A Directional-to-Directional (DtD) MAC Protocol for Ad hoc Networks

by

Emad Shihab

B.Eng, University of Victoria, 2006

A Thesis Submitted in Partial Fullfillment of the
Requirements for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Electrical and Computer Engineering

A Directional-to-Directional (DtD) MAC Protocol for Ad hoc Networks

by

Emad Shihab

B.Eng, University of Victoria, 2006

Supervisory Committee

Dr. Lin Cai, Supervisor
(Department of Electrical and Computer Engineering)

Dr. Hong-Chuan Yang, Department Member
(Department of Electrical and Computer Engineering)

Dr. Jianping Pan, Outside Member
(Department of Computer Science)

Dr. Sudhakar Ganti, External Examiner
(Department of Computer Science)

Supervisory Committee

Dr. Lin Cai, Supervisor
(Department of Electrical and Computer Engineering)

Dr. Hong-Chuan Yang, Department Member
(Department of Electrical and Computer Engineering)

Dr. Jianping Pan, Outside Member
(Department of Computer Science)

Dr. Sudhakar Ganti, External Examiner
(Department of Computer Science)

Abstract

The use of directional antennae in ad-hoc networks has received growing attention in recent years because of the benefits including, high spatial reuse, higher antenna gains, etc. At the same time, using directional antennae introduces new challenges. For example, the problem of deafness where receiver nodes may not hear handshake messages because their antennae beams are not pointing in the direction of the sender. To address these issues, new directional MAC protocols are required. In the literature, the existing directional MAC protocols assumed that nodes can operate in both directional and omni-directional modes. However, using both directional and omni-directional modes of operation leads to the asymmetry-in-gain problem and defeats the purpose of using directional antennae [1].

In this thesis, we propose a directional-to-directional (DtD) MAC protocol where both the sender and the receiver operate in directional mode only. The first part of our design studies the issues related to directional MAC protocols and we use this knowledge to carefully design the DtD MAC protocol. The DtD MAC protocol is fully distributed, does not require synchronization, eliminates the asymmetry-in-gain problem and alleviates the problems due to deafness.

To evaluate the performance of the DtD MAC protocol, we build an analytical model that measures the saturation throughput of the DtD MAC protocol in terms of the number of nodes contending for the channel, the packet payload size and the antennae beamwidth. The analytical results were verified through extensive simulations.

We show that the DtD MAC protocol can provide significant throughput improvement in ad-hoc networks if the number of antennae sectors is chosen appropriately. Furthermore, we study the fairness of DtD MAC using Jain's Fairness Index. Finally, the performance of the DtD MAC protocol is evaluated for the high data rate Millimeter Wave (mmWave) technology. The results obtained are promising and show that DtD MAC can improve the performance of networks using such high data rate technologies.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ACK	Acknowledgement
AoA	Angle of Arrival
BEB	Binary Exponential Backoff
BO	Backoff
bps	Bits per second
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to second
DATA	Data packet
DCF	Distributed Coordination Function
DCTS	Directional Clear To Send
DIFS	Distributed Inter-Frame Space
DNAV	Directional Network Allocation Vector
DRTS	Directional Request To Send
DtD	Directional-to-Directional
DVCS	Directional Virtual Carrier Sending
FDMA	Frequency Division Multiple Access
GHz	Gigahertz
GPS	Global Positioning System
Gbps	Gigabit per second
LHS	Left hand side
MAC	Medium Access Control
Mbps	Megabit per second

mmWave	Millimeter Wave technology
PHY	Physical layer
RHS	Right hand side
RTS	Request to send
SIFS	Short Inter-Frame Space
SINR	Signal to Interference plus Noise ratio
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
UWB	Ultra-Wideband technology
WLAN	Wireless local area network
WPAN	Wireless personal area network

List of Symbols

$ACK_{TIMEOUT}$	Timeout value for ACK packet
BO_i	BO time between the $(i-1)^{th}$ and i^{th} DRTS
BO_{max}	Maximum BO time
$Carrier\ sense$	Carrier sense time
C_D	Channel capacity using directional antenna
C_O	Channel capacity using omni-directional antenna
$DATA_{MaxNum}$	Maximum number of retries for DATA packets
$DATA_{TIMEOUT}$	Timeout value for DATA packet
$Datarate_M$	Data rate for a node with M antenna sectors
$E[access\ delay]$	Average access delay
$E[BO_f]$	Average BO time spent in the failure state
$E[BO_s]$	Average BO time spent in the success state
$E[DRTS\ Txs]$	Average time spent transmitting DRTS packets
$E[P]$	Payload size
G_C	Channel gains
G_R	Receiver antenna gain
G_{RD}	Directional receiver antenna gain
G_{RO}	Omni-directional receiver antenna gain
G_T	Transmitter antennae gain
G_{TD}	Directional transmitter antennae gain
G_{TO}	Omni-directional transmitter antenna gain
H	$(PHY + MAC)$ Header length
k_M	Directional to omni-directional gain ratio with M antenna sectors
M	Number of directional antennae sectors
N	Number of active nodes

p	Conditional failure probability
p_1	Probability of receiver node being idle at time of transmission
p_2	Probability that transmitter signal is strong enough at the receiver
p_3	Probability that no stations in the sender's beam initiating a transmission in the receivers direction in the $(2t_{rts} + 2)$ slot times
P_{id}	Transition probability from the idle state to the defer state
P_{if}	Transition probability from the idle state to the failure state
P_{ii}	Transition probability of staying in the idle state
P_{io}	Transition probability from the idle state to the overhear state
P_{ir}	Transition probability from the idle state to the receiver state
P_{is}	Transition probability from the idle state to the success state
P_{di}	Transition probability from the defer state to the idle state
P_{fi}	Transition probability from the failure state to the idle state
P_{oi}	Transition probability from the overhear state to the idle state
P_{ri}	Transition probability from the receive state to the idle state
P_{si}	Transition probability from the success state to the idle state
P_R	Received power
P_T	Transmission power
SNR_D	Signal to Noise ratio with directional antenna
SNR_O	Signal to Noise ratio with omni-directional antenna
T_d	Average time period spent in each defer state
T_f	Average time period spent in each failure state
TH	Throughput in bits per second

T_i	Average time period spent in each idle state
T_o	Average time period spent in each overhear state
T_r	Average time period spent in each receive state
t_{rts}	Number of time slots required to transmit one DRTS packet
T_s	Average time period spent in each success state
W	Bandwidth
W_{min}	Minimum contention window size
W_{max}	Maximum contention window size
α	Duration of one time slot
θ	Antenna beamwidth angle
ξ	Propagation delay
$\pi^{'}$	Steady state probability that the continuous time semi-Markov state process resides in the idle state at any time
π_d	Defer state probability
π_f	Failure state probability
π_i	Idle state probability
π_o	Overhear state probability
π_r	Receive state probability
π_s	Success state probability
$\tau(p)$	Packet transmission probability

Acknowledgment

First and foremost, I would like to thank Allah for blessing me with this opportunity. Then, I would like to thank my supervisor Dr. Lin Cai for her endless support. Without the many answers to my door knockings, your great patience and fruitful guidance I would not be the researcher I am today. I will be forever grateful.

I would also like to acknowledge the unaccountable support I received from Dr. Jianping Pan. I thank you for all your answers to my many questions. I thank you for inspiring in me a person who interprets results instead of one who just reads them. My group partners Ivan Zhang, Fengdan Wan, Haoling Ma and Yeting Yu thank you for being there and bearing with me during the best and the worst of times.

To all my friends, Haytham El Miligi, Mohammed Fayed, Ahmed Awad, Ahmed Abudllah, Mohammed Marsono, Omar Ishkintana and all the others who I do not mention here, thank you for making me a better person. I am truly blessed to be surrounded by such unique and intriguing characters.

Dr. Ahmed Hassan, thank you for listening to me and giving me excellent advice. Thank you for all the discussions which evolved my ability to write effectively. Your honest feedback and guidance is sincerely appreciated.

Last and certainly not least, I would like to thank my grandparents, parents and brothers for believing in me and sacrificing all they had to see me cross this finish line. I pray day and night, to one day, return a small portion of what you have given me. Your emotional, academic and financial support is invaluable to me. To my wife, I thank you for your patience, kindness and guidance. You are truly a special and wonderful person. I am grateful to have you in my life.

Emad Shihab, Victoria, BC, Canada

Dedication

To my father Dr. Yousef Shihab, mother Dr. Shehnaz Nadir Ali and brothers Ayman and Essam

Chapter 1

Introduction

In this thesis, we propose a directional-to-directional (DtD) Medium Access Control (MAC) protocol for ad hoc networks where both source and destination nodes use directional antennae exclusively to carry out their communication.

1.1 Motivations and problem formulation

The use of directional antennae in ad hoc networks has received growing attention in the past few years [2], driven by the benefits of directional antennae. These benefits include high spatial reuse, longer transmission range, lower interference, etc. In addition, new technologies that operate at high frequencies (60GHz), such as Millimeter Wave (mmWave), need to use directional antennae to perform well [3]. This is because, at such high frequencies, the signal suffers from high path loss due to oxygen absorption and atmospheric attenuation, which can be compensated in part by the high antenna gain of directional antennae.

At the same time, using directional antennae poses new challenges. Designing efficient wireless MAC protocols to deal with these challenges is key to the success of using directional antennae in ad hoc networks. Some directional MAC protocols were proposed in [4–7] that were specifically designed to work with directional antennae. Most of these protocols are based on the IEEE 802.11 Distribute Coordination Function (DCF) MAC protocol and use different flavors of the four way handshake to cope with the challenges introduced by the use of directional antennae. In addition to using the Request To Send/Clear To Send (RTS/CTS) message exchanges, some of these protocols (such as in [8]) make use of a Directional Network Allocation Vector (DNAV) and Angle of Arrival (AoA) caching. DNAV is a mechanism used by nodes to keep records of the ongoing transmissions by their neighbors in each direction. AoA caches the angles of signals that a node overhears, whether they are intended for them or not. Using DNAV and AoA helps nodes discover which direction their neighbors are located in.

One basic assumption that all these MAC protocols make is that nodes can operate in both, directional and omni-directional modes. Omni-directional mode is used by idle nodes so they can hear any Directional RTS (DRTS) that is sent by their neighbors. This alleviates the problems caused by deafness [9] (discussed in more detail in Sec. 2.4.4). At the same time, implementation cost may be higher if nodes need to be equipped with two types of antennae, directional and omni-directional. Furthermore, operating in both directional and omni-directional mode may defeat the purpose of using directional antennae [1] due to the asymmetry-in-gain problem [10] (discussed in more detail in Sect. 2.4.2). In [10], the authors studied the effect of transmitting control packets omni-directionally and concluded that the omni-directional transmission of some control packets will in fact impede the ability of directional antennae to achieve better throughput.

To overcome the aforementioned problems, we propose equipping nodes with a *single* directional antenna, whether it is switched beam or steerable. However, using directional-only mode introduces new challenges at the MAC layer. For example, the deafness problem is magnified by manyfold now. Also, nodes can only sense one direction at any time; therefore, it has less chance of setting its DNAV for all ongoing communications.

Dealing with these problems requires the use of an efficient wireless MAC protocol that can handle the new challenges posed by directional-only communication. In this thesis, we propose a wireless MAC protocol specifically designed to handle DtD communications in ad hoc networks.

The protocol is called Directional-to-Directional (DtD) MAC protocol that operates in directional-only mode. As will be shown later in this thesis, the performance of such deployment is quite different from the scheme most researchers use under the assumption that nodes can operate in both directional and omni-directional modes.

1.2 Contributions

In this thesis, we propose a new wireless MAC protocol for directional-to-directional transmission called DtD MAC. DtD MAC is built based on the assumption that nodes are equipped with a *single* directional antenna. The proposed protocol is fully distributed, which does not require synchronization, eliminates the asymmetry-in-gain problem evident in other directional MAC protocols (e.g. [5]) and alleviates the effects of deafness and collisions. The performance of the protocol is studied using three different metrics: saturation throughput, access delay and fairness. To achieve this, we build an analytical model to study the performance of DtD MAC and verify the results with extensive simulations. To gain insight into the performance of DtD MAC for high data rate technologies, we use the proposed analytical model to study the performance of the DtD MAC protocol for mmWave and the results obtained were promising.

1.3 Thesis Organization

In Chapter 2, we provide some background information, present the related work 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 also presented in this chapter.

In Chapter 3 the DtD MAC protocol is detailed. All of the components that assemble DtD MAC and their functionalities are outlined. The chapter is summed up with a discussion about the advantages of the DtD MAC protocol.

The analytical model used to study the performance of the DtD MAC protocol is presented in Chapter 4. A Markov chain is built to model the DtD MAC protocol and the antenna model are presented. Then, the derivation of the transition and steady state probabilities are shown. An expression for the saturation throughout in terms of the antenna beamwidth, the packet size and the number of channel contenders is given.

In Chapter 5 we study the performance of the DtD MAC protocol through simulations. We present simulation and numerical results for throughput, delay and fairness. We then show that the proposed DtD MAC protocol is a feasible solution for emerging wireless technologies, like mmWave. The thesis is summarized, and suggestions for future research directions are stated in Chapter 6.

