A MAC LAYER PROTOCOL FOR WIRELESS AD-HOC NETWORKS USING DIRECTIONAL ANTENNA

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Thesis of Sultan Budhwani:

A MAC Layer Protocol for Wireless Ad-Hoc Networks

Using Directional Antenna

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To my parents Saira Banu and Nadir Ali Budhwani.

ABSTRACT OF THE THESIS

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Using directional antenna in ad hoc networks, offer many benefits in contrast to their classical omni-directional counterparts. The most important benefits are the significant improvement in spatial reuse, reduction of the radio interference, increase in coverage range and subsequently an increase in network capacity on the whole. On the other hand, directional transmission increases the hidden terminal problem and the problem of deafness. To best utilize directional antennas, a suitable Medium Access Control (MAC) protocol must be designed. Current MAC protocols, such as the IEEE 802.11 standard for Wireless LANs, assume the omni-directional antenna at its Physical layer and thus do not fully exploit the capabilities of a directional antenna. In this thesis, we propose a MAC protocol for wireless ad hoc networks which fully exploits the potentials of directional antennas. The first part of our design studies the issues related to directional MAC protocols and we use this knowledge to carefully design the proposed MAC protocol for ad hoc networks using directional antennas. We evaluate our work through simulation studies performed on the network simulator – NS2. Numerical results obtained are promising and show that our protocol offers significant improvement in throughput when compared to the performance of traditional 802.11 MAC protocol and D-MAC which is a Directional MAC protocol for ad hoc networks.

TABLE OF CONTENTS

PAGE

CHAPTER

LIST OF TABLES

PAGE

LIST OF FIGURES

PAGE

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CHAPTER 1

INTRODUCTION

In this thesis, we propose a directional Medium Access Control (MAC) protocol for ad hoc networks using directional antennae which fully exploits the benefits of the directional antennae and increases the network capacity.

1.1 GENERAL CONCEPT OF AD HOC NETWORKS

Wireless networks, which use electromagnetic waves for transmitting information through the air in order to connect two or more terminals, are currently gaining popularity. There are two possibilities for enabling wireless communications: infrastructure mode and ad hoc mode. The first one relies on infrastructure that needs to be built in advance. In 802.11 infrastructure mode, all the wireless devices in the network can communicate with each other through an Access Point (AP) or communicate with a wired network as long as the AP is connected to a wired network.

The other choice is ad hoc mode whose major feature is the nonexistence of supporting structure. Each terminal having ad hoc capability could behave as a router, forwarding traffic to other terminals and/or the base station. The phrase "ad hoc" comes from the Latin which literally means "for this purpose" [1]. The nodes in ad hoc networks are autonomous; they could be laptop computers, Personal Digital Assistants (PDAs), sensors, or mobile phones. The autonomous nodes can self-organize and self-manage the network without requiring fixed infrastructure such as a base station or central controller. Nodes in an ad hoc network are free to join, move around, and leave the network without any restriction. Ad hoc networks are able to recover and continue to be functional in the case of link breakages. For instance, when nodes leave the network or nodes' hardware breaks down, the nodes that lost their links could simply ask for new routes, then the new routes can be established and the network can maintain connectivity and reachbility. Each individual node in ad hoc network is not only a host with responsibility for sending or receiving packets but a router that takes charge of forwarding packets to other nodes. If the source and the destination are not in one hop range, they use the intermediate nodes to forward the packets. In this case, the intermediate node would act as a router.

1.2 APPLICATION AND USAGE SCENARIOS

The characteristics of ad hoc networks make them well suited for a variety of scenarios such as military applications and low cost commercial applications where infrastructure does not exist or to build one would be too costly. The following are some examples where ad hoc networks can be used.

In military scenarios, aircraft are able to form an ad hoc network in the sky to communicate with one another and present a backbone for land platforms to communicate with them. The infantry can establish an ad hoc network immediately when they arrive at a battlefield to achieve communication requirements like voice, telemetry, and video. For mobile objects including warships, tanks, vehicle, and aircraft, an ad hoc network can be formed by requiring only that each object to be within the range of its closest neighbors while traditional radio technology requires a range which covers the entire topology of the network [2]. In the disaster recovery field, for example an earthquake where the supporting structures are damaged, ad hoc networks can be set up within hours to address the need of organizing and managing different search and rescue groups to work efficiently. Wireless sensor networks are another application of ad hoc networks in which sensor devices are connected in open peer-to-peer ad hoc network architecture to offer various utilizations such as monitoring traffic congestion in a city, detecting a biological weapon in the battle field and border intrusion.

Wireless mesh networks could be considered as a type of wireless ad hoc networks. Compared with mobile ad hoc networks in which routing nodes are mobile, the routing nodes in mesh networks are stationary. These mesh nodes together establish the backbone of the network. The clients' non-routing mobile nodes connect to the mesh nodes in order to use the backbone to communicate with one another and with the Internet-connected nodes to obtain Internet access. Mesh networks extend the reach of wireless networks and are ideally suited for many environments such as commercial zones, neighborhood communities and university campuses [3-4].

In summary, Wireless ad hoc networks exhibit many unique features such as easy deployment, self-organization, direct peer-to-peer communication, and maintenance free operation. There is a huge demand for developing ad hoc networks in various applications.

1.3 MOTIVATIONS AND PROBLEM FORMULATION

The use of directional antennae in ad hoc networks has received growing attention in the past few years [1-3, 5-6], driven by the benefits of directional antennae. These benefits include high spatial reuse, longer transmission range, lower interference, etc. At the same time, using directional antennae poses new challenges. For one, problem due to deafness – the deafness problem arises when the intended receiver is unable to respond with a clear-to-send (CTS) frame, while the sender continues to retransmit its request-to-send (RTS) frame. The receiver is thus designated as "deaf". The packets dropped due to the deafness problem will adversely affect the network utilization.

Currently there has been a lot of interest in terms of using directional antennas in wireless ad hoc networks [1-3, 5-6]. The broadcast nature of omni-directional antennas is one of the major causes of excessive multi-user interference. Traditional MAC protocols such as IEEE 802.11 [7] cannot achieve high throughput in wireless ad hoc network because it blocks a large portion of the spectrum [8] for each transmission. This limits the spatial reuse of the shared wireless medium. To address this problem, directional antennas or smart antennas can be used. They strongly reduce signal interferences in unnecessary directions and also significantly improve spatial reuse of the wireless channel by allowing several nodes to communicate simultaneously without interfering with each other, thereby significantly improving the capacity of ad hoc networks. To best utilize the benefit of directional antennas, a suitable Medium Access Control (MAC) protocol must be used. IEEE 802.11 [7] MAC protocol assumes the use of omni-directional antenna at its physical layer; hence it does not exploit the maximum potential when used with directional antennas.

Recently, several directional MAC protocols using smart antennas or directional antennas have been proposed for wireless ad hoc networks, one such protocol is Directional MAC (D-MAC) [5] in which all frames are transmitted directionally except for the CTS. Although sending omni-directional CTS minimizes the possibility of collisions at the receiver, but this turns out to be a conservative protocol due to the possibility of blocking neighbors from receiving data frames (without interfering the ongoing transmission) when they are in communication range of an ongoing transmission which adversely affects the network throughput. In this work, we propose a new MAC protocol for directional antennas which fully exploits the virtues of directional antenna. It particularly overcomes the above discussed problems. Simulation results show a significant improvement in overall network throughput when compared to IEEE 802.11 standard and D-MAC which is a Directional MAC protocol for ad hoc networks.

In a nutshell, our MAC protocol does the following. It maintains a Directional Network Allocation Vector (DNAV) table, wherein the information about received Clear-to-Send (CTS), total time of transmission and blocked directional antenna is recorded. The Request-to-Send (RTS) frames are sent directionally, whereas the Clear-to-Send (CTS) frames are sent on all the unblocked directional antennas. Finally DATA and ACK frames are sent using directional antennas, as a result it allows simultaneous transmission and reception of data frames thereby increasing network performance and hence network throughput. It should be noted that we use a switched antenna on our wireless nodes. We describe our antenna model in details in Section III.

1.4 ORGANIZATION OF THESIS

In Chapter 2, we provide some background information and discuss the major challenges that face the MAC layer when directional antennae are deployed. We first introduce the general design issues of Medium Access Control (MAC) and its importance. We then discuss the differences between directional and omni-directional MAC protocols and highlight the challenges facing directional MAC protocols.

The related work is presented in Chapter 3, first we discuss the handshaking mechanism of traditional 802.11 MAC protocol. This is followed by classification of directional MAC protocols and we discuss several directional MAC protocols based on Random Access Mechanism and Scheduling Mechanism.

The proposed scheme is detailed in Chapter 4, the proposed MAC layer protocol for ad hoc network using directional antennae is validated using three different scenarios followed by a detail discussion on how the deafness problem is handled and then a flowchart of the scheme is explained.

In Chapter 5 we study the performance of the proposed MAC protocol through simulations. We then show that our proposed protocol offers significant improvement in throughput when compared to the performance of traditional 802.11 MAC protocol and D-MAC which is a Directional MAC protocol for ad hoc networks. The thesis is summarized, and suggestions for future research directions are stated in Chapter 6.

CHAPTER 2

TECHNICAL BACKGROUND

This chapter describes some key features of existing wireless medium access protocols for ad hoc networks, including the 802.11 protocol. In the other half of the chapter background on directional/smart antenna and challenges facing directional MAC protocol is discussed.

2.1 WIRELESS MAC PROTOCOL BASICS

The area of wireless networking has seen exponential growth in the past decade. This growth continues as consumers drive for the so-called anywhere, anytime, connectivity. This drive brings some interesting research challenges spanning across all layers of network protocol stack. For example, at the application layer, developers are racing to provide new functionality to satisfy the consumer's needs. At the physical layer, scientists and researchers are striving to push current technologies to their limits, while at the same time, design new technologies to support high data rates.

