Cooperative MAC Design for Ad Hoc Wireless Networks

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A Thesis
in
The Department
of
Electrical and Computer Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science
Concordia University
Montreal, Quebec, Canada

April 2007

Your file Votre référence
ISBN: 978-0-494-28916-7
Our file Notre référence
ISBN: 978-0-494-28916-7

Abstract

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Cooperative diversity is proposed to combat the detrimental effects of channel fading. In this thesis, we investigate the effectiveness of cooperative diversity in interference limited ad hoc networks. The throughput performance of ad hoc networks that employ cooperative diversity techniques is examined. The negative effects of relay transmission blocking and extra time delay due to using the relay node, on the network throughput are investigated. We show that cooperative diversity based ad hoc networks inherits relay blocking problem which causes net network throughput degradation. To solve the relay blocking problem, we propose a new cooperative medium-access-control (MAC) protocol where each relay is equipped with directive antennas and the transmitter-relay-receiver transmission mode is designed using two frequency channels. Furthermore, we discuss the throughput performance considering single and multiple relay scenarios and analyze the effect of interference on the throughput. Then we investigate the throughput performance of the proposed cooperative MAC protocol in the presence of position estimation errors. In the literature, a perfect position estimation of all nodes is commonly assumed. Here, we focus on the throughput performance of the cooperative network when taking into consideration the effect of directional-of-arrival (DOA) error caused by imperfect global-positioning system (GPS) position estimation. Our results show that using adaptive antennas

at the relay becomes advantageous when the DOA error is less than 20 degrees. We noted that increasing the number of antennas (at the relay station) can improve the throughput performance but, on the other hand, the effect of node position error becomes more substantial.

Dedicated to my dearest parents......

Acknowledgments

First and foremost, I would like to express my sincere appreciation to my academic supervisor Dr. Walaa Hamouda for giving me invaluable support, constructive guidance and helpful discussion. I am thankful for his exceptional patience and kindness in answering my questions and revising my reports. Without his continuous encouragement and stimulating suggestions, I would not have succeeded.

I also want to thank all the people who helped me throughout my study at Concordia University.

Finally, I would like to thank my parents for their love, trust and encouragement. Without their support, it would have been impossible for me to accomplish what I have accomplished.

Contents

List of Figures **x**

List of Tables **xiii**

List of Acronyms **xiv**

1 Introduction **1**

1.1 Introduction 1

1.2 Motivation 1

1.3 Previous Works 4

1.4 Thesis Outline 5

2 Background **7**

2.1 Introduction 7

2.2 IEEE 802.11 7

2.2.1 The IEEE 802.11 Standard 7

2.2.2 System Architecture of IEEE 802.11 9

2.2.3 Physical Layer 12

2.2.4 MAC Layer of IEEE 802.11 14

2.3 Cooperative Communication 19

2.3.1 Amplify-and-Forward: . . . 20
2.3.2 Decode-and-Forward . . . 21
2.3.3 Coded Cooperation . . . 22
2.4 Adaptive Antenna Arrays and Beamforming . . . 22
2.4.1 Uniformly Spaced Linear Antenna Array . . . 23
2.4.2 Antenna Beamforming . . . 28
2.4.3 Least Mean Squares(LMS) Algorithm . . . 32
2.4.4 Recursive Least Squares (RLS) Algorithm . . . 33
2.5 Summary . . . 34

3 Performance Evaluation of Cooperative Ad Hoc Networks 35
3.1 Introduction . . . 35
3.2 System Model . . . 36
3.3 Physical Layer Design . . . 37
3.4 MAC Layer Design . . . 39
3.5 Performance of Cooperative Transmission . . . 40
3.6 Summary . . . 43

4 Proposed Two Channel Cooperative MAC Protocol 45
4.1 New Cooperative Protocol . . . 45
4.1.1 Physical Layer Design: . . . 46
4.1.2 Channel Reservation . . . 46
4.1.3 MAC Layer Design . . . 51
4.2 Summary . . . 55

5 Simulation Results **56**

5.1 Introduction 56

5.2 Simulation Model 56

5.3 Simulation Results 58

5.4 Summary 67

6 Conclusions and Future Work **68**

6.1 Conclusions 68

6.2 Future Work 69

Bibliography **69**

List of Figures

2.1 IEEE 802.11 protocol architecture. 9

2.2 Extended service set (ESS). 12

2.3 IEEE 802.11 MAC layer architecture. 15

2.4 Basic CSMA/CA mechanism and timing diagram for a transmission process. 16

2.5 Point coordination frame transfer. 18

2.6 A simple cooperative network. 20

2.7 Decode and forward, Amplify and forward schemes. 21

2.8 An M-element uniformly spaced linear array. 23

2.9 A simple narrow band adaptive antenna system. 29

3.1 Snapshot of a 10-station network topology with relay selection. 36

3.2 BER performance comparison between IEEE 802.11 and cooperative network with one relay. 38

3.3 Timing diagram for cooperative strategy. 40

3.4 Average throughput vs. load for 20 random topologies. 41

3.5 Throughput performance for the network topology in Fig. 3.1. 42

3.6 Cooperative scenario with relay blocking. 42

4.1 Sender-relay-destination links. 48

4.2 Sender-relay-destination links. 50

4.3 Timing diagram for the single relay new cooperative MAC protocol. . 52

4.4 Timing diagram for the multiple relay new cooperative protocol. . . . 53

4.5 Hidden terminal in relay communications. 54

5.1 Throughput vs load at SNR=25 dB, using 4-antenna elements for the new cooperative protocol and a single relay transmission. 59

5.2 Throughput performance of the new cooperative protocol with 4-antenna elements at SNR=13 dB for the single relay and multiple relay scenarios and using the fixed topology of Fig. 3.1. 60

5.3 Throughput performance at a fixed load of 1Mbps/station, using 4-antenna elements per relay node. 61

5.4 Throughput vs system load at SNR= 25dB. 62

5.5 Effect of increasing the number of antennas on the throughput performance at SNR=25dB for the fixed topology in Fig. 3.1 and at fixed load/station = 1Mbps. 63

5.6 Throughput performance at a fixed load =1Mbps/station and at SNR=25 dB (a) Single relay (Uniformly distributed DOA error) (b) Single relay (Gaussian distributed DOA error)(c) Multiple relay (Uniformly distributed DOA error) (d) Multiple relay (Gaussian distributed DOA error). 64

5.7 Throughput performance at a fixed load =1Mbps/station with 3 antennas (a) Single relay (Uniformly distributed DOA error) (b) Single relay (Gaussian distributed DOA error)(c) Multiple relay (Uniformly distributed DOA error) (d) Multiple relay (Gaussian distributed DOA error). 66

List of Tables

3.1 Transmitting, Receiving, Relay, and Blocking Stations. 43

5.1 Simulation Parameters. 57

List of Acronyms

ACK (Acknowledgment)

AF (Amplify-and-forward)

AP (Access point)

AWGN (Additive white Gaussian noise)

BER (Bit error rate)

BSA (Bit error rate)

BSS (Basic service set)

CC (Coded cooperation)

CCA (Clear channel assessment)

CDMA (Code-division multiple-access)

CFP (Contention-free period)

CMA (Constant modulus algorithm)

CP (Contention period)

CTS (Clear to send)

DBPSK (Differential binary phase shift keying)

DCF (Distribution coordination function)

DF (Decode-and-forward)

DIFS (Distributed coordination function interframe space)

DOA (Direction-of-arrival)

DQPSK (Quadrature phase shift keying)

DS (Distribution system)

DSSS (Directional sequence spread spectrum)

ESS (Extended service set)

FHSS (Frequency hopping spread spectrum)

GFSK (Gaussian frequency shift keying)

GPS (Global positioning system)

IBSS (Independent basic service set)

IFS (Interframe space)

IR (Infrared)

LAN (Local area network)

LMS (Least mean square)

LS (Least squares)

LLC (Logical link control)

MAC (Medium access control)

MANET (Mobile ad hoc networks)

MIB (Management information base)

MIMO (Multiple input multiple output)

MMSE (Minimum mean square error)

MPDU (MAC protocol data unit)

NAV (Network allocation vector)

NIC (Network interface card)

OSI (open systems interconnection)

PHY (Physical layer)

PIFS (Point coordination function IFS)

PCF (Point coordination function)

PLCP (Physical layer convergence protocol)

PMD (Physical medium dependent)

PDU (Protocol data unit)

QoS (Quality of service)

RF (Radio frequency)

RLS (Recursive least mean square)

RTS (Request to send)

RRTS (Relay ready-to-send)

REACK (Relay acknowledgement)

SAP (service access point)

SIFS (Short IFS)

SNR (Signal to noise ratio)

STA (Wireless LAN station)

SS (Spread spectrum)

SSID (Service set identifier)

VCS (Virtual carrier sense)

WLAN (Wireless LAN)

Chapter 1

Introduction

1.1 Introduction

1.2 Motivation

Mobile ad hoc networks (MANET) are distributed and infrastructure-less networks in which a number of mobile stations can communicate with each other over wireless links. Peer-to-peer communication from a source station to a destination station can be achieved in an ad hoc network without the help of any centralized control or access point. All mobile nodes in an ad hoc network share the same radio frequency (RF) channel. This type of network is widely used where an infrastructure-less network is preferable like in military environments, natural catastrophic conditions, or in any commercial applications like in hotel lobbies, airport waiting rooms etc. Different standards for MANETs are available such as IEEE 802.11 [1] for wireless local area network (WLAN), the defense advanced research projects agency's (DARPA) global mobile information system (GLOMO) [2] for metropolitan area network (MAN), HOMERF [3] for home networks, BLUTOOTH [4] for devise networks and smart dust and wireless integrated network sensors (WINS) for sensor networks [5].

Communications over a wireless channel is limited by different practical impairment like interference, channel fading, path loss and shadowing. The use of diversity [6] can mitigate the effect of channel fading and improve the signal quality at the receiver. The impairments caused by multipath fading and the time varying nature of the wireless channel must be considered in designing an ad hoc wireless network. The broadcast nature of the radio channel introduces characteristics in ad hoc wireless networks that can be exploited in the form of cooperative diversity [7], a strategy whereby cooperating nodes between the source and its destination forward the received data generated by the source to the destination after some processing at each relay terminal.

The distributed coordinated function (DCF) of the IEEE 802.11 is designed for wireless stations communicating in ad hoc scenarios. The carrier-sense multiple-access with collision avoidance (CSMA/CA) of the IEEE 802.11 allows stations to communicate with each other by sharing a single channel. In this case when two stations are granted access to the channel, then the other neighboring stations remain silent and wait for future access to the channel. Within the context of relay networks, these silent neighboring nodes of the transmitter and/or the receiver stations can be used as relay stations to improve the received signal quality at the destination node. This type of cooperative diversity [6] has been widely discussed in the literature (see [7]-[13] and references therein). In these works, different cooperative strategies can be employed at the relay node. One common technique, referred to as amplify-and-forward (AF) mode, uses the relay to amplify the received signal (according to power constraints) before retransmission to the destination node. In a more complex cooperative strategy, known as decode-and-forward (DF) mode, the received signal from the source is first demodulated, decoded, and then regenerated for subsequent transmission to the destination node. In these two main cooperative strategies, the relay stations play the role of virtual antennas at the source station by re-sending the received signals to the destination node through different independent fading channels.

In this thesis, we examine a cooperative medium access control (MAC) protocol for the IEEE 802.11 based MANET where each station (source, destination, and relay) is equipped with a single antenna element and the transmission data rate is fixed for all stations. The throughput results from the analysis have revealed that this type of single channel cooperative diversity offers significant performance gains at the physical layer but it can also bring overall throughput degradation in the network. This is simply due to the relay blocking problem where the employment of relay transmission blocks the relay neighboring stations from possible transmissions. Here, we solve the relay blocking problem by designing a new cooperative MAC protocol that employs adaptive antennas at the relay stations. We then analyze the throughput performance in two different scenarios; using single and multiple relays transmissions. Without loss of generality, in our study, we consider the AF mode of operation discussed in [11] where we examine the performance of our cooperative strategy in interference limited ad hoc networks.

1.3 Previous Works

The idea of cooperative relay networks was first discussed in 1971 by Van Der Meulen [14] where the classical models for a class of three terminal communication channels were examined. Later, a novel work on cooperative communication for relay channels was presented by Cover and Gamal in [15]. In their work, the authors mainly focused on the information theoretic properties of the degraded relay channels. Though there were some isolated works done in this field in the 80's and 90's, not until recently cooperative communication networks have received a great deal of attention. The use of multiple relays have been examined in many references including [16]-[23]. In multipath fading channels, Sendonaris *et. al.* in [7], [24], and [25] were first to propose the concept of user cooperation diversity where it was applied to code-division multiple-access (CDMA) cellular systems. In [7] and [25], two mobile users act as 'partners', each sending its own data as well as a portion of its partner's to a common destination. It is shown that, in an information theoretic sense, cooperation enlarges the rate region and increases the sum rate of the two mobiles [25]. In [24], the same authors discussed cooperative diversity as a mean to increase the uplink capacity of cellular networks.

Although Sendonaris *et. al.* [25] were first to introduce cooperation between mobile stations, the work of Laneman *et. al.* [9] has contributed to possible low-complexity two-stage relay strategies considering certain design constraints. Three types of relaying structures are discussed in [9], (i) Fixed relaying, (ii) Selective relaying, and (iii) Incremental relaying. Each of these relaying techniques can employ AF or DF at the relay station. Other works on the use of multiple antennas in relay channels include the work in [26], [27]. Different from our work, in [26], [27] antennas are used for diversity gains and not for interference cancellation purposes.

It is clear from the above works that cooperative diversity can provide the benefits of spatial diversity without the need for physical arrays. However, most of existing works focus on improving the peer-to-peer link quality in the single-user scenario by using coding or power and rate allocation. In ad hoc networks, how to efficiently and fairly allocate resources among multiple users and their relays is still a challenging task.

The DCF of the MAC layer protocol defined in the IEEE 802.11 standard is usually used in ad hoc networks. Using CSMA/CA, all nodes in an ad hoc network contend for a single channel access. In [12], a MAC protocol based on user cooperation to improve the performance of the IEEE 802.11 WLAN was proposed. The focus of this protocol was mainly to improve the data rate of mobile stations far from the access point by cooperation of an intermediate node.

However, very few studies have focused on the impact of cooperative diversity on system performance [28], [29] especially in ad hoc networks. In ad hoc networks, using cooperative relay in general expands the range of signal radiation compared to direct communication and hence increased interference range.

In [30], an analytical model for evaluating the quality of service (QoS) in wireless ad hoc networks was developed. In this work, transmission blocking probability was derived and chosen for the QoS figure of merit. In [10], the work of [30] is further extended to the case of cooperative networks.

1.4 Thesis Outline

The rest of the thesis is outlined as follows.

In Chapter 2, we briefly review the basic concepts of IEEE 802.11 wireless local area networks, cooperative networks and adaptive antenna arrays.