Chapter 2

Background and Related Work

2.1 Wireless MAC protocol basics

The area of wireless networking has seen explosive 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 the network protocol stack. For example, at the application layer, developers are racing to provide new functionality to satisfy the consumers needs. At the physical layer, scientists and researches are striving to push current technologies to their limits, while at the same time, design new technologies to support higher 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 [11], 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 protocols can be divided into two main categories: distributed protocols and centralized protocols [12]. 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 three major access techniques [13]: Frequency Division Multiple Access (FDMA) [14], Time Division Multiple Access (TDMA) [15] and Code Division Multiple Access (CDMA) [16]. 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 a pseudo-noise code sequence that has a chirp 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 is that nodes send short control messages before transmitting to let others know of their near future communications.

One of the most widely deployed distributed wireless MAC protocols is the IEEE 802.11 Distributed Coordination Function (DCF) [17]. In the following, we describe the operation of the IEEE 802.11 DCF MAC protocol.

2.2 IEEE 802.11 DCF

The IEEE 802.11 DCF MAC protocol was designed to operate using omni-directional antennae. In the basic mode of DCF, a node intending to transmit a packet senses the channel first. If the channel is sensed idle for Distributed InterFrame Space (DIFS) time, the node transmits. If the channel is sensed busy or becomes busy during the DIFS time, the node continues to sense the channel until the channel is idle for DIFS time. After the channel 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 be waiting simultaneously. DCF 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 W_{max}. The backoff counter decrements by 1 for every time slot that the channel is sensed idle. If the channel becomes busy during this backoff stage, 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, such as the hidden terminal problem. In Fig. 2.1 , the hidden terminal problem can be explained as follows. If node S sends a packet to R and at some time, Z transmits, a collision occurs at R. This is because Z cannot sense the transmission from S and is hidden to S. To alleviate the hidden terminal problem in ad hoc networks, a four-way handshake mechanism is used.

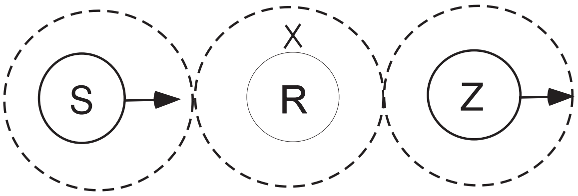


Figure 2.1: Hidden terminal problem using omni-directional antennae

Using the four-way handshake, after the channel is sensed idle for DIFS 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 Short InterFrame Space (SIFS) time. Once the CTS frame is successfully received by the initial sending node, it can then continue to transmit its data packet 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 their Network Allocation Vector (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.

This four-way handshake is very effective because it reduces the length of the 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 during collisions is reduced [18].

2.3 Directional Wireless MAC protocols

Due to the advantages that can be achieved by using directional antennae, the design of MAC protocols for directional antennae has received growing attention in the past few years. These advantages are: higher spatial reuse, reduced interference to other nodes, greater transmission range and lower power usage. These benefits improve the performance of ad hoc [19] and Wireless Mesh Networks (WMNs) [20]. In addition, it is desirable for new technologies that operate at high frequencies, such as mmWave [21] at 60 GHz which uses directional antennae to perform well [3].

mmWave has emerged as one of the most promising candidates for up to multi-gigabit wireless indoor communication systems [22]. One of the major advantages making the mmWave technology increasingly popular is the huge unlicensed bandwidth available (from 57-64 GHz) [21]. In addition, the bandwidth at the 60 GHz frequency is continuous and less restricted in terms of power limits than Ultra-Wideband (UWB). The antennae size at 60 GHz can be very compact which permits nodes to be equipped with multiple antenna sectors. However, at such high frequencies the signal suffers from high path loss due to oxygen absorption and atmospheric attenuation. Therefore, using directional antennae with high antenna gain is desirable. At the same time, these advantages introduce new challenges at the MAC layer. For example, nodes with directional antennae may not be able to listen to all directions, and therefore, miss an incoming RTS packet (called deafness).

It is obvious that MAC protocols that were originally designed for use with omni-directional antennae (such as IEEE 802.11 DCF) do not perform well when directional antennae are used [5].

Thus, new MAC protocols are emerging (such as in [4–7,23]) that were specifically designed to work with directional antennae. Most of these protocols are based on the IEEE 802.11 DCF MAC protocol and use different flavors of the four way handshake to cope with the challenges introduced by the use of directional antennae. In addition to using the RTS/CTS message exchanges, some protocols (such as [8]), use the DNAV and AoA mechanisms to discover which direction their neighbors are located in.

2.4 Challenges facing directional MAC protocols

In this section, we discuss some of the difficulties to design MAC protocols for nodes that use directional antennae exclusively. Problems such as neighbor discovery, the hidden terminal and deafness have been discussed in great detail in [8] and [9]. The next few sections present scenarios that help explain and hence understand these problems.

2.4.1 Neighbor discovery

Neighbor discovery is a challenging problem when directional antennae are used [24–26]. When using omni-directional antennae, the problem is quite different because each node transmits omni-directionally. Therefore, nodes can discover their one hop neighbors quite easily. However, when directional antennae are used, nodes can only sense part of their neighbors at any time instant (the neighbors that it is beamformed towards and the subset of neighbors which are, at the same time, pointing towards the source node itself). Reference [27] classified neighbor discovery algorithms into two categories: direct discovery algorithms and 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. Gossip based algorithms are based on the fact that nodes gossip about each others' location information. For the latter, it is assumed that each node knows its location using locating devices such as Global Positioning System (GPS). To achieve gossip based discovery, nodes can randomly scan the network and exchange Hello messages 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 Asymmetry-in-gain problem

The asymmetry-in-gain problem is evident in ad hoc networks where nodes are equipped with both, directional and omni-directional antennae. Referring to Fig. 2.2, the asymmetry-in-gain problem occurs when node S's omni-directional transmission does not reach node R, however, node R is within node S's directional radial range. This problem magnifies the deafness problem if control packets are sent omni-directionally or idle nodes listen omni-directionally. However, using directional-only transmissions solves this issue.

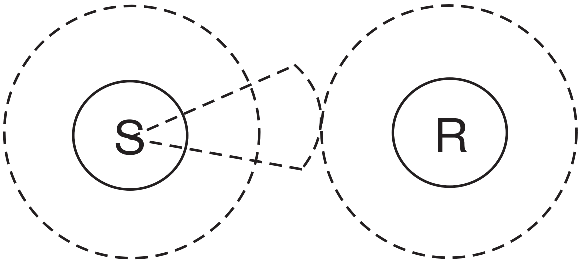


Figure 2.2: Asymmetry in gain problem

2.4.3 Directional hidden terminal

The directional hidden terminal problem occurs when a sender orients its antenna towards a new direction, without being aware of the channel condition. Referring to Fig. 2.3, node S sends a DRTS (directional RTS) to node R which replies with a DCTS, and the DATA/ACK exchanges are ongoing. Node C was engaged in communication with node B. When node C finishes its communication with B, it would like to send packets to R (or other nodes in the direction of R). If node C sends a 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 R.

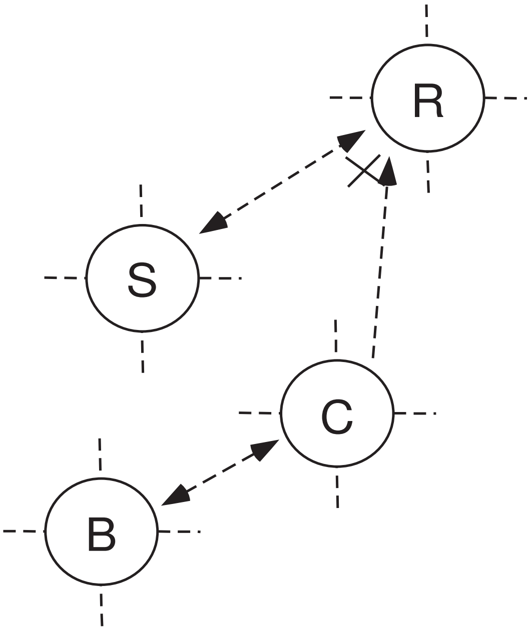


Figure 2.3: Hidden terminal problem in directional antennae

2.4.4 Deafness

Deafness in directional antennae networks is one of the most difficult problems to solve. The work in [9] and [28] gave a comprehensive description of this problem. In this section, we will give an outline of these problems and focus on the points that are essential for this thesis.

Generally speaking, deafness is caused when a sending node S does not get a reply from the intended receiving node R because R is beamformed towards a direction that is away from S. There are a few reasons why the receiving node R is pointing in a direction away from S. We classify these situations as follows:

- **Destination engaged in communication:** Refereing to Fig. 2.4, we can see that if nodes S and R are engaged in communication, if a node C wants to communicate with node S it will not have its DRTS being replied to. This is because node S is engaged in communication and is beamformed towards another direction.

- **Persistent hearing of DATA:** The persistence hearing of DATA problem is only evident in some directional MAC protocols, but not all. Considering the scenario in Fig. 2.5, this problem occurs when nodes S and R are in communication and idle nodes in the transmission path (i.e. node B) set their DNAV and beamform in the direction of the DATA (i.e. towards node S) to receive the DATA. Now if a node C would like to communicate with node B it is unable to do so, because node B is deaf.

- **Idle destination not pointing in the direction of source:** As shown in Fig. 2.4, even if node R is not engaged in communication, it might still not hear the DRTS from S because it might be pointing in another direction. This issue is evident in directional-only ad hoc networks.

2.4.5 Increased collision due to ineffective carrier sensing

Using directional antennae, the collision problem becomes more significant. For example, in Fig. 2.6, since nodes A and S sense and transmit directionally, they cannot sense each other's transmission. In this case, A's transmission would collide with S's transmission at node R.

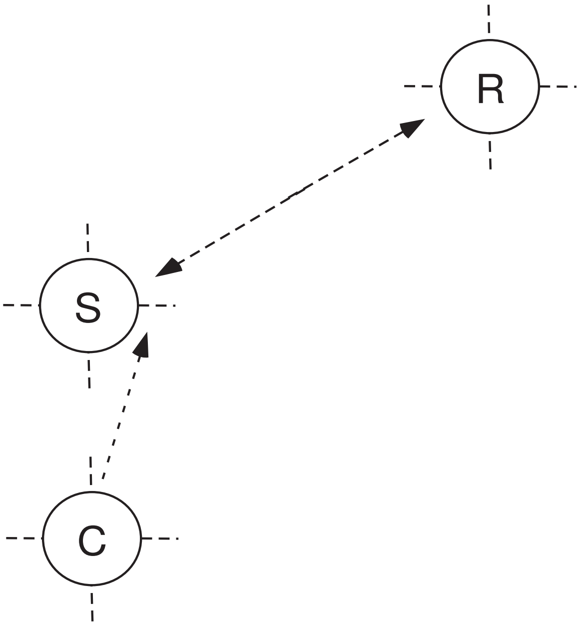


Figure 2.4: Destination engaged in communication

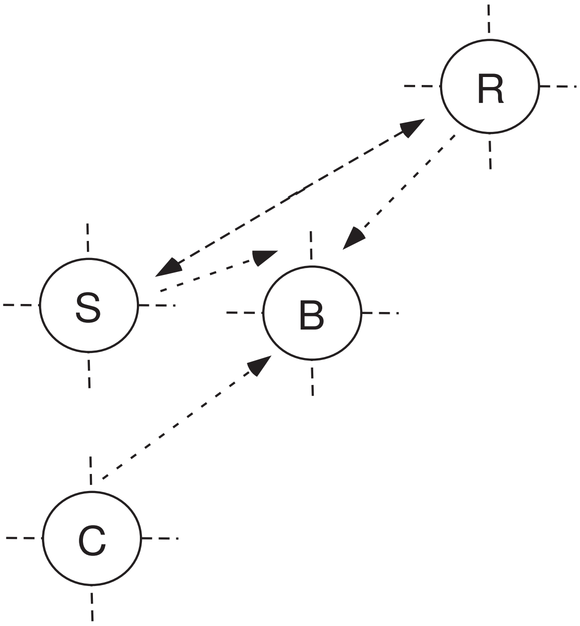


Figure 2.5: Persistent hearing of DATA

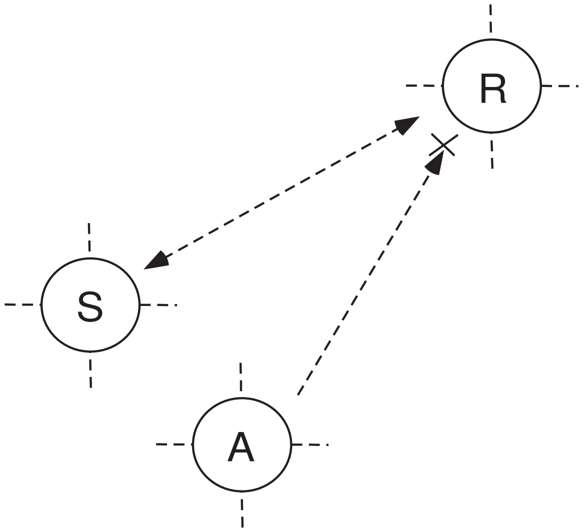


Figure 2.6: Collision problem

2.5 Related work

In recent years, an increasing number of directional MAC protocols have been proposed. These protocols can be classified into two categories: directional-to-omni-directional MAC protocols and directional-to-directional MAC protocols. Directional-to-omni-directional protocols assume that nodes can operate in both directional and omni-directional mode. They often use directional mode at the sender and omni-directional modes at the receiver to eliminate the deafness problem. On the other hand, using two types of antennae introduces other issues such as the asymmetry-in-gain problem. Directional-to-directional MAC protocols assume the use of directional antennae at both the sender and the receiver, which has its advantages and disadvantages. For example, the deafness problem becomes much more significant when the receiver operates in directional mode. At the same time, the asymmetry-in-gain problem no longer exists when the only mode of operation is directional. It is up to the MAC protocol to introduce mechanisms to deal with these situations in an efficient manner.