One specific area that needs to be carefully addressed to ensure the continued success of wireless networking is Medium Access Control (MAC). Since the wireless medium is open and shared [5], any node may broadcast at any time. In fact, multiple nodes may access the wireless medium at the same time. Wireless MAC protocols set defined rules to force distributed users/nodes to access the wireless medium in an orderly and efficient manner. A wireless MAC protocol should be able to efficiently regulate/coordinate users sharing the medium and achieve the following objectives:

- Efficiency: The network resources can be efficiently utilized.
- Fairness: Every user has a fair share of the medium.
- Stability: The network will not be driven to congestion collapse.
- Limited delay: Users should experience a bounded delay.
- Scalability: The MAC protocol should scale well to a growing number of users.
- Low power consumption: Energy consumption to the users should be relatively low, especially if the users are mobile.

Wireless MAC protocol can be divided into two main categories [9]:

- Centralized protocols
- Distributed protocols

Centralized MAC protocols employ a centralized controller or access point which controls access to the medium. In this case, all nodes need to hear and talk to the controller. Centralized MAC protocols are often based on tree major access techniques [10]: Frequency Division Multiple Access (FDMA) [11], Time Division Multiple Access (TDMA) [12] and Code Division Multiple Access (CDMA) [13]. FDMA assigns individual channels at different frequencies to the individual users. TDMA systems divide the radio spectrum into time slots, and in each slot only one user is allowed to either transmit or receive. In CDMA systems, a narrowband signal is multiplied by a very large bandwidth signal called the spreading signal. This spreading signal is pseudo-noise code sequence that has a chip rate which is orders of magnitude greater than the data rate of the message. All users in the CDMA system have the same carrier frequency, but have their own pseudo-random codeword which is approximately orthogonal to all other codewords. This way, the receiver performs a time correlation operation to detect the desired codewords and all other codewords appear as noise.

Distributed MAC protocols allow nodes to communicate without reserving the resource through the centralized controller. They often employ collision avoidance mechanisms to reduce the chance of collisions. One example nodes sense the wireless shared channel for predefined time before using the channel to avoid the collisions with the ongoing communication.

In the following section, we describe the operation of some of the IEEE 802.11 MAC protocols i.e. IEEE 802.11 Distributed Coordination Function (DCF) and Carrier Sense multiple access with collision avoidance (CSMA/CA) protocols.

2.2 THE IEEE 802.11 STANDARD

In this section, we present an overview of the conventional IEEE 802.11 standard that is widely used in ad hoc networks. IEEE 802.11 Distributed Coordination Function (DCF) and Carrier Sense multiple access with collision avoidance (CSMA/CA) protocols are presented in detail.

2.2.1 IEEE 802.11 DCF

In IEEE 802.11 DCF MAC protocol, both physical channel sensing and virtual channel sensing are used and it assumes the omnidirectional antenna at its physical layer. In the basic mode of DCF operation, a node intending to transmit a packet senses the wireless channel first for a predefined period of time. If the channel is sensed idle for this time i.e. Distributed InterFrame Space (DIFS) time, the node transmits. If the channel is sensed busy or becomes busy during this DIFS time, the node continues to sense the channel until the channel is idle for DIFS time. After the channels is sensed idle for DIFS time, the node then backs off for a random interval to minimize the probability of collision with others who may have sensed the channel idle for DIFS time simultaneously.

IEEE 802.11 DCF MAC protocol uses an exponential backoff algorithm. Before each transmission, a node chooses a uniformly distributed counter between 0 and W – 1. After every unsuccessful transmission, W is doubled in value up to a maximum value Wmax. The backoff counter decrements by 1 for every time slot that the channel is sensed idle. If the channel becomes busy during this backoff state, the counter is frozen. If the backoff counter reaches zero, the node transmits its DATA frame.

The basic mode works well in a single-hop network. However, in multi-hop ad hoc networks it encounters new challenges. To start with, there is the hidden node problem illustrated in Figure 2.1(a), where four wireless nodes are illustrated. The radio range is such that A and B are within each other’s communication range and can potentially interfere with one another. C can also potentially interfere with both B and D, but not with A. Now consider what happens when A is transmitting to B as shown in Figure 2.1(a). If C senses the medium, it will not hear A because A is out of range, and thus falsely conclude that it can transmit to B. if C does start transmitting, it will interfere at B, wiping out the frame from A. The problem of a node not being able to detect a potential competitor for the medium because the competitor is too far away is called the hidden node problem. To mitigate the hidden node problem in ad hoc networks, a four-way handshake mechanism is used which is described in the following sub section.

Now let us consider the reverse situation: B transmitting to A, as shown in Figure 2.1(b). If C senses the medium, it will hear an ongoing transmission and falsely conclude that it may not send to D, when in fact such a transmission would cause bad

Figure 2.1. (a) Hidden node problem (b) exposed node problem.

reception only in the zone between B and C, where neither of the intended receivers is located. This is known as the exposed node problem.

2.2.2 Four-Way Handshake Mechanism

Using the four-way handshake, after sensing the channel idle for DIFS time and the backoff counter reaches zero a transmitting node sends a RTS frame. When the receiving node detects the RTS frame, it responds with a CTS frame after waiting for a Short InterFrame Space (SIFS) time, SIFS is less than DIFS as shown in Figure 2.2. Once the CTS frame is successfully received by the transmitter node, it can then continue to transmit its data packets followed by an Acknowledgment (ACK) from the receiver, RTS and CTS frames carry information about the length of the transmission which is used by neighboring nodes to set or update the Network Allocation Vectior (NAV). Therefore, when a station is hidden from the transmitting station, by detecting the RTS frame, it can delay its transmission, and thus avoid collision.

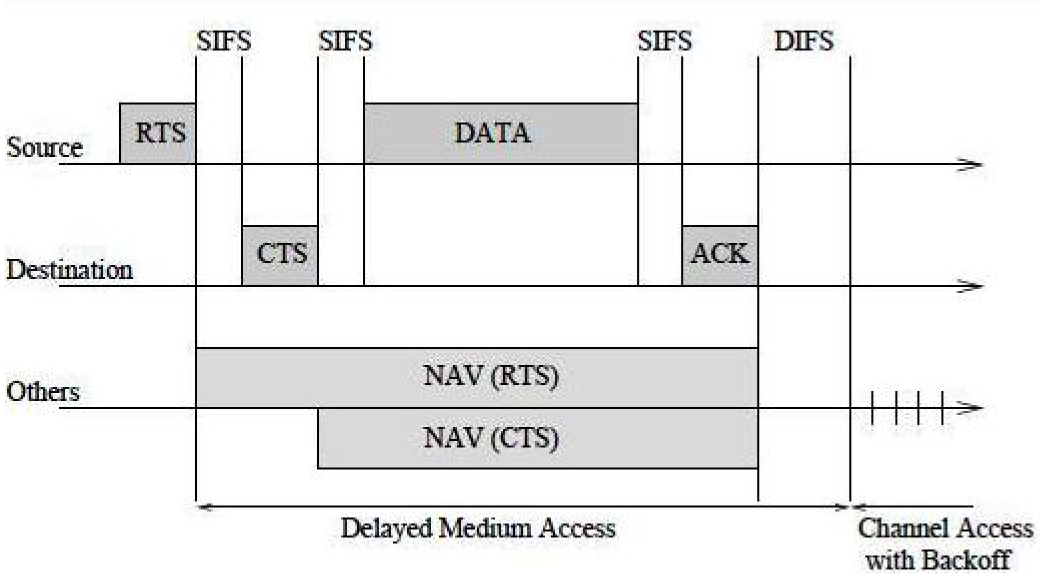

Figure 2.2. Virtual carrier sense.

Despite these precautions (using four-way handshake), collision can still occure. For example, node B and C could both send RTS frame to A at the same time. This will collide and be lost. In the event of this collision, an unsuccessful transmitter (i.e., one that does not hear a CTS within the expected time interval) waits a random amount of time and tries again later. On the other hand, this four-way handshake is very effective because it reduces the lengh of frames involved in contention. In fact, if both transmitting stations employ the RTS/CTS mechanism, collision occurs only on the RTS frames, which is smaller than data packets. Thus, the channel time wasted duing collisions is reduced [14].

2.2.3 Virtual Carrier Sense (VCS)

Virtual carrier sensing along with RTS/CTS mechanism is used to alleviate the hidden terminal problem in an ad hoc networks. In this section we will describe the working of virtual carrier sensing. The IEEE 802.11 standard defines two kinds of carrier sensing mechanisms, aiming to avoid collision in a shared wireless channel. They are as follows [15].

- Physical Carrier Sensing (PCS)
- Virtual Carrier Sensing (VCS)

Virtual Carrier Sense works in the MAC layer and offers a good solution to the hidden terminal problem by using Network Allocation Vector (NAV) and RTS/CTS handshaking mechanism. NAV is a timer that specifies the time period during which the station is not allowed to transmit. Figure 2.2 (p. 9) illustrates how the VCS works. At first, a source station wishing to transmit broadcasts an RTS packet which includes the information of the source address, destination address, and the duration of the transmission to follow. By receiving the RTS packet, the destination station responds with a CTS packet if the medium is idle after an SIFS time. The CTS packet includes the same information as the RTS packet. The neighbors of both source station and destination station overhear the RTS and/or the CTS and set their VCS timer according to the duration info specified in RTS/CTS packets. The surrounding stations then use this information to schedule the time for the next medium sensing. This process guarantees a station which did not receive the RTS is able to hear the CTS and set its VCS accordingly. RTS and CTS frames are very small in size when compared with the data frame. As a result, if any collision happens during the RTS/CTS handshaking, the bandwidth waste is very small compared to the case where collision happens during the data frame transmission (when not employing RTS/CTS mechanism).

2.3 DIRECTIONAL/SMART ANTENNA BASIC

This section deals with the smart antennae; in the section we describe the basics of smart antenna and two most important types of Directional/Smart antennae.

An antenna (or aerial) is a transducer designed to transmit or receive electromagnetic waves. In other words, antennas convert electromagnetic waves into electrical currents and vice versa.

An antenna in a communications system is a kind of the port through which Radio Frequency (RF) energy is radiated from the transmitter to the outside space for transmission purposes, and in reverse, from the outside space to the receiver for reception purposes. An omnidirectional antenna radiates or receives RF energy equally in all directions. Smart antennas actually should be referred to as smart antenna systems because the antenna is not smart. It is the antenna system that can control the antenna array intelligently to form a directional radiation pattern. The smart antenna can be considered a pattern controllable antenna. It consists of a number of antenna elements arranged spatially and interconnected electrically through complex weights. The radiation pattern of the antenna array is determined by the weights based on Digital Signal Processing (DSP).