In Chapter 3, we present the system model, including the PHY and MAC layers of conventional cooperative ad hoc networks and evaluate its performance. The performance is then compared with the standard IEEE 802.11 ad hoc network considering both additive white Gaussian noise (AWGN) and fading channel conditions. The relay blocking problem is also discussed in this chapter.

Chapter 4, presents detailed description of the proposed new cooperative MAC protocol for both single and multiple relay cases.

In Chapter 5, the simulation results for the proposed protocol are presented and compared to the IEEE 802.11 protocol and the conventional cooperative protocol that inherits relay blocking problem. The performance is compared for both single and multiple relay networks while taking into consideration different practical aspects like interference, number of antenna elements at the relay, error due to imperfect global positioning system (GPS) information.

Finally, chapter 6 provides a summary of the thesis and some directions for future work.

Chapter 2

Background

2.1 Introduction

This chapter presents some general ideas and fundamental concepts concerning the IEEE 802.11 standard, cooperative diversity techniques and adaptive antennas to be used later in our work. Section 2.2 focuses mainly on the architecture and services of the IEEE 802.11 standard. In section 2.3, cooperative diversity is discussed briefly. Finally, the adaptive antenna arrays and beam-forming techniques are introduced in section 2.4.

2.2 IEEE 802.11

2.2.1 The IEEE 802.11 Standard

A WLAN is designed to provide a data communication system where data is transferred between users without the need of any wiry infrastructure. Due to its fast advancement on providing reliable wireless connectivity, mobility, installation flexibility, economic viability over wired LANs, WLANs are gaining commercial popularity and attracted a broad range of customers.

The IEEE P802.11 committee published the first internationally sanctioned standard, 802.11 WLAN specifications in 1997, to satisfy the need of wireless communication for a group of possibly fixed, portable or moving stations situated in a local area. Mainly the bottom two layers of open systems interconnection (OSI) model i.e. physical layer and data link layer and their interaction with upper layers are defined by IEEE 802.11 standardization committee. Different issues like DCF and point coordination function (PCF) are defined [1] to provide services for both real time audio-video communication (by PCF) and data communications (by DCF). Some other important subjects that are covered by this specification are data privacy and encryption, power management, cellular architecture, roaming procedures in IEEE 802.11 WLANs.

From the protocol architecture of IEEE 802.11 in Fig. 2.1 the coverage of this standard is shown as the lower two layer of OSI reference model namely PHY and MAC layer. The data link layer is subdivided into two layers, the logical link control (LLC) layer and the MAC layer. The physical layer defines specifications regarding different choices of transmission technologies to use, like frequency hopping spread spectrum (FHSS), direct sequence spread spectrum (DSSS), infrared (IR) etc. The PHY layer is subdivided into two layers, the physical layer convergence protocol (PLCP) and the physical medium dependent sub-layer (PMD). The PLCP layer provides clear channel assessment signal (CCA), and regardless of the transmission technology used it provides common physical service access point (SAP). Modulation, encoding/decoding

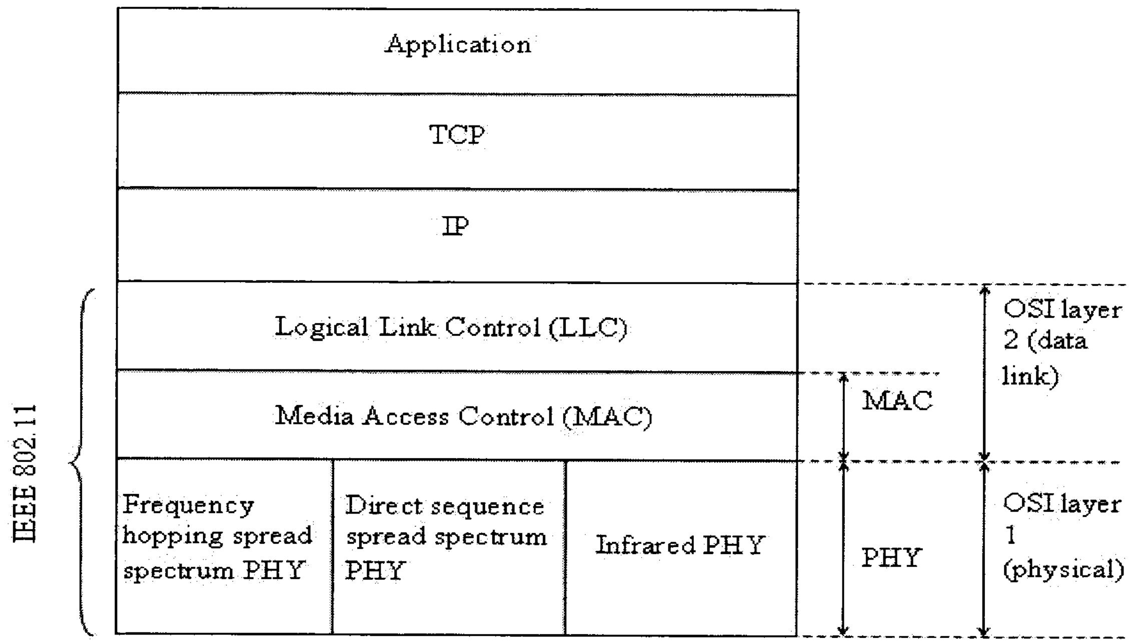

Figure 2.1: IEEE 802.11 protocol architecture.

of radio wave signal is handled by PMD.

The function of MAC layer is to provide a control system to access the shared channel by multiple users using suitable schemes, fragmentation and encryption of data.

2.2.2 System Architecture of IEEE 802.11

The IEEE 802.11 WLAN is built based on a cellular architecture where each cell is controlled by an access point. Depending on the requirement of coverage more than one access point can be used to form a multiple-cell wireless network where mobile stations can get connected through any of the access points. In IEEE 802.11 standard each cell is called basic service set (BSS). The architectural components to construct an IEEE 802.11 WLAN are discussed below in brief.

Wireless LAN Station

The WLAN station (STA) is the lower most component of IEEE 802.11 WLAN architecture. It is the basic component and contains MAC and PHY layer to access the wireless media. A station could be a notebook, computer, an access point (AP) or any intelligent wireless terminals that are compatible to all the 802.11 station services such as authentication, privacy, and data transmission. The 802.11 protocols are implemented in a network interface card (NIC) of a wireless station.

Basic Service Set (BSS)

The basic service set (BSS) is the basic cell defined in an 802.11 WLAN nomenclature. This is the building block of IEEE 802.11 WLAN and it comprises a set of stations managed either by DCF or PCF coordination functions. The area covered by any BSS is called basic service area (BSA).

Independent Basic Service Set (IBSS)

The WLAN topology where a group of stations form a self-contained, distributed network and communicate to each other in a peer-to-peer fashion without any access to a distribution system is referred as independent basic service set (IBSS) . This type of network topology is called mobile ad hoc network.

In an IBSS, mobile stations can communicate directly with each other without any access point. Any two mobile stations can communicate if they are neighbors of each other by one hop or multi hop communication if a route can be established between them.

Infrastructure Basic Service Set

An infrastructure basic service set is a BSS with an AP. All mobile stations within the range of the AP can communicate with other mobile stations via the AP. The AP may also be connected with a distribution system (DS).

Distribution System (DS)

A WLAN may contain more than one BSS. A DS acts like a backbone where all the BSSs are connected. So interconnection between mobile stations existing in different BSS can occur via their individual APs which are connected by the DS. Thus, a DS provides an AP to AP communication to exchange frames for stations in their respective BSSs. A DS may be itself wireless or a wired network like IEEE 802.3 Ethernet networks, IEEE 802.4 token bus networks.

Extended Service Set (ESS)

The wireless coverage area of a WLAN can be extended by connecting several BSSs which are interconnected through a DS. The whole extended WLAN is called extended service set (ESS) (see Fig. 2.2).

DS is the backbone of the wireless LAN and it determines the destination for traffic received from a BSS. The DS also decides on the route of the traffic. Each network connected by DS in a ESS holds an identifier which is known as service set identifier (SSID). In order to participate in the WLAN the SSID should be known. SSID separates different WLANs in the whole ESS. A portal is used to connect DS to the WLANs via the APs that forms the inter-networking unit to other LANs.

Any other network users intended to connect to the ESS from outside distinguish

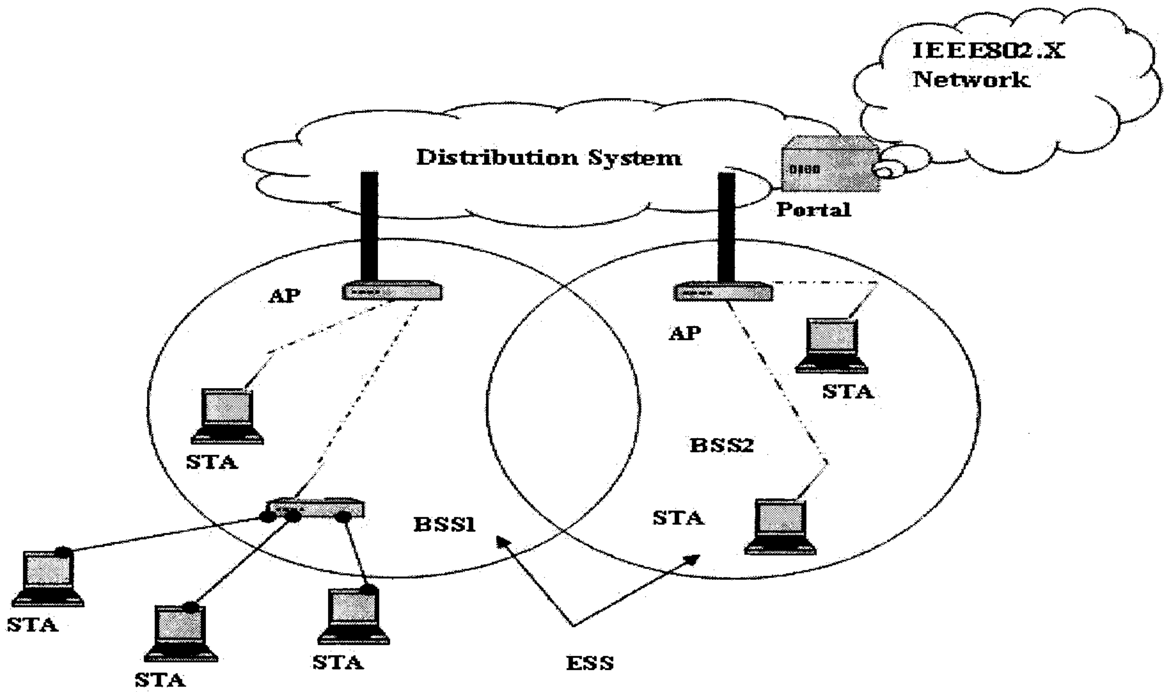

Figure 2.2: Extended service set (ESS).

the ESS along with all other mobile stations like a single MAC layer network. Thus all stations are considered physically stationary by network users. From other users outside the ESS, the mobility of the stations is concealed. By this way it is possible to connect with other users that might not use the IEEE 802.11 protocol.

2.2.3 Physical Layer

The physical layer of IEEE 802.11 WLAN is responsible for the carrier sensing, modulation techniques, encoding and decoding techniques and some physical management tasks like channel tuning, physical management information base (MIB) maintenance etc.

The IEEE 802.11 WLAN has three techniques defined to operate with its PHY layer: (i) FHSS, (ii) DSSS, and (iii) IR. In what follow, we give an overview of these three techniques.

Frequency Hopping Spread Spectrum

Frequency hopping (FH) is one type of spread spectrum (SS) techniques. SS performs very robust to mitigate different practical impairments like interference, channel fading that results form multipath propagation. FHSS allows simultaneous existence of multiple networks within the same vicinity by employing different frequency sequences for different networks. FHSS uses 79 non-overlapping hopping channels each with 1 MHz channel bandwidth to transmit data signal over the 2.4 GHz (ISM) band. Any particular channel is defined by using a pseudo-random hopping pattern. Gaussian frequency shift keying (GFSK) modulation is used for FHSS. Also, 1 Mbps and 2 Mbps data rates can be achieved by respectively using a 2-level and 4-level GFSK.

Direct Sequence Spread Spectrum

In DSSS technique the channels are separated by spreading code. The method is simply to take the signal of a given bit rate and modulate it into a signal that occupies a much larger bandwidth. The DSSS transmission system of IEEE 802.11 also uses ISM 2.4 GHZ band [31]. 1 Mbps and 2Mbps data rates are offered by DSSS by using respectively differential binary phase shift keying (DBPSK) and differential quadrature phase shift keying (DQPSK) modulation. Eleven channels have been defined to operate without interfering with each other by at least 30MHz gap.

Infrared

The IEEE 802.11 allows another type of PHY layer transmission technique which is based on the near-visible light range of 850 to 950 nanometers infrared. The line-of-sight is not required for communicating in this standard so the transmitter and receiver do not have to point to each other but also employ a point-to-multi-point communication. Reuse of frequency is quite simple as a thin wall can shield an IEEE IF based network from another IEEE IF based network. 10 to 20 meters of distance can be covered in a interference free, probably indoor conditions but at outdoor conditions the system cannot operate.

2.2.4 MAC Layer of IEEE 802.11

The MAC layer is designed to support various tasks required to efficiently provide services to a number of users sharing the same medium. The task of the MAC layer includes channel allocation procedures, protocol data unit (PDU) addressing, error checking, frame formatting, fragmentation and reassembly.

Three different types of frames are mainly used in IEEE 802.11: (i) data frames, (ii) control frames, and (ii) management frames. Different management tasks like station association and disassociation with the AP, timing and synchronization, and authentication and de-authentication are managed by the management frames. Control frames are used to control the sequence of the packet transmission and notification of the status of packet transmission. For example control frames are used for handshaking (request to send (RTS) / clear to send (CTS) etc.) during the contention period (CP), for positive acknowledgments (ACK) during the CP, and to end the contention free period (CFP). On the other hand, the data is transferred by the data frames.

The MAC [1] can control the medium to operate in both contention free and contention mode. In contention mode, all the stations in the network contend to get access to the channel for packet transmission whereas in contention free mode there is no need for contention period to access the channel and a centralized AP is required. Depending on the application and the nature of WLAN, two different sets of access methods are defined in MAC layer of IEEE 802.11. First one is the DCF which provides support for asynchronous data transfer of MAC service data units (MSDU). On the other hand, the PCF is the modified version of the DCF to offer support for connection-oriented real time transfer of MSDUs. The PCF may be implemented by an AP, where each station connects with the AP and the AP manages the grant of medium access to the stations. Fig. 2.3 shows the MAC layer architecture of the IEEE 802.11.

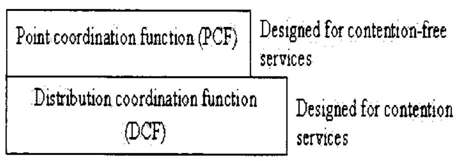

Figure 2.3: IEEE 802.11 MAC layer architecture.