2.5.1 Directional-to-omni MAC protocols

Ko *et al.* [5] proposed a directional MAC protocol, called DMAC, that sends a directional RTS when at least one of the antenna beams is blocked or an omni-directional RTS otherwise. An RTS is followed by an omni-directional CTS from the receiver. DATA and ACK packets are transmitted directionally. DMAC improves the performance of ad hoc networks by leveraging the gains provided when directional antennae are used. However, DMAC assumes that all nodes know the location of their neighbors using technologies such as GPS. This can be a costly and impractical assumption that may prohibit the use of DMAC in ad hoc networks.

To address the case where location information may not be available, Nasipuri *et al.* [4] proposed a directional MAC protocol where mobile nodes do not have any location information. The protocol uses directional RTS/CTS exchanges to enable the source and destination to identify each other's direction. Idle nodes listen to ongoing transmissions in omni-directional mode. Transmitting nodes first send a omni-directional RTS packet to the destination. If the intended receiver hears the RTS, it responds with a omni-directional CTS and takes note of the antenna beam at which it received the RTS from. Then, DATA and ACK packets are transmitted directionally (in the direction that the CTS/RTS was received). Nodes that overhear these RTS/CTS exchanges use this information to defer their transmission. Although the location information issue is addressed here, the authors assume that directional and omni-directional gains are equal in their protocol. In addition, using the directional RTS/CTS exchanges to determine the location of the destination increases the overhead of the transmission.

Based on the assumption of network wide synchronization, Wang *et al.* [29]

proposed a directional protocol for ad hoc networks that assumes system-wide synchronization, called SYN-DMAC. In SYN-DMAC, there are three phases: random access, DATA and ACK. In the random access phase, multiple node pairs contend for the channel access. Parallel collision-free DATA is sent during the DATA phase. Finally, parallel collision-free ACKs are sent during the ACK phase. Although the idea of collision-free DATA and ACK transmissions is appealing, achieving network wide synchronization is difficult and increases the cost of deployment.

To handle the case where nodes are mobile in ad hoc networks, Wang *et al.* [30] proposed a directional MAC protocol, called CDMAC, where node pairs locally coordinate multiple simultaneous DATA/ACK transmissions. In CDMAC, idle nodes operate in omni-directional mode and RCT/CTS packets are sent omni-directionally. CDMAC uses a frame structure, which consists of three phases: a contention resolution phase, where nodes use a collision resolution algorithm to contend for the medium; a collision-free DATA transmission phase, where multiple node pairs exchange DATA packets; and a contention-free ACK phase, where nodes acknowledge correctly received DATA packets. Although their performance evaluations show that CDMAC performs well in dense and mobile networks, CDMAC suffers from the asymmetry-in-gain problem. In addition, the authors use of omni-directional control packet exchanges reduces the spatial reuse. Furthermore, the authors mention that CDMAC may not be suitable for sparse networks.

To study the use of directional antennae in multi-hop ad hoc networks, Choudhury *et al.* [8, 31] proposed a directional MAC protocol, called MMAC. MMAC attempts to exploit the higher transmission range of directional antennae by attempting to form the longest possible links. This is achieved by propagating the RTS packet over multiple (directional or omni-directional) nodes/hops and then sending the CTS, DATA, and ACK over one directional hop. Although such an approach can significantly improve throughput, intermediate paths may not be available to propagate the RTS to the destination. In addition, if nodes are engaged in communication prior to the request to propagate the RTS, the connection establishment may be severely delayed.

The work by Singh *et al.* [32] and Huang *et al.* [33] proposed busy tone-based directional MAC protocols. The protocols call for idle nodes to listen in omni-directional mode. In case a node receives a sender busy tone, it beamforms towards the sender and transmits a receiver-tone. DATA and ACK are then exchanged. Although busy tone protocols have their advantages, they often require two channels to operate (one for data and another to transmit the busy tone). This may not be preferable due to cost, or bandwidth limitations. In addition, if multiple nodes transmit the busy tone simultaneously, spatial reuse may be reduced.

All of the directional MAC protocols discussed here assume the operation in both, directional and omni-directional modes. Generally speaking, omni-directional mode is utilized by nodes when they are idle or is used by nodes to transmit control packets. This assumption eliminates the deafness problem. However, such an assumption introduces the asymmetry-in-gain problem. In addition, it was shown in [1] that transmitting some control packets omni-directionally defeats the purpose of using directional antennae (in terms of spatial reuse and throughput gain). For these reasons, directional MAC protocols where nodes operate in directional mode exclusively are desirable. In the next section, we discuss some of the current directional-only MAC protocols.

2.5.2 Directional-to-directional MAC protocols

Zhang *et al.* [34, 35] proposed a TDMA based MAC protocol that uses directional only transmission and reception, called LiSL/d. In their protocol, time is divided into frames and each frame is divided into three sub-frames. The first of the three sub-frames is used for neighbor discovery, the second is used for data reservation and the third of the sub frames is used for data transmission.

The work by Takata *et al.* [36] and Jakllari *et al.* [37, 38] proposed the use of polling based directional MAC protocols. In [36], nodes maintain a polling table and polls potential deafness nodes using Ready To Receive (RTR) frames after the completion of every dialog. In [37, 38], a node polls its one hop neighbors to obtain their location information and schedules transmissions/receptions. At the scheduled time, nodes (the sender and receiver) point their antennae towards each other and carry their communication exclusively using directional antennae. A frame structure which consists of search, poll, and data transfer slots is used. During the search slots, nodes discover each other (by pointing in randomly chosen directions) and the two agree to communicate on a regular basis in one of the polling segments. In the polling slots, nodes schedule data transfers. In the data transfer slots, data packets are exchanged according to the schedule set during the polling.

All of the aforementioned directional-to-directional protocols have one main advantage, they eliminate the asymmetry-in-gain problem. However, they all require network synchronization. This assumption of network synchronization is difficult and costly to implement in practical networks. Furthermore, in the case where frames are used, the optimal frame duration is a system parameter that may be difficult to obtain in dynamic network conditions. In the case where a poll list is maintained, the list may become outdated in highly dynamic networks. Also, the neighbor discovery time is proportional to the number of antennae sectors used (need at least one frame for every direction). Finally, it is a waste of resources to have nodes poll all of their one-hop neighbors or have nodes poll their one-hop neighbors after the completion of every dialog.

A practical directional-only MAC protocol needs to address two main issues: synchronization and deafness. Although the current related work has been successful in solving the asymmetry-in-gain problem that is introduced by omni-directional MAC protocols, the synchronization issue still remains unsolved. In addition, using frame structures to solve the deafness problem in multi-hop ad hoc networks is not practical and scalable.

2.5.3 Performance of Directional MAC protocols

Spyropoulos *et al.* [39] extended Gupta-Kumar work [40] to derive the asympotic capacity bounds for ad-hoc networks using directional antennae. The authors noted that by scaling antenna parameters such as number of antenna elements, the capacity could be improved. In [41], the capacity scaling results have been derived in terms of the antenna beamwidth. It was shown that throughput can be improved by a factor of $\frac{2\pi}{\sqrt{\alpha\beta}}$, where α and β are the transmitter and receiver antenna beamwidths, respectively.

Hsu *et al.* [42] proposed a directional ALOHA protocol, called D-ALOHA. D-ALOHA uses a control channel to exchange topological information among nodes. More importantly, the authors derive mathematical formulas to characterize the throughput performance of their directional random access scheme.

An analytical model was developed in [43] to study the saturation throughput performance of directional-to-omni-directional CSMA/CA MAC protocols in ad-hoc networks. The model assumes IEEE 802.11 DCF type operation with directional transmission and omni-directional reception. The saturation throughput performance is given in terms of the number of channel contenders, packet size and antennae beamwidth. The analytical framework provided valuable insight into the performance of directional contention-based MAC protocols. The model was validated through simulations and proved to be accurate.

2.5.4 Other related work

The implementation of testbeds that use directional antennae in ad hoc has been considered in recent research. Ramanathan *et al.* [44] demonstrated how the use of directional antennae can offer up to 10 factors of throughput improvement compared to the case when omni-directional antennae are used. Choudhury *et al.* [45] designed a prototype and studied the different aspects of beamforming (deafness, spatial reuse, etc..) from the MAC and routing perspectives. Bhagwat *et al.* [46] discussed the challenges of implementing a rural network using 802.11 and directional antennae. They mentioned that range extension capabilities using directional antennae may be heavily utilized in specific outdoor environments.

Takai *et al.* [6] proposed the Directional Virtual Carrier Sensing (DVCS) for directional MAC protocols. DVCS consists of three main mechanisms: AoA caching, Beam locking and unlocking and DNAV setting. The AoA mechanism caches each signal that it overhears, whether the signal is intended for itself or not. This AoA information is used by sending nodes later on to determine the direction of the intended receiver. The beam locking and unlocking mechanism is used by sending and receiving nodes to lock their antennae patterns to maximize the received power. These beam patterns are obtained during the sending/reception of the RTS/CTS packets. The beam patterns are unlocked after reception of the ACK packet. Finally, nodes maintain a NAV entry, called DNAV for each direction. These DNAV entries differ from the conventional NAV entries in that they have a direction and width associated with them.

In [1], Wang *et al.* studied the effect of transmitting control packets omni-directionally. They concluded that the omni-directional transmission of some control packets will in fact defeat the purpose of using directional antennae to achieve better throughput. Simulation results with random network topologies proved that using

DRTS and DCTS schemes indeed outperform the omni-directional schemes in terms of both, throughput and delay.

Considering the advantages of lower cost, no asymmetry-in-gain problem, and high spatial reuse by using directional antennae, we propose a fully distributed directional MAC protocol for ad-hoc networks that exclusively uses directional antennae, called DtD MAC. Similar to PMAC, our protocol eliminates the asymmetry-in-gain problem and alleviates the effects of deafness and collisions. However, unlike PMAC the proposed protocol does not require synchronization or polling.

To evaluate the performance of DtD MAC, we extend the analytical model proposed in [43] to consider the directional receiver case. To validate the analytical model used, we performed extensive simulations using Qualnet v4.0 [47].

Chapter 3

The Directional-to-Directional (DtD) MAC protocol

In this chapter, we outline the architecture of the DtD MAC protocol. Each section describes the functionality and purpose of each component used in the protocol design. These components were carefully designed to meet the challenges that face directional-to-directional transmissions.

To give a brief overview of the DtD MAC protocol, sending nodes cache location information about their neighboring nodes. This information is later used to determine which direction it should send Directional RTS (DRTS) packets in. Idle nodes (potential receivers) continuously scan through their antenna sectors to emulate omni-directional operation. If they hear a DRTS intended for themselves, they lock in the respective direction and respond with a Directional CTS (DCTS). Nodes that overhear ongoing communications set their DNAVs to refrain from interrupting ongoing communications in those directions.

The next few sections will detail the mechanisms used to achieve the operation of the DtD MAC protocol.

3.1 Continuous sector scanning by idle nodes

To minimize the effect of deafness, having idle nodes switch their sensing directions continuously in a clockwise (or anti-clockwise) fashion is a key. In essence, such a behavior emulates the presence of an omni-directional antenna at the receiver. Idle nodes spend $DRTS + SIFS + \chi_{BO}$ time in each sector. χ_{BO} is added to compensate for the time that a sending node may spend backing off. The derivation of this value is discussed in more detail in Sec. 3.6

Any node that hears a transmission on one of its beams, sets their DNAV and continues to scan sequentially through all the other beams. First, following such an approach would solve the deafness due to persistent hearing of DATA problem. Second, this mechanism also reduces the chance of a sender finding the receiver pointing to another direction. Third, this mechanism would increase the number of neighbors that set their DNAV. Or in other words, this would reduce the number of nodes that do not hear other's handshake messages. Hence, alleviating the directional hidden terminal problem.

This gain, comes at the cost of increasing the number of handshake packets that need to be sent by the sender. This increased cost can be explained as follows: node S in Fig. 3.1 would like to engage in communication with node R. Assuming that these two nodes are not synchronized. Further, assume that node R was idle and was continuously switching between beams. In the worst case scenario, node S would send $2M$ DRTS packets to establish a connection with node R, where M is the number of antenna sectors.

The need for this is derived from the introduction of the continuous sector scanning mechanism. The more general case of this mechanism is explained in the next section.

3.2 DRTS and DCTS

In multi-hop ad hoc networks, most MAC protocols exchange RTS/CTS messages between nodes to initiate communication. The main purpose of using these control packet exchanges is to address the hidden terminal problem. In Sec. 2.4.3, we outlined the hidden terminal problems due to directional transmission of the RTS/CTS packets.

Since nodes are not synchronized, nodes may change their direction and attempt to send in a direction that is already busy (another pair of nodes are in communication). To solve this issue, nodes should sense the medium for a sufficiently long period of time before sending their RTS message. This sensing period is set to be equal to the transmission time of a DATA packet and a SIFS period. This way, a sending node will always overhear the ACK or DATA packet of the on-going transmission taking place in a certain direction and refrain from transmitting to avoid collisions.