Smart antenna systems can be divided into two categories [9-10, 16]:

- Switched Beam Smart Antenna systems
- Adaptive Array Smart Antenna systems

Both types of antennae are discussed in detail in the sub section below.

2.3.1 Switched Beam Smart Antenna Systems

Basic switched beam antenna architecture contains a bunch of directional antennae to cover 360 degree 2-D coverage and a logical control unit for beam selection, a switch unit for activating the right beam and a Beam Forming Network (BFN). The switched beam smart antenna system is a simple and cheap technology. It merely employs a basic switching function for selecting among separate antennas or predefined array beams.

Figure 2.3 shows the Smart switched beam antenna system, only a single beam pattern could be used at any given time. Such an antenna system could increase coverage

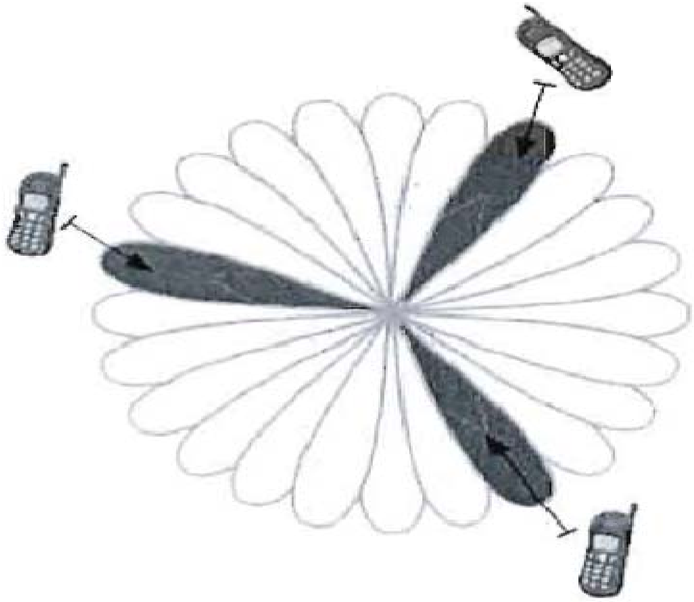

Figure 2.3. Switched beam coverage pattern.

range up to 200 percent over conventional omnidirectional antenna depending on the propagation environment, hardware and software used. It could also suppress interference arriving from directions away from the active beam's center. However, from Figure 2.3 we should notice one shortcoming of the switched beam system is that the limited predefined main beams are only available for certain prefixed directions. In the case that the user is located between two predefined main beams, the base station is not able to achieve any directional gain from the antenna system although we could increase the number of beams to mitigate this problem [11].

Switched beam smart antenna systems work well in clean areas with low or no interference. However, in high interference environments, switched beam antennas are further limited due to their predefined fixed beam characteristic and the fact that they lack the ability to reject interference. Compared with switched beam which only allows base stations to switch among several fixed beams in predetermined directions, the adaptive array antenna system is capable of steering main beams dynamically towards desired users and null toward interfering signals by using advanced signal processing techniques. The adaptive array antenna system is described in detail in the following section below.

2.3.2 Adaptive Array Smart Antenna Systems

By employing advanced signal processing functionality, the adaptive array has the ability to adapt to radio environment changes such as a user's movement. When a user is moving, the adaptive array system changes its antenna pattern smoothly to follow the user, always providing highest gain in the user's direction. Figure 2.4 illustrates the pattern of an adaptive antenna system. It shows the main lobe coverage extension toward the target user and nulls directed toward two interferers. The core idea of adaptive beam forming is to change the complex weight value of each element according to the changing radio environment. By multiplying these complex weight values to the output of each element, the system is able to generate the desired radiation pattern that matches the traffic conditions and offers the highest beam gain in the desired direction. Many adaptive algorithms have been developed aiming to compute the optimal complex weight which contains amplitude and phase information used for beam steer. Note that the direction of the main beam is determined by amplitudes and phases of the antenna elements of the adaptive array system.

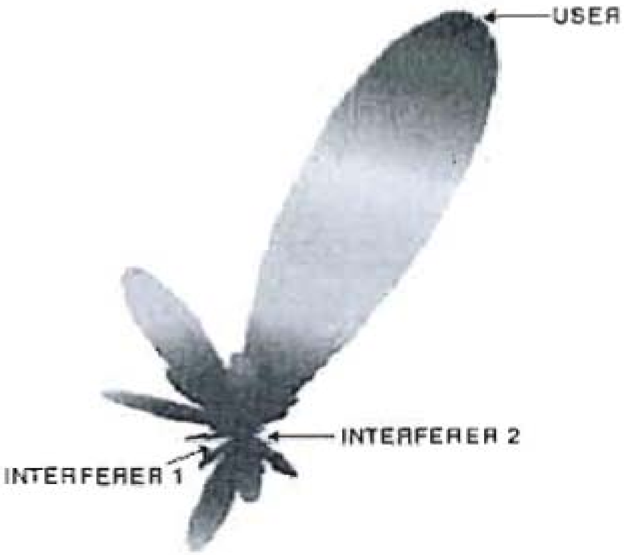

Figure 2.4. Adaptive array antenna pattern. Source: V. Bahl. (2006). ***Wireless mesh networks: From theory to deployed systems.*** **[Online]. Available: http://conferences.sigcomm.org/sigcomm/2006I?tutorials**

Adaptive algorithms could be classified into two categories: blind adaptive algorithms which require no reference signal and non-blind adaptive algorithms which require reference signal [17]. An example of blind adaptive algorithm is constant modulus algorithm (CMA) where the algorithm itself generated the required reference signal from the received signal based on the characteristics of the received signal structure. On the other hand, in non-blind adaptive algorithms, the reference signal that has a high correlation with the desired signal is provided. Examples of trained adaptive algorithms consist of Least Mean Square (LMS) algorithm, Recursive Least Square (RLS) algorithm, Sample Matrix Inversion (SMI) algorithm. According to these algorithms, the training signal is sent from the transmitter to the receiver during the training period and used by the algorithm to update its complex weights.

2.4 CHALLENGES FACING DIRECTIONAL MAC PROTOCOLS

In this section, we describe some of the challenges associated when designing MAC protocols using directional antennae. Problems such as neighbor discovery, hidden terminal and deafness have been discussed in detail in [8] and [12].

2.4.1 Neighbor Discovery

Neighbor discovery is a challenging problem when directional antennae are used [18-20]. When using omnidirectional antennae, the problem is quite different because each node transmits omnidirectionally. Therefore, nodes can discover their one hop neighbors quite easily. However, when directional antennae are used, nodes are only sense part of their neighbors at any time instant. In literature there are many papers on neighbor discovery algorithms. Neighbor discovery algorithms are classified into two categories:

- Direct discovery algorithms
- Gossip based algorithms.

Direct discovery algorithms are based on the fact that nodes discover their neighbors when they hear a transmission from the respective neighbor. Whereas Gossip based algorithms are based on the fact that nodes gossip about each other’s location information. It assumed that each node knows its location at all times using location devices such as Global Positioning System (GPS). To achieve gossip based discovery, nodes can randomly scan the network and exchange Hello message which contain neighbor information when they first join the network. To achieve direct neighbor discovery, mechanisms such as AoA caching can be used. In this case, nodes can sense and cache signals that it overhears. This way, nodes can discover their one-hop neighbors directly.

2.4.2 Directional Hidden Terminal

This is a very common issue when using directional antennae. This occurs when a sender orients its directional antenna towards a new direction, without being aware of the channel condition. In Figure 2.5, node *S* sends a DRTS (directional RTS) to node *R* which replies with a DCTS (directional CTS) and the DATA/ACK exchanges are ongoing. Node *C* finishes its communication with *B*; it would like to send packets in the direction of *R*, if node *C* sends DRTS in the direction of *R*, a collision will occur at *R*. This occurs because *C* did not hear the DRTS or DCTS of nodes *S* and/or *R*.

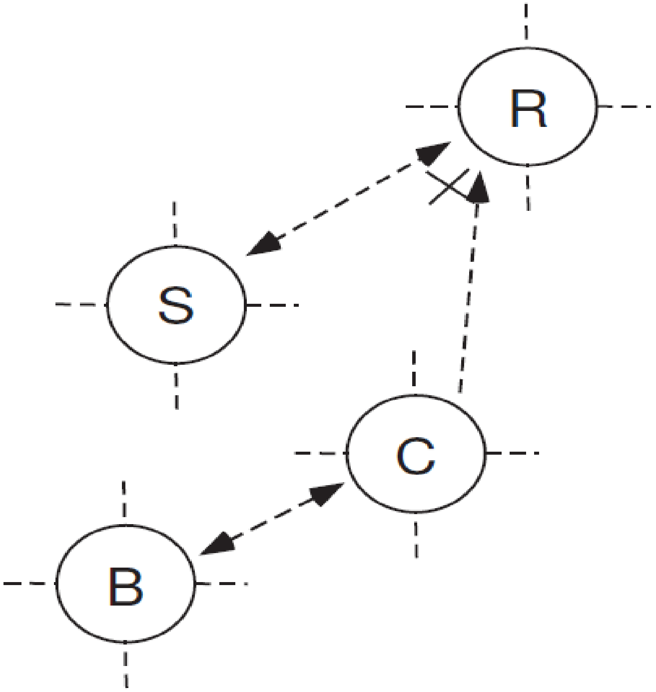

Figure 2.5. Hidden terminal problem in directional antennae.

2.4.3 Deafness

Deafness in MAC protocol using directional antennae is one of the most difficult problems to solve. The deafness problem arises when an intended receiver is unable to respond with a CTS frame, while the sender continues to retransmit its RTS frame. The receiver is thus designated as “deaf”. Due to the fact that the sender node does not know that the receiver node is “deaf”, the sender node will continue to retransmit the RTS frames and will finally drop the data packets when it reaches the RTS- retransmission- limit. The packets dropped due to the deafness problem will adversely affect the network utilization.

There are few reasons why the receiver points its directional antenna away from the sender i.e., designated as “deaf”. One of the reasons is illustrated in the Figure 2.6, where if nodes S and R are engaged in communication, if a node C wants to communicate with node B it will not have its DRTS being replied to. This is because node B is engaged in communication and its beam formed towards another direction hence node B is designated as “deaf” node.

