation can increase the transmission rate or improve the reliability for a given rate through distributed protocols. Capacity in the presence of relay nodes is a classical problem in information theory [11], which recently received much attention [5].

2.4 Cooperative Diversity

Cooperative diversity relies on two principles, first due to the broadcast nature of wireless medium; most transmissions can be heard by multiple nodes in the network with no additional transmission power and bandwidth. Secondly, different nodes have independent channel fading statistics to a given destination node and the destination can listen, store, and then combine signals from different nodes. Figure 2.2 shows the source node broadcasts its message in phase 1. The message is received by the relay node and the destination node. In second phase, the relay node transmits the received signal during phase 1 to the destination node. The destination node receives two copies of the transmitted signal via two independent paths. Hence, cooperative diversity is achieved.

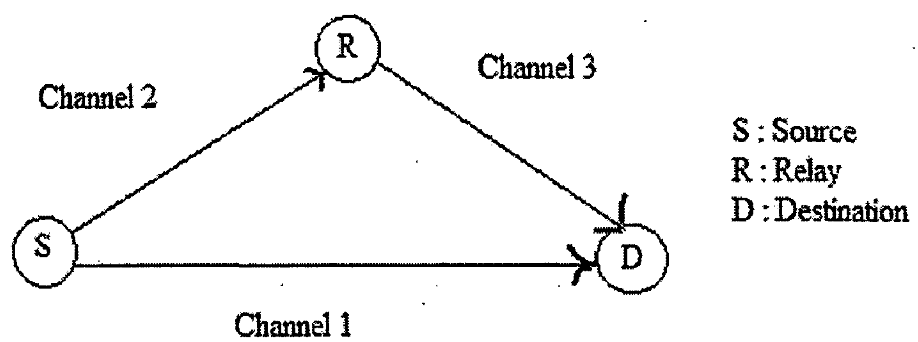

Figure 2.2: Single-relay cooperative communication system.

Three cooperative relaying strategies are given below:

1) Decode and Forward Method (DF)

In this method [2], a user attempts to detect the bits of the other user (or partner) and then retransmits the detected bits as shown in Figure 2.3. The partners may be selected by the base station, or through some other technique that provides optimum partner selection. Here we have considered two users cooperating with each other for providing a second data path for diversity. It should be noted that it is possible for a cooperating node to decode symbols incorrectly resulting in error propagation. So the perfect regeneration at the relays may require retransmission of symbols or use of Forward Error Correction (FEC) depending on the quality of the channel between the source and the relays. This may not be suitable for a delay limited networks. A simple code-division multiple access (CDMA) implementation of decode-and-forward cooperative signaling is shown in [5]. In this scheme, two users are cooperating with each other. Each user has its own spreading code, denoted by $c_i(t)$. The two user's data bits are denoted $b_i^{(n)}$ where $i = 1, 2$ are the user indices and n represents the time

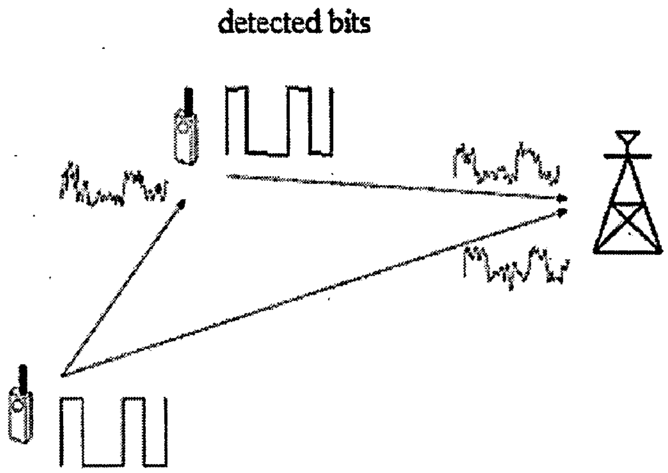

Figure 2.3: Decode and forward [2].

index of information bits. Factors a_{ij} denote signal amplitudes, and thus represent power allotted to user's own bits versus the bits of the partner. The term $\hat{b}_i^{(n)}$ denotes the partner's hard-detected estimate of other user ith bit. Each signaling period consists of three bit intervals. Denoting the signal of user 1 as $X_1(t)$ and the signal of user 2 as $X_2(t)$, $X_1(t)$ and $X_2(t)$ are as shown

$$X_1(t) = a_{11} b_1^{(1)} c_1(t), \quad a_{12} b_1^{(2)} c_1(t), \quad a_{13} b_1^{(2)} c_1(t) + a_{14} \hat{b}_2^{(2)} c_2(t) \tag{2.1}$$

$$X_2(t) = a_{21} b_2^{(1)} c_2(t) \;, \; a_{22} b_2^{(2)} c_2(t) \;, \; a_{23} \hat{b}_1^{(2)} c_1(t) + a_{24} b_2^{(2)} c_2(t) \tag{2.2}$$

In the first and second intervals, each user transmits its own bits. Each user then detects the other user's second bit, and in the third interval, both users transmit a linear combination of their own second bit and their estimate of the partner's second bit, each multiplied by the appropriate spreading code. These transmitted signals are shown in eqn.(2.1) and eqn.(2.2). The transmit powers of the users in the first, second, and third intervals are variable, and by changing the relative transmit powers according to the conditions of the uplink channel and the inter-user channel, this method provides adaptability to channel conditions. The powers are allocated through the factors a_{ij} such that an average power constraint is maintained.

2) Amplify and Forward Method (AF)

Amplify-and-forward is conceptually the simplest among the cooperative signaling methods. Each user in this method receives a noisy version of the signal transmitted by its partner. The

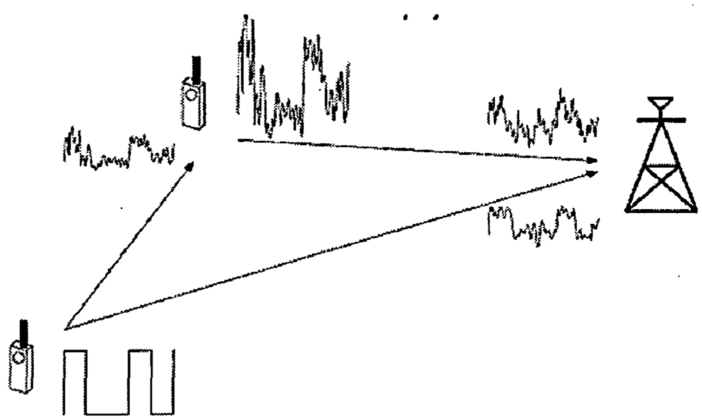

Figure 2.4: Amplify and forward [2].

user then amplifies and retransmits this noisy signal as shown in Figure 2.4. The destination will combine the information sent by the user and partner and will make a final decision on the transmitted signal. Although the noise component present in the signal received from the user is also amplified by the partner during its amplification process, the destination still receives two independently-faded versions of the signal and is thus able to make better decisions for the transmitted signal. In this method, it is assumed that the destination knows the inter-user channel coefficients to do optimal decoding, so some mechanism to estimate this information must be provided. Another potential challenge is that sampling, amplifying, and retransmitting analog values is technologically nontrivial. Systems employing decode and forward method perform slightly better than those employing amplify and forward method at low average Signal- to-Noise Ratio (SNR) while both have same performance at high SNR [12]. Figure 2.5 compares Bit Error Rate (BER) performance of both systems.

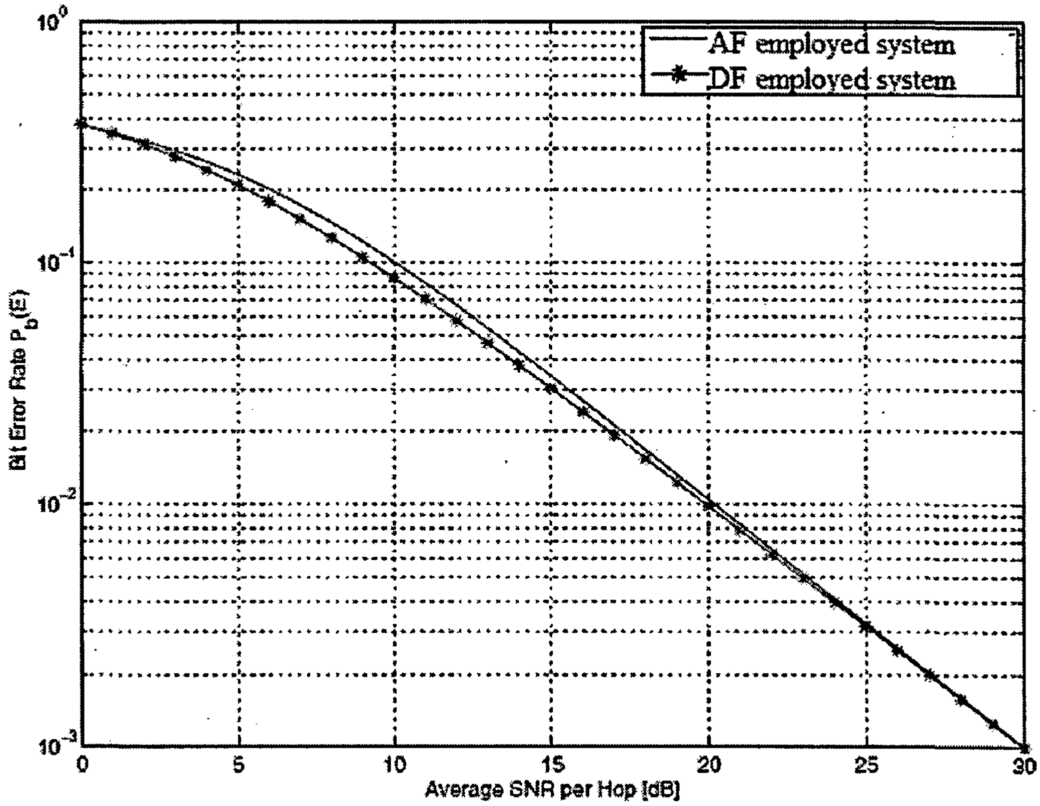

Figure 2.5: Comparison between the BER of systems employing AF and DF technique [12].

3) Coded Cooperation (CC)

In this strategy, different portions of each user's code word are sent via independent fading paths. The users divide their source data into blocks that are augmented with cyclic redundancy check (CRC) code. Each of the users' data is encoded into a codeword that is segmented into two parts containing N1 bits and N2 bits, respectively. Let the original codeword has N1 + N2 bits. The codeword is punctured into two parts with first partition containing N1 bits and the second containing N2 bits called as the puncture bits. Similarly, the data transmission period for each user is divided into two time segments of N1 and N2 bit intervals, respectively called as frames as shown in Figure 2.6.

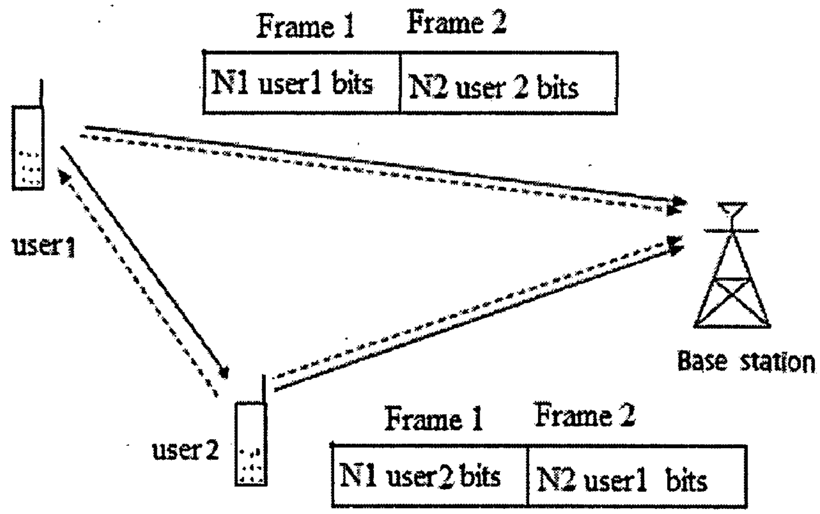

Figure 2.6: Coded cooperation [2].

In the first frame, each user transmits a code word comprising N1-bit code partition and it also tries to decode the transmission bits of its partner. If the user succeeds in decoding the bits of its partner, in the second frame the user calculates and transmits the second code partition of its partner, containing N2 code bits. Else, the user transmits its own second code partition containing N2 bits. Thus, each user always transmits a total of N = N1 + N2 bits per source block over the two frames.

2.5 Signaling Techniques for Cooperative Communication

The cooperative transmission protocol schemes used by relays can be either amplify and forward or decode and forward depending on how the received signals is processed at the relay before being forwarded to the receiver. Generally, both amplify and forward and decode and forward algorithms consist of two transmission phases as shown in Figure 2.7 [4]. In the first phase, a transmitter sends the information to its receiver and all potential relays. During the second phase, the relays transmit the information to the receiver.

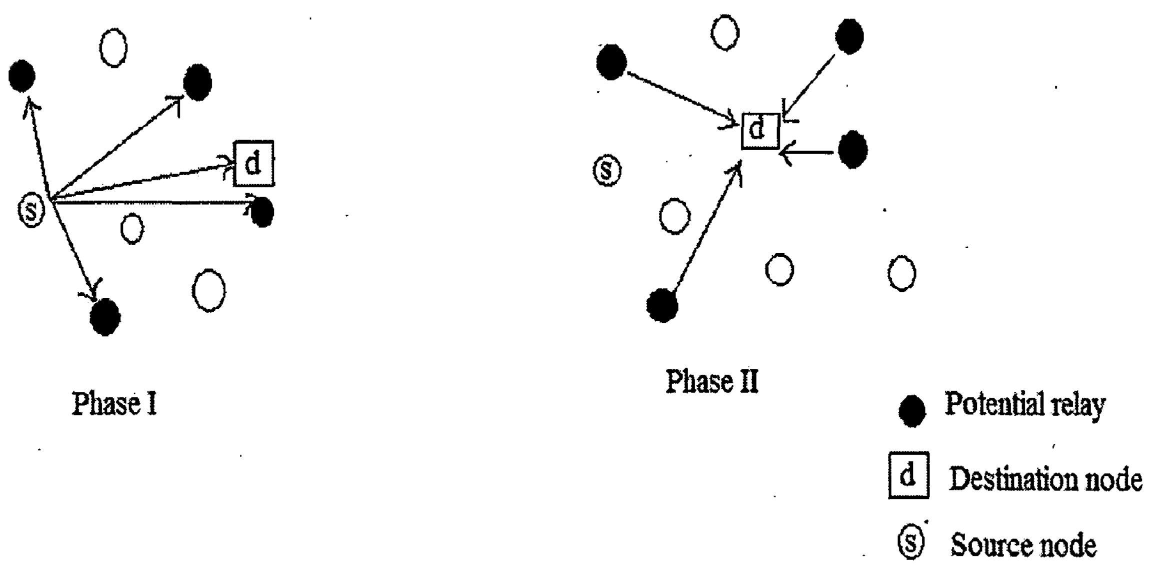

Figure 2.7: Two phases in cooperative diversity. Phase I: Source broadcasts frames, Phase II: Selected relay nodes retransmit the frames.

Cooperative diversity (CD) schemes can be categorized into fixed and adaptive. In fixed CD schemes, the partner always forwards the information to the destination. In contrast, the partner of an adaptive CD scheme decides whether or not to forward the information based on either inter user channel quality (in case of amplify and forward) or feedback from the destination or checking cyclic redundancy check (CRC) of the frame of bits (in case of decode and forward). If the partner decides not to forward, then it may repeat transmitting its own information sent in the earlier time slot or remain silent. The adaptive relaying scheme can be categorized as selection and incremental [13]. For the selection relaying, the partner always forwards the information if it has error free information. On the other hand, incremental relaying forwards only when a request is made from the destination.

To date, various cooperative diversity systems have been proposed and analyzed. According to how relays react during the second phase, cooperative system proposed in the literature can be categorized into different schemes. Some of these schemes are listed in Figure 2.8.