In addition, to guarantee that the sender captures the receiver, it sends at most $2M$ DRTS packets in the direction of the receiver. This number can be explained by the fact that since the nodes are not synchronized, a receiving node may beamform in the direction of the sender just after a DRTS was sent. Therefore, a sender needs to keep sending DRTS packets to ensure that the receiver can eventually capture one DRTS packet in its direction.

If the direction of the receiver is not known, then a sender randomly chooses a new direction and transmits $2M$ DRTS in that direction, and so on. If the sender goes through all the sectors in this fashion, and no response is received from the intended receiver, then the sender may backoff and retry later. In the worst case, a sender would have to send $2M$ packets in M directions for each retry. This would cause the sender to send $2M^2$ DRTS packets.

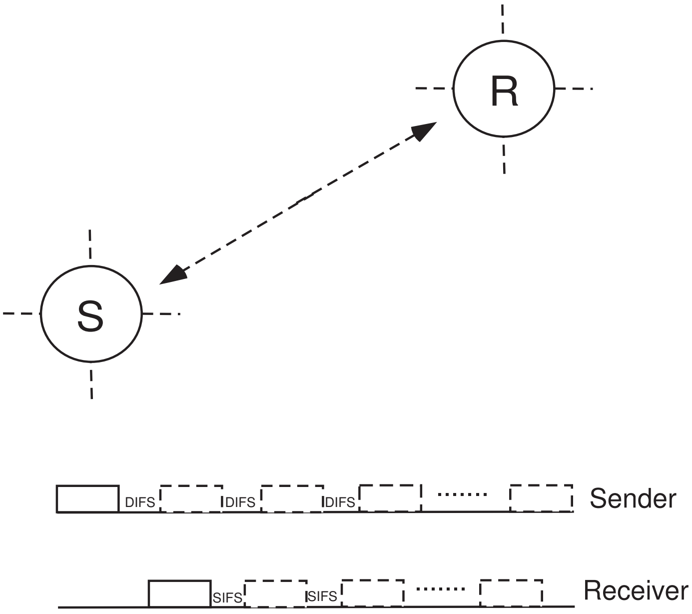


Figure 3.1: Handshake procedure

A node that receives a DRTS caches the AoA and responds with a DCTS in the direction of the sender, if it is the intended receiver. After sending the DCTS, the receiver locks its antenna in the direction of the sender and waits for the DATA. If the DATA is not received within the $DATA_{TIMEOUT}$ time, the receiver unlocks its antenna and continues sector scanning.

3.3 DATA and ACK

Upon receiving a DATA packet that is intended for it, the receiving node replies with a directional ACK that acknowledges the DATA received. If a sending node does not receive an ACK within an $ACK_{TIMEOUT}$ time, it backs off and sends the DATA packet again for $DATA_{MaxNum}$ times.

For high data rate communications, to reduce the overhead of control messages (DRTS and DCTS), the sender can send a burst of DATA packets after it receives the DCTS successfully. This is done to improve the efficiency of the MAC protocol since for high data rate technologies the data and control time is almost the same.

3.4 Directional Network Allocation Vector (DNAV)

NAVs are used in the IEEE 802.11 MAC protocol. Each node maintains a NAV that is updated from the duration field of the overheard RTS/CTS packets. For directional antenna case, the use of a similar mechanism was proposed in [6] and [8]. This mechanism keeps a NAV value for each beam of the antenna. The number of values kept depends on the number of sectors. In the DtD MAC protocol, we also use this DNAV mechanism.

3.5 Angle of Arrival (AoA) caching

To improve the efficiency of the MAC protocol, senders need to estimate the direction of the intended receiving node. To achieve this, each node estimates and caches the AoA of signals it overhears. This AoA caching mechanism was first introduced in [6]. In their scheme, nodes cache the AoA of packets that are intended for it or not. This AoA information is then used by the node if it has DATA to transmit to one of its neighbors. The AoA information is updated every time a node receives or hears a signal from one of its neighbors. Before sensing the medium, a sending node checks its AoA cache to determine the direction that the receiver is in. If the DNAV for that specific direction is not blocked (i.e. the medium is free), then it senses the medium for $DATA + SIFS$ time in the direction of transmission and send a DRTS in the direction of the receiver.

If the AoA is unavailable for the intended neighbor, the DRTS packets are sent to one of the sectors randomly and continues to try the other sectors until the transmission has been attempted on each of the sectors at least once. Upon receiving the first DCTS packet, the sender caches the AoA of the receiver and sends the DATA directionally towards the receiver.

3.6 Backoff

In omnidirectional MAC protocols, if no CTS is replied by the receiver, a sender should backoff (BO) a random period before retry, and the average BO time is exponentially increased after each failed transmission. This is because the unsuccessful RTS transmissions are most likely due to collisions, and increasing the BO time can reduce the collision probability. However, when using directional antennae, the deafness problem is introduced, and most of the DRTSs are not replied due to deafness. Therefore, the Binary Exponential Backoff (BEB) algorithm used in the IEEE 802.11 MAC protocol may not be efficient in the DtD MAC protocol. Since a sender is required to send up to $2M$ DRTS packets in each direction, it may be required to increase its BO window $2M$ times during this stage. To ensure that a sending node can capture its intended receiver within at most $2M$ DRTS tries and to alleviate the effect of deafness, we propose a random BO scheme: for the $2i-1$th DRTS ($i = 1, 2, ..., M$), the contention window size W_{2i-1} is randomly chosen from $[0, W_{\max})$, and for the $2i$th DRTS, W_{2i} is randomly chosen from $[W_{\max} - DRTS - SIFS - W_{2i-1}, W_{\max})$. This BO scheme is designed to ensure that an idle receiver can capture a DRTS no matter which direction it begins to sense, as explained below.

First, without synchronization, an idle node should spend at least $(DRTS + SIFS + BO_{max})$ in each direction to ensure that if there are DRTSs coming from that direction, the idle node can capture at least one of them. Second, in the worst case, the idle node will spend $(M - 1)(DRTS + SIFS + BO_{max})$ time in other directions before it senses the sender's direction, so the sender should ensure that the duration between the beginning of the first DRTS to the beginning of the $2M$th DRTS should be longer than $(M-1)(DRTS+SIFS+BO_{max})$:

$$\begin{aligned}&(2M-1)(DRTS+SIFS)+\sum_{i=2}^{2M}BO_i\\&\geq(M-1)(DRTS+SIFS+BO_{max}).\end{aligned} \tag{3.1}$$

where BO_i is the BO time before the i^{th} DRTS. To ensure (3.1), a sufficient condition is

$$BO_{2i-1}+BO_{2i}\geq BO_{max}-DRTS-SIFS, \tag{3.2}$$

for $i=1,2,\cdots,M$.

If $BO_{2i-1}\in[0,BO_{max})$, then choose BO_{2i} from $[BO_{max}-DRTS-SIFS-BO_i,BO_{\max})$ will ensure (3.2). Therefore, our BO scheme can ensure an idle receiver to capture at least one DRTS from the sender. The key parameter in the BO scheme is W_{max}, which should be appropriately chosen to make the tradeoff between collisions and channel time being wasted during BO.

3.7 Control flow of the DtD MAC protocol

Fig. 3.2 outlines the flow process of the normal operation mode of the protocol. As can be observed, a sender only attempts to send after it senses the medium in the direction of transmission for $DATA+SIFS$ time and when the DNAV entry in the direction of the receiver is not set. If the direction of the receiver is not known, then the sender sends the packet in a randomly chosen direction. In both cases, a maximum of $2M$ DRTS packets are sent in any direction. This is because we would like to guarantee access to the receiver if the receiver is not engaged in another communication. After sending the DRTS, a node waits in the direction it sent the DRTS for the DCTS to return. If the DCTS is not received, then the sender should backoff and send the

DRTS again. If the DCTS is received, then the node continues to send the DATA and wait for the ACK.

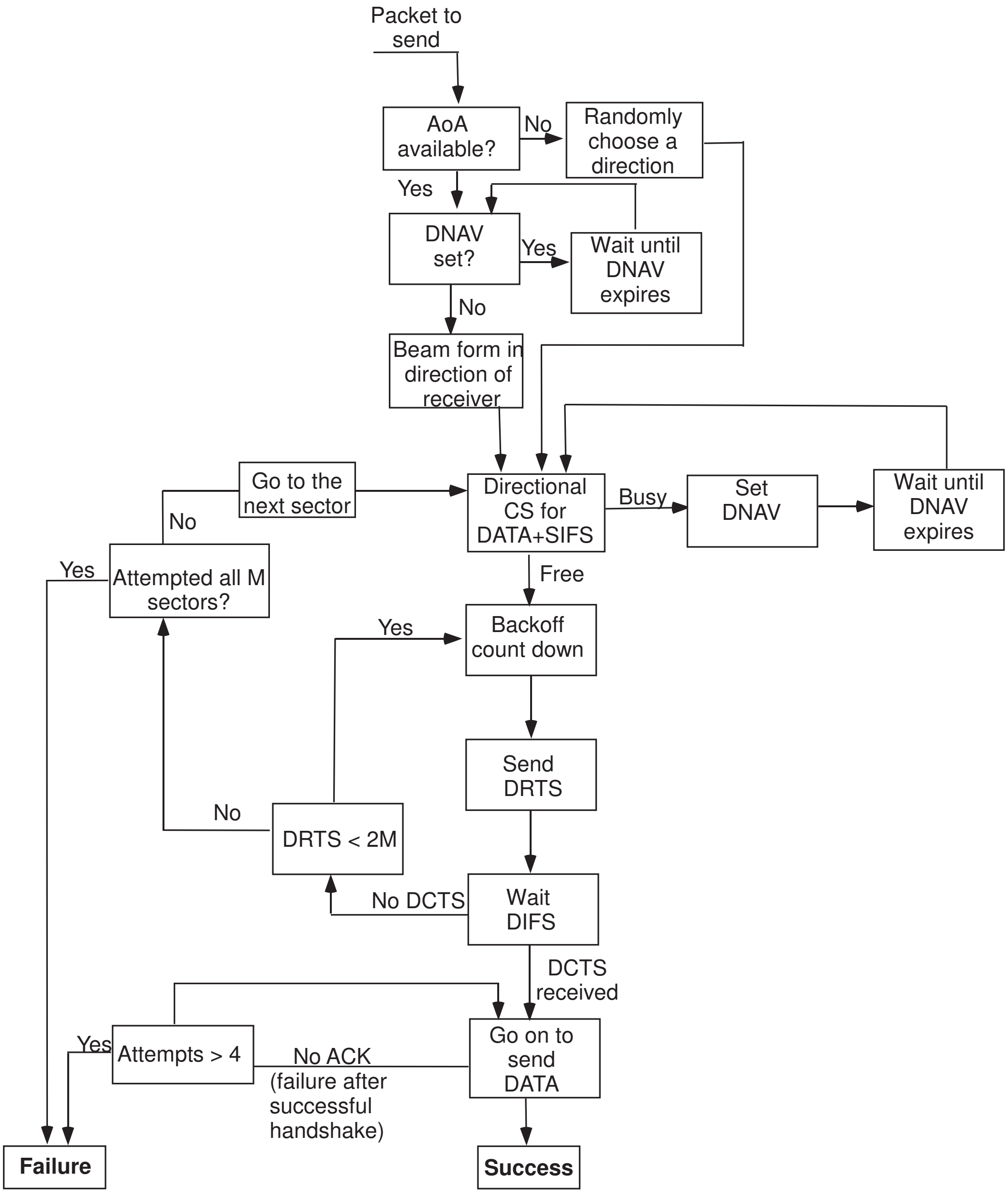


Figure 3.2: Control flow of MAC protocol

3.8 Advantages of the DtD MAC protocol

The advantages of the DtD MAC protocol are many folds. In this section we highlight the four main advantages of the DtD MAC protocol.

- **Eliminate asymmetry-in-gain problem:** The asymmetry-in-gain problem is caused by the use of both directional and omni-directional antennae within the same network. This problem is caused by the fact that directional antennae have a higher gain than omni-directional antennae. Since we only use directional antennae in our protocol, we eliminate this problem. This advantage increases directional range, which in turn, can benefit routing in terms of computing shorter paths [37].

- **Fully distributed:** The DtD MAC protocol does not require any centralized controller and can operate in a fully distributed manner. This is an major advantage that is unmatched in any other protocol that uses directional antennae exclusively. This advantage increases the feasibility of implementation and deployment of directional antennae at both sender and receiver in next generation ad hoc networks.

- **Eliminate the need for synchronization:** Sending multiple DRTS packets in each direction allows the network to operate without synchronization, while at the same time, guaranteeing access to a node (if it is idle). This is a major practical advantage, since synchronization is difficult and costly in heterogenous ad hoc networks.

- **Alleviate the effects of deafness and collision:** Since each sender is required to sense the medium for DATA+SIFS time in the direction of its next head-of-line packet prior to sending, DtD MAC can reduce the chance of collisions due to deafness. The fact that a sender is required to send multiple DRTS packets in each direction, alleviates the effect of deafness. This advantage improves the overall throughput performance of DtD MAC.

These advantages highlight the fact that DtD MAC is practical and is ready to be deployed in ad hoc networks.

In the next chapter, we present the analytical model we used to analyze the performance of the DtD MAC protocol. This model measures the saturation throughput in terms of the number of channel contenders, the packet size, and antennae beamwidth. We also provide an expression that is used to approximate the access delay of the DtD MAC protocol. These analytical models help us gain more insight into the performance of the DtD MAC protocol

Chapter 4

Performance analysis of the DtD MAC protocol

In this chapter we outline the analytical model used to study the performance of the DtD MAC protocol. We first introduce the antenna model. We then use it to calculate the network saturation throughput, followed by the estimation of access delay.