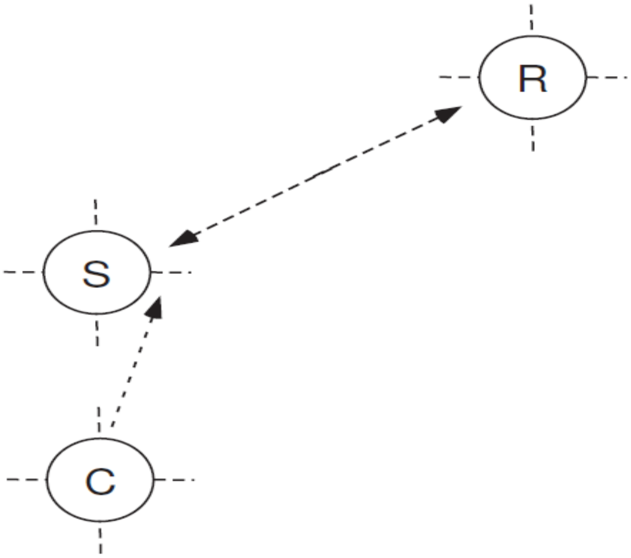

Figure 2.6. Problem of deafness.

2.4.4 Increased Collision Due to Ineffective Carrier Sensing

The collision problem becomes more significant, when using directional antennae. Figure 2.7 shows one such example, here node S is already communication with node R and node A sense and transmit directionally to node R, node A and node S cannot sense each other’s transmission. In this case, A’s transmission would collide with S’s transmission at node R.

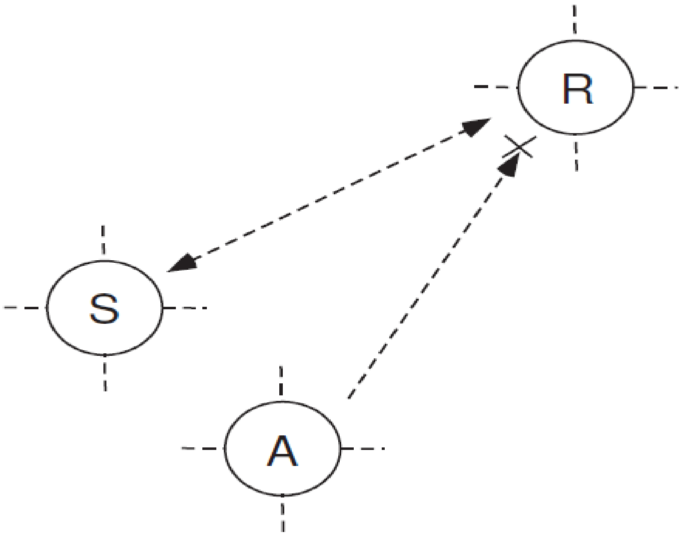

Figure 2.7. Collision problem.

CHAPTER 3

LITERATURE REVIEW

Currently there has been a lot of interest in terms of using directional antennae in wireless ad hoc networks [1-3, 5-6]. Hence an increasing number of directional MAC protocols have been proposed. In this section we will discuss few MAC schemes using directional antennas at its physical layer. And also describe the IEEE 802.11 handshake mechanism in detail.

3.1 IEEE 802.11 HANDSHAKE MECHANISM

IEEE 802.11 [7] employs a channel access scheme called Distributed Coordination Function (DCF) which is a contention-based MAC protocol based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [7] and assumes the use of omnidirectional antennas at the physical layer. Most of the current MAC protocols, such as IEEE 802.11 MAC standard, use a handshake mechanism implemented by exchanging small control frames named Request-to-Send (RTS) and Clear-to-Send (CTS). The successful exchange of these two control frames reserves the channel, as shown in Figure 3.1, for transmission of potentially longer data frame and a short acknowledgement (ACK) frame.

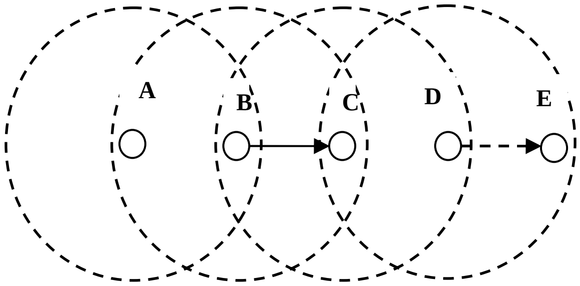

Figure 3.1. IEEE 802.11 handshake mechanism.

In 802.11 MAC protocol, any node that intends to transmit data must first send a RTS frame before it can start transmitting data frame. For example, in Figure 3.1, node B broadcasts a RTS frame; this short control frame contains the length of the data frame that will eventually follow, for its intended receiver, node C. Upon receiving the RTS successfully, node C replies with a CTS frame so that node B can start transmitting data frame. When node C successfully receives the data frame, it immediately sends out an ACK frame to node B. All the nodes within the radio range of node B and C will overhear one or both of those control frames, detect this transmission and avoid transmitting for the entire duration of the upcoming transmission between node B and C. This handshaking mechanism definitely avoids the collision due to hidden-terminal in wireless LAN environments. However, it is clear that this mechanism can waste a large portion of network capacity by reserving the wireless medium over a long duration. In essence, it does not mitigate the "exposed terminal" problem. For instance, if node D has data frames for node E while node B and C are communicating with each other, node D has to defer its transmission to E until the transmission from node B to C is completed though owning to the positional location and radio range of this network (Figure 3.1, p. 18), a communication between nodes D and E would not have interfered with a communication between nodes B and C.

3.2 MAC LAYER SCHEMES FOR AD HOC NETWORKS USING DIRECTIONAL ANTENNAE

The use of a directional antenna could increase the transmission range and hence make it possible to communicate directly with distant nodes, reduces the interference in other directions and also makes simultaneous communication possible even when nodes are in each other's radio range (spatial reuse). To utilize these advantages of directional antennae, many directional MAC protocols have been proposed. Figure 3.2 shows the classification of MAC protocols using directional antenna. We will describe some of the protocols in this section.

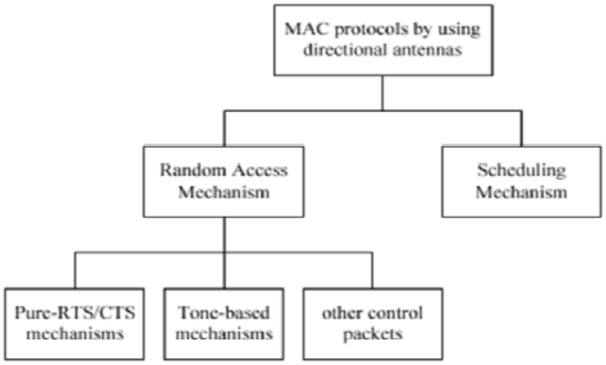

Figure 3.2. Classification of directional MAC protocols.

3.2.1 Vaidya's Directional MAC (D-MAC) Protocol Schemes

Young-Bae-Ko, Jong-Mu Choi and Nitin H. Vaidya [5] proposed a very interesting directional MAC protocol based on IEEE 802.11 protocol for ad hoc networks named "MAC protocol using directional antennas in IEEE 802.11 based ad hoc networks" and/or "Directional MAC (D-MAC) protocol". They proposed two schemes based on this protocol to alleviate the possibility of collision in the network.

3.2.1.1 ASSUMPTIONS

The Directional MAC (D-MAC) schemes assume that:

- Each node knows its exact location and the location of its neighbors using GPS or any other methods.
- Each node is equipped with multiple directional antennas or single electronically steerable parasitic array antenna system.
- Simultaneous transmissions by the same node in two different directions are not allowed.
- If node X received RTS or CTS related to other nodes, then node X will not transmit anything in that direction until that other transfer is completed. That direction or antenna element would be said to be "blocked"
- While one directional at some node be blocked, other directional at the same nodes may not be blocked, allowing transmission using the unblocked antenna

3.2.1.2 DIRECTIONAL MAC (D-MAC) PROTOCOL SCHEME 1

The Directional MAC (D-MAC) Schemes [5] are similar to IEEE 802.11 in many ways; it utilizes the directional antenna for sending the RTS (DRTS), whereas CTS are transmitted in all directions (OCTS). The Data and ACK packets are sent directionally. Any other node that overhears the OCTS only blocks the directional antenna on which the OCTS was received. The operation of D-MAC scheme 1 could be depicted using the scenario shown in Figure 3.3. Suppose that node B intends to send data to C and also suppose that there are no active transmissions within B's neighborhood. Thus, Node B transmits a directional RTS (DRTS) containing the B's physical location information to node C. If C receives the DRTS from B successfully, it replies with an omnidirectional CTS (OCTS) to

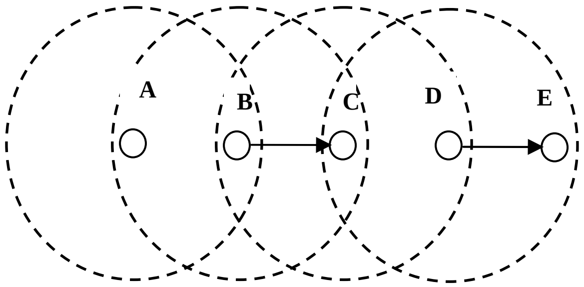

Figure 3.3. Operation of DMAC Scheme 1.

node B. This OCTS includes the location of node C and location of node B. All the nodes overhearing O-CTS from node C will block their respective directional antennas in the direction of transmission between node B and C. After a successful DRTS/OCTS exchange, node B starts transmitting data directionally and receives a directional ACK from Node C.

Now, during the proposed length of transmission between nodes B and C, assume that node D has data to transmit to node E. Note that the directional antenna of node D that points towards node C is blocked, since node D would have overheard the O-CTS (Omnidirectional Clear-to-Send) from node C on this directional antenna. Hence node D knows that its data transmission to node E would not interfere with the ongoing data transfer from node B to C. Therefore, node D can send a D-RTS frame to node E on that particular antenna. Eventually data frames follow. This can improve performance by allowing simultaneous transmissions between neighboring nodes.