Distributed Coordination Function (DCF)

The basic access system is defined by the DCF which is based on the CSMA/CA mechanism. By carrier sensing, stations monitor the channel to determine whether the medium is idle or busy. If the medium is busy, the stations wait until the channel becomes idle to avoid collision. If any two stations are allowed to transmit by the protocol immediately after the channel becomes idle, then collisions may occur. Since collision detection is not possible, to solve this problem, the IEEE 802.11 WLAN defines a randomized backoff time by which the contending stations are allowed to attempt for the channel occupation. Fig. 2.4 shows the basic CSMA/CA operation.

Inter frame spacing of certain minimum period is used to prioritize different frame

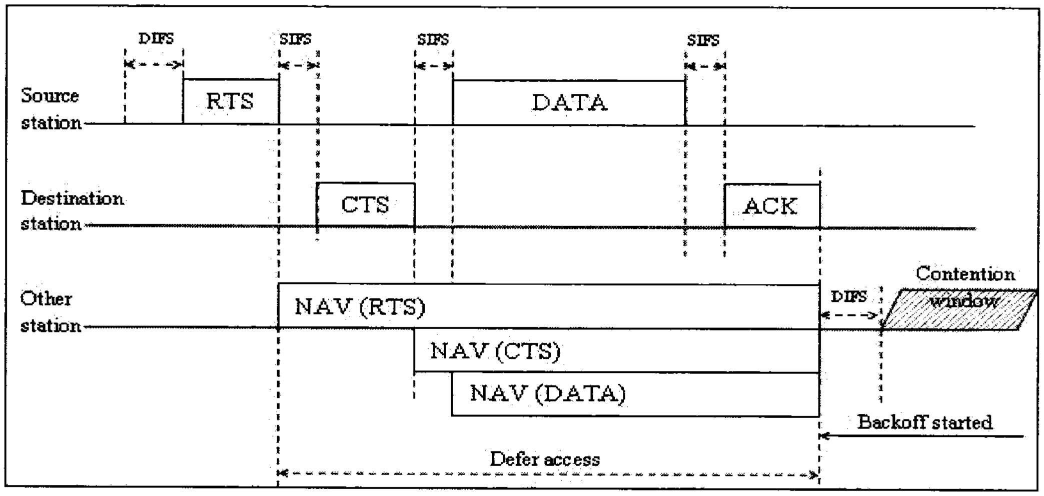

Figure 2.4: Basic CSMA/CA mechanism and timing diagram for a transmission process.

transmissions. All stations are obliged to stay silent for the inter-frame space (IFS). Different types of IFS are defined in the IEEE standard [1]. High priority frames must only wait for the short IFS (SIFS) period before they contend again for the channel. The DCF IFS (DIFS) is used by the DCF to transmit data and management MDPUs. Similarly, the PCF IFS (PIFS) is intermediate in duration and is used by the PCF to gain priority access to the channel at the start of a CFP.

CSMA/CA works as follows. A station wishing to transmit senses the channel to determine the status of the medium. If no activity is detected, the station waits for an additional, randomly selected period of time and then transmits if the medium remains free. If the channel is sensed idle for a period of DIFS then the station can use the channel to transmit.

If the bit error rate (BER) of the received packet is within the threshold limit, the receiving station issues an ACK frame. Upon reception of this ACK, the transmitter knows that the process is completed. On the other hand, if the ACK frame is not detected by the sending station a collision is assumed and the data packet is retransmitted later.

Now to reduce the throughput loss due to the hidden terminal problem [32] which occurs when two terminals transmitting at the same time and not hearing each others transmissions, an optional RTS/CTS handshaking mechanism is introduced in CSMA/CA.

By employing a virtual carrier sense (VCS) mechanism the information of channel reservation time requirement is broadcasted to keep the neighboring stations aware of the current transmission. At first, a RTS packet is sent by the source station, which contains the information of the source, destination, and the duration of the following transmission. By receiving the RTS, the destination node responds if the medium is free with a CTS. The CTS packet contains the same information as the RTS. The neighbors of the sender and the receiving stations receive the RTS and/or the CTS packets and set their VCS indicator which is called network allocation vector (NAV), according to the given duration specified by these frames. The neighboring stations then use this information to schedule the time for their next channel sensing. By this process, the probability of collision is reduced. This is simply because a station that did not receive the RTS transmission can hear the CTS and mark the channel as busy until the end of the transmission. The duration information given in the RTS also protects the transmitter area from collision during the ACK (from stations that are out of range of the ACK frame). RTS and CTS frames are very small in size compared to the data frame. Thus, if any collision occurs during the RTS/CTS packet transmission then the bandwidth waste is very small compared to the case where collision occurs in the data frame (when not using RTS/CTS packets).

Point Coordination Function (PCF)

Figure 2.5 shows the operation of the PCF. The PCF is an optional capability which is performed by the point coordinator (PC) in the AP within a BSS. The PCF is required to coexist with the DCF and it logically covers on top of the DCF as shown in Fig. 2.5. It performs frame transfer for connection-oriented, contention-free systems. The PCF depends on the point coordinator (PC) to perform polling, enabling polled stations to transmit without contending for the channel.

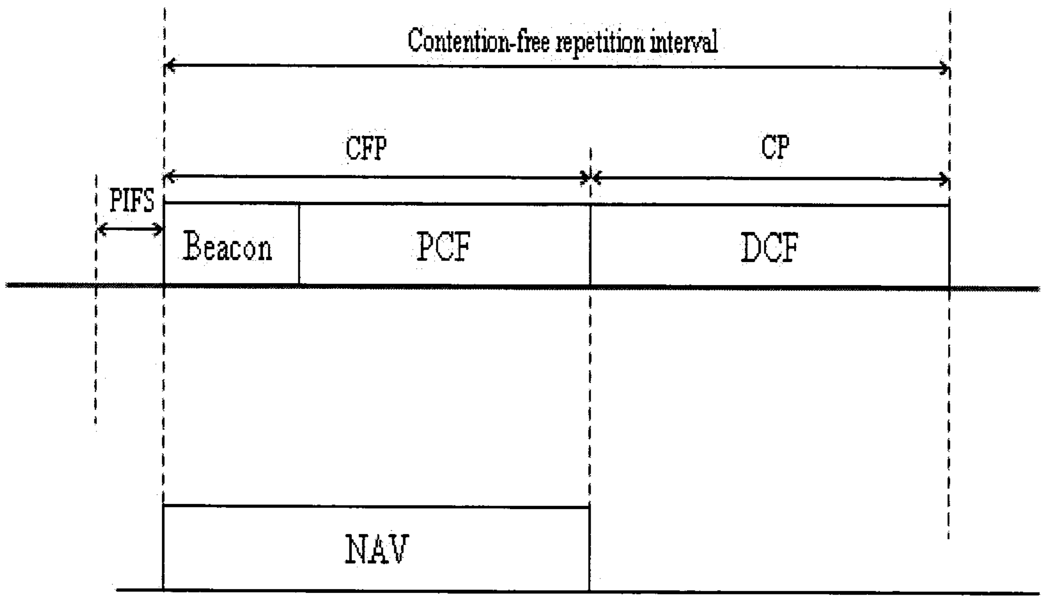

Figure 2.5: Point coordination frame transfer.

The CPF repetition interval determines the frequency to contention-free traffic, and the remainder is provided for contention-based traffic. A beacon frame is used to initiate the CFP repetition. The AP is responsible for the beacon transmission. The structure of the CFP repetition interval and the coexistence of the PCF and DCF is presented the Fig. 2.5. The AP determines the procedure to operate the CFP during any given repetition interval. Depending on the traffic load, the AP may vary the

CFP time and provide the remaining time of the repetition interval for the DCF.

We modelled the MAC layer of the MANET to assist the PHY layer with cooperative communication in order to improve the signal quality by achieving diversity gain through cooperative communication over the fading channels. Thus, the next section gives a brief discussion on the cooperative communication.

2.3 Cooperative Communication

In mobile wireless communication, the transmission through the radio channel is attenuated and suffers from the detrimental effects of channel fading. Fading causes the transmitted signal to randomly fluctuate in signal level and significantly weakening the received signal at the destination terminal [33]. Therefore, wireless communications demand well-built systems to combat attenuation and fading caused by propagation in the wireless channel.

The solution of the problem can be found by employing diversity techniques [2] where more than one statistically independent channels are created between the sender and destination station. Thus providing the destination terminal with multiple and independent copies of the same transmitted symbol. The destination terminal then combines these multiple copies of the same transmitted symbol properly which eventually improves the received signal quality at the receiver. Diversity can be achieved by utilizing multiple antennas at the transmitter and/or receiver ends which is known as multiple input multiple output (MIMO) system [34]. The same diversity gain can be achieved without the use of multiple antennas but using simple cooperation between mobile stations to form multiple independent paths between the sender and destination stations. Fig. 2.6 depicts an example of a basic cooperative communication. In a cooperative network, the relay terminal helps the communication of a given source and destination pair by simply forwarding the signals received from by the source terminal to the destination.

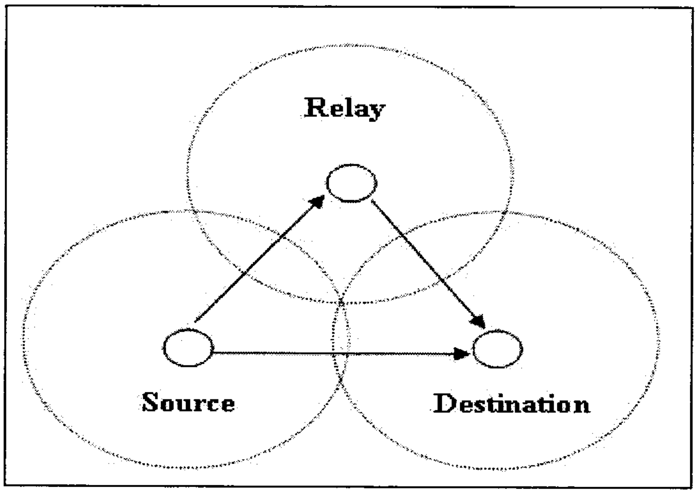

Figure 2.6: A simple cooperative network.

There are mainly three different cooperation modes that can be used. They are namely, amplify-and-forward (AF), decode-and-forward (DF) and coded cooperation (CC) [35] (see Fig. 2.7). In the thesis we utilized the first and most simple form of cooperation mode which is AF. In the following sections a brief discussion on the schemes will be presented.

2.3.1 Amplify-and-Forward:

AF, as the name implies, is a simple form of cooperative signaling where each mobile station wishes to cooperate receives the noisy version of the signal transmitted by its partner and then retransmits after amplification. In this method, it is assumed that the paths between the cooperating stations to the destination station and the path between the source station to the destination station are statistically independent.

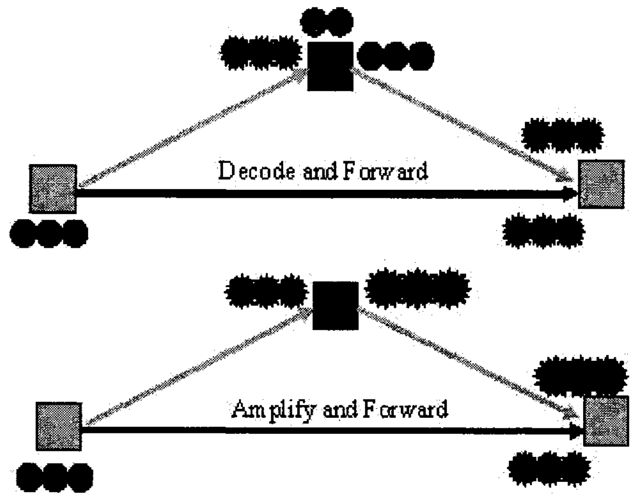

Figure 2.7: Decode and forward, Amplify and forward schemes.

Before retransmission, each partner station has to adaptively amplify the received signal to boost up the power of the received signal.

Decision about the transmitted bit is made at the receiving station from the combined information where for optimal decoding is based on the assumption of the two paths to be known at the destination station. To obtain an estimation of the channel coefficients at the destination station some feedback is required.

2.3.2 Decode-and-Forward

In this technique a relay station first detects the data signal received from the source station. Following the detection process, the detected signal is regenerated and re-transmitted to the destination station. At the receiver, diversity gain is achieved by receiving signals from more than one independent channel path. This method prevents amplifying and retransmission of the noise at the relay receiver as the case of AF. The disadvantage of this scheme is that if the detection is unsuccessful, the performance becomes poor. To alleviate this limitation a hybrid DF scheme is proposed in which two different cooperative modes are employed in an adaptive way [36].

That is cooperation mode is for low instantaneous signal to noise ratio (SNR) channel conditions and non-cooperation is for high SNRs.

2.3.3 Coded Cooperation

Coded cooperation is a method where the system is designed to integrate channel coding in the cooperative network [37], [38]. In this case, different segments of each user's (partners) code word are sent via independent fading paths where each user attempts to transmit incremental redundancy to its partner. If the partner cannot assist, the users automatically go back to non-cooperative mode and all this process is automatically managed through code design without exchanging any feedback between the users.

In the thesis, the AF cooperation mode is used by the mobile stations where the relay station receives the signal from the source station and relays it to the destination station by using adaptive antenna arrays. By using adaptive antennas the relay beamforms toward the direction of the destination station. Using GPS system the information of direction-of-arrival (DOA) of the destination station is known to the relay. The following section describes the beamforming techniques used in adaptive antenna arrays.

2.4 Adaptive Antenna Arrays and Beamforming

Array beamforming techniques can produce controllable beam-patterns with desired beam width. The array pattern can be dynamically formed to optimize some characteristics of the signal. By employing beam scanning a single main beam of an array is steered and the direction can be varied either continuously or in small discrete steps. The side-lobes of the beam-pattern can be suppressed in such a way to reduce interference to other users.

Adaptive beamforming is performed by utilizing a set of antenna elements to form an adaptive antenna array. An array consists of multiple antenna elements that are arranged spatially and interconnected electrically to produce a directional radiation pattern. In the adaptive antenna technology, the radiation pattern is changed by regulating the amplitude and relative phase of the different array elements. In general, the antenna array can be formed by using any combination of antenna elements. Usually a structure based on some geometrical regularity is maintained with equal antenna elements while designing an adaptive antenna array.