4.1 Antenna Model

Two types of practical directional antennae are Phased Array antenna and Switched-beam antenna.

A phased array antenna achieves beam steering by constantly changing the phase of the antenna elements that constitute the array. However, there is a phase difference between individual array elements in practice. This bears a significant effect on the beamwidth as the beam is steered [48]. The number of the elements constituting the antennae array, their management, their relative displacement along with the phase differences, all contribute to the overall radiation pattern of the antenna.

This obviously modifies the sidelobes and/or backlobes of the radiation pattern [6]. However, the ability of phased array antennae to steer their beams in any direction makes them an ideal choice for wireless networks [49].

A switched beam antenna is equipped with a number of directional antenna elements oriented in some pre-defined directions [50]. The switched beam antenna can electronically switch between beams, thus exhibiting some degree of steering. It is cost effective compared to the phased array antenna [51]. However, its limited beam-steering capability makes the transmitter-receiver beam alignment rigid.

In this work, we use a switched beam antenna at each node that comprises of M fixed beam patterns, where $M = \frac{2\pi}{\theta}$. In our study, we vary θ from $30°$ to $180°$. We assume that a node can either transmit or receive directionally at any one given instance of time. In all cases, all the nodes in the network use antennae with identical fixed beamwidth.

To consider the physical gains of using directional antennae, the receiver power is based on the following model

$$P_R = P_T \times G_T \times G_R \times G_C, \tag{4.1}$$

where P_T,G_T,G_R and G_C denote the transmission power, transmitter antenna gain, receiver antenna gain, and channel gain, respectively. At the transmitter, we adjust the achievable data rate according to the number of antenna sectors M. Using Shannon's channel capacity equation, we can derive the achievable data rate using directional antennae (denoted with subscript D) and that using omni-directional antennae (denoted with subscript O) as

$$C_O = W \log_2(SNR_O + 1), \tag{4.2}$$

and

$$C_D = W \log_2(SNR_D + 1), \tag{4.3}$$

where $SNR_D = \frac{G_{TD}G_{RD}}{G_{TO}G_{RO}} \times SNR_O$. Assuming that the sending and receiving nodes use identical antennae, we obtain

$$k_M = \frac{C_D}{C_O} \approx \frac{log_2(G_D^2) + log_2(SNR_O)}{log_2(G_O^2) + log_2(SNR_O)}, \tag{4.4}$$

assuming G_O to be unity and G_D to be proportional to M, then

$$k_M \approx \frac{2log_2 M + log_2(SNR_O)}{log_2(SNR_O)}, \tag{4.5}$$

and the data rate for a node with M antennae sectors is given as

$$Datarate_M = k_M \times Datarate_O, \tag{4.6}$$

where $Datarate_O$ is the achievable data rate for omni-directional antenna.

4.2 Network throughput analysis

In this section, we derive the throughput capacity of the DtD MAC protocol. This analysis expresses the system's MAC-layer saturation throughput. This measure is an indication of the throughput that can be achieved, assuming that all nodes in the network are continuously loaded for transmission.

Consider a system that consists of N stations. Each station is equipped with an antenna that has M sectors. All stations are assumed to be uniformly distributed. In addition, each source node randomly picks a destination for its packets. Each node can be in one of 6 states. Each node's state process is represented as a discrete time Markov chain as shown in Fig. 4.1. When in the *idle* state, a node is considered to be backing off and the channel is observed to be idle. The *success* state is the state at which a node resides after completing a successful packet transmission. The *receive* state is the state at which a node successfully receives a packet. The *failure* state is the state at which a node failed to transmit a packet. The *defer* state is the state at which a node enters when it has a packet to send, but is forced to defer transmission due to an entry in its DNAV. The *overhear* state denotes the state where a node overhears other nodes but decides not to defer.

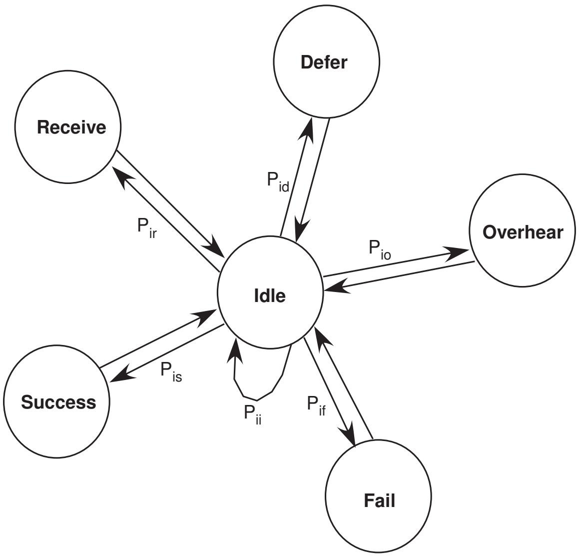


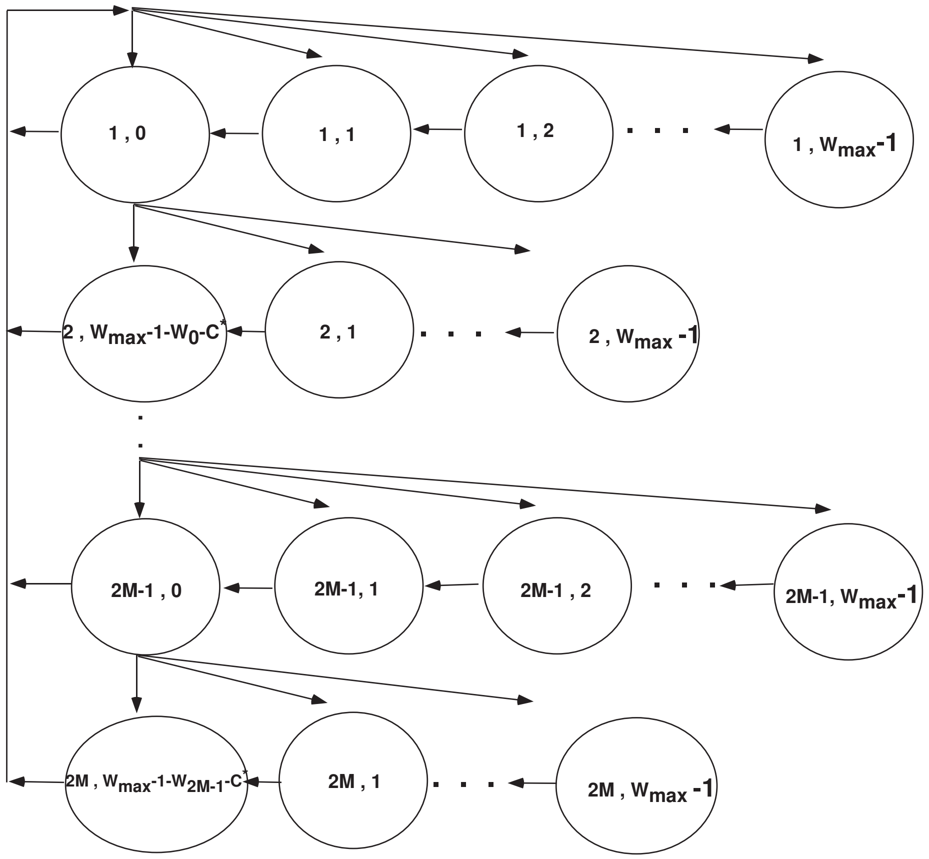
Figure 4.1: Node Markov chain state diagram

Let τ denote the packet transmission probability and p denote the conditional failure probability. The random BO scheme used in the DtD MAC protocol is shown in 4.2, and using the same approach as [18], we note that

$$b_{i-1,0} \times p = b_{i,0} \rightarrow b_{i,0} = p^i \times b_{1,0} \qquad 1 \ < \ i \ < \ 2M \tag{4.7}$$

Owing to the chain regularities, for each $k \in [0, W_{max} - 1]$, $b_{i,k}$ is given as

$$b_{i,k} = \begin{cases} \frac{W_{max}-k}{W_{max}} (\sum_{j=1}^{2M} b_{j,0})(1-p) & i = 1, \\ (\frac{p \times b_{i-1,0}}{W_{max}})[\sum_{W_{i-1}=0}^{W_{max}-1} \sum_{k=W_{max}-1-C-W_{i-1}}^{W_{max}-1} (1 - \frac{k}{1+W_{i-1}+C})] & \text{i even, } 1 < i \leq 2M, \\ \frac{p \times b_{i-1,0}(W_{max}-k)}{W_{max}} & \text{i odd, } 3 \leq i \leq 2M-1, \end{cases} \tag{4.8}$$



* C= DRTS+SIFS number of slots

Figure 4.2: Random backoff mechanism used in the DtD MAC protocol

and making use of the fact that $\sum_{j=1}^{2M} b_{j,0} = \frac{b_{1,0}(1-p^{2M})}{1-p}$, and by imposing the normalization condition, we obtain

$$\begin{aligned}
1 &= \sum_{i=1}^{2M}\sum_{k=0}^{W_{max}-1} b_{i,k} \qquad (4.9)\\
&= [\frac{(W_{max}-1)(1-p^{2M})b_{1,0}}{2} + \sum_{i=1}^{M}(p^2)^i b_{1,0}\frac{5+6C-W_{max}}{4}\\
&+ p^3\sum_{i=1}^{M-2}(p^2)^i b_{1,0}\frac{W_{max}-1}{2}]\\
&= \frac{b_{1,0}}{2}[(W_{max}-1)(1-p^{2M}) + (\frac{5+6C-W_{max}}{4})\frac{p^2-p^{2M+2}}{1-p^2} + (W_{max}-1)\frac{p^3-p^{2M+1}}{1-p^2}]
\end{aligned}$$

Solving for $b_{1,0}$, τ is calculated as the summation of all $b_{i,0}$ $\forall$ $i \in$ [1,2M], and given as

$$\tau = \frac{b_{1,0}}{1-p}, \tag{4.10}$$

which can be represented in terms of p, W_{max} and M as

$$\tau(p) = \frac{2(1+p)}{(W_{max}-1)(1-p^2)(1-p^{2M}) + (\frac{5+6C-W_{max}}{4})(p^2-p^{2M+2}) + (W_{max}-1)(p^3-p^{2M+1})}, \tag{4.11}$$

Next, we need to calculate p, the conditional failure probability. Letting the steady state probabilities of the nodal state Markov chain be denoted as π_i, π_s, π_r, π_f, π_d, and π_o, and the average time periods that a node stays in the corresponding states be T_i, T_s, T_r, T_f, T_d, and T_o, respectively. We define the continuous-time state process $X = \{X_t, t \geq 0\}$ by defining the node state variable at time t, X_t, which denotes the state into which the system transitioned at the last transition time occurring before time t. We set $\pi^{'}$ to represent the percentage of time that the node resides in the idle state

$$\pi^{'} = \frac{\pi_i T_i}{\pi_i T_i + \pi_s T_s + \pi_r T_r + \pi_f T_f + \pi_d T_d + \pi_o T_o}. \tag{4.12}$$

Now consider a node, T whose next packet is to be forwarded to a neighboring node R, then the probability of failure of T's packet at an arbitrary time t_0 is given by

$$\begin{aligned} p &= 1 - Pr\{success \mid a\ transmission \\ &\quad attempted\} \\ &= 1 - p_1 p_2 p_3, \end{aligned} \tag{4.13}$$

where

$$p_1 = Pr\{receiver\ node\ is\ idle\ at\ t_0\} = \pi'. \tag{4.14}$$

We do not consider the probability of the receiver pointing in the direction of the sender when calculating p_1 because it is assumed that the sender will always capture the receiver by sending $2M$ DRTS packets. p_2 is then given by

$$\begin{aligned} p_2 &= Pr\{sender's\ signal\ is\ strong\ enough\ at \\ &\quad receiver\}. \end{aligned}$$

For simplicity, in our analysis we assume that $p_2 = 1$. p_3 is defined as follows

$$\begin{aligned} p_3 &= Pr\{no\ stations\ in\ the\ senders\ beam \\ &\quad initiate\ a\ transmission\ in \\ &\quad the\ receivers\ direction\ in\ the \\ &\quad 2t_{rts} + 2\ slot\ times\} \\ &= (1 - Pr\{a\ station\ located\ in \\ &\quad senders\ beam\} Pr\{it\ transmits\} \\ &\quad Pr\{it's\ transmission\ is\ in\ direction \\ &\quad of\ the\ receiver\})^{(N-2)(2t_{rts}+2)} \\ &= (1 - \pi' \tau (\frac{1}{M})^2)^{(N-2)(2t_{rts}+2)}. \end{aligned}$$