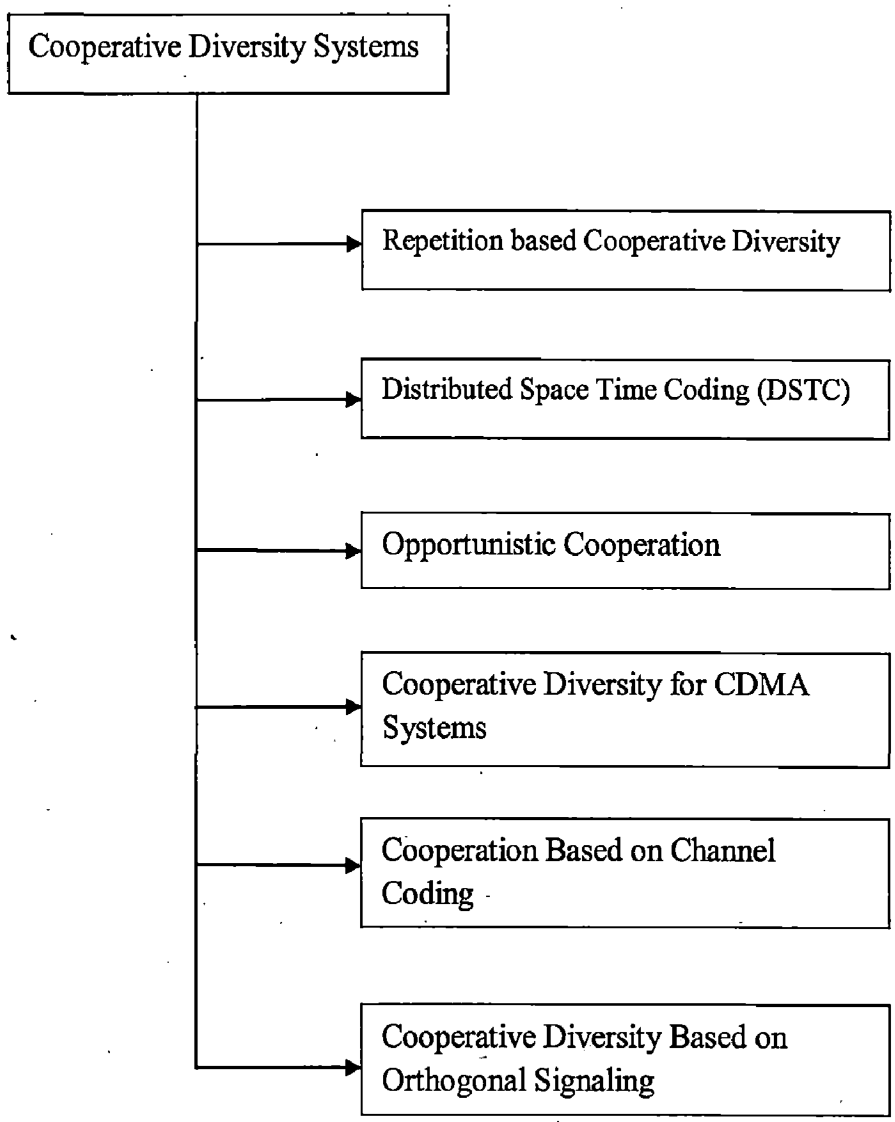

Figure 2.8: Different cooperative diversity schemes.

Most of the analysis of cooperative diversity systems focuses on pairs of cooperating terminals only. However, in a multi-user scenario it is still not clear who the cooperating relay should be. In many practical scenarios, all the nodes in the network are not simultaneously involved in transmission; therefore protocols are needed for selecting nodes, called relays, for cooperative transmission. In the following subsections, we focus on different distributed schemes proposed in the literature.

2.5.1 Cooperative Diversity with Orthogonal Transmission

A variety of low complexity cooperative diversity protocols are proposed based on repetition for frequency non-selective half duplex systems [1], [4], [13]. These protocols employ different types of processing at the partner (cooperating user), as well as different type of combining at the destination terminals. That may be characterized as fixed and adaptive (selection and incremental) relaying. Here, channel allocation for different senders is made across the entire frequency band as shown in Figure 2.9. Furthermore, subchannel allocation for different relays is made across the time span in each frequency sub-band as shown in Figure 2.10. Each subchannel contains a fraction $1/m^2$ of the total degree of freedom in the channel where m is the number of users in the non-cooperative diversity systems. Similar to non-cooperative transmission each sender and partner uses the fraction 1/m of the total degree of freedom in the channel to transmit to the destination.

The fixed amplify and forward scheme proposed in [13] can be viewed as repetition coding from two users, except that the partner amplifies its own receiver noise. The sender to partner channel fading coefficient is utilized at the partner to amplify the signal. Therefore, it is important to have accurate channel state information. The destination receiver can use maximum ratio combining to decode the information from two sub blocks of the received signal. In fixed regenerate and forward scheme, the partner can decode the information either by fully decoding the source message to estimate the source codeword or by estimating symbol by symbol. The regenerated signal is transmitted by the partner according to the repetition coding scheme. To combine the transmission from the sender and the partners, a suitably modified matched filter is employed at the destination. The selection relaying scheme functions based on the channel quality between the sender and the partner (inter user). If the inter user channel quality falls below a certain threshold the sender simply continues its transmission to the destination in the form of repetition. If the inter user channel quality lies above the threshold, the partner forwards what it receives from the sender. The performance of selection regenerate and forward cooperative diversity scheme is analyzed

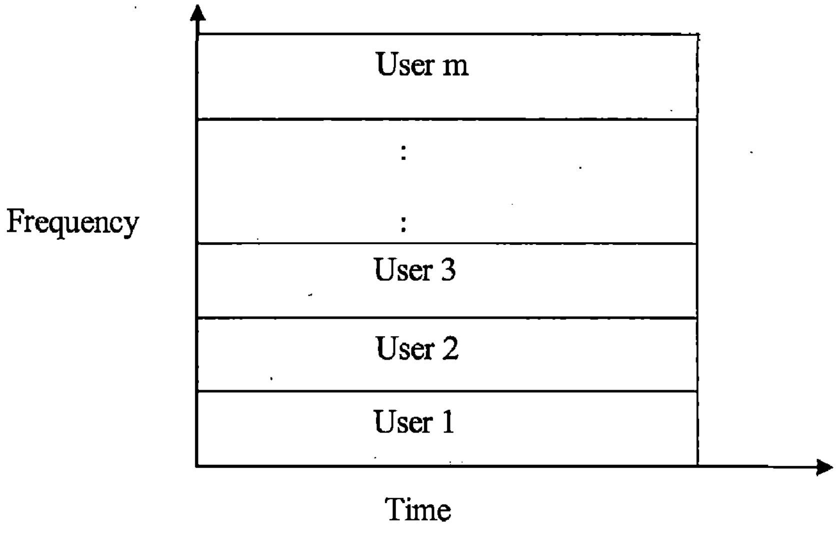

Figure 2.9: Channel allocation for m users in non-cooperative medium-access control.

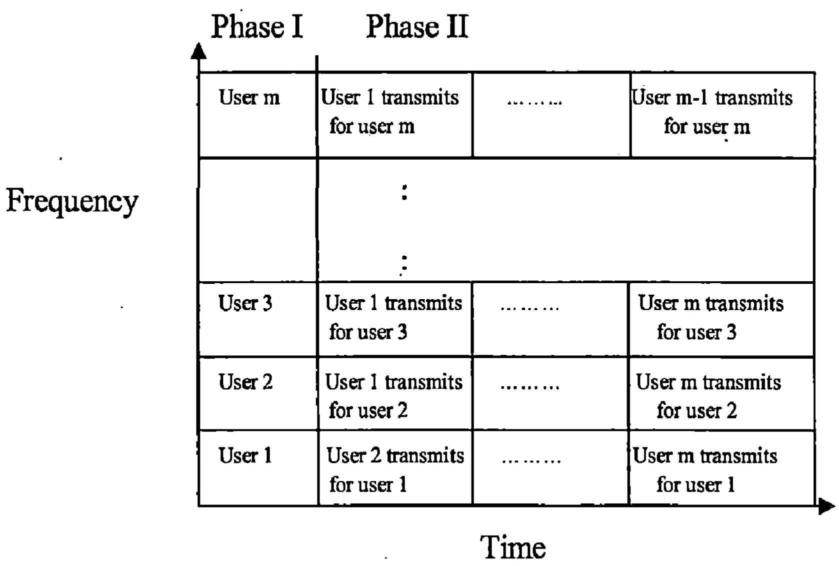

Figure 2.10: Subchannel allocation for m users in repetition based cooperative diversity medium-access control.

for more than two terminals in [4]. It is shown in [4] that repetition protocol offers full spatial diversity for multiuser cooperation to achieve diversity gain. However, full spatial diversity benefits of the repetition based cooperative diversity scheme come at a price of decreasing bandwidth efficiency with the number of cooperating users. The repetition-coded transmission of both fixed and selection relaying loses an additional 3 dB from the two antenna transmit diversity bound at high SNR. To overcome the problem, incremental relaying was proposed. Here, the partner forwards what it receives from the sender if the feedback from the destination indicates that the direct transmission from the sender to the destination alone was not successful. This scheme shows improvement over fixed and selection relaying but it has lots of implementation and complexity issues such as resource allocation to the partner transmission for short duration (one frame duration) etc.

Both fixed amplify and forward and incremental amplify and forward achieve diversity order of two. The performance of the fixed regenerate and forward scheme is mainly dependent on the inter user channel quality. By contrast, incremental amplify and forward overcomes the drawbacks of fixed amplify and forward and fixed regenerate and forward by relaying the information only when necessary. Incremental amplify and forward is useful in developing higher layer network protocols that select between direct transmission and cooperative diversity. There are costs associated with these cooperative protocols. Cooperation with half-duplex operation requires twice the bandwidth of direct transmission for a given rate, and leads to larger effective SNR losses for increasing spectral efficiency.

A selection regenerate and forward scheme for cooperative diversity networks is proposed in [14]. The influence of the data rate, path loss and network geometry on the cooperative scheme is studied with the assumption that inter user channel quality is always good. In this scheme, the channel is divided into two sub channels in the time domain which demands a bandwidth twice as large compared to the non-cooperative diversity scheme. In addition, the scheme wastes radio resources when the inter user channel incurs error.

In [15], a cooperative diversity system based on regenerate and forward and superposition modulation at the partner is proposed. At the partner, the sender's and the partners' information is modulated using superposition modulation proposed. The destination decodes the information using a maximum a posteriori probability (MAP) detector. This system outperforms the regenerate and forward cooperation schemes by 1-2 dB at the expense of a more complex receiver.

So far, all the systems mentioned above assume that perfect channel state information (CSI) is available at the receiver or the CSI can be estimated. In slow-fading scenarios, CSI can be estimated from training sequences. However, CSI may not be accurately obtainable if the fading coefficients vary quickly. Since the coherence time decreases in a fast fading situation, estimation of CSI substantially reduces the data transmission rate as we have to insert pilot tones to estimate CSI. Cooperative diversity systems based on differential modulation are proposed and analyzed in [16] for amplify and forward protocol. The system proposed can handle the differentially modulated transmission from the sender to the destination without CSI.

2.5.2 Cooperative Diversity Based on Space-Time Coding

Full spatial diversity benefits of the repetition based cooperative diversity algorithms come at a price of decreasing bandwidth efficiency with the number of cooperative terminals. An alternative approach to improve bandwidth efficiency of the algorithms is proposed in [4] based on space-time codes (STC) called distributed space-time coding (DSTC). In this case, partners utilize a suitable STC in the second phase. Therefore all the partners can transmit simultaneously on the same subchannels as shown in Figure 2.11. Similar to the non-cooperative scheme, repetition based cooperative diversity scheme utilizes 1/m of the total degree of freedom in phase II. In contrast, each partner employing DSTC transmits in ½ the total degree of freedom in the channel. By requiring more computational complexity in the terminals, DSTC can achieve full diversity without any feedback. An outage analysis is given in [4] on a random coding argument. But in practice, the number of users participating in the cooperative event is unknown. In cooperative operation, the signals transmitted from some of the antennas may get lost due to deep fading. To overcome this problem, the columns of the code matrix should be orthogonal to each other. Space-time block codes based on orthogonal design is a better option for this situation. The DSTC system has a major disadvantage of

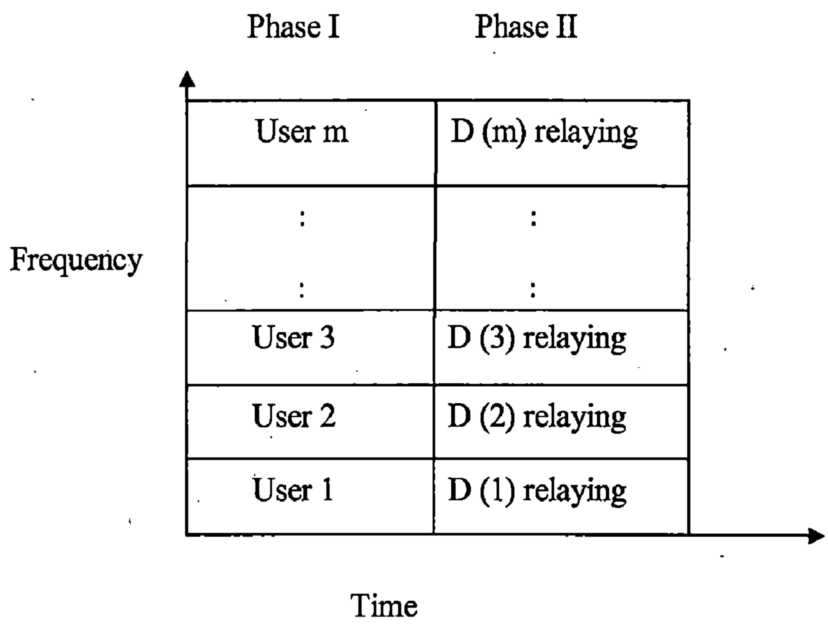

Figure 2.11: Channel allocation for m users in distributed space-time coded cooperative diversity medium-access control.

synchronous reception in Phase II at the destination as different propagation delays occur among the partners to destination links.

2.5.3 Cooperative Diversity for CDMA Systems

A new form of cooperative strategy employed by two users based on a combination of block Markov encoding and backward decoding is proposed in [5]. The information theoretic capacity, outage and coverage analysis in [5] demonstrates the potential benefits of cooperation. It is also shown that the cooperation is beneficial for both users in terms of increasing the achievable rates and decreasing the probability of outage. In addition, cooperation can also be used to increase the cell size of a cellular system. For the information-theoretic analysis, a possible code-division multiple-access (CDMA) implementation is proposed and extended for high rate CDMA systems using multiple spreading codes. In addition, the potential uses of cooperation in cellular and wireless ad hoc networks are discussed.

A. Sendonaris et al [5] investigated CDMA cooperative structure in terms of probability of error for both optimal receiver and low complexity suboptimal receiver. It was shown that cooperative diversity not only offers improvement in throughput but also increases the coverage of a cell. Benefits of cooperation, when a mobile using multiple CDMA code for high rate systems, were also studied. Finally, it was shown that cooperation is superior to no cooperation at the expense of complexity even though the mobile does not have channel phase information. The authors of [5] indicate that their scheme is not necessarily optimal, which paves the way for an optimal cooperative diversity scheme. The sub optimum receiver given in [5] also has some limitations in performance and practical implementations. In addition, the scheme wastes transmit power of both users when inter user channel exhibits errors.

2.5.4 Cooperation Based on Channel Coding

A different framework based on channel coding called coded cooperation, is proposed in [17]. The key ideas of the scheme are cooperation through partitioning a user's codeword and avoiding error propagation through error correction by the partner. Instead of repeating the symbols, the codeword of each user is partitioned into two sets; one partition is transmitted by the sender and the other by the partner through partial or complete decoding. Various forward-error correcting block or convolutional code can be used in conjunction with either puncturing or product codes for cooperation. Rate Compatible Punctured Convolutional (RCPC) code is selected and analytical derivation of pair-wise error probability of the scheme is given and compared with the simulation results in [17].

In case of turbo coding, the source broadcasts a recursive systematic convolutional code to both the partner and the destination. The partner decodes, interleaves and re-encodes the message and forwards it to the destination. The destination detects the data by introducing both direct and regenerated messages into an iterative decoder. The performance of the coded cooperation schemes is bounded by the tradeoff between coding gain and diversity gain. Furthermore, channel coding, which is used in this scheme, is designed for non-cooperative diversity systems. A development of channel coding which accounts for the effects of all the channels which are associated with cooperative transmission is helpful in optimizing the performance of a coded cooperation system.