2.4.1 Uniformly Spaced Linear Antenna Array

A linear array is formed by arranging the centers of all the antenna elements along a straight line. If the space distributions between the antenna elements of a linear array are equal then it is called uniformly spaced linear antenna array which is shown in Fig. 2.8. Fig. 2.8 shows a plane wave incident on the array with d distant between

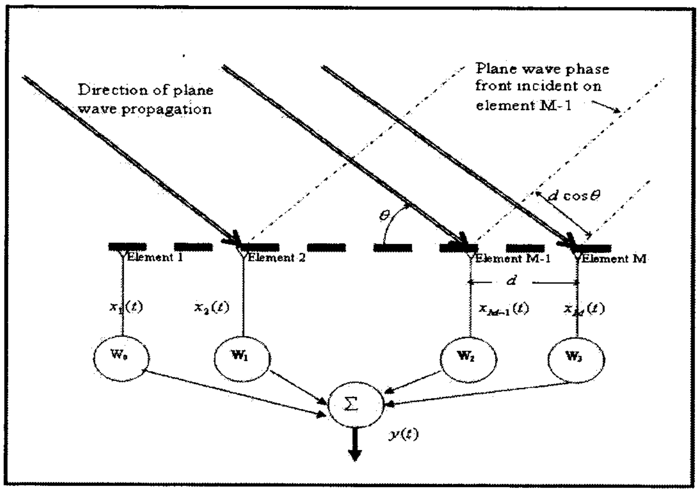

Figure 2.8: An M-element uniformly spaced linear array.

array elements from a direction θ, which is called the direction-of-arrival (DOA) of the received signal.

The received signal at the first element is given by,

$$z_1(t) = \alpha(t)\cos(2\pi f_c t + \phi(t) + \delta). \tag{2.4.1}$$

where $\alpha(t)$ is the signal amplitude, f_c is the signal carrier frequency and $\phi(t)$ is the phase of information component and δ is a random phase. The complex representation of the signal can be expressed as,

$$x_1(t) = \alpha(t)\exp(j(\phi(t) + \delta)). \tag{2.4.2}$$

In what follows, we consider the first antenna element as the reference element. Then the relative distance travelled by the plane wave on the second element is $d\cos(\theta)$ and the associated delay is,

$$\tau = \frac{d\cos(\theta)}{C}. \tag{2.4.3}$$

where C, is the speed of light (3×10^8m/s). Then, the received signal at second element can be written as,

$$z_2(t) = z_1(t-\tau) = \alpha(t-\tau)\cos(2\pi f_c(t-\tau) + \phi(t-\tau) + \delta). \tag{2.4.4}$$

As the carrier frequency is greater than the channel bandwidth, we can write (2.4.4) as,

$$z_2\left(t\right)=\alpha\left(t\right)\cos\left(2\pi f_c t-2\pi f_c \pi+\phi\left(t\right)+\delta\right). \tag{2.4.5}$$

Also, the complex envelop of $z_2\left(t\right)$ can be expressed as,

$$\begin{aligned} x_2\left(t\right) &= \alpha\left(t\right)\exp\left(j(-2\pi f_c\tau+\phi\left(t\right)+\delta)\right) \\ &= x_1\left(t\right)\exp\left(-j2\pi f_c\tau\right). \end{aligned} \tag{2.4.6}$$

From equation (2.4.6) and equation (2.4.3), $x_2\left(t\right)$ can be found as,

$$\begin{aligned} x_2\left(t\right) &= x_1\left(t\right)\exp\left(-j2\pi f_c\frac{d\cos\theta}{V_c}\right) \\ &= x_1\left(t\right)\exp\left(-j\frac{2\pi}{\lambda}d\cos\theta\right). \end{aligned} \tag{2.4.7}$$

where λ is the carrier wavelength. Similarly, the signal at ith element can be expressed as,

$$x_i\left(t\right)=x_1\left(t\right)\exp\left(-j\frac{2\pi}{\lambda}(i-1)d\cos\theta\right). \tag{2.4.8}$$

where $i=1,2,.....,M$. And M is the total number of antenna elements. Now, let us define,

$$\mathbf{x}(t) = \begin{bmatrix} x_1(t) \\ x_1(t) \\ \vdots \\ \vdots \\ x_M(t) \end{bmatrix}. \tag{2.4.9}$$

and

$$\mathbf{a}(\theta) = \begin{bmatrix} 1 \\ \exp\left(-j\frac{2\pi}{\lambda}d\cos\theta\right) \\ \vdots \\ \vdots \\ \exp\left(-j\frac{2\pi}{\lambda}(M-1)d\cos\theta\right) \end{bmatrix}. \tag{2.4.10}$$

From equation(2.4.10) and (2.4.9), $\mathbf{x}(t)$ can be presented as,

$$\mathbf{x}(t) = \mathbf{a}(\theta)\, x_1(t). \tag{2.4.11}$$

where $\mathbf{a}(\theta)$ is called the steering vector and $\mathbf{x}(t)$ is called the input vector. There are K different signals arrive at the antenna array with different DOA. We denote the signals by $s_1(t) \ldots . s_K(t)$ with respective DOA $\theta_1 \ldots .. \theta_K$. Then, the combined received signal can be expressed as,

$$\mathbf{x}(t) = \sum_{i=1}^{K} \mathbf{a}(\theta_i)\, \mathbf{s}_i(t) + \mathbf{n}(t) \tag{2.4.12}$$

where,

$$\mathbf{a}(\theta_i) = \begin{bmatrix} 1 \\ \exp\left(-j\frac{2\pi}{\lambda} d\cos\theta_i\right) \\ \vdots \\ \vdots \\ \exp\left(-j\frac{2\pi}{\lambda}(M-1) d\cos\theta_i\right) \end{bmatrix} \tag{2.4.13}$$

and $\mathbf{n}(t)$ is the additive white Gaussian noise vector at the array element. The vector representation of the received signal is,

$$\mathbf{x}(t) = \mathbf{a}(\theta)\, \mathbf{s}(t) + \mathbf{n}(t) \tag{2.4.14}$$

where,

$$\mathbf{a}(\theta) = [a(\theta), ..., a(\theta_k)] \tag{2.4.15}$$

and

$$\mathbf{s}(t) = \begin{bmatrix} s_1(t) \\ s_2(t) \\ \vdots \\ \vdots \\ s_K(t) \end{bmatrix}. \tag{2.4.16}$$

2.4.2 Antenna Beamforming

In adaptive beamforming, an optimal weight vector is obtained which provides a minimum value of a particular cost function. The minimum mean square error (MMSE) and least squares (LS) are two most popular cost functions used in communication systems [39]. By minimizing the cost functions, the output signal quality is maximized. In these techniques, the square of the difference between a locally generated estimated desired signal and the array output is minimized by finding an optimal value for the weight vector. We consider the adaptive beamforming configuration shown in Fig. 2.9.

In the MMSE approach, the cost function to be minimized is,

$$J(w) = E\left[\left|\mathbf{w}^H\mathbf{x}_t - d_{k,t}\right|^2\right] \tag{2.4.17}$$

where index t is used for time. The desired estimated signal is d_t and $\mathbf{w}^H\mathbf{x}_t$ is the array output where $\mathbf{x}_t$ is the array input signal.

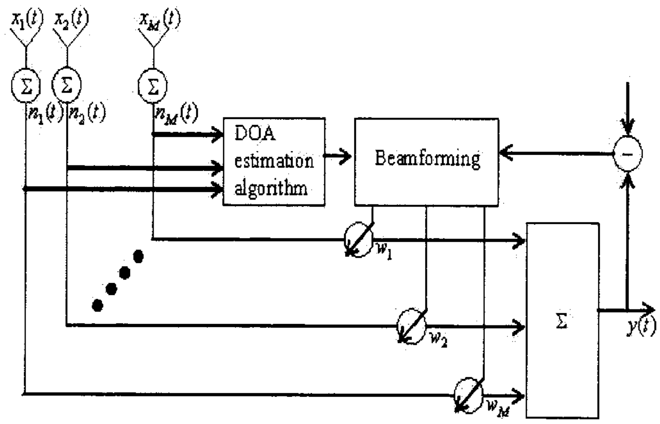

Figure 2.9: A simple narrow band adaptive antenna system.

Now let us rewrite $\mathbf{x}_t$ in terms of the desired signal and interfering signal,

$$\mathbf{x}_t = a(\theta_0)\,\mathbf{s}(t) + \sum_{i=1}^{K_u} a(\theta_i)\,u_i(t) + n(t) \tag{2.4.18}$$

where $n(t)$ is the noise vector and θ_0 is the desired signal DOA. The interfering signals are $u_1(t), u_2(t), ...u_K(t)$. and $\mathbf{s}(t)$ is the desired signal with angel θ_0.

The array output, $y(t)$, for M element array is given by,

$$y(t) = \sum_{i=1}^{M} w_i^{\star} x_i(k). \tag{2.4.19}$$

In vector form,

$$\mathbf{y}(t) = \mathbf{w}^H \mathbf{x}_t \tag{2.4.20}$$

where

$$\mathbf{w} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ \vdots \\ w_M \end{bmatrix}. \tag{2.4.21}$$

The cost function is the expected value of the squared error between the array output and the desired signal at time index t . Thus, the cost function in (2.4.17) can be written as,

$$J(\mathbf{w}) = \mathbf{w}^H E\left[\mathbf{x}_t\mathbf{x}_t^H\right]\mathbf{w} - E\left[d_{k,t}^H\mathbf{x}_t^H\right]\mathbf{w} - \mathbf{w}^H E[\mathbf{x}_t d_{k,t}^\star] + E\left[d_{k,t}d_{k,t}^\star\right], \tag{2.4.22}$$

where E denotes expected value, superscript H is the hermation transpose and superscript $\star$ denotes conjugate operator. The vector function in (2.4.22) is minimized by finding the position where the gradient of the function when it goes to zero. Thus, we can write,

$$\begin{aligned} \nabla J(\mathbf{w}_k) &= 2E\left[\mathbf{x}_t\mathbf{x}_t^H\right]\mathbf{w}_k - 2E[\mathbf{x}_t d_{k,t}^\star] \\ &= 2\mathbf{R}\mathbf{w}_k - 2\mathbf{p} \end{aligned} \tag{2.4.23}$$

where $\mathbf{R}$ is the correlation matrix of the data vector and $\mathbf{p}$ is the cross-correlation between the data vector and the desired signal,

$$\mathbf{R} = E\left[\mathbf{x}_t\mathbf{x}_t^H\right] \quad (2.4.24)$$

$$\mathbf{p} = E[\mathbf{x}_t d_t^*]. \quad (2.4.25)$$

Now, equating the gradient of the cost vector to zero, we find the optimum value for $\mathbf{w}$ which minimizes $J(\mathbf{w})$ as,

$$\mathbf{w} = \mathbf{R}^{-1}\mathbf{p}. \quad (2.4.26)$$

This equation is referred to as the optimum Wiener solution [39].

Now the Weiner solution is complex to implement. Therefore, another approach is to obtain the solution using adaptive techniques.

The idea of adaptive beamforming is to vary the complex weight of each element used in the antenna array to maximize reception in a particular direction. This can be achieved by estimating the signal arrival from a desired direction and rejecting other signals of the same frequency from other directions. Signals having same frequency contents but from different transmitter can be separated at the receiver by exploiting the knowledge of the signal arrival directions. In this case, the complex weights of the antenna elements is used to shift the peaks of the antenna beampattern to the direction of desired signal and the nulls to interfering users. In a simple case, the weights may be chosen to give one central beam in some direction, e.g., in the direction of a desired node. The weights can then be slowly regulated to steer the beam to get maximum signal strength.

Basically adaptive algorithms can be classified into two types. The first type requires reference signal, known as non-blind adaptive algorithms and the second requires no reference signal and called blind adaptive algorithms [39].

In blind adaptive algorithms, the reference signal is generated from the received signal by using the underlying characteristics of the received signal structure. The constant modulus algorithm (CMA) [39] is an example of blind adaptive algorithm.

On the other hand in non-blind adaptive algorithms a reference signal is provided which has high correlation with the desired signal. Examples of trained adaptive algorithms include least mean square (LMS) algorithm [39] and the recursive least mean square (RLS) algorithm [39]. Note that the reference signal can be provided in digital communications through synchronization signals.

In what follows, we discuss the operation of both the LMS and RLS algorithms.

2.4.3 Least Mean Squares(LMS) Algorithm

The LMS algorithm computes the weights using steepest descent method [39]. It minimizes the mean square error by updating the coefficients using the estimated error gradient. The weight vector is given by

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \frac{1}{2}\mu\left[- \nabla \left(E[e^2(n)]\right)\right]. \tag{2.4.27}$$

where μ is the step size parameter that controls the speed of convergence of the LMS algorithm. By choosing large values of μ, the algorithm converges fast but there may be instability around the minimum value. The update equation of the LMS is given by

$$\begin{aligned}\mathbf{w}(n+1) &= \mathbf{w}(n) + \mu x(n)[d^*(n) - \mathbf{x}^H(n)\mathbf{w}(n)] \\ &= \mathbf{w}(n) + \mu x(n)e^*(n). \end{aligned} \tag{2.4.28}$$

In the LMS, an arbitrary value is assigned for the initial weight vector at $n = 0$. Then, the algorithm finds the minimum mean square error and at each step the weight is updated using (2.4.28). The operation of the LMS algorithm can be summarized as,

output signal

$$y(n) = w^H \mathbf{x}(n), \tag{2.4.29}$$

error signal

$$e(n) = d^*(n) - \mathbf{y}(n), \tag{2.4.30}$$

update

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu \mathbf{x}(n)e^*(n). \tag{2.4.31}$$

2.4.4 Recursive Least Squares (RLS) Algorithm

The RLS algorithm uses the method of least squares to adjust the weight vector. The RLS algorithm converges with an order of magnitude faster than the LMS algorithm if the signal to noise ratio (SNR) is high. Different from the LMS, the RLS algorithm utilizes the information contained in the input signal from the start time of the algorithm.

2.5 Summary

In this chapter, important concepts of the IEEE 802.11 standard, cooperative communication and adaptive antennas have been presented. A review of some basic concepts related to adaptive antennas, including beamforming and well known adaptive algorithms are also discussed.

Chapter 3

Performance Evaluation of Cooperative Ad Hoc Networks

3.1 Introduction

In this chapter the throughput performance of a cooperative diversity based ad hoc network similar to the one proposed in [12] is examined through simulation and subsequently it is compared with the IEEE 802.11 standard in both AWGN and fading channels. The system model, including the PHY and MAC layers for conventional cooperative ad hoc networks is presented and the pros and cons of using cooperative diversity in terms of the overall system throughput are identified and evaluated using extensive simulations. We show that although the application of cooperative diversity techniques can offer significant performance gains at the physical layer, it can bring overall throughput degradation in the network due to the relay blocking problem defined in this chapter.

3.2 System Model

In our simulation model, mobile stations are placed randomly in a 200 meter by 200 meter area (as shown in Fig 3.1). To simplify the simulations, we consider a network with 10 stations. The first 1-5 stations are selected as transmitting stations with fixed destination stations 6-10, respectively (1→6, 2→7, and so on, where $x \rightarrow y$ signifies transmission from station x to station y). The radio range for each station is assumed to be the same and equal to 100 meters. Stations positioned within the radio range of any transmitting station are considered as neighbors to that particular station. In what follows, we describe the operation of the PHY and MAC layers in conventional cooperative networks.