Next, we need to derive the transition and steady state probabilities. Using (4.11),(4.12) and (4.13), we obtain the transition probabilities to be

$$P_{is} = P_{ir} = \tau(1-p), \tag{4.15}$$

$$\begin{aligned} P_{ii} &= (1-\tau)Pr\{no\ stations\ start\ to\ transmit \\ &\quad DRTS\ or\ DCTS\ in\ its\ direction\} \\ &= (1-\tau)(1-\pi'\tau(\frac{1}{M})-\pi' P_{ir}(\frac{1}{M}))^{N-1}, \end{aligned}$$

$$P_{if} = \tau p, \tag{4.16}$$

$$P_{si} = P_{ri} = P_{fi} = P_{di} = P_{oi} = 1. \tag{4.17}$$

The calculation of P_{id} and P_{io} is more involved. To simplify the calculation we make use of the fact that the ratio of the number of packets per packet type is as follows: RTS:CTS:DATA:ACK is M:(1-p):(1-p):(1-p). Then, we can write P_{id} as follows

$$\begin{aligned} P_{id} &= Pr\{sender\ successfully\ receives \\ &\quad incoming\ packet\ that\ is\ not\ intended \\ &\quad for\ it\}Pr\{incoming\ packet\ is \\ &\quad DRTS/DCTS\}Pr\{it\ is\ oriented\ to \\ &\quad the\ direction\ of\ next\ packet\} \\ &\approx (1-P_{ii}-P_{is}-P_{ir}-P_{if}) \times p_3 \\ &\quad \times \frac{M+(1-p)}{M+(1-p)+(1-p)+(1-p)} \times \frac{1}{M}, \end{aligned}$$

and P_{io} can then be easily obtained as

$$P_{io} = 1 - P_{ii} - P_{is} - P_{ir} - P_{if} - P_{id}. \tag{4.18}$$

By solving the balance equations for the steady state probabilities, we obtain

$$\pi_i = \frac{1}{2 - P_{ii}}, \tag{4.19}$$

$$\pi_s = P_{is}\pi_i = \pi_r, \tag{4.20}$$

$$\pi_f = P_{if}\pi_i, \tag{4.21}$$

$$\pi_d = P_{id}\pi_i, \tag{4.22}$$

$$\pi_o = P_{io}\pi_i. \tag{4.23}$$

The corresponding time intervals that a station stays in individual states are given as

$$T_i = \alpha, \tag{4.24}$$

where α denotes a BO slot time duration.

$$\begin{aligned} E[T_s] &\approx M \times DRTS + M \times SIFS + DCTS \\ &+SIFS + H + DATA + SIFS + ACK \\ &+DATA + DIFS + E[BO_s], \end{aligned}$$

where H and $E[BO_s]$ denote the MAC and PHY headers and the average BO spent in a successful transmission, respectively. $E[BO_s]$ is given by

$$\begin{aligned} E[BO_s] &= \sum_{i=0}^{2M-1} E[BO(i) \mid (i+1)\ DRTS\ Tx] \\ &\quad \times Pr\{(i+1)\ DRTS\ Tx\}. \end{aligned}$$

Assuming that the receiver captures the i^{th} DRTS with probability $\frac{1}{2M}$ (uniform distribution), $E[BO_s]$ is given by

$$\begin{aligned} E[BO_s] &\approx \frac{1}{2M} \times \frac{1}{2} \sum_{i=0}^{2M-1} \frac{5W_{max} - 2(DRTS - SIFS)}{8} \\ &\approx \frac{5W_{max} - 2(DRTS - SIFS)}{16}. \end{aligned}$$

The time spent in the receive state, T_r is

$$\begin{aligned} T_r &= DRTS + SIFS + DCTS \\ &\quad + SIFS + H + DATA + SIFS + ACK \\ &\quad + DIFS. \end{aligned}$$

The average time spent in the failure state, $E[T_f]$ is

$$E[T_f] \approx 2M \times (DRTS + DIFS) + E[BO_f],$$

where $E[BO_f]$ is given as

$$\begin{aligned} E[BO_f] &\approx \frac{1}{2}\sum_{i=0}^{2M-1} \frac{5W_{max} - 2(DRTS - SIFS)}{8} \\ &\approx M \times \frac{5W_{max} - 2(DRTS - SIFS)}{8}. \end{aligned}$$

The time spent in the defer state, T_d is equal to the time spent in the success state and is given as,

$$T_d = T_s, \tag{4.25}$$

The length of the overhear duration is given estimated as

$$\begin{aligned} T_0 &= \frac{M}{(M+3-3p)} DRTS \\ &+ \frac{(1-p)}{(M+3-3p)} DCTS \\ &+ \frac{(1-p)}{(M+3-3p)} (H + DATA) \\ &+ \frac{(1-p)}{(M+3-3p)} ACK \; + \; DIFS. \end{aligned}$$

The antennae switching time is assumed to be small and is ignored in all of our calculations.

An iterative method is used to calculate the optimal τ, p and π'. Then, the saturation throughput (in bps) of a network with N active nodes is calculated as

$$TH = \sum_{x=1}^{N} (TH\ of\ node\ x)$$
$$= N \frac{\pi_s E[P]}{\pi_i T_i + \pi_s E[T_s] + \pi_r T_r + \pi_f E[T_f] + \pi_d T_d + \pi_o T_o},$$

where E[P] is the average payload size of a data packet in bits.

4.3 Access Delay

In this section, we study the average access delay of the DtD MAC protocol assuming the sender knows the direction of the receiver. In this calculation of access delay we are mainly concerned with the overhead that is introduced due to the sector scanning mechanism introduced in the DtD MAC protocol. Therefore, we consider the case when two nodes are attempting to communicate with each other. This calculation needs to consider three main factors: the DRTS transmission time, the carrier sense time and the BO time between the DRTS transmissions. Therefore, the average access delay can be represented as

$$E[access\ delay] = M \times DRTS\ Tx\ time + Carrier\ sense\ time + E[BO]. \quad (4.26)$$

Since on average M DRTS packets will be sent, the DRTS transmission time can then be given as

$$E[M\ DRTS\ Tx\ time] \approx M \times \frac{DRTS\ pkt\ size}{Base\ Data\ rate}. \quad (4.27)$$

The carrier sense time is fixed and can be calculated as

$$Carrier\ sense\ time = \frac{Data\ pkt\ size}{Data\ rate} + SIFS. \quad (4.28)$$

The BO time is calculated based on the fact that at most $2M$ DRTS trials will be attempted for each direction. Then $E[BO]$ can be given as

$$E[BO] = \sum_{i=0}^{2M-1} E[BO(i) \mid (i+1)\ DRTS\ Tx\ time] \times\ Pr\{(i+1)\ DRTS\ Tx\ time\}. \tag{4.29}$$

Assuming that the receiver captures the i^{th} DRTS with probability $\frac{1}{2M}$ (uniform distribution), $E[BO]$ is given by

$$\begin{aligned} E[BO] &\approx \frac{1}{2}\sum_{i=0}^{2M-1} \frac{5W_{max} - 2(DRTS - SIFS)}{8} \\ &\approx M \times \frac{5W_{max} - 2(DRTS - SIFS)}{8} \end{aligned}$$

Plugging (4.30),(4.28) and (4.27) into (4.26), we can determine the average access delay for a given node, where the sender and receiver are equipped with directional antennae that contain M sectors.

In the next chapter, we present our simulation results that were used to validate the analytical model. We study the performance of DtD MAC in terms of saturation throughput, access delay and fairness.

Chapter 5

Performance Evaluation

In this chapter we present our simulation results and compare them to the analytical results obtained in chapter 4. Network throughput, fairness index and delay for the high data rate mmWave technology are presented and discussed.

5.1 Simulator augmentation

To simulate the DtD MAC protocol, the Qualnet simulator [47] was augmented to support directional reception. Qualnet is one of the few simulators that support directional transmission. However, its receiver model was based on omni-directional reception. We implemented the new DtD MAC protocol in Qualnet.

To accomplish directional reception, we attached two additional variables to the node object that represent θ_1 and θ_2. θ_1 and θ_2 were assigned values between 0 and 360 degrees and defined the beamwidth of the antenna sector. These were adjusted depending on the number of sectors at each node. If the packet was addressed for the receiving node, then reception was processed. Otherwise, the node caches the AoA and/or sets its DNAV and incoming packet is ignored.

In Algorithm 1, we present the receiver pseudo code. The first thing done upon reception is checking if the packet received is sent towards my sector. This is done by sensing the signal strength in the direction of reception. In lines 2 through 6, the address in the header of the received packet is checked. If the destination address matches the receiver's address, then packet is marked as 'my packet' by setting a boolean variable. Lines 7 through 9 deal with the case where the received packet is not intended for the receiver. In this case, the DNAV is set and the AoA of the sender is cached. Otherwise, lines 10 through 13 deal with the case where the packet is intended for the receiver. They strip the header of the received packet and send it to the upper layers.

Algorithm 1 Receive packet

```
Require: PKT object p
 1: if in my sector then {if pkt in my sector}
 2:    if $p \Rightarrow address = my\ address$ then {if pkt is addressed for me}
 3:       $mypkt \Leftarrow True$
 4:    else
 5:       $mypkt \Leftarrow False$
 6:    end if
 7:    if $mypkt\ != True$ then {if frame not my frame}
 8:       set DNAV
 9:       cache AOA
10:    else
11:       strip hdr
12:       send to upper layers {if pkt is mine}
13:    end if
14: end if
```

In addition, idle nodes were changed so that they do not listen in omni-directional mode. To achieve this, we incremented the θ_1 and θ_2 variables of idle nodes every time step. The initial θ_1 and θ_2 of each node was randomly chosen. When nodes enter reception mode, their direction (i.e. θ_1 and θ_2) is locked for the entire length of the reception.

Furthermore, transmitting nodes were required to sense for $DATA+SIFS$ time. This time was calculated based on the length of the $DATA$ packet. Also, the short retry limit (i.e. retry for DRTS packets) was changed to reflect the operation of the DtD MAC protocol, which requires the short retry limit per direction to be $2M$.

Algorithm 2 shows the pseudo code for the transmitter. Lines 1 through 5 check if the direction of the intended receiver is available or not. If the direction is not stored in the cache, then a random direction is chosen. Line 6 checks if the DNAV in the respective direction is set or not. If the DNAV is set, then in line 18 we set a timer that waits till the DNAV timer expires. Otherwise, in line 7 we start the carrier sense for $DATA + SIFS$ time. If the sense is successful, we start the BO countdown and transmit when it reaches zero (lines 8 through 10). Otherwise, if the carrier sense is not successful we set the DNAV timer.

In Algorithm 3, we present the pseudo code for the transmit packet procedure. If the packet to be sent is a DRTS packet, then in lines 2 through 13 we increment the variable that keeps track of how many DRTS packets were sent, we check if this number has reached the maximum limit for the current sector and check if we have attempted all sectors. If we have reached the DRTS retry limit in the current sector, then we move to the next sector. We send the DRTS and lock in this direction, in anticipation of a DCTS. In lines 14 through 17, we simply wait for $SIFS$ time and then transmit the DCTS in the direction of the received DRTS. Lines 18 through 21 deal with the case when a DATA packet is to be transmitted. Lines 22 to 25 show the case where an ACK is to be transmitted. After the ACK, the sector is unlocked

Algorithm 2 Send packet

```
Require: node object n and DtDMAC object d
if AoA available then
    $D \Leftarrow x$ {if direction available then set direction}
else
    $D \Leftarrow random\ x$ {otherwise set random direction}
end if
if $mustWaitForDNAV = False$ then {check if DNAV in direction is set}
    if sense in direction D success then {sense for sufficiently long before sending}
        Start BO
        if $BO\ count = 0$ then {if BO counts down}
            transmit PKT {transmit DRTS}
        else
            continue BO {otherwise continue BO}
        end if
    else
        $MustWaitForNAV \Leftarrow True$ {set DNAV entry}
    end if
else
    $set\ timer\ to\ wait\ for\ DNAV$ {wait for DNAV}
end if
```

and we continue the sector scanning.

Finally, the timeout handle of the MAC protocol was augmented to implement the operation of the DtD MAC protocol. For example, we augmented the simulator so that packets are not dropped after $2M$ retries. Instead, the retry counter is reset, the sector is incremented and the transmission is retired for $2M$ times in the new direction.

Algorithm 4 shows the pseudo code that handles the timeout events of the various timers. Lines 1 through 3 handle the case where a timeout occurs while in the 'Wait for ACK' state. In this case, we retransmit the ACK. In lines 4 through 11, the case where a timeout occurs when in the 'Wait for DNAV' state. If there is a message in the transmit buffer, then it is sent after waiting for DIFS time. Otherwise, we set the state to idle. In lines 12 through 17, we handle the case where a timeout occurs during the 'Wait for CTS' and 'Wait for DATA' states.

The full source code can be obtained online [52].

5.2 Simulation parameters

To verify the analytical model, extensive simulations are run. We implemented the DtD MAC protocol in Qualnet v4.0. We use the 802.11b PHY layer model. The values of the parameters used in the simulations are listed in Table 5.1. The system is loaded by seven Constant Bit Rate (CBR) traffic flows. The nodes are uniformly distributed in a 200 x 200 m^2 area. The offered load used to measure the throughput performance is 5 Mbps. The network topology is randomly generated by Qualnet. The simulation runs for 100 seconds and the results are the average of 6 runs that use different random seeds. The 95% confidence interval widths for the simulation results are plotted. These parameters are used in all our simulations, unless otherwise explicitly stated.