2.5.5 Information Theoretic Study on Cooperative Diversity

Information theoretic study provides diversity-multiplexing tradeoff bounds and analysis of average Symbol Error Probability (SEP) and outage probability. Generally, a Multiple Input and Multiple Output (MIMO) system provides both diversity gain and multiplexing gain. But, there is a fundamental tradeoff between how much of each type of gain any MIMO system can get. The diversity and multiplexing tradeoff, which is actually the tradeoff between the Bit Error Probability (BEP) and the data rate of a system, is studied in [10]. Similar analysis is done in [4], [13] for cooperative diversity schemes such as amplify and forward, regenerate and forward and DSTC. It shows that repetition-based and space-time coded cooperative diversity offer full diversity. However, the latter scheme offers larger diversity order than the former and can be effectively utilized for higher spectral efficiency.

2.6 Diversity and Multiplexing Trade-off

Multiple antenna channels provide spatial diversity, which can be used to improve the reliability of the link. The basic idea is to supply to the receiver multiple independently faded replicas of the same information symbol, so that the probability that all the signal components fade simultaneously is reduced. Consider uncoded BPSK signals over a single antenna fading channel [10]. The probability of error at high SNR (averaged over fading gain as well as additive noise) is

$$P_e(SNR) \approx \frac{1}{4} SNR^{-1}$$

In contrast, transmitting the same signal to a receiver equipped with 2 antennas, the error probability is

$$P_e(SNR) \approx \frac{3}{16} SNR^{-2}$$

It can be seen that by having the extra receive antenna, the error probability decreases with

SNR at a faster speed of SNR^{-2} [10]. This phenomenon implies that at high SNR, the error probability is much smaller. Since the performance gain at high SNR is dictated by the SNR exponent of the error probability, this exponent is called the diversity gain. Besides providing diversity to improve reliability, multiple antenna channels can also support a higher data rate than single antenna channels. In the high SNR regime, the capacity of a channel with m transmit antennas, n receive antennas and i.i.d. Rayleigh faded gains between each antenna pair is given by [10]:

$$C(SNR) = \min\{m, n\} \log SNR + O(1)$$

The channel capacity increases with SNR as $\min\{m,n\}\log SNR$ (bps/Hz), in contrast to log SNR for single antenna channels. This result suggests that the multiple-antenna channel can be viewed as $\min\{m,n\}$ parallel spatial channels, hence the number $\min\{m,n\}$ is the total number of degrees of freedom to communicate [10]. Now, one can transmit independent information symbols in parallel through the spatial channels. This idea is also called spatial multiplexing.

Let R(SNR) (bits/symbol) be the rate of the code C(SNR). A scheme is said to achieve spatial multiplexing gain r and diversity gain d if the data rate

$$\lim_{SNR \to \infty} \frac{R(SNR)}{\log SNR} = r$$

and the average error probability

$$\lim_{SNR \to \infty} \frac{P_e(SNR)}{\log SNR} = -d.$$

According to the theorem given in [10], the optimal tradeoff curve d*(r) versus r is given by the piecewise linear function connecting the points $(k, d^*(k))$, k = 0, 1,..., $\min\{m,n\}$, where

$$d^*(k) = (m-k)(n-k)$$

In particular, $d^*_{max} = mn$ and $r^*_{max} = \min\{m, n\}$.

The trade-off curve is shown in figure 2.12.

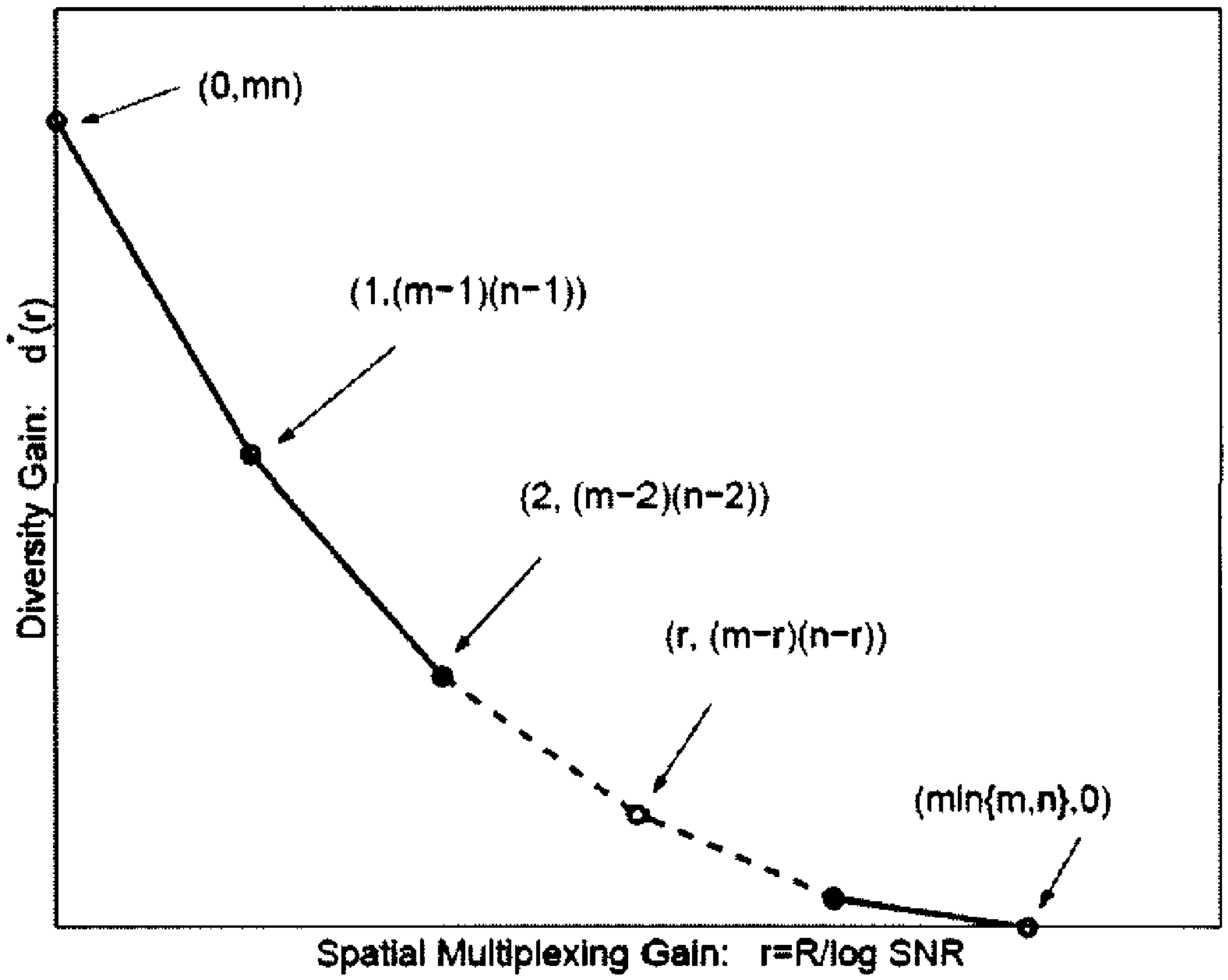

Figure 2.12: Diversity-multiplexing trade-off curve [10].

A system can be parameterized by the pair (SNR, R_{norm}) where

$$R_{norm} = \frac{R}{\log(1 + SNR\sigma^2_{s,d})}$$

R_{norm} is called as the spectral efficiency normalized by the maximum achievable spectral efficiency [4]. As SNR varies, there occurs a trade-off between the diversity order and normalized spectral efficiency for a relay selection protocol. It is also called as diversity-multiplexing trade-off. The outage probability can be approximated as [4]:

$$\Pr(I < R) = SNR^{-\Delta(R_{norm})}$$

where I is the maximum average mutual information between input and output and

$$\Delta(R_{norm}) = \lim_{SNR \to \infty} -\frac{\log(\Pr(I < R))}{\log SNR}$$

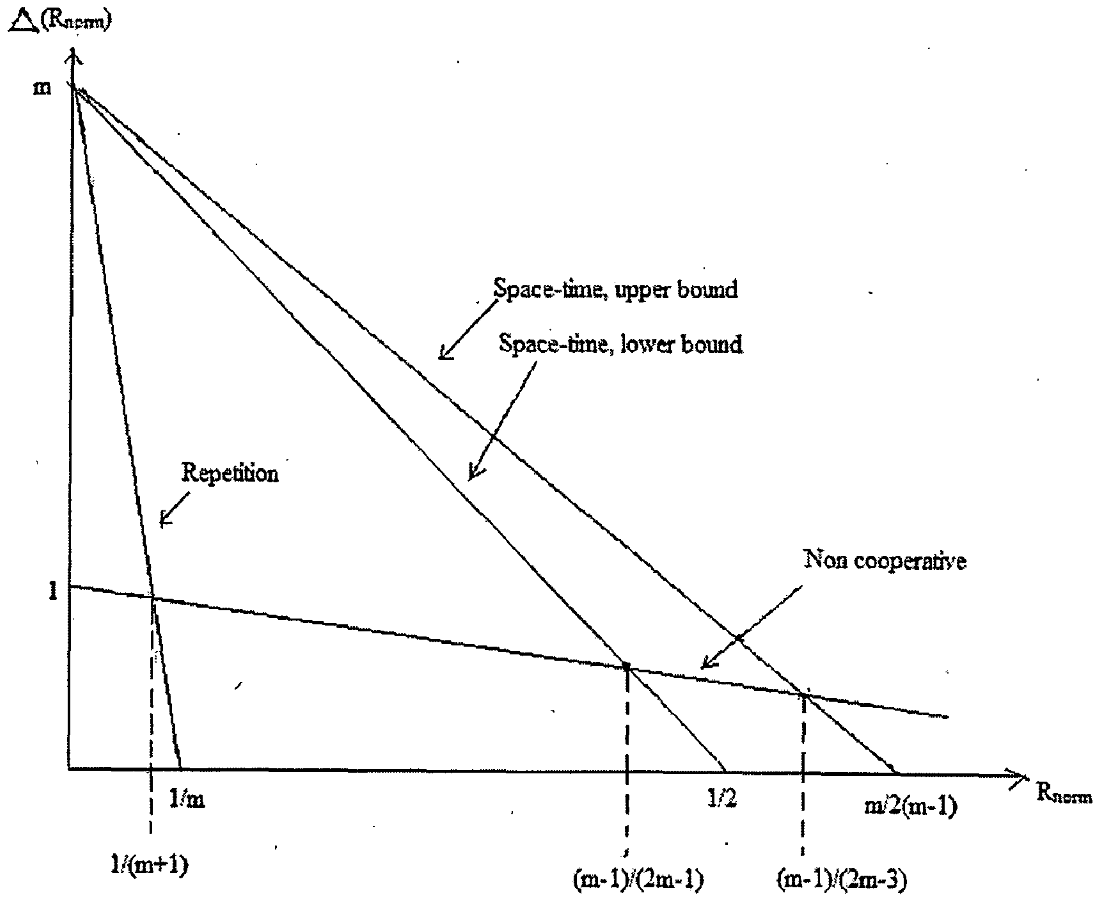

Figure 2.13: Diversity order versus R_{norm} curve for non-cooperative transmission, repetition-based cooperative diversity and space-time-coded diversity [4].

Figure 2.13 compares the diversity exponents, along with the corresponding trade-off for non-cooperative transmission for which $\Delta(R_{norm}) = 1 - R_{norm}$. Both repetition-based and space–time-coded cooperative diversity offer full diversity m as $R_{norm} \to 0$ [4]. Clearly, space–time-coded cooperative diversity offers larger diversity order than repetition-based algorithms and can be effectively utilized for higher spectral efficiencies than repetition-based schemes [4].

2.7 Diversity Combining Techniques

Diversity combing is a technique that combines multi-branch signals to one enhanced signal. Generally, it can be classified as selection combing (SC), equal gain combining (EGC) and maximum ratio combining (MRC) [18]. The SC selects the best signal among all the branches. It is very simple to implement and gives worse performance by ignoring other branches. EGC gives equal weights for all the branches by considering the phase of the received signal and sum all of them as one signal. Since it gives the same weight to both weak signal branches as well strong signal branches, the weak signal may destroy the information carried by the strong signal. EGC is better than SC. MRC gives weight to each branch proportional to the signal amplitude and then all the branches are summed up. That means the branches with strong signal are further amplified while weak signals are attenuated. MRC needs accurate signal amplitude and phase information for proportional weighting. However, the performance of MRC scheme is far better than those of the other two.

Chapter 3
CHANNEL MODELING

The modeling of wireless channel deals with understanding the propagation of a signal through a given medium and developing a mathematical representation of the channel's effect upon the transmitted signal. It enables designers to predict the behavior of the received signal which is useful for the design of better and more efficient transmitters and receivers. So far, a large number of models have been proposed to characterize propagation in wireless communication systems. The channel models can be memory-less or may contain memory. Memory-less channels do not produce inter-symbol interference (ISI) or fading and their modeling is also easy while modeling a discrete channel with memory is relatively complex. Figure 3.1 shows a binary symmetric channel. The input and output alphabets are both binary i.e. 0 or 1, and the channel transition probabilities are symmetrical. It can be stated that Pr (0 | 0) = Pr (1 | 1) = $(1-p)$ and Pr (1 | 0) = Pr (0 | 1) = p, where p is the error probability. The channel is symmetric as its zeroes and ones are affected by the channel in the same manner. For a memory less channel, the error probability will affect every symbol in the same manner. So this is an example of discrete channel model that is memory less.

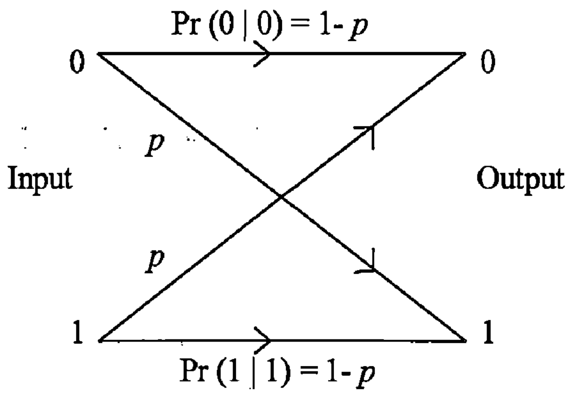

Figure 3.1: Binary symmetric channel transition diagram.

However for the channel having memory, the error probability depends upon the previous bits transmitted. Wireless communication channels generally have memory and correlation between input and output symbols. Experimental data shows that the channel can be viewed as operating in one of a finite number of possible channel states where the state can be characterized in terms of Bit Error Rate (BER) or Signal-to-Noise Ratio (SNR) range. The switching process between the states is represented by a finite state Markov model [19].

3.1 Preliminaries of Markov Chain

A Markov chain is a discrete – state random process in which the evolution of the state of the process that begins at a time t (continuous-time chain) or n (discrete-time chain) depends only on the current state X(t) or X_n and not how the chain reached its current state or how long it has been in that state. In a discrete-time Markov chain, X_{n+1} depends only on X_n and not on any X_i for $1 \leq i < n$, i.e.

$$\Pr(X_{n+1} = s_i \mid X_n = s_j \wedge X_{n-1} = s_k \wedge \ldots\ldots \wedge X_1 = s_1) = \Pr(X_{n+1} = s_i \mid X_n = s_j) \quad (3.1)$$

Let **S** = { s_0, s_1, s_2,.....,s_{K-1} } denote a finite set of states and { S_n }, n = 0,1,2,...., be a constant Markov process. Since constant Markov process has the property of stationary transitions, the transition probability is independent of time index n and can be written as:

$$t_{j,k} = \Pr(S_{n+1} = s_k \mid S_n = s_j) \quad (3.2)$$

The probability of state k at any time index n without any information at other time indices can be defined as:

$$p_k = \Pr(S_n = s_k)\,,\quad k \in \{0, 1, 2, \ldots, K\text{-}1\} \quad (3.3)$$

$$\sum_{k=0}^{K-1} p_k = 1 \quad (3.4)$$

A K x 1 steady state probability vector $\boldsymbol{\pi}$ can be defined with its elements p_k as in above eqn. (3.3). In many cases, this vector can be served as the set of initial state probabilities [20]. Note that eqn.(3.2) and eqn.(3.3) must satisfy the equilibrium condition which states that for any given state k, the incoming flow and outgoing flow must be equal.

The steady state probability vector can be calculated from the matrix equations

$$\pi^t P = \pi^t \tag{3.5}$$

$$\pi^t C = I \tag{3.6}$$

where π^t is the transpose of π, C is a column matrix whose entries are 1's and I is the identity matrix.