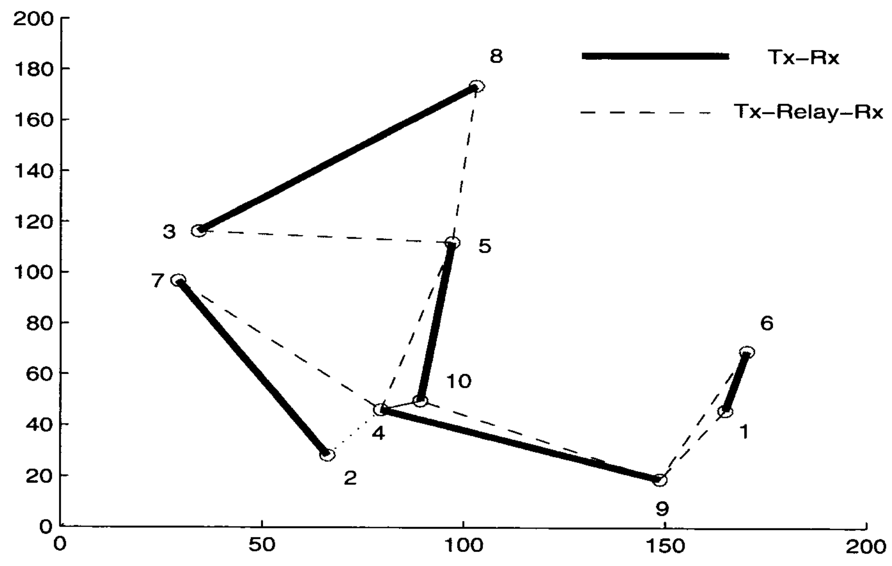

Figure 3.1: Snapshot of a 10-station network topology with relay selection.

3.3 Physical Layer Design

At the transmitter, data frames are transmitted using binary phase shift keying (BPSK) modulation. The channel rate for all transmitting stations is fixed to 1 Mbps. The channels between each pair of stations are modelled as independent identically distributed (i.i.d.) slowly varying flat fading channels. That is, we assume that the fading coefficient is fixed for one frame transmission but change independently from one frame to another. Also, we define a threshold as BER$<10^{-5}$. Packets received at the receiving stations with BER less than this threshold are marked as successful packets. For data frames, cooperative diversity is achieved by using amplify and forward cooperation. In this case, the transmission scheme used is defined as follows. During the first time slot, the source sends data symbol x_1 to both the destination and relay nodes. The received signals at the destination and relay nodes during the first time slot, are then given respectively by

$$y_{SD} = h_{SD}\sqrt{E_{SD}}x_1 + z_0 \tag{3.3.1}$$

and

$$y_{SR} = h_{SR}\sqrt{E_{SR}}x_1 + z_1. \tag{3.3.2}$$

At next time slot, the relay amplifies the received signal in (3.3.2) for subsequent transmission to the destination. The received signal at the receiver is then given by

$$y_{RD} = \alpha h_{RD} y_{SR} + z_2 \tag{3.3.3}$$

where $E_{SR} = E_{SD} = E$ represents the transmitted symbol energy on the different links, z_i, $i = 0, 1, 2$, is the additive white Gaussian noise with power spectral density $N_0/2$. Then, h_{SD}, h_{SR}, h_{RD} model the fading between the different nodes, and are assumed to be independent complex Gaussian random variables with variance 0.5 per dimension. Note that at the relay, we use an automatic gain control (AGC) where the average transmitted energy per symbol, E_{RD}, is controlled by the relay gain $\alpha = \sqrt{\frac{E_{RD}}{E(|y_{SR}|^2)}}$ with E denoting expectation. Figure 3.2 shows a performance comparison between the IEEE standard and the cooperative network in AF mode. As seen, the use of cooperative diversity can significantly improve the performance of the ad hoc network. Note that in these results, we only consider a single relay between the source and destination nodes.

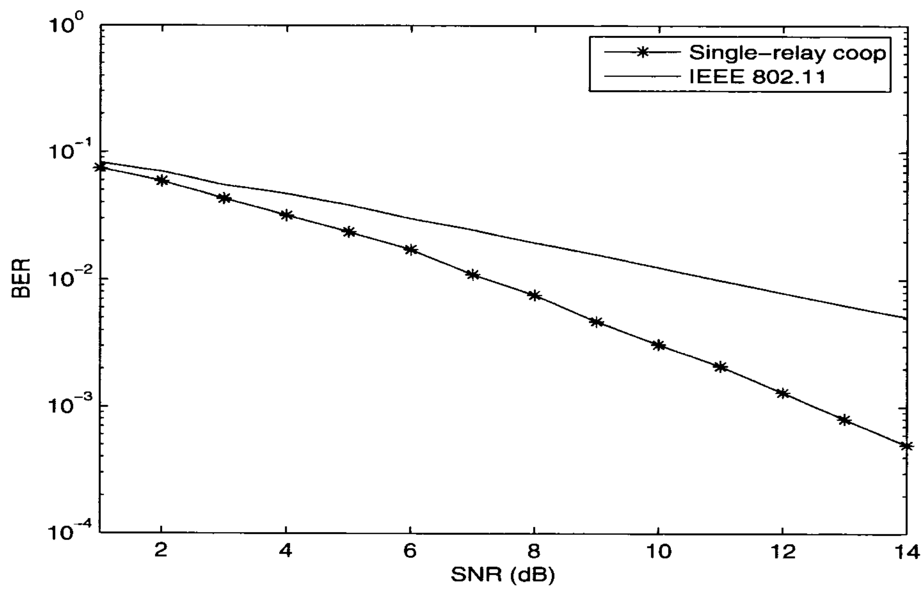

Figure 3.2: BER performance comparison between IEEE 802.11 and cooperative network with one relay.

3.4 MAC Layer Design

At first, a station initiates the transmission by sending RTS packet. If the destination node is not engaged in communication with some other node, it replies back with a CTS packet (see the timing diagram in Fig. 3.3). During the exchange of these control packets, if a neighboring station is able to assist by cooperation, it acknowledges the source and destination nodes by transmitting a relay ACK packet (RACK). Since more than one neighboring station can reply by RACK, we consider a selection criterion based on the shortest distance from the source node. Now, the NAV for neighboring stations is delivered and renewed by the RTS, CTS and relay acknowledgement packets. In this case, the neighboring stations of the transmitter and receiver have to defer their transmissions for the amount of time delivered by the NAV. Note that, the neighbors of the relay station also have to defer their transmission for a period equal to two data-packet transmissions (i.e., time = 2× frame length/channel rate). Upon selecting the relay node, the source notifies the corresponding relay using a relay ready-to-send (RRTS) packet. Following this, the source starts its transmission by sending a data packet. The destination and the relay stations receive this packet. When the source finishes its transmission, the relay station starts forwarding (after amplification) the received packet to the destination node. The destination then acknowledges the source with an ACK if the achieved BER is less than the prescribed threshold (i.e., $<10^{-5}$).

It is worth mentioning that the selection criterion of the relay station is discussed in [13] where relays are selected by considering a number of decision constrains such as: minimum distance, minimum load, and minimum interference. Over fading channels, the channel state for different links should also be included in the selection criteria.

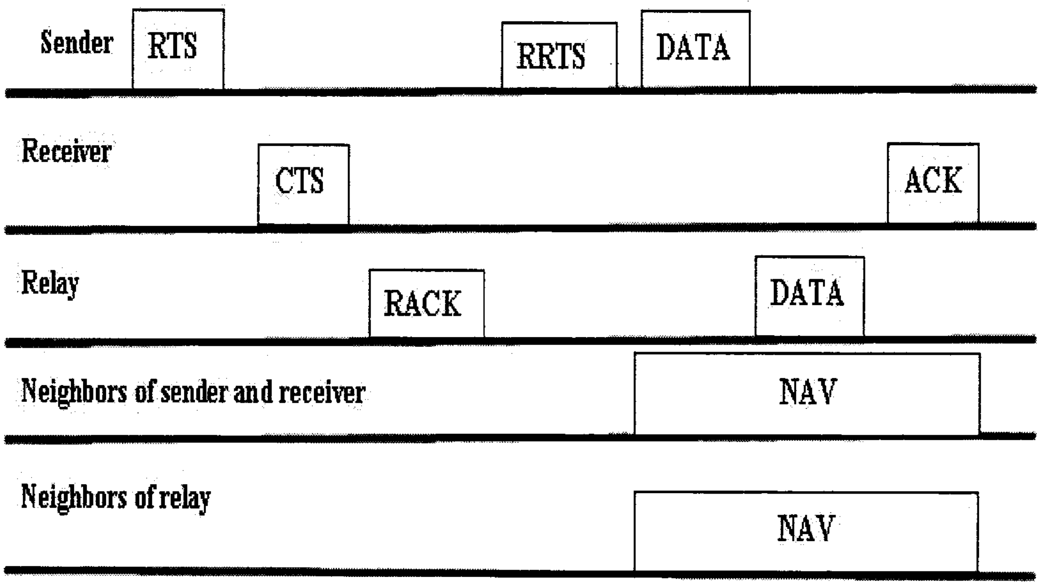

Figure 3.3: Timing diagram for cooperative strategy.

For simplicity, we assume that the station closer to the transmitter and receiver stations is selected as the relay station. A snapshot of the 10-station topology with relay selection is shown in Fig. 3.1.

3.5 Performance of Cooperative Transmission

In what follows, we investigate the performance of the cooperative ad hoc network strategy discussed in the previous section. The throughput is defined as the total system throughput, which is the number of successful received frames per second (control frames are not included).

In Fig. 3.4, we simulate the 10-user system over an ensemble of 20 different random topologies and obtain the average throughput at different system loads. According to Fig. 3.4, it is clear that cooperative networks can achieve better throughput performance than the IEEE 802.11 standard.

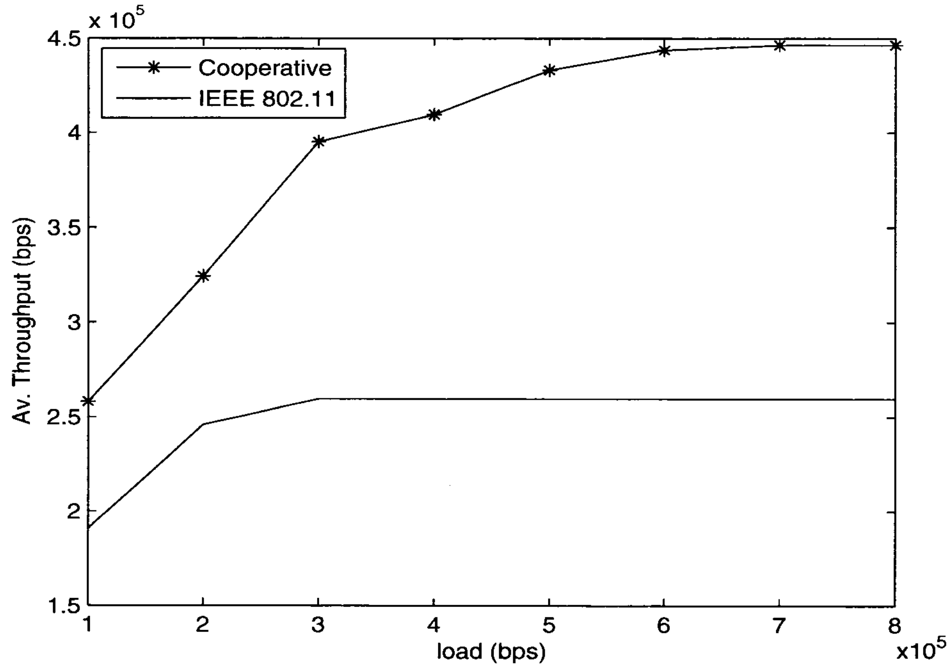

Figure 3.4: Average throughput vs. load for 20 random topologies.

To examine the effect of fading on the throughput performance of the IEEE 802.11 with and without cooperative diversity, in Fig. 3.5, we perform a comparison with the AWGN channel. Note that the large throughput degradation in fading channels is due to the large packet error rate compared to the throughput performance on AWGN channels. Although the performance of the cooperative network is better than the IEEE 802.11 over fading channels, it is still far from the AWGN channel.

We observed that the throughput achieved using cooperative networks is limited by two major factors (beside the effect of fading): (i) The same data packet is transmitted twice which requires at least two frame length/channel rate amount of time for one successful frame transmission. (ii) As mentioned earlier, to avoid collision at the receiving station, only the relay or the source station is allowed to transmit at a time. Based on this transmission scheme, the neighboring nodes to the relay station are blocked for a period of at least two frame transmissions before they can

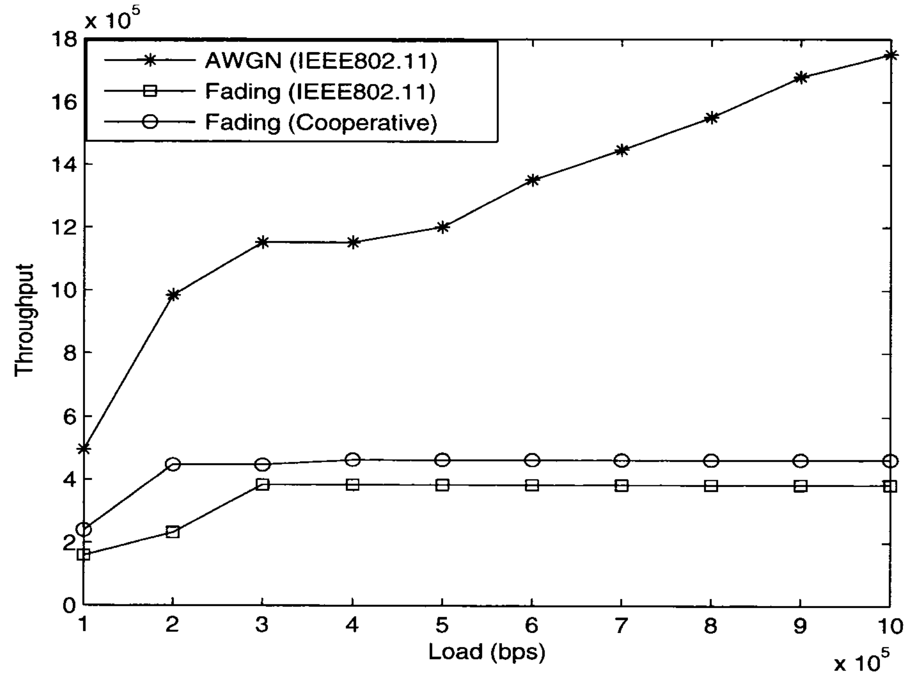

Figure 3.5: Throughput performance for the network topology in Fig. 3.1.

contend again for the channel. To illustrate, Fig. 3.6.(a) shows a cooperative scenario where by using station 3 as a relay to the destination station 6 results in transmission blocking for stations 2→7. This, in turn, results in a decrease in the overall network throughput. On the other hand, if neighboring stations to the relay are allowed to communicate then interference will be present as shown in Fig. 3.6.(b) and (c).