Algorithm 3 Transmit packet

Require: *PKT object p*

```
if $P = DRTS$ then {if pkt is DRTS}
    $DRTSNum++$
    if $DRTSNum = DRTSmax$ then {if attempted 2M times}
        if Attempted all M sectors then {check to see if all M sectors were attempted}
            drop DRTS {if so drop pkt}
        else
            $SECTOR++$ {go to next sector}
        end if
    else
        Tx DRTS in direction D
        lock direction {lock in anticipation of DCTS}
    end if
end if
if $P = DCTS$ then {Tx DCTS after SIFS time}
    wait for SIFS
    Tx DCTS
end if
if $P = DATA$ then {Tx DATA after SIFS time}
    wait for SIFS
    Tx DATA
end if
if $P = ACK$ then {ACK successfully Rx'd continue sector scan}
    $DATASuccess++$
    continue sector scan
end if
```

Algorithm 4 Handle timeout

```
Require: node state
if state = WaitForACK then
    ReTx ACk {if ACK not Rx'd within timeout then ReTX}
end if
if state = WaitForDNAV then {if NAV time is over}
    if there is msg to Tx then {and there is a msg to be sent}
        wait for DIFS
        call Send pkt {if there is pkt then Tx}
    else
        state ⇐ Idle {otherwise just idle}
    end if
end if
if state = WaitForCTS then
    ReTx CTS {if CTS not Rx'd within timeout then ReTX}
end if
if state = WaitForDATA then
    ReTx DATA {if DATA not Rx'd within timeout then ReTX}
end if
```

Table 5.1: Simulation parameters

Parameter	**Value**
N	14
Tx power	15 dbm
Data rate	2 Mbps
Base rate	1 Mbps
Rx Threshold	-81 dbm
Sensing Threshold	-91 dbm
W_{max}	64
Pkt size	512 Bytes
Communication range	200 m
SIFS	10 μS
Slot time σ	20 μS
MAC header	28 Bytes
PHY header	192 bits
DRTS	160 bits + PHY header
DCTS and ACK	112 bits + PHY header

5.3 Network Throughput

Figure 5.1 compares the throughput obtained from simulations. For $M = 1$, the original 802.11 DCF MAC is used, and for $M > 1$, the proposed DtD MAC protocol is used. The relatively small value of $W_{\max} = (64)$ chosen here is because: a) the number of nodes competing in the same direction using directional antennae is lower than that using omnidirectional antenna, and b) a large number of DRTS messages are missed due to deafness not collision. The general principle is that $W_{\max}$ could be smaller if M is larger. We observe that, as the offered load increases, the network approaches its maximum saturation throughput. We also observe that the directional antennae ($M = 2$, 4 and 6) cases achieve higher throughput than the omnidirectional antenna ($M = 1$) case, and $M = 4$ achieves the highest throughput.

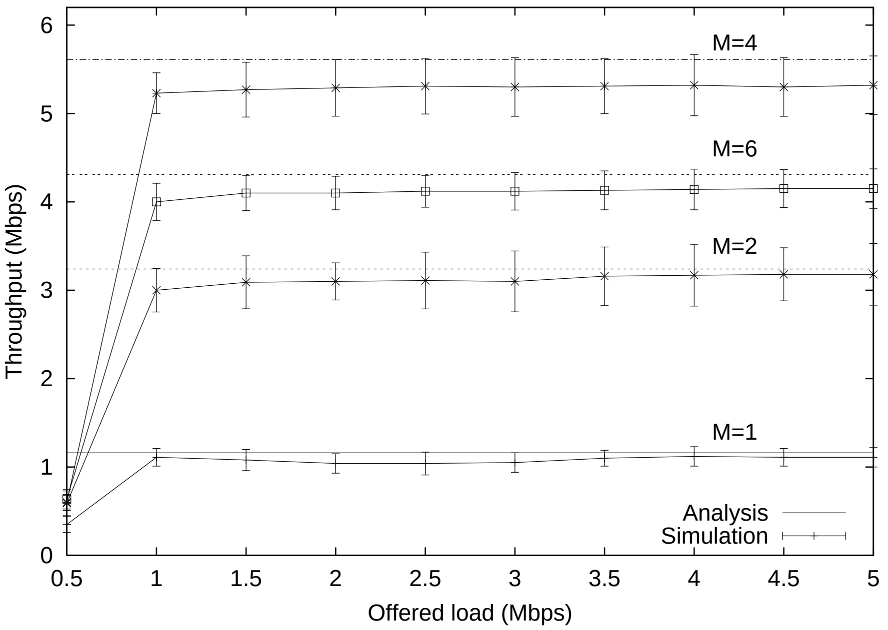


Figure 5.1: Network saturation throughput

In Figure 5.2, we plot the network throughput for increasing number of sectors, and $W_{\max}$ is chosen to be 64 and 128, respectively. From the figure, we observe that for a smaller $W_{\max}$, the throughput is higher overall. Furthermore, we can see that when the number of sectors is 2 or 4 the throughput of network is higher than the case when the number of sectors is 6. This is mainly due to the increased overhead of the control messages. This leads us to conclude that there is an optimal number of antenna sectors and $W_{\max}$ for a specific network density. A similar trend was also observed in [53].

Furthermore, Figure 5.2 shows the throughput when the directional-to-omnidirectional protocol is used [43]. When the number of sectors at the sender is small (i.e M=2), we observe a small improvement in throughput compared to the omnidirectional-to-omnidirectional case. As M, increases we see an increase in throughput, however, the DtD MAC protocol provides continues to outperform the directional-to-omnidirectional MAC protocol in terms of throughput.

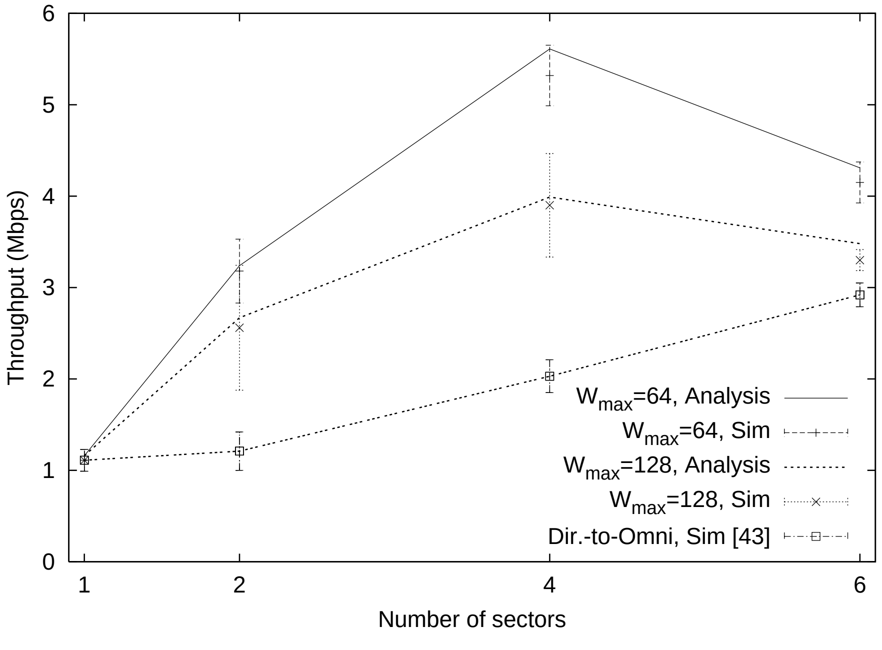


Figure 5.2: Network throughput with different number of sectors

Fig. 5.3 shows that the saturation throughput for a certain number of sectors is maximized for a specific number of nodes. Interestingly, we observe that for a higher number of antennae sectors, the number of nodes that the throughput is maximized at is higher (i.e., 14 vs. 16). This suggests that a higher number of antennae sectors is desirable for more dense networks.

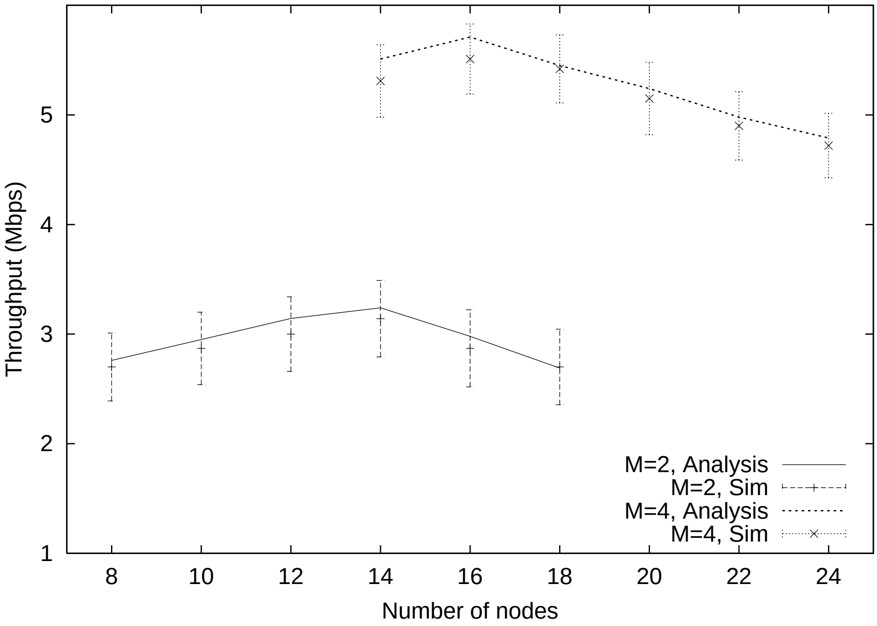


Figure 5.3: Network throughput with different number of nodes

Fig. 5.4 shows the network throughput vs. different packet sizes. We observe an expected trend, as the packet size increase the throughput increases. This is because as the payload size increases and the time needed to transmit the control packets remains the same, the efficiency also increases.

In all cases, the simulation results agree with the analytical results obtained.

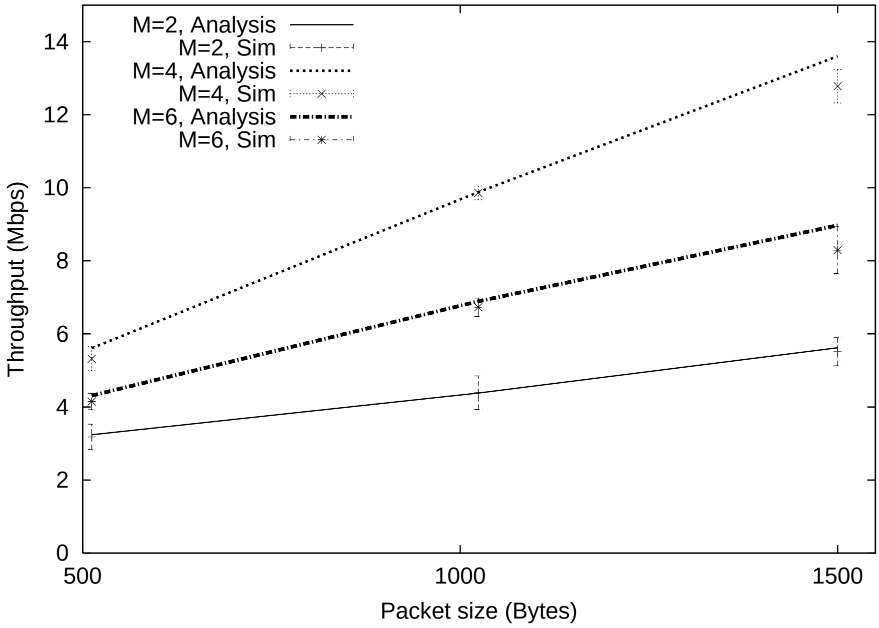


Figure 5.4: Network throughput with different packet sizes

5.4 Feasibility of the DtD MAC protocol for the mmWave technology

In this section we study the performance of the DtD MAC protocol for the high data rate mmWave technology. The base rate used is 50 Mbps and the data rate used is 1 Gbps [54]. Due to the limitations of the simulator used, we only present analytical results. Fig. 5.5 shows the saturation throughput of a 14 node network using the 512, 1024 and 1500 Byte packets. It can also be observed that as the number of sectors increases, the throughput saturates and begins to decrease. Again, this can be explained by the increasing overhead introduced by the DtD MAC protocol as M becomes large. Furthermore, we plot the same results for 100 nodes. In doing this, we found an interesting phenomenon. Not only is the throughput greater when more nodes are present, but also, the trend observed in the omni-directional case is reversed. As observed from the bottom left corner of Fig. 5.5, when the number of nodes was increased, the throughput of the omni-directional case decreased; however, the throughput of the DtD MAC protocol increased. This is because of the increase in spatial reuse that is achieved by using directional antennae. This observation leads us to conclude that the DtD MAC protocol is indeed desirable for dense networks where physical data rates are high (i.g. mmWave).

From Fig. 5.5, the saturation throughput is quite low (considering a 1 Gbps data rate and 50 Mbps base rate). Reference [54] states that the maximum payload size for the IEEE 802.15.3c (mmWave) standard is 65355 Bytes. Therefore, we plot the results for packet sizes 32767, 65355 and 2 × 65355 bytes.