A complete description of a finite-state Markov channel requires additional information on the channel quality for each state. Define a K x 1 crossover probability vector **e** with its elements e_k, $k \in \{0, 1, 2, \ldots, K-1\}$, being the crossover probability associated with state k. The overall average error probability e is

$$e = \pi^t \mathbf{e} = \sum_{k=0}^{K-1} p_k e_k \tag{3.7}$$

There are four constraints imposed on π and **e** as follows:

- $0 < p_k \leq 1$
- $\sum_{k=0}^{K-1} p_k = 1$
- $0 \leq e_k \leq 0.5$ for all $k \in \{0,1,2,..,K-1\}$
- $e_i \neq e_j$, if $i \neq j$ for all $i,j \in \{0,1,2,..,K-1\}$

3.2 Physical Layer Models

The most accurate method of conducting a network simulation involving wireless links would be to explicitly model the physical layer. This involves making each packet go through coding and modulation. Then it is followed by passing the physical layer frames through an equivalent channel with appropriate fading and noise parameters. Demodulation and decoding on the received packet are performed to determine whether it is error free or not. Most models that have been used for the analysis of the performance of data block transmission over fading channel assumed that the block transmissions were independent and identically distributed (iid). Also, many protocols were designed for an iid channel, and techniques were developed to eliminate channel memory (e.g., interleaving) [19]. A newer approach is to take advantage of the channel memory to obtain better performance, instead of destroying it. In the following section some of the existing practically viable results on modeling the physical layer are presented.

3.2.1 Two State Markov Model

Two State Markov Model also known as Gilbert-Elliott model [21] is the simplest and most widely used model for the wireless link physical layer. The model shown in Figure 3.2 has two states – a good state and a bad state. The model is characterized by the transition probabilities between the two states. Whenever the model is in the good state all the packets get through without error. Whenever the model is in the bad state all packets are dropped.

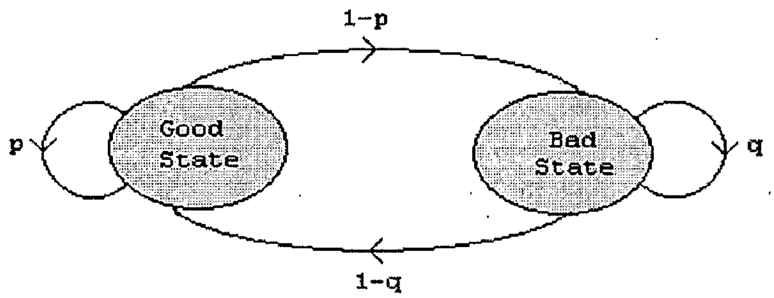

Figure 3.2: Two state Markov model.

3.2.2 Finite State Markov Model

In this approach, the channel is divided into a number of states. The structure of the finite state Markov model is shown in Figure 3.3. Each state corresponds to a range of instantaneous SNR values. Transitions are only possible to the same state or adjacent states. As a state corresponds to a range of instantaneous SNR values the Frame Error Rate (FER) when the model is in a particular state is given by the expectation of the FER over the range [20]. The division of the instantaneous SNR into the states is done such that the average time that the fading process spends in each state is the same. The model is thus defined by the FER in each state and the transition probabilities between the states. These transition probabilities can be determined analytically using the level crossing rates at the SNR values

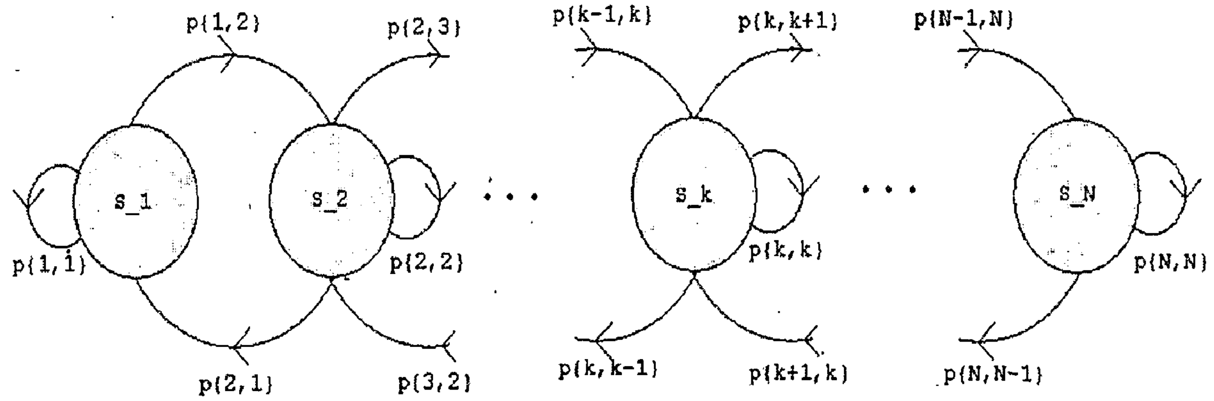

Figure 3.3: Finite state Markov model.

separating the states. The finite state Markov model approach provides better results than the two-state Markov model but is a lot more complex. The finite state Markov model performs better when the number of states is higher but this increases the number of parameters that need to be set up. Also the number of states that are needed to get good results can only be determined by trial and error. The number of states needed depends on the Doppler rate of the channel with more states being required for slower fading [22]. Some alternate approaches to set up the finite state Markov model are: partitioning the instantaneous SNR such that all states are equi-probable or partitioning based on the thresholds for an optimum Minimum Mean Square Error Lloyd-Max Quantizer for the SNR range [23].

3.3 Finite State Markov Model for Rayleigh Fading Channels

Unreasonable results can be concluded if the finite-state model does not represent a real physical channel. Therefore, the methodology in establishing the relationship between physical channels and their finite-state models is important. In this section, we describe a finite state Markov model for a typical radio communication channel, namely the Rayleigh channel that produces time – varying received SNR characterizing the channel quality in terms of the average error probability.

When a continuous waveform (CW) is transmitted, the multipath effect results in the fluctuation of the received signal envelope that is Rayleigh distributed. This channel is known as a Rayleigh fading channel. The time variation of the signal level is due to the motion of the mobile terminal and it is also called as the Doppler frequency effect. With additive Gaussian noise, the received instantaneous SNR γ is distributed exponentially with probability density function

$$p(\gamma) = \frac{1}{\gamma_0}\exp\left(-\frac{\gamma}{\gamma_0}\right), \gamma \geq 0 \qquad (3.8)$$

where, γ_0 is the average SNR.

Doppler frequency determines the fading characteristics of the signal envelope. Let f_m be the maximum Doppler frequency caused by motion at a certain speed. Let the level crossing rate of the instantaneous SNR process γ be N. It is defined as the expected rate at which the fading signal normalized to the local rms signal level, crosses a specified level Γ in a positive – going direction. As in [18], the level crossing rate of level Γ for the SNR process in the positive direction only (or in the negative direction only) is

$$N(\Gamma) = \sqrt{\frac{2\pi\,\Gamma}{\gamma_0}}\, f_m \exp\left(-\frac{\Gamma}{\gamma_0}\right) \qquad (3.9)$$

To describe the instantaneous channel quality, let $S = s_1, s_2, s_3, \dots, s_K$ denote a set of K channel states with corresponding bit – error rate e_i, $i \in \{1, 2, \dots, K\}$. As the constant Markov process has the property of stationary transitions, the state transition probability is independent of time index n and can be written as

$$p_{j,k} = \Pr(S_{n+1} = s_k \mid S_n = s_j) \qquad (3.10)$$

Furthermore, $p_{j,k}$ satisfies the following condition:

$$\sum_{k=1}^{K} p_{j,k} = 1 \quad \text{for all } j \in \{1, 2, 3, \ldots, K\} \tag{3.11}$$

It is assumed that the state transitions only happens between adjacent states because channel change is sufficiently slow and observation time is short (e.g. one frame duration), we get

$$p_{j,k} = 0, \text{ where } |j - k| > 1 \tag{3.12}$$

The steady state probability can be calculated as

$$\begin{aligned} \pi_k &= \int_{\Gamma_k}^{\Gamma_{k+1}} p(\gamma) d\gamma \\ &= \exp\left(-\frac{\Gamma_k}{\gamma_0}\right) - \exp\left(-\frac{\Gamma_{k+1}}{\gamma_0}\right) \end{aligned} \tag{3.13}$$

Let $\boldsymbol{\Gamma} = [\Gamma_1, \Gamma_2, \Gamma_3, \ldots, \Gamma_{K+1}]^t$ be received SNR thresholds in increasing order with $\Gamma_1 = 0$ and $\Gamma_{K+1} = \infty$. The channel is said to be in state k if the received SNR lies between Γ_K and Γ_{K+1}. The states are ordered with decreasing average BER values. It is assumed that for a packet transmission system, a one-step transition in the model corresponds to the channel state transition after one packet time period. The channel transitions from a given state to its two adjacent states are allowed. The transition probability from state s_k to state s_{k+1}, $P_{k,k+1}$ can be calculated by the ratio of the level crossing rate at threshold Γ_{k+1} and the average number of packets per second which are lying in state s_k. Similarly, the transition probability $P_{k,k-1}$ is calculated by the ratio of the level crossing rate at threshold Γ_k and the average number of packets per second lying in state s_k. The transition probabilities can be approximated as [23]

$$P_{k,k+1} \approx \frac{N(\Gamma_{k+1})T_p}{\pi_k}, \qquad k = 1, 2, .., K-1 \tag{3.14}$$

$$P_{k,k-1} \approx \frac{N(\Gamma_k)T_p}{\pi_k}, \qquad k = 2, 3, \ldots, K \tag{3.15}$$

The average BER for each state can be calculated for a particular modulation scheme. If the channel fading is flat and slow compared to the symbol interval, the probability of error in additive white Gaussian noise (AWGN) channels is viewed as a conditional error probability. Let the probability of symbol error as a function of SNR γ be $P_e(\gamma)$. The average probability of symbol error for state s_k is

$$P_{ek} = \frac{\int_{\Gamma_k}^{\Gamma_{k+1}} P_e(\gamma)p(\gamma)d\gamma}{\pi_k} \tag{3.16}$$

SNR Partitioning For the Finite State Markov Channel (FSMC) Model

The SNR thresholds should be set in such a way that the SNR range of each received packet during a packet time must lie in one state i.e., the SNR range of each state should be large enough to cover the SNR variation during a packet time. The next packet can only lie in the current state or one of the two adjacent states. The SNR interval of each state cannot be made too large or too small. If it is very small then it can't cover the SNR variations during one packet time and if it is very large then the time duration of the state also increases. Within a packet time period the received SNR values are distributed in a smaller range than the SNR interval for that state and packets falling in the state may have Bit Error Rate (BER) quite different from the BER for the state.

Average time duration is a very important parameter of the Finite State Markov Model. It is defined as the average period of time for which the received SNR remains between two specified SNR thresholds. Let $\bar{\tau}_k$ be the average duration of received SNR interval $[\Gamma_k , \Gamma_{k+1})$. It is the ratio of the total time the received signal remains between Γ_k and Γ_{k+1} and the total number of such signal segments, both measured during some long time interval T. Let the duration of each signal segment is τ_i.

$$\bar{\tau}_k = \frac{\sum \tau_i}{(N(\Gamma_k)+N(\Gamma_{k+1}))T}$$

$$= \frac{1}{N(\Gamma_k)+N(\Gamma_{k+1})} \text{Prob}\{\Gamma_k \leq \gamma \leq \Gamma_{k+1}\}$$

$$= \frac{\pi_k}{N(\Gamma_k)+N(\Gamma_{k+1})} \tag{3.17}$$

It is required that the average duration of k^{th} state should be a multiple of packet time, T_p. Let h_k be a constant such that

$$\bar{\tau}_k = h_k . T_p \qquad \text{for } k = 1, 2, 3, \ldots, K \tag{3.18}$$

h_k is to be determined accurately. It should be neither too large nor too small. Its value should be such that nearly all transitions of the received packets are to the current state or adjacent states.

From eqn.(3.13), (3.17) and (3.18)

$$h_k = \frac{\exp\left(-\frac{\Gamma_k}{\gamma_0}\right) - \exp\left(-\frac{\Gamma_{k+1}}{\gamma_0}\right)}{\sqrt{\frac{2\pi\,\Gamma_k}{\gamma_0}}\exp\left(-\frac{\Gamma_k}{\gamma_0}\right) + \sqrt{\frac{2\pi\,\Gamma_{k+1}}{\gamma_0}}\exp\left(-\frac{\Gamma_{k+1}}{\gamma_0}\right)} \cdot \frac{1}{f_m T_p}, \qquad k = 1, 2, \ldots, K \tag{3.19}$$

$\Gamma_1 = 0$ and $\Gamma_{K+1} = \infty$

With a given partition of the SNR values $\Gamma_1, \Gamma_2, \Gamma_3, \ldots, \Gamma_K$, we can obtain the corresponding h_k values for a fixed $f_m T_p$. Our purpose is to find the number of states K and SNR partitions ($\Gamma_2, \Gamma_3, \ldots, \Gamma_K$) with the requirement that the time durations h_k (in number of packets) are within a reasonable range. If we set the values of h_k, $k = 1,\ldots,K$ in eqn.(3.19), there will be K equations with only K-1 variables $\Gamma_2, \ldots, \Gamma_K$ and there may be no solutions for the Γ_k. Our procedure is to constrain the h_k to all be equal, i.e., $h_k = h$, $k = 1,\ldots,K$. Thus each state has the same average time duration. The K equations in eqn.(3.19) now contain K-1 SNR thresholds $\Gamma_2, \ldots, \Gamma_K$ and the duration h so that there are K variables. We may solve for these variables for each fixed K value of interest. This produces in particular a value of h for each value of K, given a certain $f_m T_p$ setting.

The total number of states of the model is to be determined according to the specific application for a given f_mT_p setting. For e.g., for a slowly varying channel with data transmission rate of 100 kbps, we can model the channel with eleven states while for the data transmission at 1Mbps the channel varies more slowly and it has to be modeled with larger number of states The product of f_mT_p characterizes the fading speed of the channel relative to the packet length. A large f_mT_p means that the channel fading rate is high. If h is larger, packets lie in each state longer and a smaller number of states are obtained for the Markov model for a fixed f_mT_p. If f_mT_p decreases, the number of states K should be increased to capture the dynamics of the channel.

3.4 Simulation Results for Markov Modeling of Rayleigh Fading Channel

In this section, results of state-transition probabilities and steady-state probabilities for two-state, three-state and eleven-state Markov model are given. All simulations are carried out in MATLAB. A Rayleigh channel generator based on Clarke's model [18] was developed to simulate the channel data profile. The simulation parameters for Markov model of Rayleigh channel are given in Table 3.1.

Table 3.1 Simulation Parameters for Markov model of Rayleigh channel

Packet Size	384 bits
Speed	5 km/h
Transmission Rate	100 kbps
Doppler Frequency f_m	8.7963 Hz
Packet Time T_p	3.84 ms
f_mT_p	0.0338

For two-state Markov model (K = 2)

The transition probabilities (P) and steady-state probabilities (π) are given below:

$$P = \begin{bmatrix} 0.5925 & 0.4075 \\ 0.3519 & 0.6481 \end{bmatrix}$$

$$\pi = [0.4143 \quad 0.5857]$$

For three-state Markov model (K = 3)

The transition probabilities and steady-state probabilities are given below:

$$P = \begin{bmatrix} 0.6021 & 0.3978 & 0 \\ 0.2044 & 0.6974 & 0.0938 \\ 0 & 0.3982 & 0.5364 \end{bmatrix}$$

$$\pi = [0.2128 \quad 0.6476 \quad 0.1394]$$

For eleven-state Markov model (K = 11)

The transition probabilities and steady-state probabilities are given below:

$$P = \begin{bmatrix} 0.5996 & 0.3114 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.0887 & 0.6072 & 0.2554 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.0734 & 0.7696 & 0.2020 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1004 & 0.7101 & 0.1811 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.1983 & 0.6284 & 0.1250 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.1728 & 0.6378 & 0.0982 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.1895 & 0.5432 & 0.0988 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.2896 & 0.5934 & 0.0576 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2260 & 0.5876 & 0.0047 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.3386 & 0.5801 & 0.0042 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1738 & 0.5834 \end{bmatrix}$$

$$\pi = \begin{bmatrix} 0.00030 \\ 0.01270 \\ 0.50740 \\ 0.26940 \\ 0.20380 \\ 0.00390 \\ 0.00061 \\ 0.00035 \\ 0.00033 \\ 0.00010 \\ 0.00010 \end{bmatrix}$$

Chapter 4
RELAY SELECTION IN WIRELESS NETWORKS

Cooperative communications for wireless networks has gained much interest due to its ability to mitigate fading in wireless networks through spatial diversity. It resolves the difficulties of installing multiple antennas on small mobile terminals. The decode-and-forward and amplify-and-forward cooperative protocols achieve bandwidth efficiency equal to ½ Symbols per Channel Use (SPCU) as two time slots are required to transmit one symbol. For a system consisting of N relays, N + 1 time slots are needed to send one symbol. Thus, the bandwidth efficiency is 1/(N +1) SPCU [24]. For high data rate traffic, bandwidth efficiency needs to be increased and this can be achieved by proper relay selection.