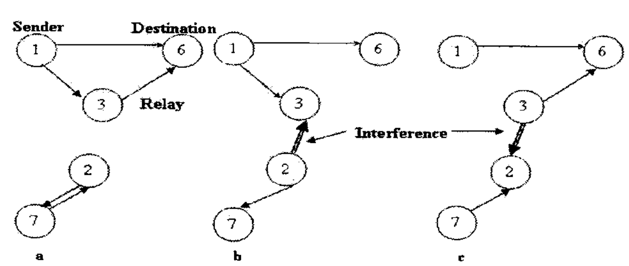

Figure 3.6: Cooperative scenario with relay blocking.

To examine the effect of relay blocking on the overall throughput performance,

Table 3.1: Transmitting, Receiving, Relay, and Blocking Stations.

Tx	Rx	Relay	Blocking Stations
1	6	9	2-7
2	7	4	1-6
3	8	5	1-6
4	9	10	-
5	10	4	-

let us consider the scenario of fixed topology in Fig. 3.1. By analyzing the topology of Fig. 3.1, one can see the existence of the relay blocking problem (see Table 3.1). As seen, station 1 has stations 4, 5, 6, 9 and 10 as its neighbors. Also, station 6 has stations 1, 4, 5, 9 and 10 as its neighbor. If station 9 is selected as a relay for 1$\rightarrow$6 transmission, then station 9 will block transmissions from stations 2 to 7 (recall that we assume stations 1 to 5 to be the transmitting stations and stations 6 to 10 as the receiving ones). Note that although station 2 is not in the neighborhood of 1 and 6, it cannot transmit to its destination station 7 because of the relay node 9. Similar case occurs when station 2 communicates with station 7 or station 3 communicates with station 8.

From the above results one can see that relay blocking, if not compensated for, can cause major throughput degradation in ad hoc networks. As a remedy, in the following chapter, we propose a cooperative strategy designed to solve the relay blocking problem.

3.6 Summary

An comprehensive approach is discussed to verify the relay blocking problem and its effect on the net throughput. The results obtained in this chapter motivates the design of a cooperative network where blocking problem should be considered in the design criteria.

Chapter 4

Proposed Two Channel Cooperative MAC Protocol

In this chapter we propose two-channel cooperative MAC protocol that utilizes adaptive antennas at the relay station. The proposed protocol is distributed and considers single and multiple relay usage.

4.1 New Cooperative Protocol

We consider an ad hoc network where each station is equipped with a GPS to determine its position, and all stations are equipped with directional antennas [40]-[43]. These directional antennas are *only* used when a station is acting as a relay where in this case, it retransmits signals to the destination node in a directional mode. This will be discussed in more details in the following section.

4.1.1 Physical Layer Design:

At the transmitter, data frames are transmitted using binary phase shift keying (BPSK) modulation. The channel rate for all transmitting stations is fixed to 1 Mbps. The channels between each pair of stations are modelled as i.i.d. slowly varying flat fading channels. That is, we assume that the fading coefficient is fixed for one frame transmission but change independently from one frame to another. Also, we define a threshold BER$<10^{-5}$. Packets received at the receiving stations with BER less than this threshold are marked as successful packets. For data frames, cooperative diversity is achieved by using amplify and forward cooperation as discussed in the previous chapter.

4.1.2 Channel Reservation

Generally, cooperative relay networks require more resources relative to conventional networks with direct transmission. A single channel or link between transmitter and receiver is sufficient for direct transmission. On the other hand, in order to incorporate cooperative diversity techniques in the network, one requires at least two links for communication with the destination. One link is for direct transmission, and another for relay transmission. This was discussed for a link level study in [9].

Moreover, there exists some limitations in current radio implementations, that is, terminals cannot transmit and receive at the same time using the same frequency band. That means the radio transceiver is half-duplex in general. By considering this limitation many researchers have proposed to use a separate frequency or a different time slot for relay transmission. The half-duplex nature of wireless terminal hardware implies the use of two orthogonal (frequency) channels. Furthermore, the use of more than two orthogonal channels for relaying will result in an increase in the system cost since more bandwidth is required to achieve a given rate of transmission for each source-destination pair.

A different approach would be to use different time slots (time division multiplexing) to maintain the orthogonal transmission and avoid collision. In this case, a single frequency channel can be used for source to destination and relay to destination transmissions but at different time slots.

In an ad hoc network scenario, cooperative transmission brings the relay blocking problem as discussed earlier. That is if two different cooperative transmissions have to be performed side by side, then relay blocking should be considered in the design and the assignment of network resources.

Considering the half-duplex nature of the transceiver, the relay transmission blocking, and channel resource allocation, we propose a two-channel cooperative protocol that incorporates adaptive antennas at the relay. As will be explained later, by allocating two channels for the proposed protocol, the relay blocking problem can be solved and the cooperative communication can be formed in a more efficient way. Note that at any given time, a node is only allowed to use one of the two available frequency channels.

In [13], the authors discussed the problem of resource allocation in cooperative ad hoc networks, where they considered a channel allocation algorithm for N number of nodes if M independent channels are available. Our protocol, on the other hand, assumes a minimum of two independent channels available to form cooperative communication and to avoid relay blocking.

We assume that there are two available frequency division multiplexing channels;

one channel is assigned to the transmitter (labeled CH-1) whereas the second channel is assigned to the relay to retransmit to the destination station (labeled CH-2). Fig. 4.1 shows a simple diagram depicting the channel assignment of our cooperative protocol. As shown in this figure, the sender transmits data using an omni-directional mode (single-antenna transmission) over CH-1 and the relay uses CH-2 in a directional mode (multiple-antenna transmission) to transmit to the destination node. Note that the relay uses directional antennas mainly to beamform to the destination station in order to minimize the effect of interference on nearby receivers of other stations. One

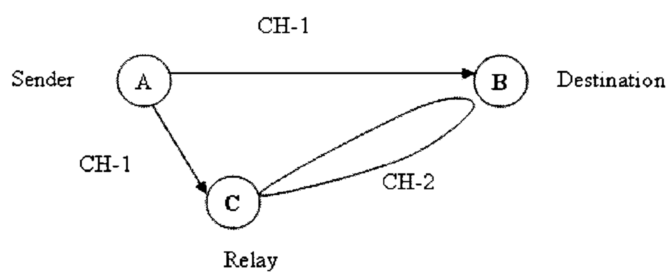

Figure 4.1: Sender-relay-destination links.

key parameter of the proposed MAC protocol is that the position of the neighboring stations are known to each station. This can be easily satisfied by sending this position information using a separate control packet or through the ongoing RTS and CTS packets. Following is a pseudo-code describing the proposed protocol.

```
for any source node n and destination r If checkresources( ) = = available
  getchannel( )
  If channel= = IDLE
    Case(Start of communication):
    send omni-directional RTS and initiate NAV
  End If
End If
If RTS transmission= = success
  send omni-directional CTS and initiate NAV
End If
If CTS transmission = = success and number of neighbors of source and destination>0
  selectrelay()
```

```
End If
If relay selection = = success
  send omni-directional Reack and initiate Relay_NAV
End If
If Reack transmission = = success
  select transmission protocol= cooperative mode
Else
  select Transmission protocol= non-cooperative mode
End If
If transmission protocol= = cooperative
  If data channel = CH1
    select Relay channel = CH2
  Else
    select Relay channel = CH1
  End If
  send Data frame using omni-directional antenna in data channel
  relay Data frame using directional antenna in Relay channel
End If
If transmission protocol= = non-cooperative
  send Data frame using omni-directional antenna
End If
If data transmission = = success and relay data= = success
  send Ack using omni-directional antenna
  send CR using omni-directional antenna
End If
Case(End of communication)
for any other source station K
sation n and r = out of range of K and station r = within range of K
If checkresources( ) = = available
  getchannel( )
  If Relay_NAV(CH1) > 0
    select Channel= CH2
  End If
  If Relay_NAV(CH2)> 0
    select Channel= CH1
  End If
End If
```

The function checkresources( ) is used to check the frequency channel availablity and getchannel( ) executes the channel sensing, access, and reservation assignments.

The function selectrelay(), mainly looks for best relay according to the relay selection algorithm. Here the cooperative distance is used for the selection matric. It evaluates the distances between the source-relay and destination-relay. Then it calculates the cooperative distances for all common neighboring stations of the source and the destination stations where the station that has minimum distance is selected. This function can be described by the following steps:

look up cooperative distances for any station m with

d_m = distance(source, m)+ distance(m, destination)

select relay, m = arg min d_m

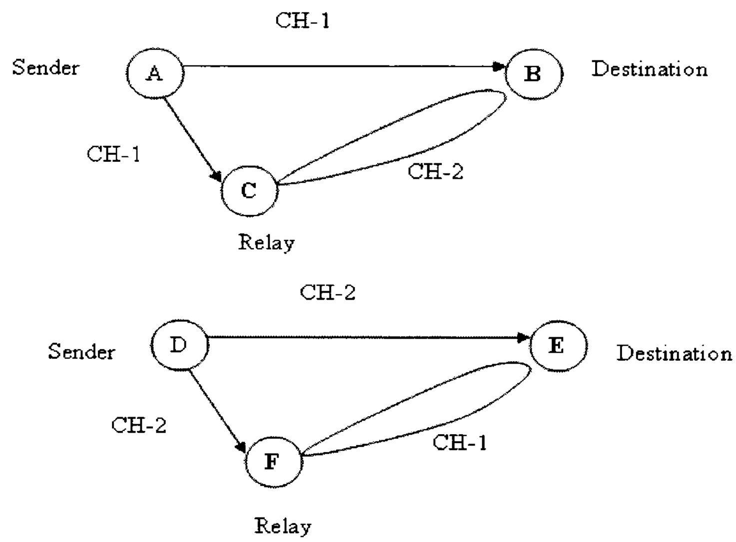

Figure 4.2: Sender-relay-destination links.

Fig. 4.2 shows the conditions on frequency channel assignments for two neighboring cooperative links. To explain, suppose station A is transmitting to station B and C is selected as the corresponding relay. Also assume that station A is using CH-1 for transmission to B. Given this, relay C will be assigned CH-2 for relaying the signal to station B. Now assume that station D and E are neighbors to station C, but out of the radio range of both stations A and B. Also consider the case where station D has data to send to E and according to the relay selection criterion station F has been selected as their relay. In this case, station D will be assigned CH-2 for transmission to E and relay F will be assigned CH-1 for relaying to station B. The reason behind this is that, relay C has to receive signals from A over CH-1 and hence, any other transmission over this channel (within the radio range of C) may cause interference at the relay C. Note that if station D uses CH-2 for transmission to E, there will be no interference at the receiver of station C. Also the use of adaptive antennas at the relay will reduce the interference level at all neighboring receivers. This of course will improve the overall system throughput.

4.1.3 MAC Layer Design

In order to clearly discuss the proposed MAC protocol, let us consider the network topology of Fig. 3.2 where station 1 sends an RTS to station 6 over CH-1. In response, station 6 replies back by CTS. From Fig. 3.2, stations 4, 5, 9 and 10 are shown to be within the range of both stations 1 and 6. If we consider a single relay transmission scenario, then one of these stations (4, 5 or 10) will be selected as the relay for 1→6 transmission. Let us assume that station 9 has been selected as the relay station. Station 9 will then send a relay acknowledgement (Reack) packet acknowledging the agreement on relay assignment. Following this, station 1 starts transmitting its data packets using CH-1 to both the destination and the relay stations. Upon receiving these data packets, station 9 amplifies and retransmits the received data to station 6 using CH-2. After successfully receiving the data, station 6 replies with an ACK packet at which the relay station 9 sends a clear-relay (CR) packet to inform its neighbors of the released connection.

Now suppose station 2 wishes to communicate with station 7. Note that stations 2 and 7 both are outside the radio range of station 1 and 6, but station 2 is within the range of relay station 9. Station 2 will receive the Reack packet sent by relay station 9. Upon receiving this packet, station 2 will learn that station 9 has been selected as a relay for the time of two successive frame transmissions. Based on this information, station 2 adjusts its relay network-allocation-vector (Relay-NAV) for a period of two frame transmissions. During this time, if station 2 wishes to transmit then it will use CH-2. Station 2 then starts its transmission to 7 by sending RTS using CH-2. In response, station 7 replies back by a CTS. Now the communication 2→7 has only station 3 as its neighboring station for relaying data. Station 3 will

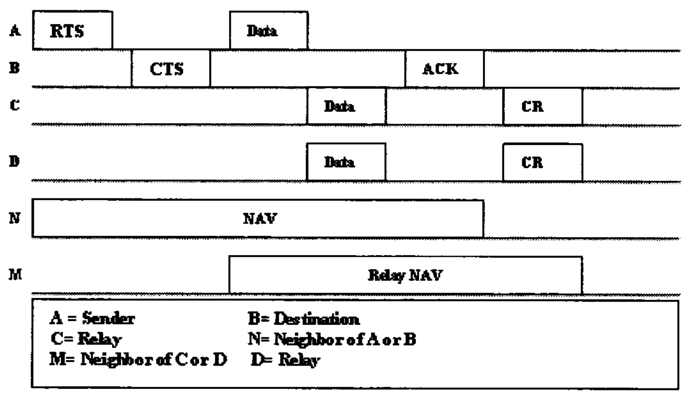

Figure 4.3: Timing diagram for the single relay new cooperative MAC protocol.

then be selected following the same protocol used for the relay station 9. Following the Reack sent by the relay station 3, station 2 commence its data transmission over CH-2 whereas station 3 relays the received data over CH-1 using the directional mode. The destination station 7 then sends an ACK packet after successfully receiving the data. Also, relay station 3 sends a CR packet to indicate the end of the Relay-NAV to its neighboring stations.

Figs. 4.3 and 4.4 depict the timing diagram for the new cooperative MAC layer protocol for single relay and multiple relay transmissions, respectively. There are two types of NAV considered; (i) one is used by the sender or destination station to inform its neighbors about the time required for the current communication on the channel, (ii) the second is a Relay-NAV where the neighbors of the relay station can learn the active duration of the relay station. Also given the Relay-NAV packet, the neighboring stations to the relay will be informed to use a certain frequency channel (CH-1 or CH-2) if they wish to communicate.

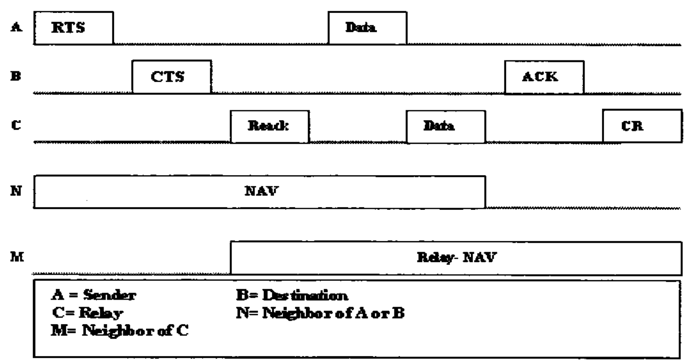

Figure 4.4: Timing diagram for the multiple relay new cooperative protocol.