Sending a DRTS frame in the direction of the intended receiver prior to the transmission of the actual data frames, instead of omnidirectional RTS (ORTS), increased the network performance [21]. It may also increase the probability of control packet collisions in some cases. We illustrated one such possible scenario in Figure 3.4. Assume node B has initiated a frame transfer to node C. Node A is unaware of this transfer because node B’s DRTS to node C has not been received by node A. Now, node A wants to send a data frame to node B. transmission of a DRTS by node A to node B may interfere with the reception of OCTS or ACK control frames sent by node C to node B. Note that node A does not defer its attempt to communicate with node B because node A has no ways of knowing the ongoing communication between node B and node C.

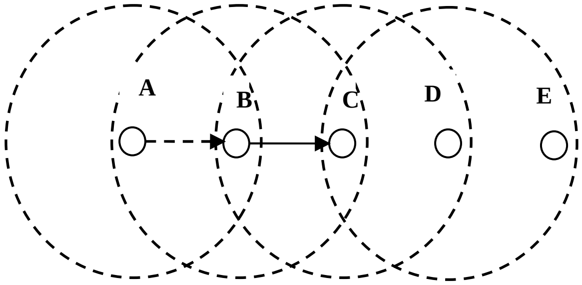

Figure 3.4. A possible scenario of collisions/deafness.

3.2.1.3 DIRECTIONAL MAC (D-MAC) SCHEME 2

Directional MAC (D-MAC) Scheme 2 [21] is proposed to reduce the probability of collisions between control frames (discussed in detail in the previous section). In this new scheme there are two types of RTS frames: DRTS and ORTS used according to the following rules – if none of the directional antennas at node X and blocked then node X will send ORTS otherwise, node X will send a DRTS provided that the desired directional antenna is not blocked. Consider the scenario depicted in Figure 3.5, assume that node B wants to send a data frames to node C, none of the antennas at B are blocked. In this case, node B will broadcast an ORTS frame. Node A receives this ORTS frame and blocks its directional antenna pointing towards B for the duration of the transfer from B to C. Now if node A wants to send data to node B, it will have to wait for the data transfer between B and C to complete as its directional antenna pointing in the direction is blocked. If node A wants to send data to node F, node A will send DRTS to node F, provided that the directional antenna pointing towards node F is not blocked.

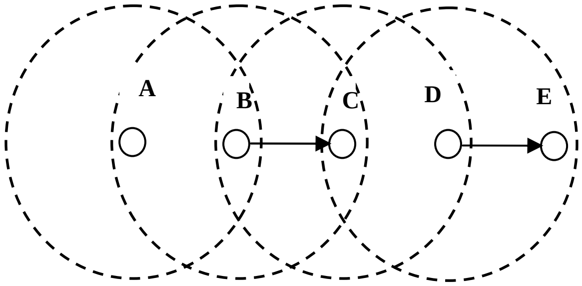

Figure 3.5. Operation of DMAC scheme 2.

3.2.2 The Mulithop RTS MAC (MMAC) Scheme

A Multihop RTS MAC (MMAC) scheme is introduced in [18] to exploit the higher transmission gain of directional antennas for transmission on multihop paths. The MMAC scheme can be considered an enhancement of the DMAC protocol. MMAC defines two types of neighbor nodes, Direction-Omni (DO) Neighbor and Direction Direction (DD) Neighbor. DO Neighbor refers to anode that has the ability to receive a directiona1 transmission even if it is in omni mode. Similarly, DD Neighbor refers to anode that can receive the directiona1 transmission only when its directiona1 receiving antenna has been pointed in the direction of the sender node. MMAC utilizes directional antennas for both transmission and reception. Each node is equipped with an omni directional antenna and an adaptive antenna. Since directional antennas provide a higher gain and communication range than omni directional antennas, anode could possibly communicate directly with the distant node. For that reason, MMAC utilized multiple hops to send RTS packets in order to establish connection with the node that is far away. The following CTS, data and acknowledgement packets are transmitted in single hop. MMAC could not solve the problems of deafness and hidden terminais, but it could compensate for the negative impact resulting from those problems, and therefore lead to improvement in performance.

MMAC scheme is presented briefly as follows using the scenario in Figure 3.6. Suppose that node A has data packet for node F. According to the MMAC scheme, the neighbor nodes can be classified into DO neighbors A-B-C-F and DD neighbors A-F. First a DRTS packet is sent by node A to F. Node D and G located between A<>F pair overhear this DRTS and hence defer transmission accordingly. When F receives the DRTS, in case that node F directs its directional antenna toward the direction of node A, the Direction-Direction (DD) link can be established directly and transmission can commence.

Otherwise, the DO neighbors would participate into the procedure of establishing the Direction-Direction communication between A<->F pair. A special type of RTS packet (called a forwarding-RTS) is used during this process. First node A transmits a forwarding-RTS packet to its DO neighbor-Node Band node B forwards it to node F via node C. Meanwhile, node A directs itself toward the direction of node F to wait for the DCTS from F. Note that node Band C forward this forwarding-RTS packet without using any backoff time

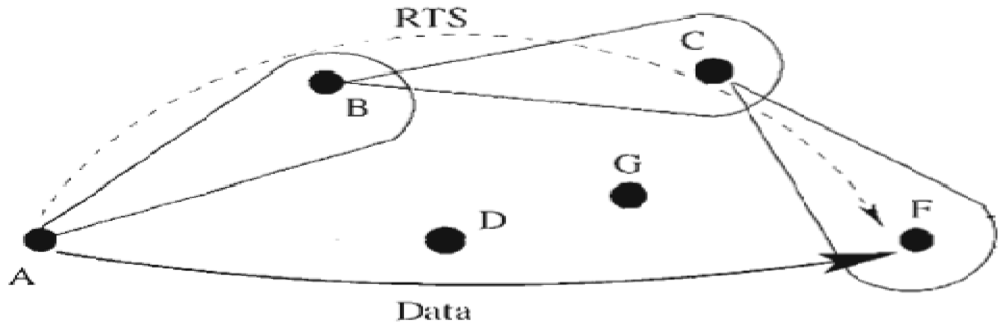

Figure 3.6. Multihop RTS MMAC scheme.

and will not update their DNAV tables in order to minimize the forwarding time consumption. Upon the receipt the forwarding-RTS, destination node F initiates a CTS packet and sends it to node A directionally. When node A receives the DCTS through DD route, the Direction-Direction (DD) link could be established successfully.

3.3 OTHER RELATED WORK

Apart from the previously discussed single-channel based directional MAC schemes, several multiple-channel based MAC protocols have also been proposed recently with the purpose of increasing the throughput. The maximum throughput of the single channel directional MAC scheme is limited by the bandwidth of that channel. By employing more channels properly, it is possible to increase the network throughput potentially. Some examples of multiple-channel MAC schemes include Dual Busy Tone Multiple Access (DBTMA), Multichannel Medium Access Control (MMAC), and Multichannel Carrier Sense Multiple Access MAC protocol. However, most of these protocols require additional spectrum resource and additional hardware.

3.4 SUMMARY

In this chapter, we reviewed the recent work in the area of ad hoc networks with directional antennas. Several medium access problems were presented first. We then discussed several recent proposed contention-based directional MAC protocols. These protocols are proposed to better exploit the capabilities of directional antennas. These proposals could achieve better throughput and end-to-end delay when compared with the IEEE 802.11. The performance also depends on topology configuration and traffic flows. The performance of network will degrade in the case that node mobility.

These proposed MAC protocols employ various antenna patterns and antenna gains when transmitting RTS/CTS/DATA/ACK. These directional MAC schemes use various methods to obtain node location information. For example, DMAC simply utilizes the extra GPS device to get the location information. MMAC and DVCS estimate the node location information by running different DOA algorithms.

CHAPTER 4

PROPOSED DIRECTION MAC SCHEME FOR AD HOC NETWORKS.

In this chapter we discuss in detail out proposed directional MAC protocol for ad hoc networks. We will talk about the antenna model used followed by proposed MAC protocol for ad hoc networks using directional antenna. We also discuss how our proposed protocol handles the problem due to directional deafness.

4.1 ANTENNA MODEL

We assume that all hosts in a region share a wireless channel and communicate on that channel. Each host is assumed to be equipped with multiple directional antennas. If the beam width of each directional antenna is θ, then the number of directional antennas required for a host is $K = 2\pi/\theta$. A directional antenna can transmit over a predefined beam pattern with a small angle. By doing so, several directional antennas (K) may be used together to cover the entire 2-dimensional space. Each beam includes one main lobe with several side lobes, each side lobe having a low gain [3]-[14]. We assume that the gain of the side lobes is negligible, thus ignoring the possibility of side lobe interference. Our antenna system is assumed to work in Omni-directional mode by using all (K) directional antennas and we also assume that the antenna system can transmit with any number of directional antenna at any given time. We also assume that a node can either transmit or receive directionally at any given instance in time, but not both [3]. A fundamental requirement of our scheme is access to positional information of a particular node and its neighbors. This can be obtained via a low-cost GPS installed in the node, triangulation, or various other methods [4]. Finally, we also assume that each node maintains a Directional Network Allocation Vector (DNAV) table in which it records the information of all the received Clear to Send (CTS) frames, duration of transmission and number of blocked directional antennas. We described our antenna model in detail in Chapter 2.

4.2 THE ALGORITHM

In this section, we illustrate our proposed MAC protocol for ad hoc network using directional antennas. Our protocol enables higher spatial reuse of the shared wireless channel thereby increasing network throughput and also eliminates the problem of deafness at receivers' end. In our protocol, the Request to Send (RTS) frames are sent directionally (which we refer to as D-RTS), whereas the CTS frames are transmitted on all unblocked directional antennas. DATA and Acknowledgement (ACK) frames are sent directionally too. It also maintains a Directional Network Allocation Vector (DNAV) table in which it records the information of all the received Clear to Send (CTS) frames, duration of transmission and number of blocked directional antennas.

In Figure 4.1, let us assume that node A has data frames for node B. Let us also assume that no other data transfers are in progress so none of the antennas on node A and B are blocked. In such a case node A sends a Directional-Request to Send (D-RTS) frame in the direction of node B. This D-RTS frame includes the physical location information of node A and the total length of the data frame that A wants to transmit to B. Upon receiving the D-RTS frame successfully from node A, node B replies with Omnidirectional-Clear to send (O-CTS) as none of the antennas on node B is blocked. This control frames include the physical location of the transmitter, (node A in our example) as well as its own location (i.e. node B in our example) and the duration of the data transmission. All the nodes hearing O-CTS from node B will block their respective directional antennas in the direction of transmission between node A and B and also update their DNAV table with duration of the transmission. After successful exchange of control frames, a data frame is sent by node A using directional antenna in the direction of node B. When node B receives the data frame, it immediately responds with an ACK to node A using directional antenna which points in the geographical location of node A.