4.1 Preliminaries of Relay Selection

In a multi-user scenario, a relay selection scheme determines when source node needs to cooperate with a relay node and which relay to cooperate with [24]. Relay selection mechanisms may be centralized or distributed. To extract transmit antenna diversity in cellular networks where multiple users communicate with a central base station, centralized relay selection can be used. The base station collects and utilizes the required information to select relays for each source-destination pair. Distributed relay selection can be implemented in the case of decentralized networks [6]. Here each node individually determines whether to cooperate or not and whom to cooperate with according to the information exchange that occurs between nodes. The distributed algorithm is usually sub-optimal, but it limits communication overhead compared to the centralized algorithm. The number of relay nodes to be selected to assist the source node is an important decision in the relay selection algorithm. Single relay selection simplifies hardware requirement at the receiver compared to multiple relay selection. However, multiple relay selection provides increase in the diversity gain of the system at the expense of complexity. Many single and multiple relay selection schemes have been proposed by different authors. Some of these [25]-[32] are listed in figure 4.1.

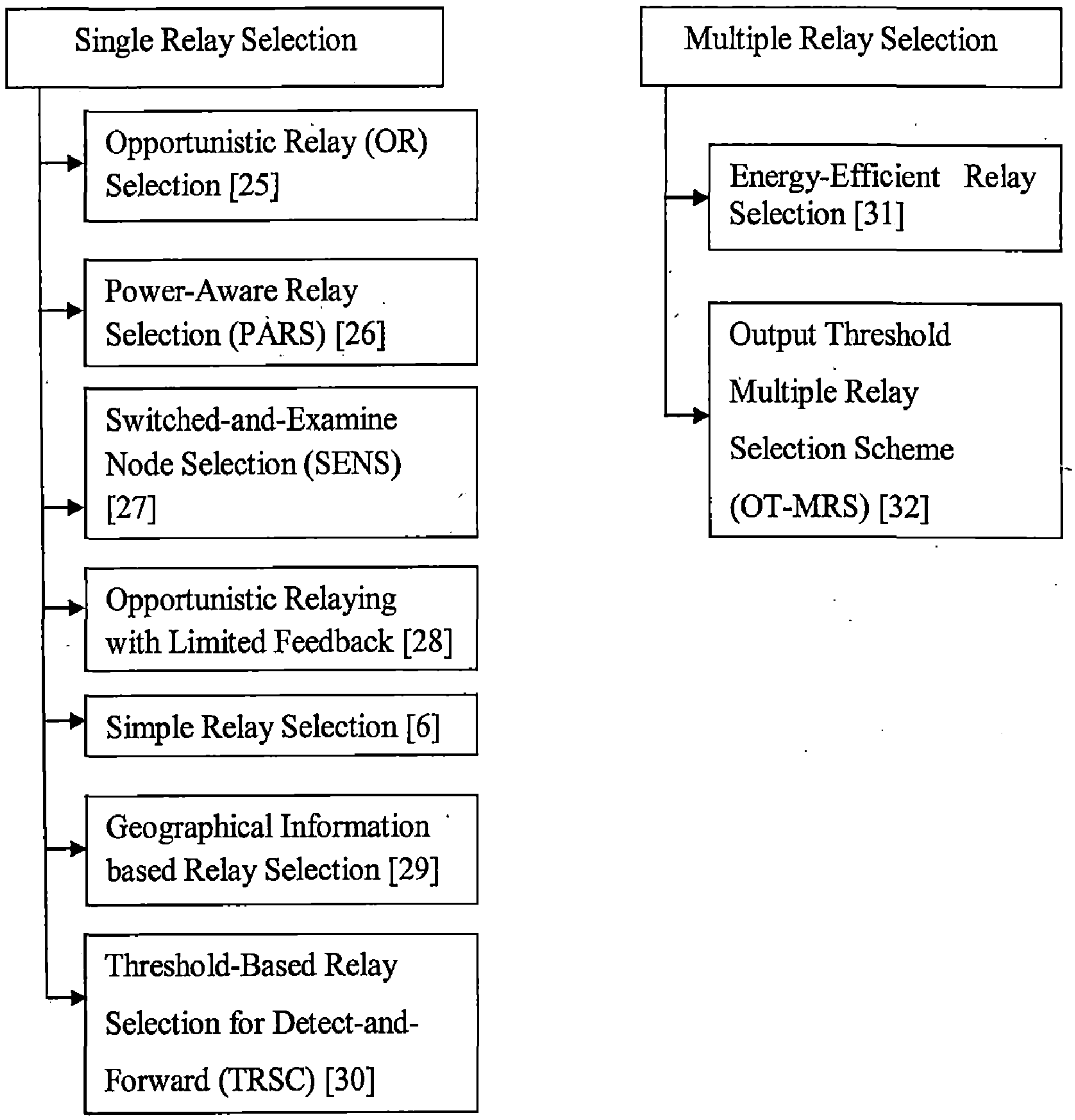

Figure 4.1: List of single and multiple relay selection schemes.

4.2 Single Relay Selection Schemes (SRS)

Some of the proposed schemes in the literature [6], [25]-[30] for single relay selection demonstrate the importance of selecting only one node to be used as a cooperative relay. A comparison of some single relay selection schemes is summarized in Table 4.1.

4.2.1 Opportunistic Relay (OR) Selection

The number of relays (which can properly receive the signal sent by a source) changes randomly in cooperative relay channel. So, the design of space-time-codes for this type of channel is identified to be an open area of research [25]. To alleviate the need of space-time-codes, A. Bletsas et al [25] proposed an OR scheme. It does not require global topology information in selecting a single relay. The OR scheme allows conventional coding scheme for communication. It assumes that each potential relay can overhear the RTS/CTS sequence between transmitter and receiver indicating the start of a transmission. A potential relay can overhear all the others, and all potential relays estimate the channel quality from the strength of the received RTS/CTS sequence. As soon as each relay receives the CTS packet, it calculates the timeout, which is inversely proportional to the end-to-end channel quality. The transmission of RTS from the source helps in estimating source to relay channel quality g_{si} and the transmission of CTS from the destination helps in estimating relay to destination channel quality g_{id}. The timeout serves as a back off and through that the relay with the earliest timeout becomes the cooperating relay, as the timer of the relay with best end-to-end conditions expires first. The back-off results in a decentralized scheme based on instantaneous channel measurements only. It is shown that the achievable diversity in OR scheme is of the order of the number of cooperating terminals even though only one relay transmits [25]. For the case, when all the potential relays may be hidden from each other, transmitter and receiver must announce the best relay. The destination informs all relays with a short broadcast message thereby inducing additional signaling overhead. To simplify the multi-user scenario, the case of three terminals has been taken with instantaneous channel quality being the deciding factor. For deciding the best relay based upon the channel estimates (g_{si} , g_{id}) performed by the set of potential relays, the following two policies have been proposed to define the parameter h_i to select the best end-to-end link between transmitter and receiver.

Policy I: $h_i = \min\{|g_{si}|^2, |g_{id}|^2\}$

Policy II: $h_i = \frac{2}{\frac{1}{|g_{si}|^2}+\frac{1}{|g_{id}|^2}} = \frac{2|g_{si}|^2|g_{id}|^2}{|g_{si}|^2+|g_{id}|^2}$

The initial timer value for relay i, v_i, is set to be inversely proportional to h_i, according to the following equation

$$v_i = \frac{\lambda}{h_i}$$

where λ is a constant and has the units of time. The best relay has its timer reduced to zero first. When the timer of a potential relay expires, it first senses the medium. If the channel is idle, it broadcasts a flag packet to announce its help (i.e. it becomes the cooperating relay). Hearing the flag packet, all the potential nodes stop their timers and back off. Since all nodes must sense the channel before making an announcement (assume that the announcement is of sufficient duration), only one node can be finally selected. If potential relays may be hidden from each other, transmitter and receiver broadcast the selected relay through a control packet. The analysis of Diversity-Multiplexing Tradeoff (DMT) was presented for opportunistic relaying [25] which is exactly the same as in cooperative diversity that uses more complex space-time coded protocols [4].

4.2.2 Power-Aware Relay Selection (PARS)

In ad-hoc networks, where the nodes are equipped with limited battery power, power conservation becomes an important issue. Relay selection protocols in such networks are designed with the intention of increasing the lifetime of a node. The OR scheme described in previous subsection does not consider the issue of power conservation in relay selection. Y. Chen et al [26] proposed PARS strategies to maximize the network life time using the Optimal Power Allocation (OPA) scheme. The OPA finds the minimum total power needed for cooperative transmission. The main idea of PARS can be explained in two steps:

Step I— OPA

Each potential relay applies the OPA algorithm on the basis of channel measurements in order to minimize the total transmit power at the given transmission rate. As a result of OPA, each relay can get the optimal transmit power for both the transmitter and each relay i. P_s^C is the optimal transmit power for the transmitter and P_i^C is the optimal transmit power for the relay i. The optimal solution that is applicable for both Amplify and Forward and Decode and Forward cooperation schemes is obtained using Lagrange multiplier method.

Step II—Relay Selection

For relay selection, PARS employs the minimum total transmit power of each pair of the transmitter and relay obtained from OPA (P_s^C , P_i^C) and the residual power level of the transmitter and each potential relay denoted by P_{rs} and P_{ri} respectively. Three mechanisms are proposed to select the best relay that is most efficient in extending the network lifetime. The first mechanism focuses on minimizing the total transmit power and needs the OPA results only. The second and third mechanisms try to maximize the residual power of each node, which is equivalent to keeping the residual power roughly the same at each node. The selected relay i*, the initial value of the timer at the transmitter, v_s, and the initial value of the timer at each possible relay, v_i , for different mechanisms are shown in the following.

Mechanism I:

$$i^* = \arg\min\{ P_s^C + P_i^C\}, \text{over } i$$

$$v_i = \lambda_1.\{ P_s^C + P_i^C\}$$

$$v_s = \lambda_1 . P_s^C$$

Mechanism II:

$$i^* = \arg\max\min\{ P_{rs}^C - P_s^C \ , P_{ri}^C - P_i^C\}, \text{over } i$$

$$v_i = \frac{\lambda_2}{\min \{P_{rs}^C - P_s^C , P_{ri}^C - P_i^C \}}$$

$$v_s = \frac{\lambda_2}{P_{rs}^D - P_s^D}$$

Mechanism III:

$$i^* = \arg\min\max\left\{\frac{P_s^C}{P_{rs}^C}, \frac{P_i^C}{P_{ri}^C}\right\}, \text{over } i$$

$$v_i = \lambda_3 . \max\left\{\frac{P_s^C}{P_{rs}^C}, \frac{P_i^C}{P_{ri}^C}\right\}$$

$$v_s = \lambda_3 \frac{P_s^D}{P_{rs}^D}$$

where λ_1, λ_2, λ_3 are constants which have the units of sec/watt, sec.watt, and sec respectively. The authors simulated and compared their results with the OR scheme in terms of the average network life time and found that PARS extends the network lifetime by about 100% as compared to OR.

4.2.3 Switched-and-Examine Node Selection (SENS)

The OR scheme [25], and its extension PARS that is based on OR [26] provide same Diversity-Multiplexing Tradeoff (DMT) as in Distributed Space Time Coding (DSTC). However, collision can occur in the OR and PARS schemes if the timers of two or more relay nodes expire at the same time [27]. It results in failing of the process. Also, the best relay node has to be found for each transmission that increases the complexity as each time Channel State Information (CSI) of all participating links is required in the relay selection. Further, all available relay nodes must maintain the listening mode during the RTS and CTS packet transmission in OR, which increases their power consumption. K. S. Hwang et al proposed an algorithm using the idea of the switched diversity with post selection [27].

The main idea of this algorithm is to reduce the load of the channel estimation. First, the channel between the transmitter and an arbitrarily selected relay node is estimated at that relay node. The received SNR at the relay node is denoted by $\gamma_{s,1}$. If the received SNR of the chosen hop is found acceptable at the relay node (i.e. $\gamma_{s,1} \geq \gamma_T$, where γ_T is the target threshold SNR), the relay node requests CSI to the receiver. If the received SNR between the relay and the receiver, $\gamma_{1,d}$, is also higher than γ_T, the given relay node is selected. However, if the first relay node is not selected due to the received SNR $\gamma_{s,1}$ or $\gamma_{1,d}$ or both lie below the threshold, the selection procedure goes through the list of nodes to find a relay node whose transmitter-relay received SNR and relay-receiver received SNR exceeds the threshold. Finally, if there is no relay node that can meet the required criteria, the minimum of the transmitter-relay received SNR and relay-receiver received SNR for each relay is compared with that of all the relay nodes in the list and the relay node corresponding to the maximum value is taken as the selected relay.

In this scheme, the relay nodes do not need to maintain listening mode all the time, rather only the node under investigation needs to be in the listening mode at any given time. Thus the power consumption of the relay nodes is reduced. By setting a suitable γ_T at relay node and the receiver, the scheme achieves the same performance of outage and Bit Error Rate as achieved in OR with less channel estimation load.

4.2.4 Opportunistic Relaying with Limited Feedback

CSI for both transmitter-relay and relay-receiver channels are required for relay selection in OR scheme [25]. As the number of users increases, the exchange of CSI also increases. Carrier Sense Multiple Access (CSMA) technique is required on the relay-receiver link that greatly increases the complexity. A. Tajer et al [28] presented a modified OR scheme that requires limited feedback and it provides the same DMT as in DSTC. The mode of operation of this protocol consists of two phases; in the first phase, the transmitter transmits the message while the relays and the receiver try to decode it. The relays indicate success or failure to the receiver by one bit of data. In the second phase, the receiver selects the best relay based on the relay-receiver channel measurement of each relay and indicates its decision with one bit feedback per relay.

The analysis shows that by limited exchange of information in the network consisting of M transmitter nodes and M receiver nodes, this protocol can achieve the same DMT as achieved by DSTC protocol. The amount of information exchanged is $\frac{2M-1}{M}$ per relay which is extensively smaller than the amount of side information required to be fed back in other protocols such as OR.

4.2.5 Simple Relay Selection

Relay selection in a network consisting of multiple sources is considered in the work of E.

Beres et al [6]. Consider a network comprising a set M of m nodes and each relay is supporting a number of source nodes. Each node $s \in M$ has data to transmit to its own receiver that does not belong to the set M and each node acts as a potential relay for other nodes in M. The proposed algorithm works as follows.

In the first phase all nodes in M use orthogonal channels to transmit information to their respective receivers, and each node decodes the information from the other $m - 1$ sources. Each node determines if it has decoded the information correctly. If node s_j has decoded the information from the transmitter s_i correctly, it declares itself as a member of the decoding set $D(s_i)$ of nodes. Members of $D(s_i)$ are eligible to relay for node s_i. $D(s_i)$ is formed for each transmitting node $s_i \in M$.

During the second phase, the receiver of each transmitter s_i picks the relay with the highest instantaneous relay-receiver channel power from its $D(s_i)$ and the selected relay forwards the information for the transmitter s_i. The relay for s_i, $r(s_i)$ is selected according to the criteria given below:

$$r(s_i) = \arg\max\left\{|g_{r_k}|^2\right\};\ \text{where } k = 1,2,\ldots |D(s_i)| \text{ and } r_k \in D(s_i)$$

where g_{r_k} denotes the relay-destination channel coefficient.

Through analysis of outage probability and simulation, it is shown that this protocol achieves full diversity order and significantly outperforms DSTC in all networks with more than three potential relays.