One should note that the proposed MAC protocol is based on the CSMA/CA similar to the IEEE 802.11 with RTS/CTS handshaking mechanism to silence the nodes in the silenced region. Also the RTS, CTS and Reack packets in our MAC protocol are transmitted using omnidirectional antennas to overcome the hidden terminal problem.

In the case of multi-channel environment, a different hidden terminal problem can occur, as shown in the scenario of Fig. 4.5. Note that this type of hidden terminal problem arises only if a node misses the Reack packet. Here node B and C are using CH-1 for communication but node A wishes to communicate with node B over the same frequency channel. In our protocol this situation can occur at the relay region when any of the stations in the territory of the relay uses the same frequency channel as the relay. To solve this problem, in our protocol we use the Relay-NAV packet to deliver the information of available channels in a relay transmission region.

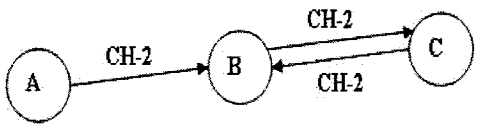

Figure 4.5: Hidden terminal in relay communications.

Another common problem that is general in networks where directive antennas are used is the deafness problem. The deafness problem occurs when a source node fails to communicate with desired receiver which is beamforming to another direction for an on-going communication. Since receiving stations employ omnidirectional antennas for reception, and only the relay uses adaptive antennas to relay the signal to the destination station, this problem shall not arise in our case.

Furthermore, the shape of the silence region or blocking region resulting from the use of directional antennas is dependent on the antenna array used. In our protocol we allow the stations around a relay, which are not close to the sender and destination stations, to communicate. This results in a reduction in the silence region of the relay, the only terminal that employs directional antennas. Therefore, the proposed MAC protocol has no more limitations on the silence region than the standard IEEE 802.11 where only neighbors of the sender and destination stations have to be silent during current transmissions.

4.2 Summary

In this chapter, we provided a detailed description of our proposed protocol. The protocol follows CSMA/CA with RTS-CTS hand-shaking to avoid collision and provides fair chances to access the channel for everyone. Cooperation is also supported through using two frequency channels and utilizing adaptive antennas at the relays to unblock stations from communication around the relay transmission regions. Networks can be formed using single relay or multiple relays.

Chapter 5

Simulation Results

5.1 Introduction

The simulation results presented in this chapter demonstrate the dramatic increase in the system capacity achieved by using our proposed 2-channel cooperative protocol. In section 5.2, the simulation model is described. In section 5.3, simulation results are presented.

5.2 Simulation Model

In the following, we use MATLAB simulations to examine the performance of the proposed cooperative protocol and other existing protocols. The MAC layer protocol based on CSMA/CA access mechanism is developed and basic standards such as the RTS, CTS, DATA, ACK packet lengths are implemented in our simulation study. These simulation parameters are summarized in Table 5.1.

We randomly generate 20 different topologies, and evaluate the average network throughput. Without loss of generality and for illustration purposes, we developed

Table 5.1: Simulation Parameters.

Number of nodes	10
Node coverage radius	100m
Network area	200m×200m
Displacement step	1m
Simulation time	1 sec
Node traffic generation rate	0.1 - 1 Mbps
Maximum packet length	8000 bits
Length of RTS/CTS/ACK	20/15/14 octets
Length of REACK/CR	20/14 octets
DIFS/SIFS/slot time	50/10/20 μsec
Channel rate	1 Mbps

our network for 10 mobile stations to better recognize the issues related to the cooperative network for distributed systems. Similar to the previous chapters, we consider a transmission scenario where station 1→6, 2→7, 3→8, 4→9 and 5→10. All stations (sender/relay/destination) receive signals in omnidirectional mode. We assume that the relay station knows the position of the destination station. Through this information, the DOA angle is estimated at the relay station and then used for antenna beamforming towards the destination. We also assume that we have a perfect position information delivered by the GPS. In this case, the relay accurately performs the beamforming.

We employ a simple single-hop routing protocol. In this routing protocol, if the destination node is out of range from the sender then the transmission can only take place if the distance between the sender and destination nodes involves a single hop. We chose to use such a simple protocol to simplify the simulation and to show the performance independent of the network layer. Of course state-of-the-art routing protocols can be employed to improve the performance of the overall network. For fair comparison, the same routing protocol is used for both IEEE 802.11 and conventional cooperative networks.

In the following, we investigate the throughput performance of the new cooperative protocol discussed in the previous chapter. Using the 10-user simplified network, we simulate and compare performance of the IEEE 802.11, conventional single-channel cooperative networks, and the proposed cooperative protocol using directional antennas over both flat-fading and AWGN channels. We also consider single and multiple relay cooperative scenarios. For the single relay case, only one relay is used for relaying the signal to the destination node. For the multiple relay case, more than one relays are used for relaying information to the destination (i.e. if available in the common neighboring region of the sender and destination stations).

5.3 Simulation Results

Fig. 5.1 examines the throughput performance as a function of the system load (per station) for different systems using the network model in Fig. 3.1 at a signal-to-noise ratio (SNR)=25 dB, for (i) IEEE 802.11 over AWGN and fading channels, (ii) An ad hoc cooperative network where relay blocking exists, (iii) The new cooperative protocol for single relay channel. (iv) The new cooperative protocol with a single relay and full rate transmission mode (i.e. the extra time delay required to relay signals is eliminated using a full rate transmission mode). We can see that by using our cooperative MAC protocol (single relay), the throughput is improved relative to the conventional cooperative network with relay blocking. Note that the BER performance improves through cooperative diversity gain, where at 25 dB the packet error rate is low and hence the throughput increases.

Let us now examine the effect of interference caused by cooperative transmission.

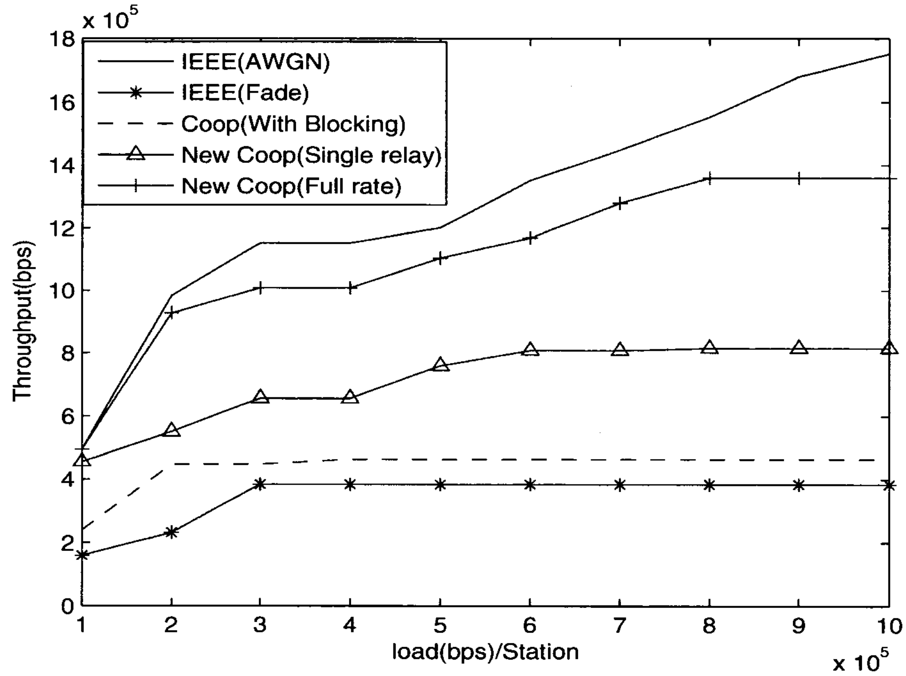

Figure 5.1: Throughput vs load at SNR=25 dB, using 4-antenna elements for the new cooperative protocol and a single relay transmission.

Interference in WLANs is mainly caused by different mobile terminals sharing the same frequency band. In traditional IEEE 802.11-based ad hoc networks, within the radio range, only one station can transmit at a time. On the contrary, our cooperative protocol allows for transmission and/or reception in the relay region. Therefore, in this relay region, one may expect the throughput performance to degrade due to interference/collisions. To overcome this limitation, we use adaptive antennas at the relay stations to allow the neighboring nodes in the relay region to communicate without blocking and with low interference levels.

At first, we considered the case where single relay is employed. From Fig. 3.1, we can see that station 7's receiver has no interference from any neighboring station (i.e. stations 1, 6 and 9 are out the radio range of 7). Let us now consider the case when multiple relays are used. In this case, all the common neighboring stations available for a sender-destination pair are considered as relay candidates for that particular link. In Fig. 3.1, we can see that station 4, 5, 10 and 9 are possible relay candidates for the 1→6 link. Then, the interference from relay 4, 5 and 10 will be received at station 7's receiver. Even though the use of multiple relays can improve the received signal quality, it will also increase the level of potential interference at the neighboring stations.

We simulate the topology of Fig. 3.1 for the new cooperative network using both single and multiple relays at SNR=13 dB. Fig. 5.2 shows the throughput performance at different system loads using single and multiple relays.

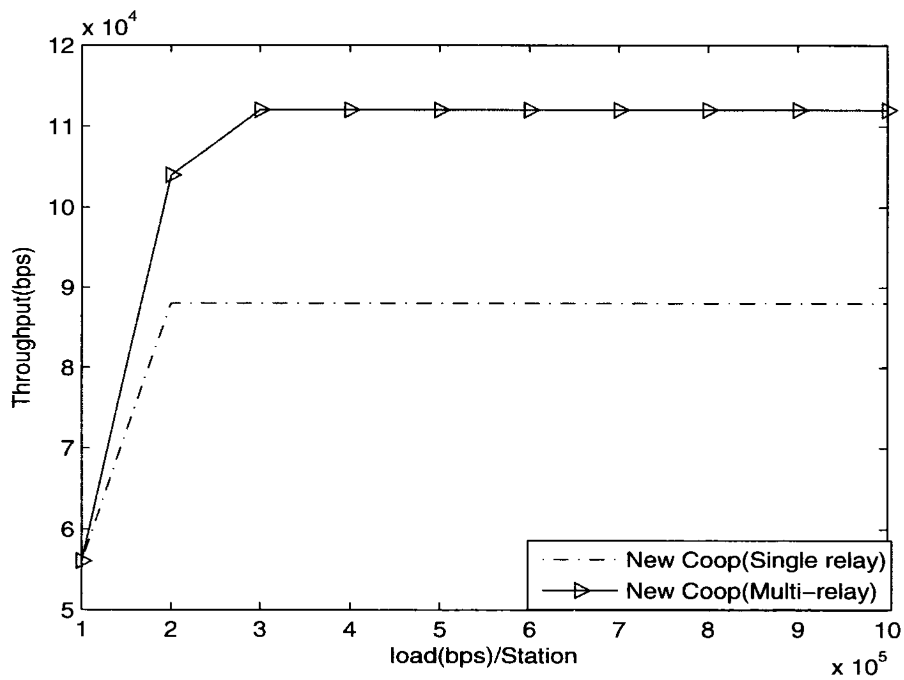

Figure 5.2: Throughput performance of the new cooperative protocol with 4-antenna elements at SNR=13 dB for the single relay and multiple relay scenarios and using the fixed topology of Fig. 3.1.

Fig. 5.3 shows the throughput performance as a function of the SNR using our new cooperative protocol for single and multiple relays at a fixed load of 0.1 Mbps/station. To examine the effect of interference, we also consider the case when no interference is present. As seen from our results, when interference is ignored, the multiple relay case always achieves better throughput performance than the single relay case. However when considering the effect of interference, the single relay case is shown to offer better throughput at relatively large SNRs (SNR>15 dB). This also justifies the throughput results shown in Fig. 5.2. To improve the throughput for the multiple relay case, a larger number of relay antennas should be used to reduce the effect of interference caused by the multiple relay transmission. This is noted in Fig. 5.3, where the use of 6-antenna elements is shown to improve the throughput relative to the 4-antenna case.

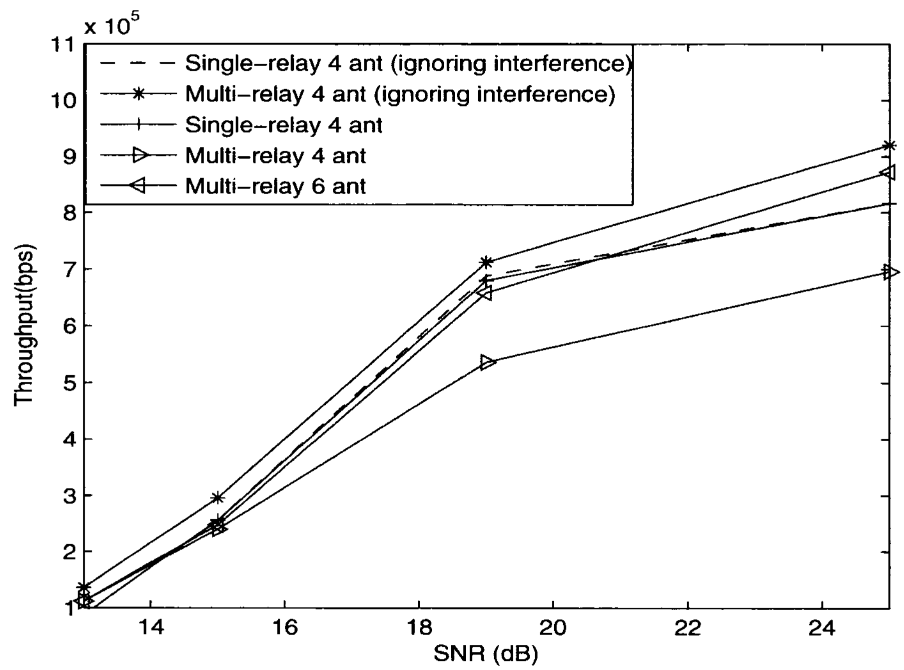

Figure 5.3: Throughput performance at a fixed load of 1Mbps/station, using 4-antenna elements per relay node.

In Fig. 5.4, one can see that using multiple relays for cooperative networking causes throughput degradation due to the relay blocking problem which could be more severe than the single relay case. The reason is that multiple relays have more blocking area than the single relay case. Using our cooperative protocol, the results in Fig. 5.4 clearly show that both the single and multiple relay cases, with 4-antenna elements, achieve significant throughput improvement relative to conventional cooperative networks (single/multiple relay). For instance, the single relay (4 antennas) compared to multiple relay (6 antennas) has almost the same throughput. Using larger number of relay antennas (see 8-antenna case), the throughput of multiple relays can be further improved by reducing the level of interference.