Now, during the proposed length of transmission between nodes A and B, assume that node C, which is within the hearing range of node B, has data to transmit to node D. Note that the directional antenna of node C that points towards node B is blocked, since node C would have overheard the O-CTS (Omnidirectional Clear-to-Send) from node B on this directional antenna. Hence node C knows that its data transmission to node D would not interfere with the ongoing data transfer from node A to B. However, this blocked antenna is

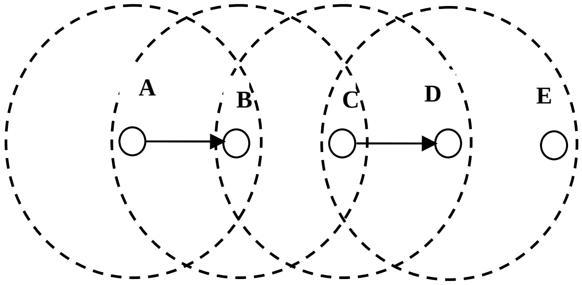

Figure 4.1. Example of using proposed scheme. Source: Y. B. Ko, V. Shankarkumar, and N. H. Vaidya. (2000, Mar.). ***Medium access control protocols using directional antennas in ad hoc networks.*** **[Online] Available: http://www.utdallas.edu/~ksarac/courses/Papers/WirelessBcast/MACusingDirectionalAntannasforAdHocNWs.pdf.**

different from the directional antenna that points towards node D. Therefore, node C can directional antenna. Hence node C knows that its data transmission to node D would not interfere with the ongoing data transfer from node A to B. However, this blocked antenna is different from the directional antenna that points towards node D. Therefore, node C can send a D-RTS frame to node D on that particular antenna. Eventually data frames follow. This can improve performance by allowing simultaneous transmissions between neighboring nodes thus increasing spatial reuse and thereby the network throughput.

In these scenario two simultaneous transmissions is possible without blocking any possible transmitter. In Figure 4.1 simultaneous transmissions between node A, B and node C, D is carried out, which is not possible using traditional 802.11 which assumes omnidirectional antenna at its physical layer and shares the bandwidth between this two connections.

Now let us consider another scenario as depicted in Figure 4.2. Let node A and B communicate with each other for some duration of time. Assume that node D has data for node C during that period of time. Node C is a neighbor of node B. Now node D sends the D-RTS in the direction of node C and expects a CTS frame from node C. Upon receiving the D-RTS frame, node C checks its DNAV table for unblocked directional antennas and then sends the CTS on all the unblocked directional antennas. Thus it sends CTS on all the

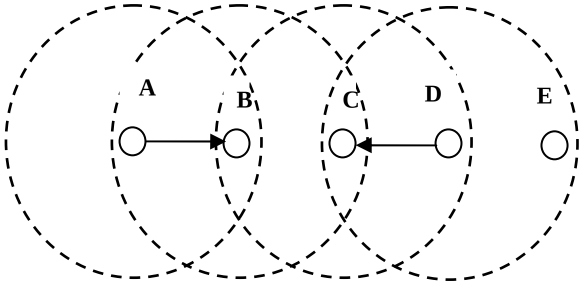

Figure 4.2. Benefit of using proposed scheme which facilitates simultaneous communication between nodes within hearing range (A to B and D to C).

antenna beams except for the one that points towards node B, thus avoiding a collision at node B. Suppose the duration of data transmission between nodes D and C lasts longer than the duration of data transmission between nodes A and B. As soon as the data transmission between nodes A and B ends, the blocked antenna of all the neighbors of node B (in this example node C) pointing in the direction of node B becomes unblocked. At this point node C should send the CTS frame in the direction of node B as well as node D. This control frame should also contain the remaining duration of data transmission between nodes C and D so that node B can update its DNAV table with the duration of transmission and block its directional antenna pointing in the direction of node C for the remaining amount of data transmission time between nodes C and D thereby avoiding a collision at node C. This feature has not been looked into in any of the existing papers in the literature [1-2, 5-6]. It substantially improves throughput when compared to the all omnidirectional transmission schemes in WLAN deploying IEEE 802.11 as validated from our simulation results.

Unlike previous scenario, both the receiver nodes are in each other's communication range as shown in Figure 4.2. Even then two simultaneous transmissions are possible without interfering with each other's transmission. This is not possible using traditional 802.11 and state of the art Directional-MAC (D-MAC) protocol which is a MAC protocol using directional antennas. In both the MAC protocols the bandwidth is alternatively shared between both the communications i,e.., node A,B and node D,C.

4.3 ADDITIONAL DISCUSSION

Let us consider Figure 4.3. Let us assume that node A has data frames for node B. Let us also assume that node B has its DNAV table set as shown in Table 4.1 i.e its antennas numbered 1, 2, 4 and 6 are blocked from receiving any transmission for durations of 30, 10, 70 and 120 ms respectively. Now, node A sends a D-RTS in the direction of node B. Upon receiving the D-RTS node B sends out CTS on all unblocked directional antennas (in this case antenna numbers 3 and 5). After successful exchange of this control frames, node A and B start communicating for some duration of time (let's say 100ms). Now directional antenna '2' of node B is blocked till 10 milli-seconds as shown in Table 4.1. According to our protocol, as soon as any antenna of node B is unblocked the next leaving CTS frame from node B should be sent on that antenna (directional antenna '2') as well in addition to the intended transmitter's direction (antenna '3' of node B in this example). This CTS frame also contains the total remaining time for data transfer from node A to node B (100-10=90 ms in this example). The entry from the DNAV table is removed when the total transmission time is expired or suitably updated as the case may be. Any node hearing this CTS frame will block their directional antenna in the direction of node B for the time duration mentioned in the CTS frame. This process repeats itself till total data is transmitted from node A to B (in this example till 100 ms), thus avoiding the interference and collision at node B there by exploiting the directional antenna to its fullest.

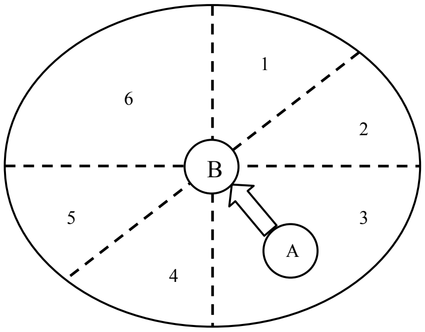

Figure 4.3. An example where node A has data frames for node B.

Table 4.1. A Record of DNAV Table Maintained at Node B

Receive Control Frame	Blocked Antennas	Total Transmission Time
CTS	1	30 ms
CTS	4	70 ms
CTS	2	10 ms
CTS	6	120 ms

4.4 DEAFNESS PROBLEM

In this sub-section we will discuss how our protocol deals with the problem of deafness. The deafness problem arises when the intended receiver is unable to respond with a CTS frame, while the sender continues to retransmit its RTS frame. The receiver is thus designated as “deaf”. Due to the fact that the sender node does not know that the receiver node is “deaf”, the sender node will continue to retransmit the RTS frames and will finally drop the data packets when it reaches the RTS- retransmission- limit. The packets dropped due to the deafness problem will adversely affect the network utilization.

The proposed protocol inherently deals with the problem of deafness at the receiver end by sending the hybrid CTS as shown in the Figure 4.4. We can also avoid this problem of deafness at the transmitter end by simply sending the hybrid RTS, following the same algorithm as the CTS to transmit the RTS as shown in the Figure 4.5. But this results in the blocking of the possible transmission thereby degrading the network throughput.

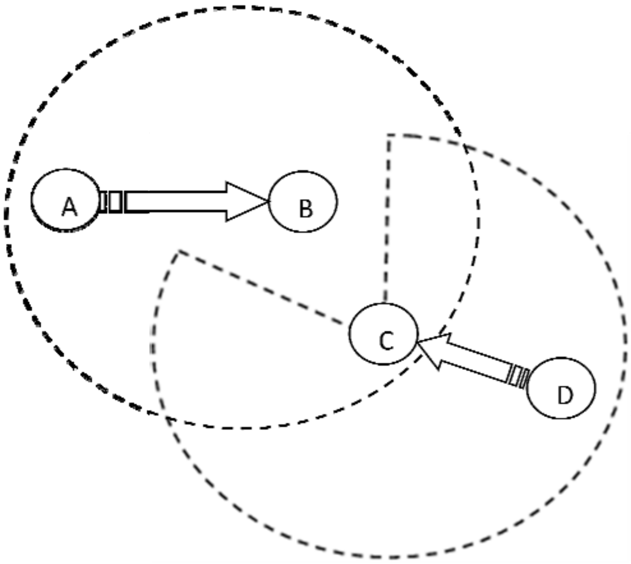

Figure 4.4. The transmission of the hybrid-CTS to overcome the deafness problem at the receiver end.