4.2.6 Geographical Information based Relay Selection

A simple geographical-information based relay selection protocol for wireless sensor networks is proposed by C. L. Wang et al [29]. The relay selection protocol is designed with an objective of minimizing the Symbol Error Probability (SEP) at the destination. It considered a cluster based relay network in which network nodes are grouped into cooperative clusters. Data is transmitted between clusters using cooperative communication.

Each source node in a cluster has M relays (r_i, $i = 1, 2, \ldots, M$) to select for transmitting the data to the destination in the next cluster. Multi-hop transmission is realized by concatenation of single cluster-to-cluster hops. Assuming the distance information is perfectly known at each node, the objective is to select the best relay to maximize the cooperation gain and, hence minimize the SEP at the destination. The proposed algorithm works as follows. First, each relay i acquires its distance from source, $D_{s,i}$ and from destination, $D_{i,d}$ to calculate its own selection metric Δ_i, and then send it to the source. Next, the source chooses the best relay (i.e. the one with the minimum metric) by the following criteria

$$i^* = \arg\min\{\Delta_i\}\,; \quad \text{where } \Delta_i = A^2 \,.\, D_{s,i}^{\alpha} + B.\, D_{i,d}^{\alpha} \,, \qquad i \in \{1,2,..,M\}$$

Δ_i indicates the SEP performance at the destination. The smaller the metric, the better is the resulting SEP performance. A and B are two parameters based on modulation scheme used and α is the path loss exponent.

Then the source broadcasts a message to others to indicate which relay is going to cooperate with it. Simulation results demonstrate that the proposed relay selection protocol can efficiently improve the system performance and can outperform the random relay selection protocol in terms of SEP.

4.2.7 Threshold-Based Relay Selection for Detect-and-Forward (TRSC)

F. A. Onat et al [30] proposed a relay selection protocol that focuses on the detect-and-forward (or demodulate-and forward) cooperative relaying protocols. Unlike decode-and-forward relaying, in detect and forward relaying the relays do not perform any error correction or detection and thus reducing the energy consumption. However, the main disadvantage of this scheme is error propagation. The relays can forward erroneous information and these errors propagate to the destination causing end-to-end detection errors. The proposed protocol is based on the idea of Threshold Digital Relaying (TDR). In TDR, a relay forwards the received data only when its received SNR is above a threshold value. The use of a threshold was to determine relays that are reliable i.e. a higher SNR translates into higher probability of correct decoding or lesser number of errors. Relay selection is performed based on the equivalent end to end Bit Error Rate (BER) of each relay channel. TRSC protocol works as follows.

In the first phase, the transmitter broadcasts its information towards the receiver, while relays are also listening to the wireless medium and receiving the signal. Then each relay i decides independently whether its detection is reliable by comparing its received SNR γ_i to a threshold value γ_T. (i.e. relay i is considered as a reliable relay if $\gamma_i \geq \gamma_T$). In the second phase, the reliable relays send a short message to the receiver which allows the receiver to estimate the channel gains (g_{id}) between itself and each reliable relay i. Then the receiver picks the relay with the highest channel gain, and feedback with a short message which informs other terminals about which relay is selected for retransmission.

It is shown that the network can achieve full diversity order (M+1) where M is the number of relays in the network. BER for the TRSC is determined through numerical optimization and the result shows that TRSC performs comparable to the equivalent instantaneous BER with no instantaneous source – relay SNR knowledge at the destination.

Table 4.1 Comparison of single relay selection schemes

Algorithm	Objective	Advantages	Limitations
Opportunistic Relaying (OR)	Performs relay selection by selecting the best relay in terms of instantaneous Channel State Information (CSI)	Improves DMT, achieves full diversity, increase the spectral efficiency	Leads to collision, complexity increases with the number of nodes, all nodes must be in listening mode
Power-Aware Relay Selection (PARS)	Uses the same idea of OR and include power constraint also. The main objective is to minimize the total transmitted power	Increases the spectral efficiency, extends the network life time, it is more efficient in terms of power	Leads to collision, complexity increases with the number of nodes
Switched-and-Examine Node Selection (SENS)	Relay selection is based on switched diversity with post selection. If a relay node is selected, it remains selected unless its received SNR does not fall below certain target threshold SNR γ_T	Reduces channel estimation load, reduces complexity in terms of power consumption and load of channel estimation, increases the spectral efficiency	Gives suboptimal solution
Opportunistic Relaying with Limited Feedback	minimizes information exchange between nodes, which is at most two bits/node in each cooperation period	Requires very limited CSI feedback, CSMA technique is not required, increases the spectral efficiency	All the potential relays must be in listening mode which is expensive in terms of power consumption
Simple Relay Selection	Selects single relay from the decoding set $D(s_i)$ which has the highest channel power to the receiver	Simplifies the system design, achieves full diversity and increases the spectral efficiency	Overhead complexity increases as it requires information exchange between all the relays and the receiver
Geographical Information Based Relay Selection	Selects the best relay based on the metric(in terms of source-relay and relay-destination distance) that minimizes the symbol error probability	Simple, low overhead required and increases the spectral efficiency	Geographical information among nodes is required and imperfect geographical information may affect the system performance
Threshold-Based Relay Selection for Detect-and-Forward (TRSC)	Determine the reliable relays by comparing source-relay SNR to a threshold, and one of the reliable relays is selected by the destination based on relay-destination SNR	Less delay as there is no need to decode the message at relay sent by the source, SNR of the source-relay links not required to be known at the destination, achieves full diversity order	Possibility of error propagation.

4.3 Multiple Relay Selection Schemes (MRS)

Although single relay selection schemes (where the destination combines only the best indirect link with the direct link) have higher bandwidth efficiency and energy saving compared to all-participate relaying scheme, but these schemes do not fully exploit the available degrees of spatial diversity. They suffer a performance loss in terms of error rate and outage probability. To achieve better tradeoff between error performance and bandwidth efficiency and to save more energy, multiple relay selection could be considered [31], [32]. Some of these schemes are detailed as follows:

4.3.1 Energy-Efficient Relay Selection

R. Madan et al [31] investigated the energy efficiency of cooperative communication based on a simple relay selection strategy. Since cooperative beam-forming has been proposed to save energy in transmitting data from the relay to the receiver, it can be used at the transmitter and multiple relays may be selected as final relay set.

The scheme works as follows: the transmitter broadcasts its message with fixed power P_s and at a fixed rate R bits/symbol (assuming that no direct transmission from the transmitter and the receiver, i.e. transmitter-receiver channel is weak enough). Only M number of relay nodes that receive and decode message successfully (i.e. received SNR > threshold SNR) send training sequences at the rate r bits/symbol and power P_t to the receiver. Through these training sequences, the receiver estimates the channel gains (g_i) between itself and each relay $i \in M$. Based on the channel gains (g_i, $i \in M$), the receiver either declares an outage probability or it selects the subsets of M with the best channel gains to the receiver, and feeds back the required Channel State Information (CSI) to them. When the relays get the knowledge of the CSI, each of the selected relay i will set the optimal transmission power (beam-forming scheme).

The simulation and numerical analysis shows that the proposed scheme outperforms non cooperative schemes as well as cooperative schemes that use either a single relay or all relays, in terms of energy savings. The proposed scheme consumes approximately 14% less total energy than the other two mentioned schemes.

4.3.2 Output Threshold Multiple Relay Selection Scheme (OT-MRS)

The idea of the proposed OT-MRS scheme [32] is to select the first n arbitrary ordered relays out of M relays such that the Maximal Ratio Combined Signal-to-Noise-Ratio of the n relayed paths and the direct path exceeds a predefined target threshold γ_T. The SNR threshold is set to a minimum value required for the successful decoding of symbols at the destination. The mode of operation of the scheme is as follows:

- Broadcast mode: During the first time slot, the transmitter broadcasts its information toward the receiver and the relays are also listening to the wireless medium and receiving the signal. In this phase, the combiner output (γ_c) at the receiver is equal to the instantaneous SNR of the direct channel $\gamma_{s,d}$.
- Cooperation mode: In this mode of operation, the first relay in the list forwards the amplified version of the transmitting message to the receiver. Thus, γ_c in this case is equal to the combined signals from direct and relayed paths and the output of the combiner becomes $\gamma_c = \gamma_{s,d} + \gamma_{1,d}$. $\gamma_{1,d}$ denotes the instantaneous SNR of the first relay to destination channel Now, γ_c is compared with γ_T. If $\gamma_c \geq \gamma_T$, no more relays are selected and γ_c is set as the output SNR. Otherwise, the remaining relays 2, 3, . . . , M −1 are selected in subsequent time-slots until the output SNR exceeds the threshold. If the SNR of M − 1 relay nodes combined with the direct SNR is still less than the target threshold, all M nodes will be chosen as the relay nodes.

The numerical and simulation result in [32] shows that the proposed scheme outperforms the optimal single relay selection schemes for low to moderate SNRs.

Chapter 5
SYSTEM MODEL, SIMULATION SET-UP AND RESULTS

This chapter describes a relay selection method applied to a network consisting of multiple relays and operating in decode-and-forward mode. The relay selection method requires neither error detection methods (e.g., CRC) at relay nodes nor feedback information at the source from the destination node and the relays [33]. Hence, it is able to achieve diversity with a low implementation complexity. Source-relay Signal-to-Noise Ratio (SNR) and relay-destination SNR of each relay is required at the destination. The destination node chooses the best available relay (on the basis of source-relay SNR and relay-destination SNR) at the end of broadcasting phase. We use Finite State Markov Model (FSMM) of Rayleigh fading channel in our proposed relay selection method. Each time the relay is selected (based on the channel state of relays), the destination node repeats the process of relay selection after the average duration of the state of the selected relay. Next, we also determine the optimal power allocation for the cooperation system.

5.1 System Model

Consider a multi-relay scenario with N relay nodes. Source (S), relay (R_i, i=1,2,..,N) and destination (D) nodes operate in half-duplex mode and are equipped with single transmit and receive antennas. Figure 5.1 shows the transmission model.

5.1.1 Relay Selection Method Based on Instantaneous SNR

Let x be modulation symbol taken from M-PSK (Phase Shift Keying) or M-QAM (Quadrature Amplitude Modulation) constellation [33]. The fading coefficients for S $\rightarrow$ D, S $\rightarrow$ R_i and $R_i \rightarrow$ D links are denoted by $a_{S,D}$, a_{S,R_i} and $a_{R_i,D}$ and are assumed to be zero-mean complex Gaussian random variables with variances $\delta^2_{S,D}$, δ^2_{S,R_i} and $\delta^2_{R_i,D}$ respectively. The channel gains between any two pair of nodes are independent and identically distributed

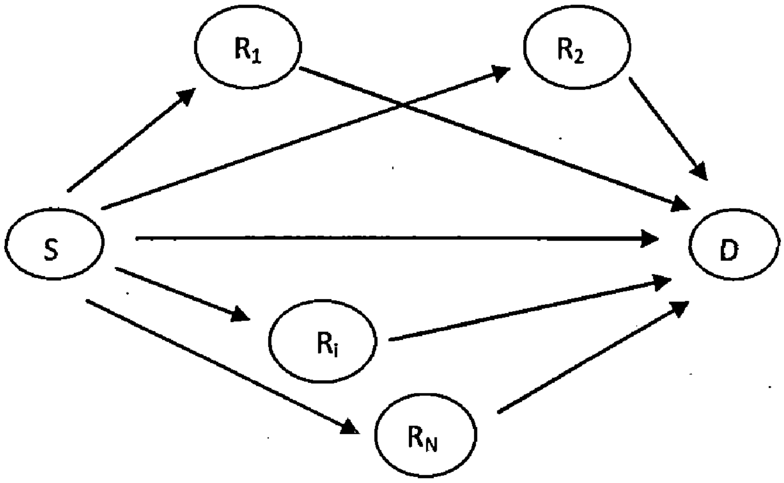

Figure 5.1: Transmission model [33].

(i.i.d.). In Phase 1, the source broadcasts its information to destination and the relays. The received signals at destination and i^{th} relay nodes are given by

$$y_{S,D} = \sqrt{P_1} a_{S,D} x + n_{S,D} \tag{5.1}$$

$$y_{S,R_i} = \sqrt{P_1} a_{S,R_i} x + n_{S,R_i} \tag{5.2}$$

where P_1 is the transmitted power at the source and $n_{S,D}$ and n_{S,R_i} model the additive noise terms and are assumed to be complex Gaussian noises with zero mean and variance N_0.

For relay selection, it is assumed that the destination node has estimates of $a_{S,D}$, a_{S,R_i} and $a_{R_i,D}$ at the end of the first time slot (i.e., Phase 1). Due to slow fading nature of channel $a_{R_i,D}$ can be estimated in advance. It is assumed that perfect CSI is available at destination. Let $\lambda_{S,D}$, λ_{S,R_i} and $\lambda_{R_i,D}$ denote the instantaneous SNRs in S→D, S → R_i and R_i → D links respectively. The destination first chooses the best relay R_{sel} based on the following criteria

$$R_{sel} = \underset{R_i}{\arg\max} \{\min(\lambda_{S,R_i}, \lambda_{R_i,D})\} \tag{5.3}$$

The destination node instructs the selected relay to participate in second time slot (i.e., Phase 2) only if SNR in direct link is less than the minimum of the SNRs in the selected relaying path, i.e.,

$$\lambda_{S,D} < \lambda_{max} = \min(\lambda_{S,R_{sel}}, \lambda_{R_{sel},D}) \tag{5.4}$$

Otherwise, the relay will not participate in cooperation phase. If allowed to cooperate, the selected relay performs decoding and forwards re-encoded symbol $\hat{x}$ with power P_2 in second time slot ($P_2 = 0$, if the relay is not allowed to participate). The signal received at destination node is therefore given by

$$y_{R_{sel},D} = \sqrt{P_2}\, a_{R_{sel},D}\hat{x} + n_{R_{sel},D} \tag{5.5}$$

where $n_{R_{sel},D}$ models the additive Gaussian noise term. The destination node then combines the received signals given by eqn.(5.1) and eqn.(5.5) using maximum ratio combining (MRC) and decodes the symbol transmitted by source.

5.1.2 Proposed Relay Selection Method Using FSMM

It is assumed that the channel fading is slow enough such that the channel condition remains in the same state from the current frame to the next frame. The estimated Channel State Information (CSI) of the current frame can be taken as the predicted CSI for the next frame. Since, the data rate is high (hundreds of kbits/s), the duration of a data block is smaller than the coherence time. When data transmission takes place, consecutive blocks of data experience approximately the same channel condition. To take the advantage of channel memory, the channel is approximated by means of a Markov model [7]. Depending upon the type of fading (fast or slow), the number of states in a Markov model of the channel can be decided. A Finite State Markov Model (FSMM) provides the set of transition probabilities and steady state probabilities which can be further utilized to obtain the average duration of each state of the channel.

As described in previous subsection, destination node knows the values of $\lambda_{S,D}$, λ_{S,R_i} and $\lambda_{R_i,D}$ at the end of the first time slot. Based on these values, it calculates the channel state of each relaying path (source-relay channel state (CS_{S,R_i}) using λ_{S,R_i} and relay-destination channel state ($CS_{R_i,D}$) using $\lambda_{R_i,D}$) and direct path (source-destination channel state ($CS_{S,D}$) using $\lambda_{S,D}$) using FSMM of Rayleigh fading channel described in Chapter 3. The destination first chooses the best relay R_{sel} based on the following criteria

$$R_{sel} = \underset{R_i}{\arg\max} \{\min(CS_{S,R_i}, CS_{R_i,D})\} \tag{5.6}$$

If the value of $\min(CS_{S,R_i}, CS_{R_i,D})$ is equal for more than one relay, the relay node with greater value of CS_{S,R_i} will be preferred and in case of equal value of CS_{S,R_i}, the relay node with greater value of $CS_{R_i,D}$ will be preferred.

The destination node instructs the selected relay to participate in second time slot. Let the average channel state duration (calculated using FSMM) of $\min(CS_{S,R_{sel}}, CS_{sel,D})$ be h. The selected relay continues to participate in cooperation for h number of packets. After the transmission of h number of packets, the whole procedure is repeated again.

5.2 Optimum Power Allocation for the Cooperation System

An asymptotic optimum power allocation for decode-and-forward cooperation protocol based on the tight SER upper bound was determined by W. Su et al [34]. Specifically, the optimum transmitted power P_1 at the source and P_2 at the relay for a fixed total transmission power $P_1 + P_2 = P$ will be determined.