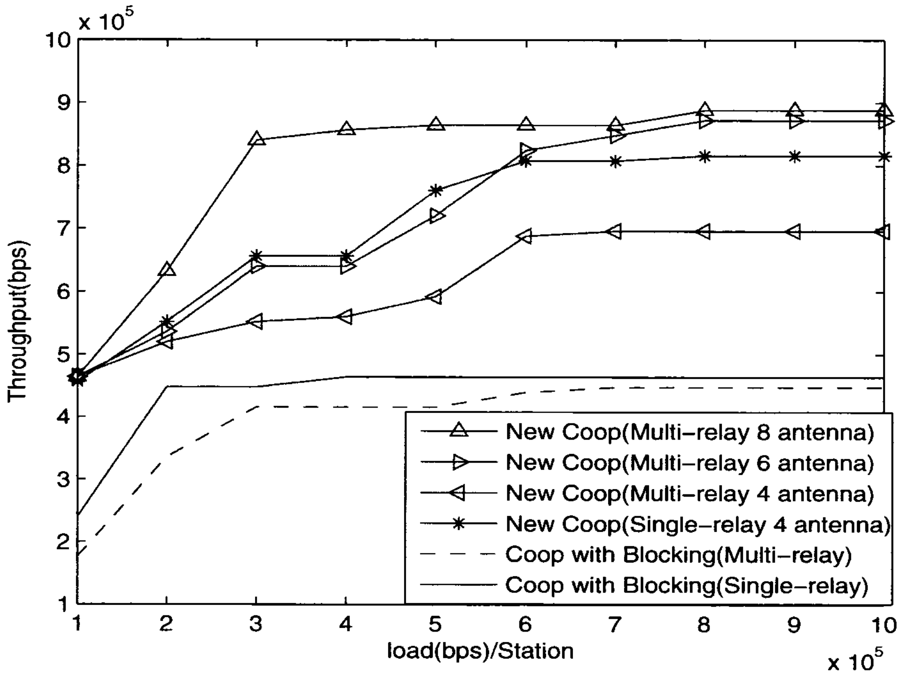

Figure 5.4: Throughput vs system load at SNR= 25dB.

In Fig. 5.5, we examine the throughput performance as a function of the number of relay antennas (for both the single and multiple relay). We have noted that the use of large number of antennas is more effective in the multiple relay case when the relay blocking region is large. For the single relay case, where the interference level in the network is low, the saturation throughput can be achieved using small number of antennas. This is different from the case of multi-relay where the saturation

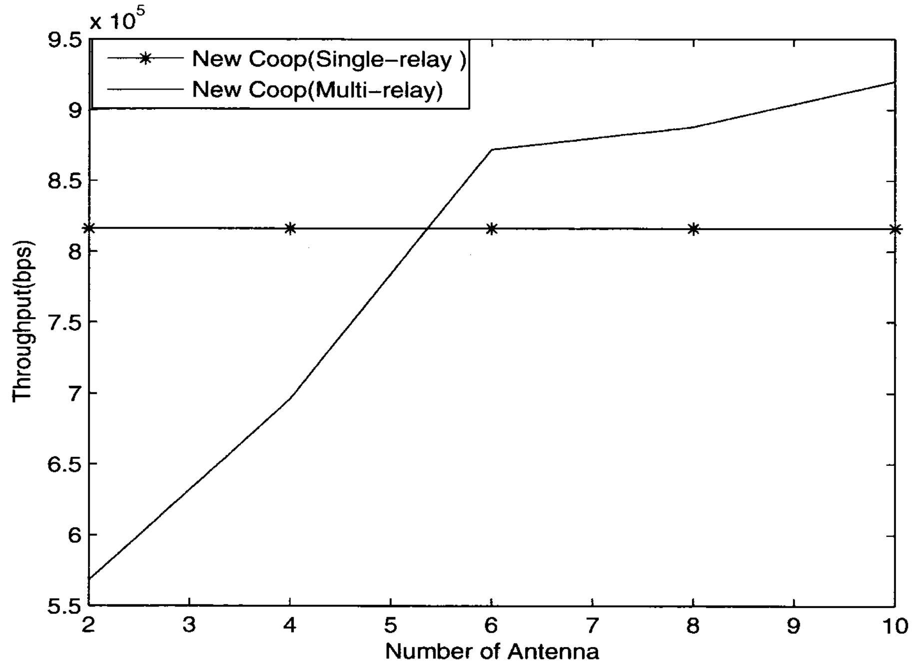

Figure 5.5: Effect of increasing the number of antennas on the throughput performance at SNR=25dB for the fixed topology in Fig. 3.1 and at fixed load/station = 1Mbps.

throughput is reached using large number of relay antennas.

Finally, we consider DOA estimation error caused by imperfect GPS estimation which is very important aspect of our system. In particular, in our simulation, we study the performance of the network considering the imperfect GPS position estimation error in the directional antenna at the relay stations. We simulated the new cooperative network both for single relay and multiple relay scenarios and introduced the DOA error caused by GPS at the relay adaptive antennas.

We set load/station for the transmitter node to 1Mbps. We assume that all mobile nodes are equipped with the same number of antenna elements.

In Fig. 5.6 the throughput performance in terms of DOA error is plotted at a fixed load =1Mbps/station for both single and multiple relay cooperative networks. Fig. 5.6 (a) and (b) are respectively for uniform and Gaussian DOA error in the case

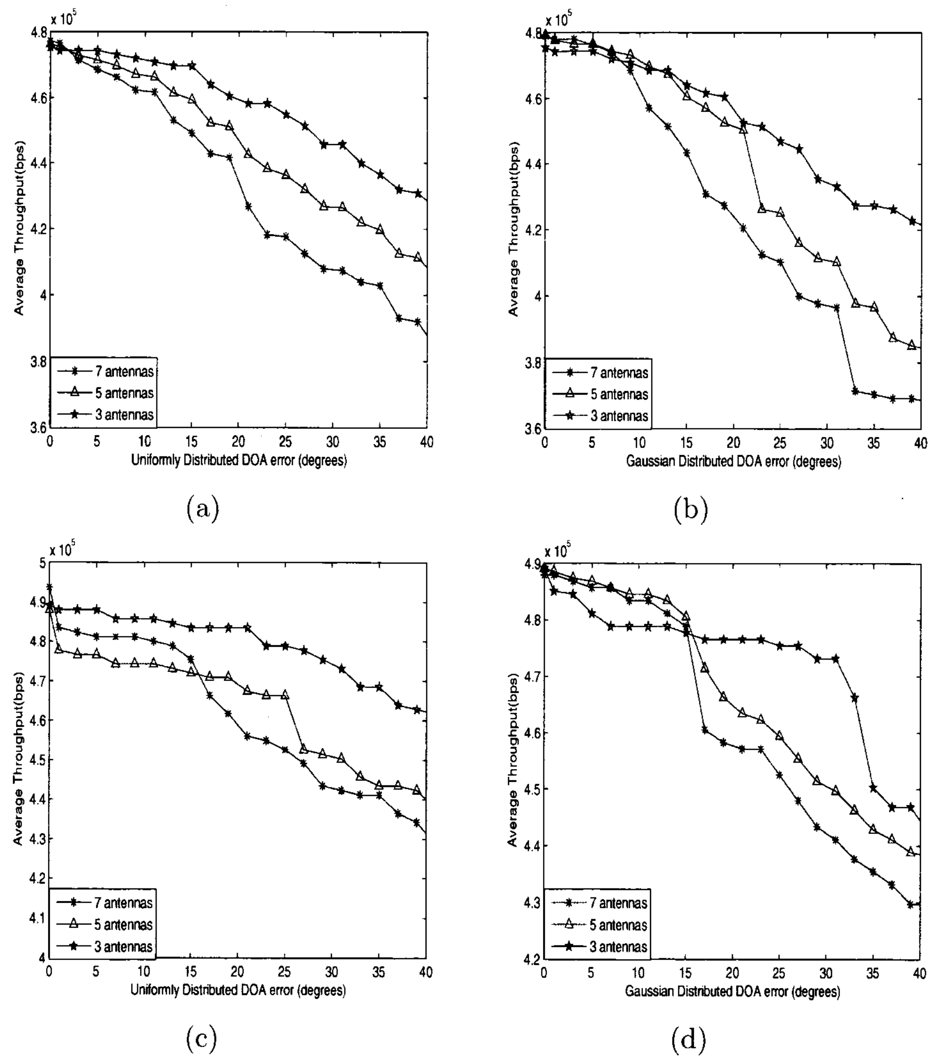

Figure 5.6: Throughput performance at a fixed load =1Mbps/station and at SNR=25 dB (a) Single relay (Uniformly distributed DOA error) (b) Single relay (Gaussian distributed DOA error)(c) Multiple relay (Uniformly distributed DOA error) (d) Multiple relay (Gaussian distributed DOA error).

of single relay network. And Fig. 5.6(c) and (d) is for multiple relay cooperative network.

From the Fig. 5.6 we can see that by increasing the number of antenna elements the average throughput decreases. The reason is that by increasing the number of antenna elements the beampattern gets narrower. Therefore, the received signal at the receiver from the relay is degraded which ultimately increases the BER at the receiver.

An interesting finding is that the interference in the network also depends on the number of antenna elements at the relay. Also, for single relay the effect of interference is less than multi-relay. But in both the cases, the throughput degrades if the number of antennas used at the relay node increases. Note that, by using multiple relay where DOA error is zero the throughput is higher than single relay since of the diversity gain offered by the multiple relays is higher more than the single relay case.

Now, we examine the throughput performance as a function of signal to noise ratio in Fig. 5.7. In the Fig. 5.7 (a) and (b) a single relay network throughput is observed as SNR. The performance of multiple relays is also verified in Fig. 5.7 (c) and (d). We observed previously that at small number of antennas the performance of multiple relay network is not significantly higher than the single relay network since in multiple relay network the interference effect is greater. We can see from the figure that the throughput increases at higher SNRs for both single and multiple relay networks.

From the above results it is clear that as the number of antenna elements increases the average throughput also degrades as the DOA increases for the multi-relay network. Note that the multi-relay case achieves higher throughput than the single relay

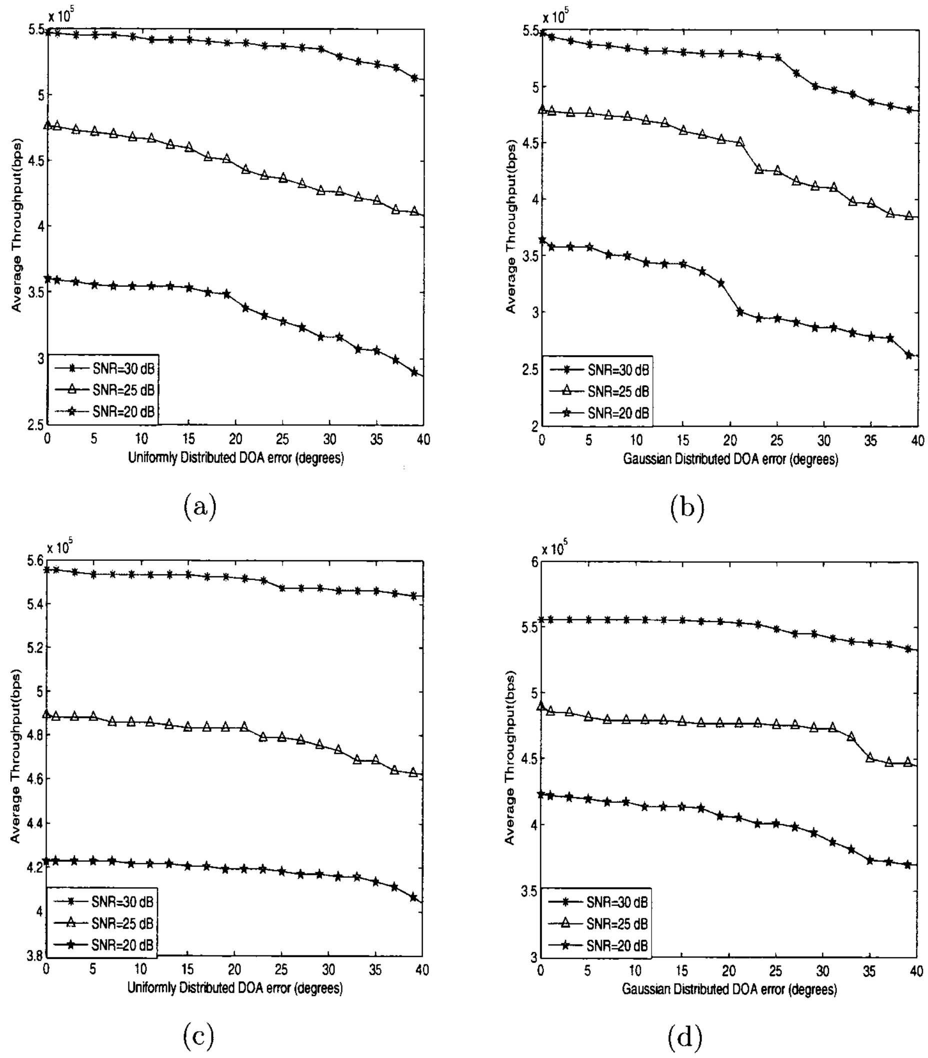

Figure 5.7: Throughput performance at a fixed load =1Mbps/station with 3 antennas (a) Single relay (Uniformly distributed DOA error) (b) Single relay (Gaussian distributed DOA error)(c) Multiple relay (Uniformly distributed DOA error) (d) Multiple relay (Gaussian distributed DOA error).

network due to the larger diversity gain in multi-relay network. We have seen before, for the case when there is no DOA error and no interference, the multi-relay always performs better in terms of the average network throughput. However, if interference is considered then the multi-relay case needs more antenna elements to achieve better throughput than single relay. On the other hand, when we are considering DOA errors it is shown that by increasing number of elements the effect of DOA error gets worse and the throughput decreases.

5.4 Summary

In this chapter, simulation results are presented for the new cooperative protocol for both single and multiple relays. The effect of interference, number of antenna elements, DOA error caused by imperfect GPS estimation are considered to verify the throughput performance of the new cooperative protocol.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

- In this thesis, the relay blocking problem in existing cooperative ad hoc networks was discussed.
- A new cooperative protocol based on the MAC layer of the IEEE 802.11 has been proposed and analyzed for both single and multiple relay channels. The proposed protocol is shown to solve the relay blocking problem.
- Our results show that the use of directional antennas becomes advantageous for multiple relay communications. It was also shown that using multiple relays can improve the QoS (i.e., BER) of the particular link, at the expense of increasing the level of interference of other neighboring links.
- We noted that by increasing the number of antennas (at the relay station) one can reduce the effect of interference and hence, improve the overall network throughput specially in the case of multiple relay channels.

- Also in our simulations, we showed the throughput loss occurred due to DOA error resulted from imperfect GPS estimation. The throughput loss due to DOA error increases if the antenna elements are increased, different from the effect of interference where the throughput loss decreases if the number of antenna elements are increased.

6.2 Future Work

- In our simulations, we considered an ad hoc network consisting of 10 stations. The number of stations can be increased to find out the throughput performance in large network and dense network scenarios.
- In our results, we considered a relay selection based on the shortest distance from source and destination, future works should focus on relay positions, interference power, fading channel coefficients, load per stations etc. to select the best relay.
- The new cooperative MAC can also be evaluated in multi hop cooperative communications.
- Also, the cross layer design can also be extended to incorporate efficient routing protocols to support cooperative communications in the network.

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