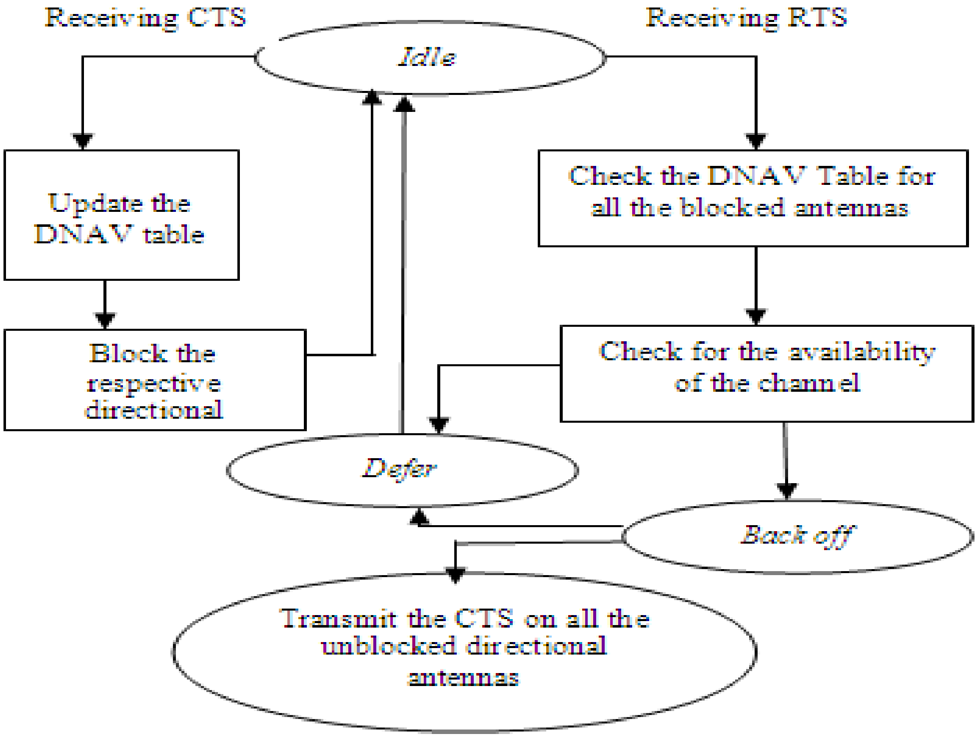

Figure 4.5. Flowcharts of our algorithm from the receiver's perspective.

CHAPTER 5

PERFORMANCE EVALUATION

In this chapter, we present performance results obtained using the network simulator ns-2. The results shows the performance gain of our proposed scheme over the traditional IEEE 802.11 and D-MAC in terms of network throughput.

5.1 INTRODUCTION TO NS2 SIMULATOR

NS (version 2.30) is an object-oriented, discrete event driven network simulator developed at UC Berkely written in C++ and OTcl (Tcl script language with Object-oriented extensions). It implements network protocols such as TCP and UPD, traffic source behavior such as FTP, Telnet, Web, CBR and VBR, router queue management mechanism such as Drop Tail, RED and CBQ, routing algorithms such as Dijkstra, and more. NS also implements multicasting and some of the MAC layer protocols for LAN simulations. NS2 includes a tool for viewing the simulation results, called NAM (Network Animator). NAM is a Tcl/TK based animation tool for viewing network simulation traces and real world packet trace data. NS has a rich library of network and protocol objects. There are two class hierarchies: the compiled C++ hierarchy and the interpreted OTcl one, with one to one correspondence between them. The compiled C++ hierarchy allows us to achieve efficiency in the simulations and faster execution times. This is in particular useful for the detailed definition and operation of protocols. This allows one to reduce packet and event processing time. Then in the OTcl script provided by the user, we can define a particular network and topology, the specific protocols and applications that we wish to simulate (whose behavior is already defined in the complied hierarchy) and the form of the output he we wish to obtain from the simulator.

5.2 SIMULATION SETUP

In this section, we present performance results obtained using the network simulator ns-2 [22]. In order to test the performance of our protocol, we compare it with the IEEE 802.11 standard protocol for WLANs and D-MAC [5] which is a one of the MAC protocols for directional antennas. The results show the performance gain of our proposed scheme over the traditional IEEE 802.11 and D-MAC in terms of network throughput. In our simulation we consider a rectangular area of dimensions 1000m X 1000m where 12 nodes are uniformly distributed. The transmission range of each node is 250m. The wireless link bandwidth is 2Mbps. The data packet size is assumed to be 1460 bytes. We also assume that an omni-directional transmission is achieved by using all of the sectors of the directional beams. Hence the transmission range of directional antenna is equal to the range of omni-directional antenna (250m). We assume that each node is equipped with six switched beams each of 60 degree beam width. Each simulation is performed for duration of 900 seconds. Table 5.1 summarizes the parameters used in our simulation.

Table 5.1. Simulation Parameters

Dimension	1000 x 1000 Sq. meters
Number of Nodes	12
Transmission range	250 meters
Link Bandwidth	2 Mbps
Data Packet Size	1460 Bytes
Beam Width	60°
Simulation time	900 Sec
Unit of Measure	Kilo bits per second (Kbps)

5.3 SIMULATION RESULTS

To evaluate the performance of our proposed protocol we consider four different scenarios which is sufficient to prove the merits of our scheme. The performance metric used is aggregate throughput achieved by the network (Kbps).

5.3.1 Throughput Performance Analysis for Scenario I

Scenario I: We first evaluate the performance of the scenario demonstrated in Figure 5.1. It consists of two TCP connections: one connection is between node 1 and node 2 and the other is between node 3 and node 4. Simulation results show that the throughput obtained by our protocol is significantly higher than IEEE 802.11 because simultaneous

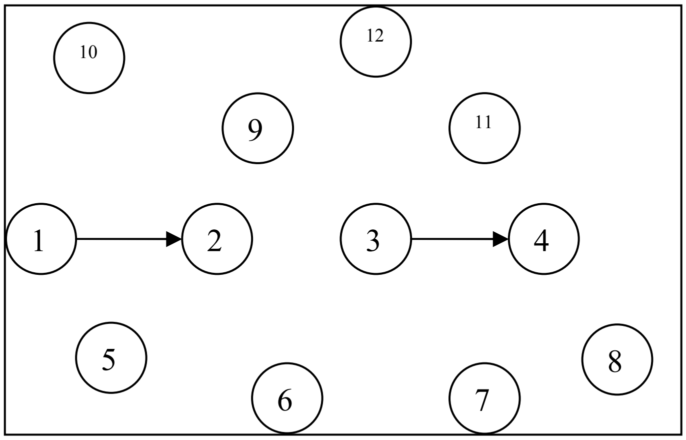

Figure 5.1. The network topology depicting Scenario I.

transmission on both the TCP connection is allowed by using our protocol which is not possible when using IEEE 802.11. Furthermore the total network throughput of IEEE 802.11 is comparable to that of a single TCP connection of both the directional MAC protocols. This is because the bandwidth is shared between two TCP connections of IEEE 802.11 which alternately uses the bandwidth thus yielding a throughput of 936.1 Kbps and 336.4 Kbps respectively in the two connections as depicted in Table 5.2. This bandwidth is otherwise available to a single connection when using directional MAC protocols as demonstrated in the values in Table 5.2. On the other hand, if we were to compare our scheme with D-MAC under the topology depicted in Figure 5.1, we would see almost an equivalent performance in terms of throughput. This is because D-MAC works in the same fashion as our scheme under the circumstances (connection established in Figure 5.1) depicted in Figure 5.1. Hence the simulation results are almost same for both the directional MAC protocols. The difference between our scheme and DMAC is brought about in Scenario III which we discuss shortly.

Table 5.2. Amount of Data Transmission between Node Pairs in Three Different Protocols in Scenario I

	802.11	DMAC	Our Protocol
1 → 2	936.139	1313.662	1490.770
3 → 4	336.448	1277.208	1188.427
Total	1272.587	2590.870	2679.197

5.3.2 THROUGHPUT PERFORMANCE ANALYSIS FOR SCENARIO II

Scenario II: Our second experiment examines the scenario shown in Figure 5.2. It consists of two TCP connections: one is between node 2 and node 1 and the other is between node 3 and node 4. This is the best scenario for the use of directional antenna, as the total network throughput is more than scenario I. The reason behind increased throughput in scenario II is the negligible probability of collision amongst control frames. If we compare our scheme with D-MAC under the topology depicted in Figure 5.2, we would see almost an equivalent performance in terms of throughput as shown in the Table 5.3 because both the protocols function in the same way to get the best out of directional antennas.

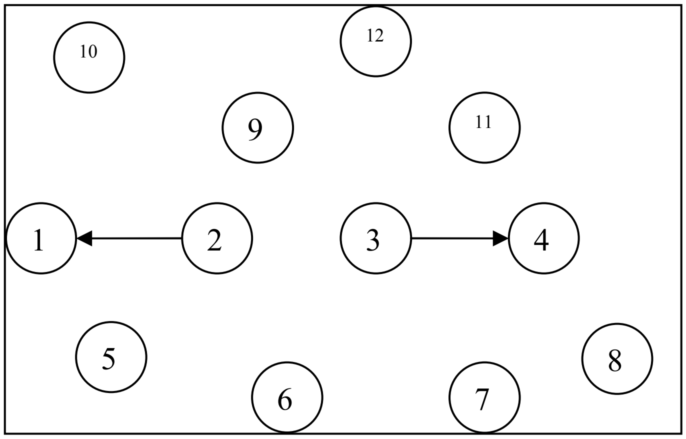

Figure 5.2. The network topology depicting Scenario II.

Table 5.3. Amount of Data Transmission between Node Pairs in Three Different Protocols in Scenario II

	802.11	DMAC	Our Protocol
2 → 1	645.372	1103.981	1352.258
3 → 4	620.493	1510.003	1431.980
Total	1265.904	2613.101	2784.239

5.3.3 THROUGHPUT PERFORMANCE ANALYSIS FOR SCENARIO III

Scenario III: In Figure 5.3 we simulate a scenario which showcases the novelty of our protocol. This scenario has not been simulated in any of the existing papers in the literature [1-2, 5-6]. It also consists of two TCP connections: one is from node 1 to node 2 and the other is from node 4 to node 3. Unlike the other two previous scenarios, the receiver nodes in Scenario III are within each other's hearing range. Using 802.11 and D-MAC, we would not have been able to have simultaneous transmission on both the TCP connections as the receiver's signals would have interfered with each other. The bandwidth would have been alternately shared between these two connections as was the case in our experiment. In contrast, our scheme was able to perform simultaneous transmission on both links owing to the directional transmission capabilities of the antennas used and thus yielded much higher throughput values than 802.11 and D-MAC as seen in Table 5.4. Network throughput of scenario III is slightly more than scenario I and almost equal to scenario II. The reason being the probability of collision of control frames is more in scenario I than any other scenarios. In all the experiments evaluated in this paper the throughput of directional MAC is better than IEEE 802.11-the reason is that the directional MAC allows simultaneous transmission on both TCP connections. Comparing with D-MAC [5], our scheme outperforms D-MAC in this scenario. This is because D-MAC does not allow simultaneous communication when two receivers are in each other's transmission range, which is the case in scenario III. However D-MAC behaves slightly better than IEEE 802.11 because it minimizes the retransmission of useless RTS frames due to timeout by introducing Directional Wait-to-Send (D-WTS) frame.