With knowledge of the channel coefficients $a_{S,D}$ and $a_{R_i,D}$, the output of the MRC detector at the destination can be written as

$$y = a_1 y_{S,D} + a_2 y_{R_i,D} \tag{5.7}$$

where $a_1 = \sqrt{P_1} a^*_{S,D}/N_0$ and $a_2 = \sqrt{P_2} a^*_{R_i,D}/N_0$. Assume that the transmitted symbol x has average energy 1, then the SNR of the MRC output is

$$\gamma = \frac{P_1 |a_{S,D}|^2 + P_2 |a_{R_i,D}|^2}{N_0} \tag{5.8}$$

If all the channel links $a_{S,D}$, a_{S,R_i} and $a_{R_i,D}$ are available i.e $\delta^2_{S,D} \neq 0$, $\delta^2_{S,R_i} \neq 0$ and $\delta^2_{R_i,D} \neq 0$, then the SER of the system with M-PSK or M-QAM modulation can be upper bounded as [34]

$$P_s \leq \frac{N_0^2}{b^2} \cdot \frac{1}{P_1 \delta_{S,D}^2} \left(\frac{A^2}{P_1 \delta_{S,R_i}^2} + \frac{B}{P_2 \delta_{R_i,D}^2} \right) \tag{5.9}$$

where in case of M-PSK signals, $b = b_{PSK} = \sin^2\left(\frac{\pi}{M}\right)$ and

$$A = \frac{M-1}{2M} + \frac{\sin\left(\frac{2\pi}{M}\right)}{4\pi} \tag{5.10}$$

$$B = \frac{3(M-1)}{8M} + \frac{\sin\left(\frac{2\pi}{M}\right)}{4\pi} - \frac{\sin\left(\frac{4\pi}{M}\right)}{32\pi} \tag{5.11}$$

while in case of M-QAM signals, $b = b_{QAM}/2$, $b_{QAM} = 3/(M-1)$ and

$$A = \frac{M-1}{2M} + \frac{K^2}{\pi} \tag{5.12}$$

$$B = \frac{3(M-1)}{8M} + \frac{K^2}{\pi} \tag{5.13}$$

To determine optimum power allocation based on this upper bound, minimize the term $(A^2 P_2 \delta_{R_i,D}^2 + B P_1 \delta_{S,R_i}^2)/(P_1^2 P_2)$ in eqn.(5.9) under the power constraint $P_1 + P_2 = P$. Taking the derivative over P_1 and setting the resulting derivation as zero,

$$B\delta_{S,R_i}^2 (P_1^2 - P_1 P_2) - 2A^2 \delta_{R_i,D}^2 P_2^2 = 0 \tag{5.14}$$

Solving the above equation with the power constraint $P_1 + P_2 = P$, the optimum power allocation obtained is

$$P_1 = \frac{\delta_{S,R_i} + \sqrt{\delta_{S,R_i}^2 + 8\left(\frac{A^2}{B}\right)\delta_{R_i,D}^2}}{3\delta_{S,R_i} + \sqrt{\delta_{S,R_i}^2 + 8\left(\frac{A^2}{B}\right)\delta_{R_i,D}^2}} P \tag{5.15}$$

$$P_2 = \frac{2\delta_{S,R_i}}{3\delta_{S,R_i} + \sqrt{\delta^2_{S,R_i} + 8\left(\frac{A^2}{B}\right)\delta^2_{R_i,D}}} P \quad (5.16)$$

5.3 Results and Discussion

We present the performance of relay selection method proposed in subsection 5.1.2 through simulations. We compare the proposed method with the method described in subsection 5.1.1. Next, we compare the performance of the Optimal Power Allocation (OPA) with that of equal power case (in which no power allocation algorithm has been applied). All the simulation results were carried out in MATLAB environment.

5.3.1 Relay Selection Based on Instantaneous SNR

If the optimal power allocation algorithm is not applied in a relay selection method, we say that the method employs Equal Power Allocation (EPA). Performance results are obtained using the simulation parameters shown in Table 5.1.

Table 5.1 Simulation parameters for relay selection based on instantaneous SNR

Number of relay nodes, N	2, 3, 4
Modulation scheme	QPSK (M=4), BPSK (M=2)
Variances $\delta^2_{S,D}$, δ^2_{S,R_i} and $\delta^2_{R_i,D}$	1
Power P_1, P_2	1
Performance measure	SER

Figure 5.2 and Figure 5.3 show the plot of SNR versus SER using QPSK and BPSK modulation respectively with different number of available relays in the network. From the results, it is observed that achievable diversity order increases with the number of available relays. These results match with the previous work done by M. M. Fareed et al [33].

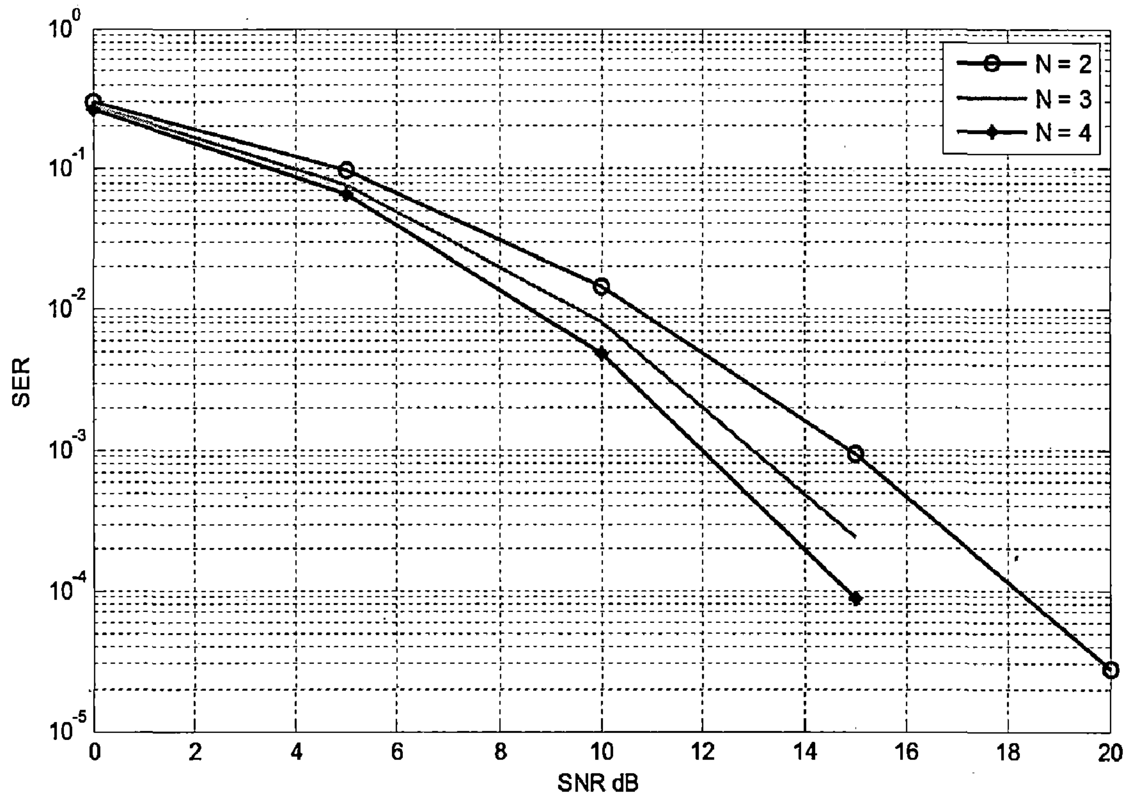

Figure 5.2: SER for 2, 3 and 4 relays using QPSK.

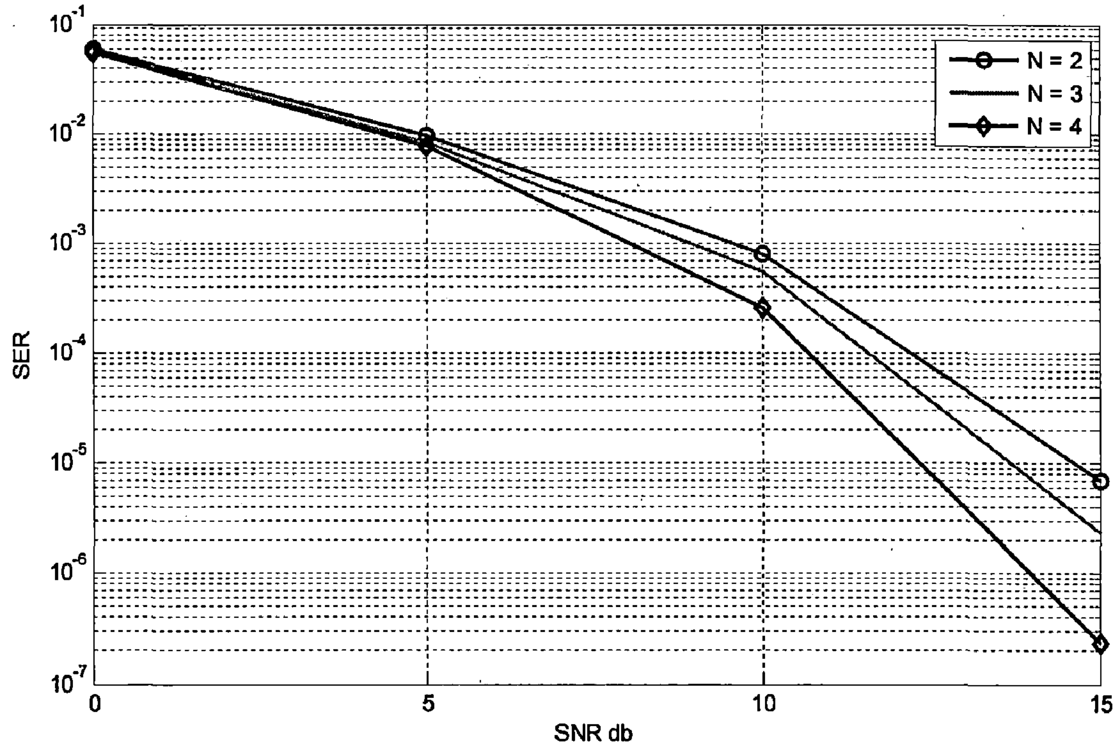

Figure 5.3: SER for 2, 3 and 4 relays using BPSK.

To show the effect of OPA, we simulated the system with QPSK modulation and compared the performance (in terms of SER) of OPA with that of EPA case. Figure 5.4 shows that for a three-relay network, performance improvement of nearly 1 db is obtained for a target SER of 10^{-3}. For a two-relay network, OPA provides nearly 0.5 db improvement. This result compares well with the result in [33].

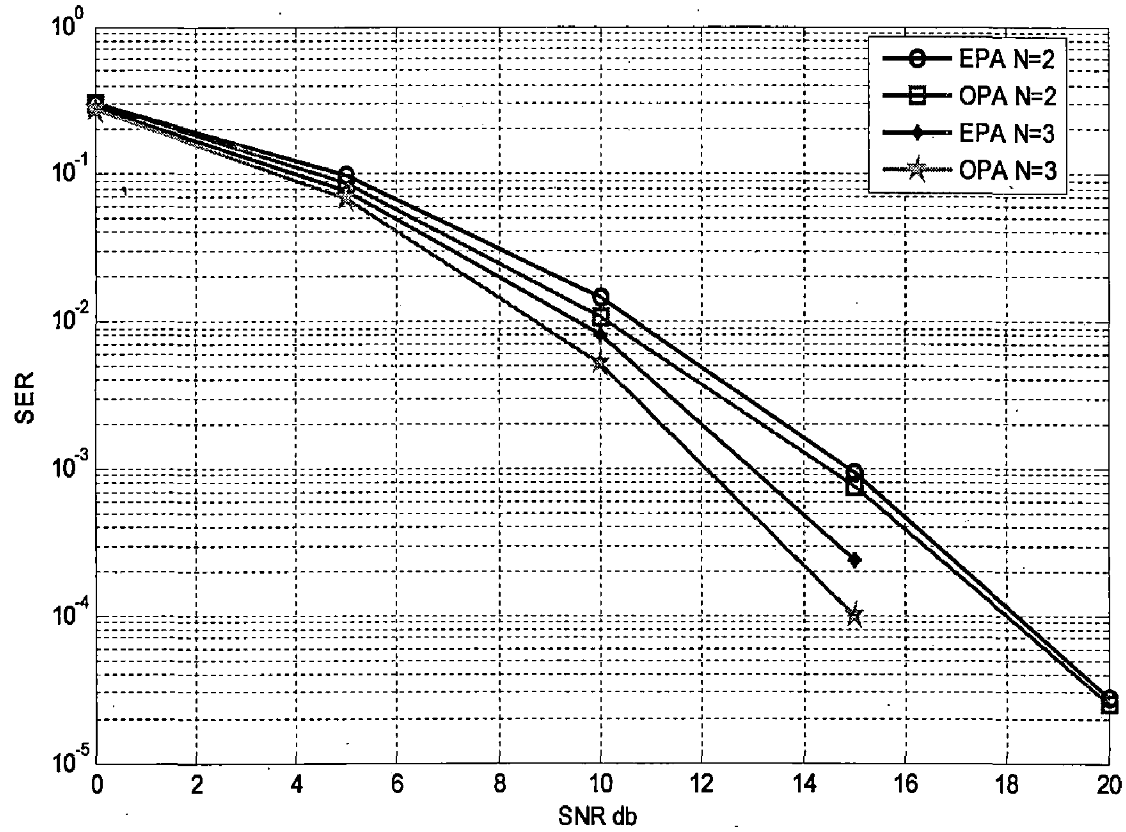

Figure 5.4: SER performance of 2 and 3-relay network with EPA and OPA.

5.3.2 Proposed Relay Selection Using FSMM

In the proposed method, we use our results of transition probabilities and steady-state probabilities obtained in chapter 3. Performance results are obtained using the simulation parameters shown in Table 3.1 and Table 5.1.

Figure 5.5 shows the plot of SNR versus SER using QPSK modulation and two-state, three-state and eleven-state Markov model. With two-state and three-state Markov model, full diversity cannot be extracted and the response does not improve on increasing the number of

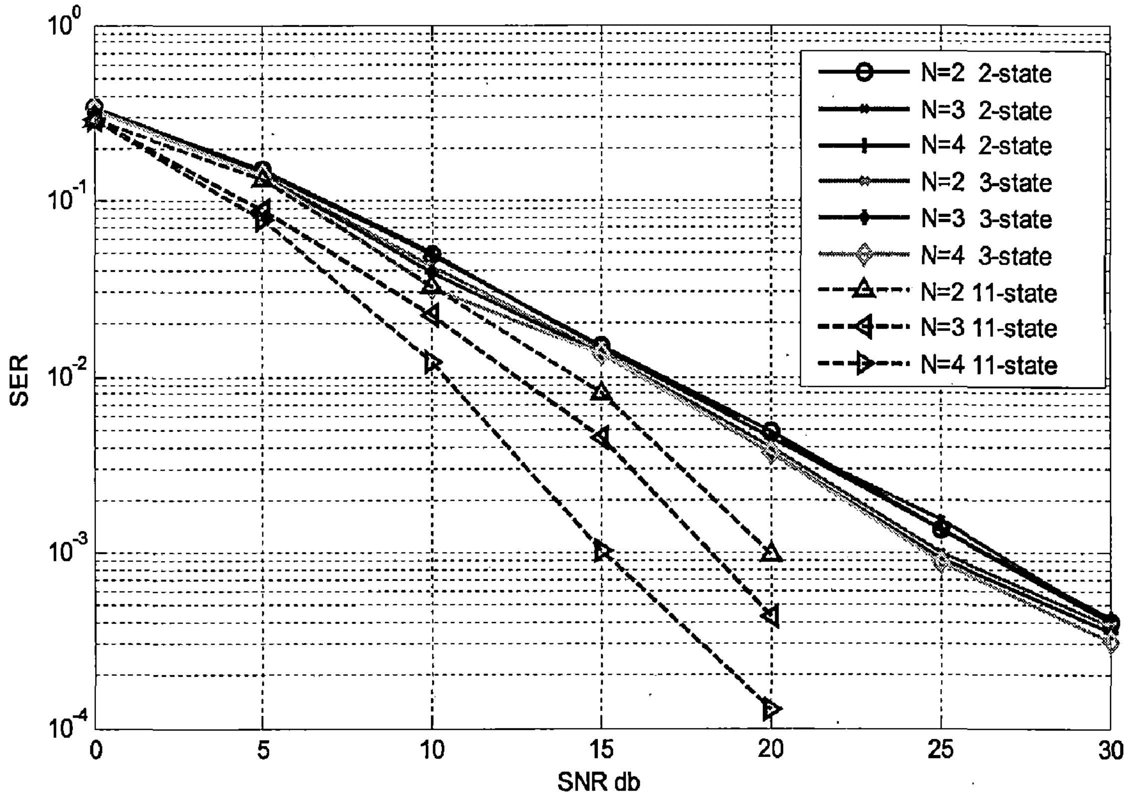

Figure 5.5: SER for 2, 3 and 4 relays using two-state, three-state and eleven-state Markov model.

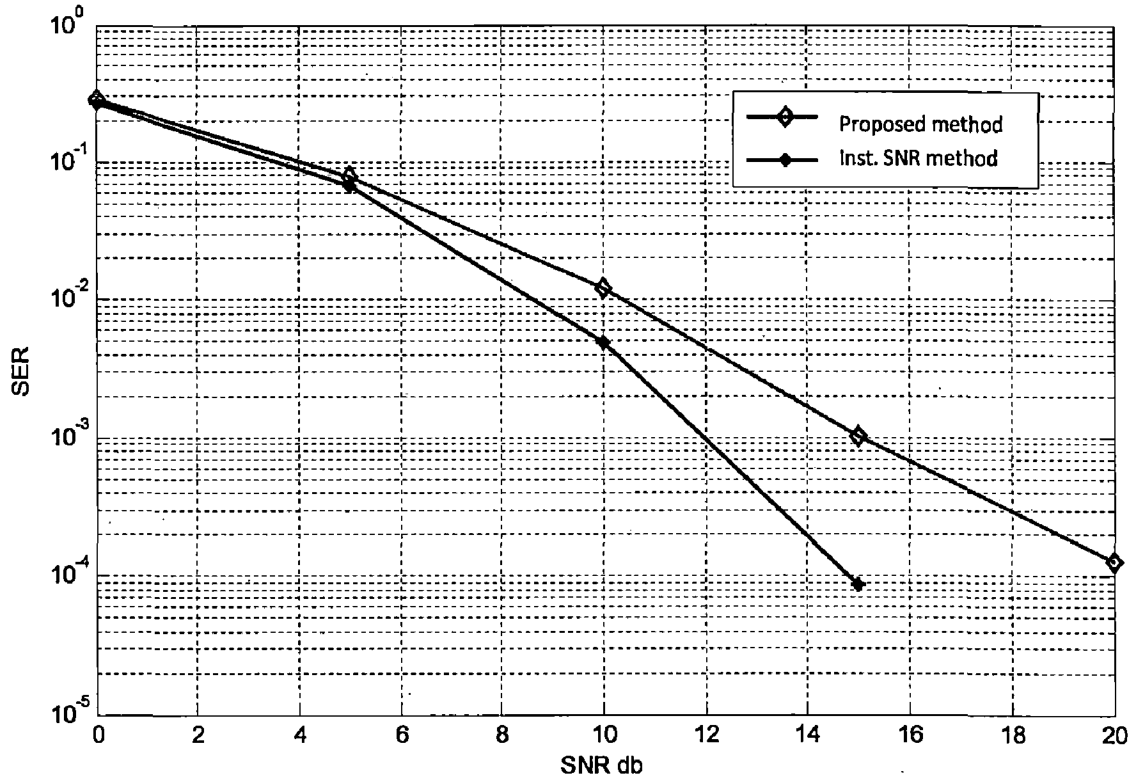

Figure 5.6: Comparison of proposed method with the method based on instantaneous SNR.

relays. This happens because smaller number of states (K) of the channel produces larger SNR interval for each state (from eqn.(3.19)). For a large SNR interval, different packets lying in a state may have their Bit Error Rate (BER) values much different from the average BER of that state [23]. Therefore, relay selected based on the resulting channel state may be inappropriate. Thus, it will be incorrect to use average BER to represent the actual BER of the packet. With eleven-state Markov model, diversity advantage improves on increasing the number of relays.

We compared the proposed method (using eleven-state Markov model) with the method described in subsection 5.1.1. A 4-relay network is considered and QPSK modulation is used. Figure 5.6 shows that the proposed method is able to extract the diversity benefit but it is outperformed by the method based on instantaneous (Inst.) SNR. However, the proposed method provides low complexity as relay is not selected after every data packet transmission. In addition, signaling overheads in relay selection get reduced.

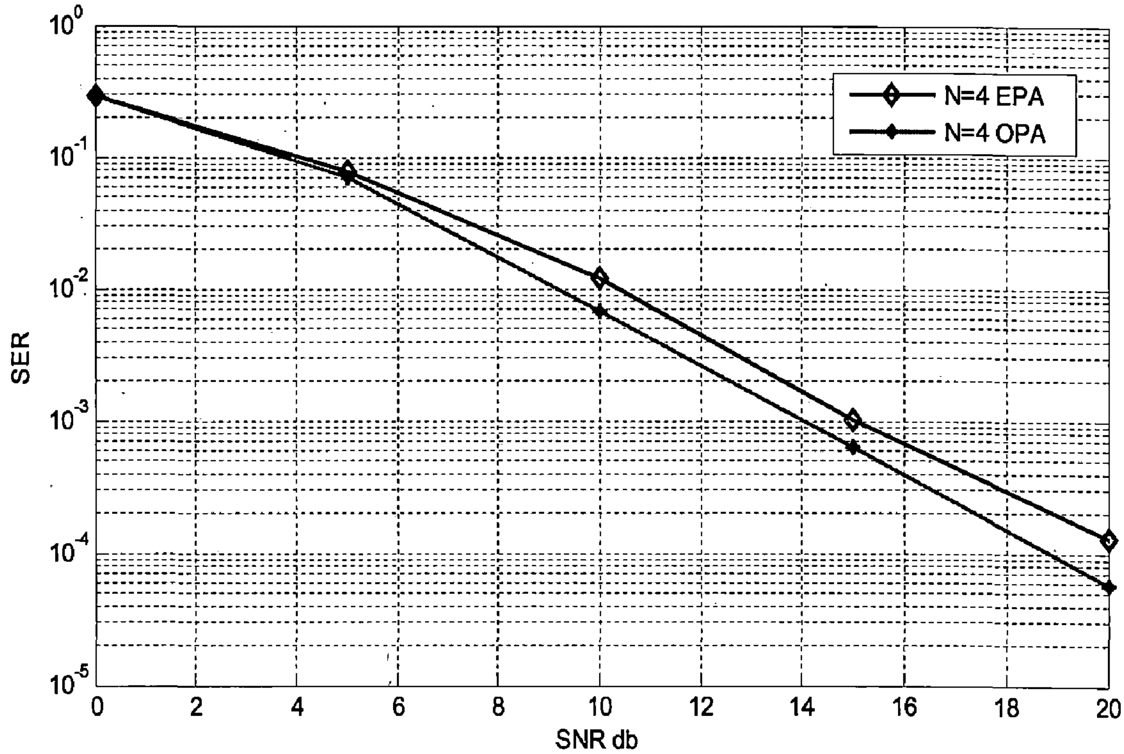

Figure 5.7: SER performance of 4-relay network with EPA and OPA.

We applied OPA in the proposed method (using eleven-state Markov model) for a 4-relay network and simulated the system with QPSK modulation. The performance (in terms of SER) of OPA is compared with that of EPA case. Figure 5.7 shows that OPA results in performance improvement of nearly 1 db for a target SER of 10^{-3}. This result can be compared with Figure 5.4.

Chapter 6
CONCLUSIONS

Relay selection plays an important and vital role of maximizing the diversity gain achieved in wireless cooperative communication systems. This dissertation work has focused on study of relay selection methods to achieve better performance with reduced power consumption and complexity. A method for relay node selection based on instantaneous Signal-to-Noise Ratio (SNR) is able to achieve diversity gain [33] and the results of the method have been matched. A new method has been proposed which uses Finite State Markov Model (FSMM) of Rayleigh fading channel to utilize the channel memory. Optimal Power Allocation (OPA) has been applied to improve Symbol Error Rate (SER) performance.

Based on simulation results, it is observed that the relay selection method proposed in [33] is able to extract the full diversity order of N+1 in a cooperative network with N relays. In our method, full diversity cannot be extracted using two-state and three-state Markov model. Using eleven-state Markov model, diversity advantage improves, but it is outperformed by the method in [33] and hence there is a scope of further improvement. However, it saves additional signaling overheads and provides low complexity since relay node is not selected after each data packet transmission.

Based on SER performance analysis, we determine OPA for the cooperation system. Theoretical and simulation results show that equal power allocation is not optimum and OPA depends on the channel link quality. For a target SER of 10^{-3}, OPA results in performance improvement of nearly 1 db over equal power allocation case.

Future Work

Here, some suggestions are given to continue the work performed in this dissertation in future.

- Relay selection in a decentralized network can be performed using FSMM. Then, all the available relays in the network will determine their channel states for source-relay and relay-destination path. Depending on the channel states, each relay can determine whether it could be a suitable candidate or not.

- We evaluated the performance of the relay selection scheme for single source-to-destination pair. This can be extended to multiple transmitter-receiver scenario as considered by E. Beres et al [6].

- Achieving high spectral efficiency in wireless services is one of main design considerations. Along with relay selection, adaptive modulation and coding can be performed based on channel quality to obtain better throughput.

- Investigating relay selection problem for multi-hop networks can be considered for the future work.

REFERENCES

[1] J.N. Laneman, G.W. Wornell and D.N.C. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks", in Proc. IEEE International Symposium on Information Theory (ISIT), Washington, DC, pp.294, June 2001.

[2] A. Nosratinia, T.E. Hunter and A. Hedayat, "Cooperative communication in wireless networks", IEEE Communications Magazine, vol. 42, no. 10, pp. 74-80, October 2004.

[3] J.N. Laneman and G.W. Wornell, "Energy-efficient antenna sharing and relaying for wireless networks", in Proc. IEEE Wireless Communications and Networking Conf. (WCNC), Chicago, IL, September 2000.

[4] J.N. Laneman and G.W. Wornell, "Distributed space–time–coded protocols for exploiting cooperative diversity in wireless networks", IEEE Transactions on Information Theory, vol. 49, no.10, pp. 2415–2425, October 2003.

[5] A. Sendonaris, E. Erkip and B. Aazhang, "User cooperation diversity—part I, II", IEEE Transactions on Communications, vol. 51, no.11, pp. 1927–1948, November 2003.

[6] E. Beres and R. Adve, "Selection cooperation in multi–source cooperative networks", IEEE Transactions on Wireless Communications, vol. 7, no.1, pp. 118–127, January 2008.

[7] M. Zorzi, R. R. Rao and L. B. Milstein, "On the accuracy of a first-order Markov model for data transmission on fading channels", in Proc. IEEE ICUPC, pp. 211-215, November 1995.

[8] H. Takagi and L. Kleinrock, "Optimal transmission ranges for randomly distributed packet radio terminals", IEEE Transactions on Communications, vol. 32, no. 3, pp. 246-257, March 1984.

[9] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block coding for wireless communications: Performance results", IEEE Journal on Selected Areas in Communications, vol. 17, no. 3, pp. 451-460, March 1999.

[10] L. Zheng and D. Tse, "Diversity and multiplexing: A fundamental trade-off in multiple antenna channels", IEEE Trans. Information Theory, vol. 49, pp. 1073-1096, May 2003.

[11] T. M. Cover and A. E. Gamal, "Capacity theorems for the relay channel", IEEE Transactions on Information Theory, vol. 25, no. 5, pp. 572-584, September 1979.

[12] M. O. Hasna and M. S. Alouini, "Performance analysis of two-hop relayed transmissions over Rayleigh fading channels", in Proc. IEEE Vehicular Technology Conference, Niagara Falls, Canada, vol.4, pp. 1992- 1996, December 2002.

[13] J. N. Laneman, D. N. C. Tse and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior", IEEE Transaction on Information Theory, vol. 50, no. 12, pp. 3062 - 3080, December 2004.

[14] E. Zimmermann, P. Herhold and G. Fettweis, "A novel protocol for cooperative diversity in wireless networks", in Proceedings of The Fifth European Wireless Conference - Mobile and Wireless System Beyond 3G, Barcelona, Spain, February 2004.

[15] E. G. Larsson and B. R. Vojcic, "Cooperative transmit diversity based on superposition modulation", IEEE Communications Letters, vol. 9, no. 9, pp. 778 - 780, September 2005.

[16] Q. Zhao and H. Li, "Performance of differential modulation with wireless relays in Rayleigh fading channels", IEEE Communications Letters, vol. 9, no. 4, pp. 343- 345, April 2005.

[17] T. E. Hunter and A. Nosratinia, "Performance analysis of coded cooperation diversity", in Proceedings IEEE International Conference on Communications, Vol.4, pp. 2688- 2692, May 2003.

[18] T. S. Rappaport, "Wireless Communications: Principles and Practice", Prentice Hall, Upper Saddle river, New Jersey, USA, 2002.

[19] B. Vucetic and J. Du, "Channel modeling and simulation in satellite mobile communication systems", IEEE Journal on Selected Areas in Communications, vol. 10, no. 8, October 1992.

[20] H. S. Wang and N. Moayeri, "Finite-state markov channel–a useful model for radio communication channels", IEEE Transactions on Vehicular Technology, vol. 44, no. 1, pp. 163-171, February 1995.

[21] E. N. Gilbert, "Capacity of a burst noise channel", Bell System Technology Journal, vol. 39, pp. 1253-1266, September 1960.

[22] B. Vucetic, "An adaptive coding scheme for time – varying channels", IEEE Transactions on Communications, vol. 39, no. 5, May 1991.

[23] Q. Zhang and S. A. Kassam, "Finite – state Markov model for Rayleigh fading channels", IEEE Transactions on Communications, vol. 47, no. 11, November 1999.

[24] A. S. Ibrahim, A. K. Sadek, W. Su and K. J. R. Liu, "Relay selection in multi-node cooperative communications: when to cooperate and whom to cooperate with?", IEEE Global Telecommunications Conference, pp. 1-5, November 2006.

[25] A. Bletsas, A. Khisti, D. P. Reed and A. Lippman, "A simple cooperative diversity method based on network path selection", IEEE Journal on Selected Areas in Communications, vol. 24, no. 3, pp. 659–672, March 2006.

[26] Y. Chen, Y. Guanding, P. Qiu and Z. Zhang, "Power-aware cooperative relay selection strategies in wireless ad hoc networks", IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications, pp. 1-5, September 2006.

[27] K. S. Hwang and Y. C. Ko, "An efficient relay selection algorithm for cooperative networks", IEEE 66th Vehicular Technology Conference, Baltimore, MD, pp.81-85, September 2007.

[28] A. Tajer and A. Nosratinia, "Opportunistic cooperation via relay selection with minimal information exchange", IEEE International Symposium on Information Theory (ISIT), Nice, France, pp. 1926-1930, June 2007.

[29] C. L. Wang and S. J. Syue, "An efficient relay selection protocol for cooperative wireless sensor networks", IEEE Wireless Communications and Networking Conference (WCNC), Dresden, Germany, pp. 1-5, April 2009.

[30] F. A. Onat, Y. Fan, H. Yanikomeroglu and H. V. Poor, "Threshold-based relay selection for detect-and-forward relaying in cooperative wireless networks", EURASIP Journal on Wireless Communications and Networking, pp. 1-9, April 2010.

[31] R. Madan, N. B. Mehta, A. F. Molisch and J. Zhang, "Energy-efficient cooperative relaying over fading channels with simple relay selection", IEEE Transactions on Wireless Communications, vol. 7, no. 8, pp. 3013-3024, August 2008.

[32] G. Amarasuriya, M. Ardakani and C. Tellambura, "Output-threshold multiple-relay-selection scheme for cooperative wireless networks", IEEE Transactions on Vehicular Technology, vol. 59, no. 6, pp. 3091–3097, July 2010.

[33] M. M. Fareed and M. Uysal, "A novel relay selection method for decode-and-forward relaying", in Proc. CCECE, Niagara Falls, Canada, pp. 135-140, May 2008.

[34] W. Su, A. K. Sadek and K. J. R. Liu, "SER performance analysis and optimum power allocation for decode-and-forward cooperation protocol in wireless networks", IEEE Wireless Communications and Networking Conference, vol. 2, pp. 984-989, March 2005.