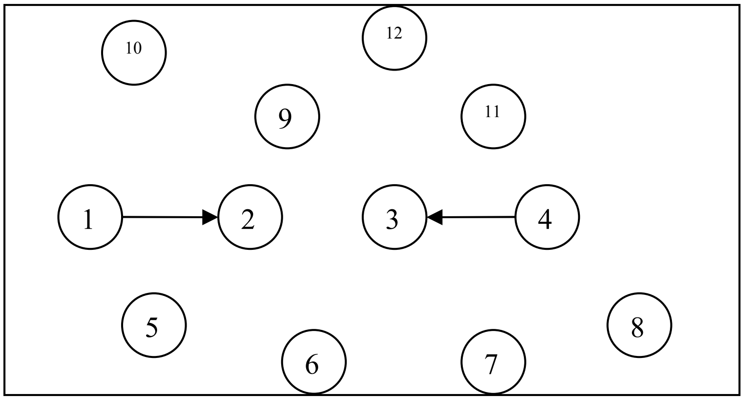

Figure 5.3. The network topology depicting Scenario III. It illustrates the novelty of our protocol.

Table 5.4. Amount of Data Transmission between Node Pairs in Three Different Protocols in Scenario III

	802.11	DMAC	Our Protocol
1 → 2	911.883	203.660	1761.863
4 → 3	383.726	1251.512	995.252
Total	1295.610	1455.172	2757.128

5.3.4 AT-A-GLANCE THROUGHPUT COMPARISON OF OUR PROPOSED

Figure 5.4 summarizes the above simulation results. It provides “at-a-glance” snapshot of the throughput comparison of our proposed scheme versus IEEE 802.11 MAC protocol and DMAC [5]. The 3 set of bar graphs denote the throughput obtained under three different network topologies, namely Scenarios I, II and III as discussed earlier in this section. The Y-axis in Figure 5.4 denotes throughput in Kbps. As we see from the figure, throughput of our scheme is significantly higher than IEEE 802.11 under all scenarios. This gain in throughput is attributed to mainly the use of directional antenna which greatly increases network capacity by utilizing the available bandwidth more efficiently through the deployment of our MAC protocol. Our MAC scheme shows outstanding performance especially in Scenario III, where two receivers are in each-other’s hearing range yet are able to carry-on simultaneous communication. Under such a daunting topology as Scenario III, we still see a significant increase in throughput when compared to IEEE 802.11 as well as DMAC which is directional MAC protocol, where such simultaneous communication will not be possible at all.

5.3.2 A Comparison of the Number of RTS Retransmissions

Our scheme also eliminates unnecessary RTS re-transmissions. To illustrate this point, we create a topology of 8 nodes with a maximum of 4 pairs of communication being carried on as depicted in Figure 5.5. In the first scenario, we assume that only connection 1 between nodes 0 and node 1 when node 0 sends an RTS to node 1, node 1 responds with a CTS and data transmission begins. Thus there are no RTS re-transmissions.

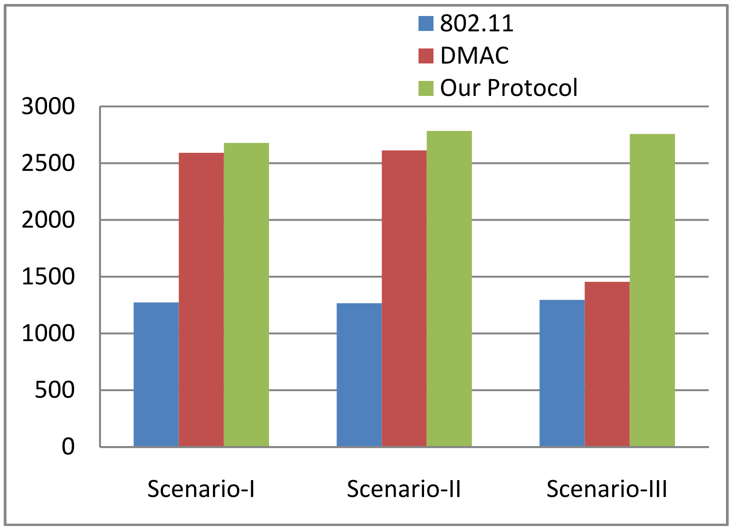

Figure 5.4. Throughput (in kbps) comparison of our scheme with 802.11 and DMAC under Scenarios I, II and III.

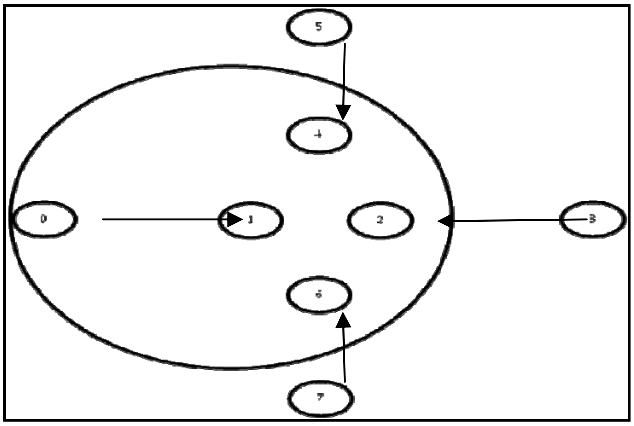

Figure 5.5. A topology with four different connections between node 0 and node 1 (marked as connection 1) between node 3 and 2 (marked as connection 2) between node 7 and 6 (marked as connection 3) and between node 5 and 5 (marked as connection 4).

Now, when node 3 sends an RTS to node 2 to establish connection 2, node 2 that is within the hearing range of node 1, is aware of the ongoing communication between node 0 and 1 and realizes that if it sends a CTS response to node's 3 RTS, then it will interfere with the data reception at node 1. Thus it refrains from sending CTS to node 3 and will actually not send one, till the communication between nodes 0 and1 is over. However node 3 not having received a CTS response from node 2 will assume that its RTS got “lost in transmission” and hence will keep re-transmitting the RTS to which node 2 will turn a deaf ear. In contrast, when using our proposed protocol, this problem won’t exit. In such a scenario node 2 will transmit a CTS directionally to node 3 thus eradicating the repeated RTS re-transmission problem. The number of RTS re-transmissions in the system further increases when node 7 wants to establish connection number 3 with node 6 and further more when node 5 wants to establish a connection (we mark it as connection number 4 in Figure 5.5, p. 39) with node 4.

Figure 5.6 quantifies the number of RTS retransmissions that happen in the system when the following connection attempts are made: 1 connection (indicated by ‘I’ in the X-axis of Figure 5.6), 2 connections, 3 connections and finally 4 connections. As seen in Figure 5.6, the Y-axis denotes the number of RTS retransmits that happens due to the above number of connection attempts in the topology depicted in Figure 5.5 (p. 39). In contrast, our scheme (denoted by the red line) yields 0 RTS re-transmissions, as each node responds with CTS at all time on only the unblocked directional antennas. The utility of this hybrid CTS response is three folds – (a) it avoids collision with exiting receiving node in its radio range and (b) it eradicates the problem of deafness by simply responding with the CTS for every RTS received or blocking all the possible RTS when the node is active receiver (i.,e “deaf node”) finally (c) it eliminates the problem of useless RTS retransmissions thus saving valuable network resources, especially bandwidth.

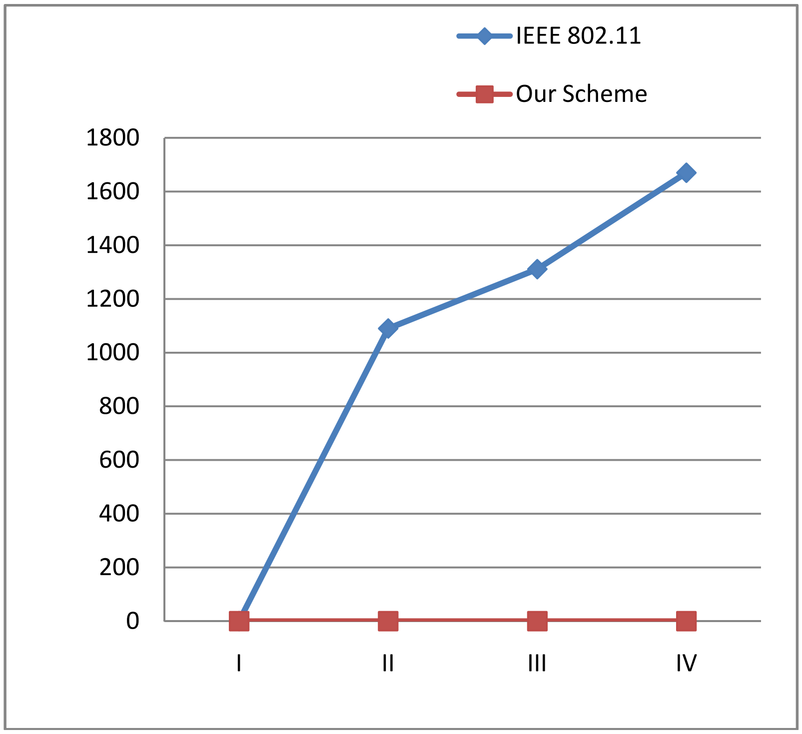

Figure 5.6. A comparison of the number of RTS retransmissions.

CHAPTER 6

CONCLUSION AND FUTURE WORK

In this thesis, we propose a novel MAC protocol for ad hoc networks using directional antenna. We use a switched beam antenna for data transmission. Our MAC protocol maintains a Directional Network Allocation Vector (DNAV) table, wherein the information about received Clear-to-Send (CTS), total time of transmission and blocked directional antenna is recorded. The Request-to-Send (RTS) frames are sent directionally, whereas the Clear-to-Send (CTS) frames are sent on all the unblocked directional antennas. Finally DATA and ACK frames are sent using directional antennas. As a result it allows simultaneous transmission and reception of data frames amongst neighboring nodes thereby increasing network throughput. Our proposed protocol outperforms conventional IEEE 802.11 and D-MAC (scenario III). Simulation result shows significant increase in throughput when compared to IEEE 802.11 and D-MAC. Future work includes implementing our scheme for multi-hop transmissions using directional antennas.

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