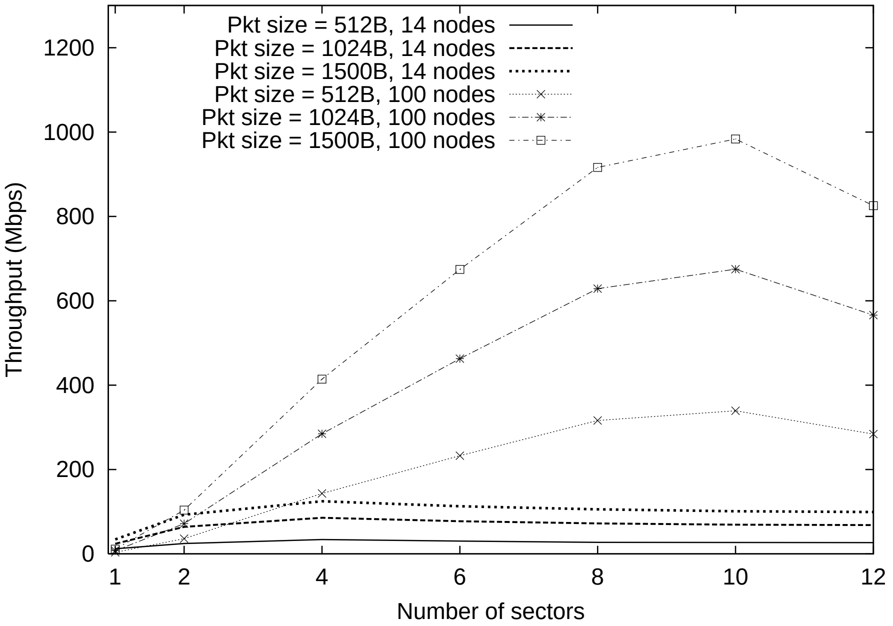


Figure 5.5: mmWave Network throughput using small packet sizes, 14 and 100 nodes

From Fig. 5.6, the network throughput using packets of this size is in the order of 0.5 ∼ 4 Gbps. This proves the feasibility of the DtD MAC protocol for high data rate technologies.

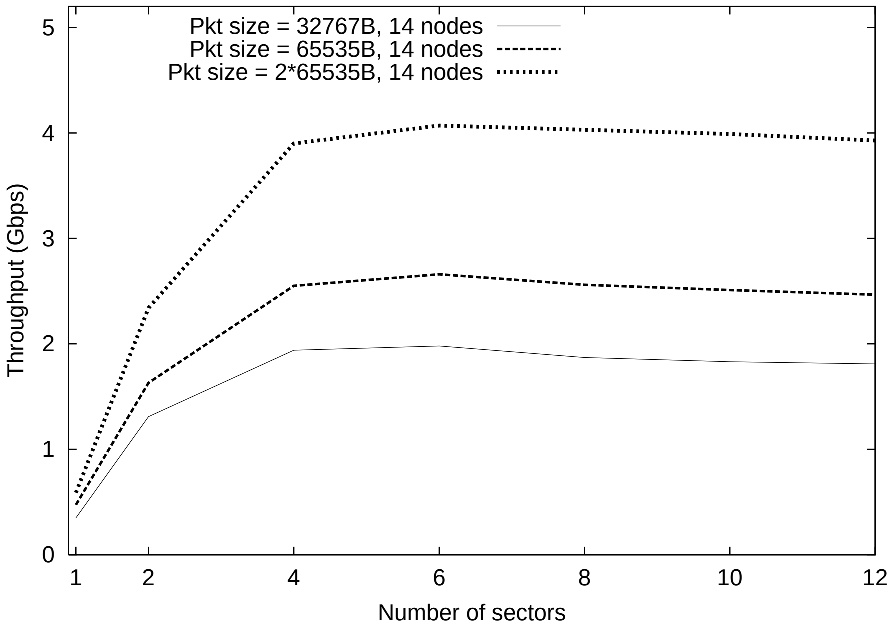


Figure 5.6: mmWave Network throughput using large packet sizes

5.5 Access delay of the DtD MAC protocol

In this section we study the average access delay performance of DtD MAC. We consider two cases, the narrowband case and the case where the high data rate mmWave technology is used. We define the average access delay as in (4.26) to be the transmission time of DRTS packets, the carrier sense time and the backoff time spent in between successive DRTS transmissions.

To focus on access delay only, in our simulations we consider 2 nodes (a sender and a receiver) and measure the amount of time that the sender requires to begin sending data. In Fig. 5.7, we plot the average access delay for an increasing number of sectors. We can observe that as the number of antenna sectors increases, the access delay also increases. This is due to the fact that more DRTS packets need to be sent when the number of sectors increases. In addition, it can be observed from Fig. 5.7

that the packet size also affects the access delay. This is due to the fact that the carrier sense time depends on the data packet size.

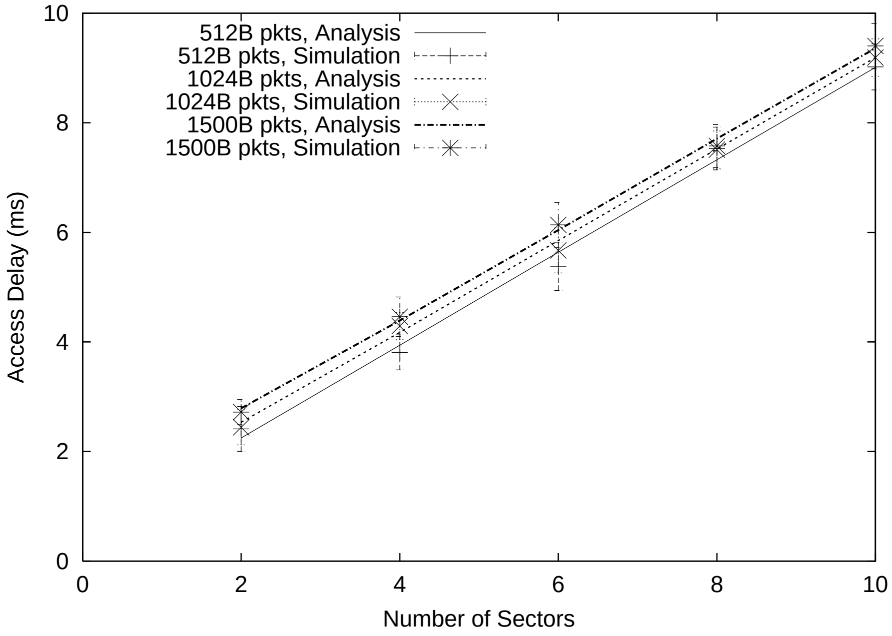


Figure 5.7: Access Delay for different number of sectors

Fig. 5.8 plots the access delay with respect to the number of sectors when the high data rate mmWave technology is used. Because the base rate (50 Mbps) and the data rate (1 Gbps) are much higher, the access delay is lower. This leads us to conclude that DtD MAC can perform well for the high data rate mmWave technology. In addition, using more directional antenna sectors is more feasible for mmWave.

5.6 Fairness of the DtD MAC protocol

To measure the fairness of the DtD MAC protocol, we use Jain's fairness index [55]. The index uses throughput of a given node $(x_1, x_2, ..., x_i)$ within a group as a measure of fairness. It defines the fairness index as

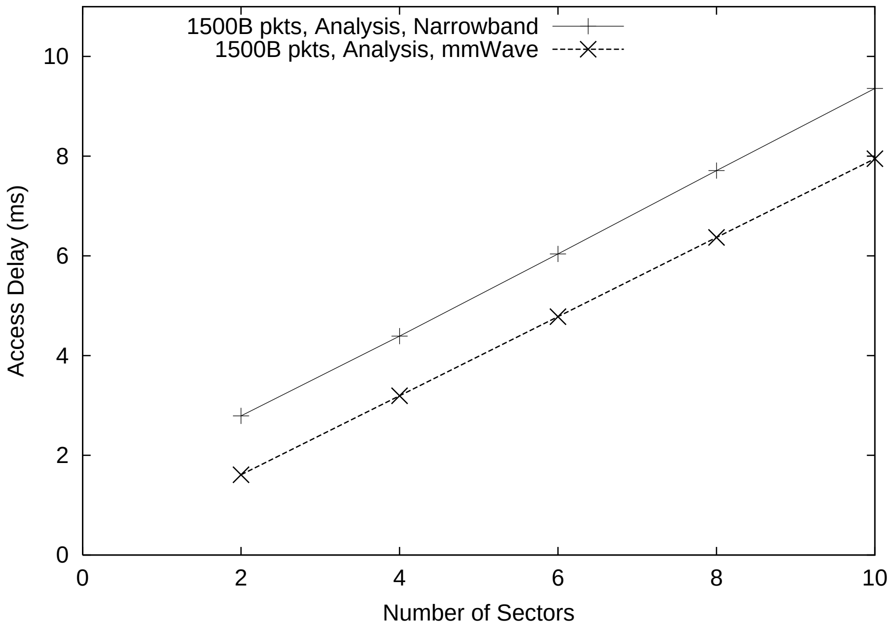


Figure 5.8: Access Delay for mmWave with respect to number of sectors

$$f(x_1, x_2, ..., x_i) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \sum_{i=1}^{n} x_i^2}. \tag{5.1}$$

The values of the fairness index are between 0 to 1, where 1 indicates ideal fairness and $1/n$ indicates that the fairness is skewed towards one specific node. Using a random topology, we calculate the fairness index when the network is loaded. The results are plotted in Fig. 5.9. For the sake of comparison, we calculated the fairness index when using an omni-directional antenna and show that DtD MAC can outperform the omni case. As the offered load increases and the network becomes more congested, the fairness of the omnidirectional case decreases while DtD MAC continues to achieve a high level of fairness. This high fairness index measure can be explained by the fact that DtD MAC uses directional DRTS and DCTS control messages and reserves less area than using omnidirectional RTS/CTS control messages.

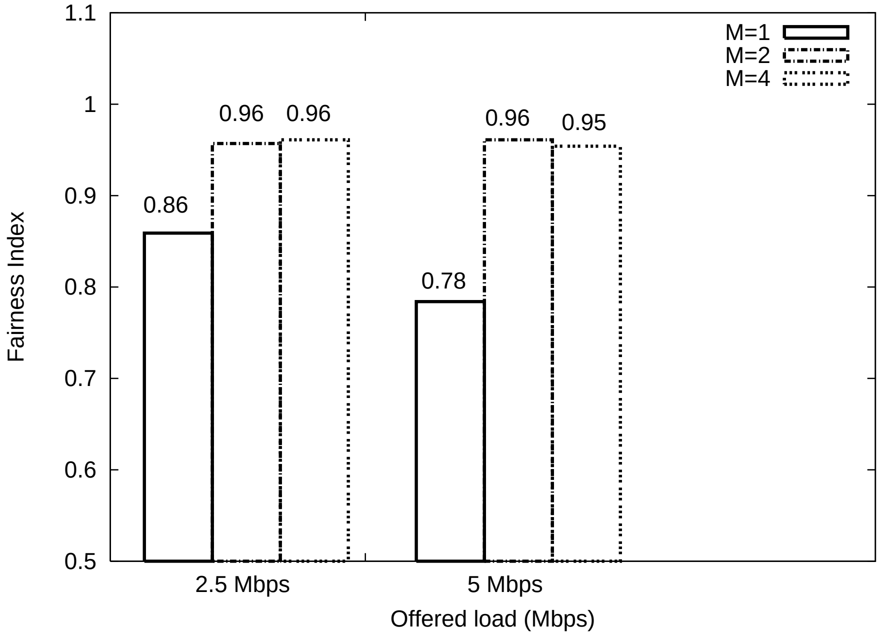


Figure 5.9: Fairness index under loaded conditions for varying number of M

Chapter 6

Conclusion and future work

6.1 Conclusions and summary of contributions

In this thesis, we have outlined the design of the DtD MAC protocol that supports directional-to-directional transmissions. The DtD MAC protocol is fully distributed, does not require synchronization, eliminates the asymmetry-in-gain problem and alleviates the effect of deafness in directional antennae networks. The performance of the protocol has been studied through an analytical model and verified by simulations. We showed that DtD MAC can improve throughput and fairness.

The feasibility of the DtD MAC has also been studied for the high data rate mmWave technology and the results are promising. It has been shown that as the number of nodes in a network increases, the DtD MAC protocol can significantly improve throughput when the number of antennae sectors is appropriately chosen.

The contributions of this thesis are threefold. First, we design the DtD MAC protocol that uses directional transmission and reception exclusively. Then, we built an analytical model to study the performance of the DtD MAC protocol, in terms throughput and delay performance. Finally, we verified the correctness of the analysis through extensive simulations. Although the results obtained are promising, some issues still remain open.

6.2 Limitations and further research issues

There are three main open issues that need to be addressed. Due to the fact that the deafness problem is magnified in networks with directional-only antennae, we need to carefully design a BO algorithm that ensures the stability of the network under congestion, and at the same time, perform efficiently under light network load. In addition, the current protocol scans all sectors for the same amount of time in a uniformly distributed manner. Can we do better?

6.2.1 Deafness

The effect of the deafness problem on the DtD MAC protocol is a serious issue that needs to be further studied. It is also magnified by the fact that there is no network synchronization. Sending a sequence of DRTS packets can solve this problem, but it may not be the most efficient solution. One particular area that can be enhanced to alleviate the effect of this inefficiency is the backoff between successive DRTS transmissions. Using BEB between successive DRTS transmission is wasteful. At the same time, BEB is desirable in congested network conditions. If nodes could identify if the network is really congested, or if they are just experiencing deafness and adaptively choose a backoff strategy, the performance of DtD MAC could significantly improve. Studying proper backoff strategies is an interesting issue that we look forward to studying in the near future.

6.2.2 Channel Utilization

To study the efficiency of the DtD MAC protocol, we measure the time that a node spends transmitting data over the time it takes for the entire transmission. For every data packet, a node needs to send M DRTS packets on average, carrier sense for $DATA + SIFS$ time and takes the time for backoff. To improve the channel utilization, it is desired to reduce this 'overhead' time. In addition, we can easily observe that as M increases, the utilization decreases (even with antennae gain taken into consideration). Efficient solutions to this problem are required to improve the performance of the DtD MAC protocol.

6.2.3 'Smart' sector scanning

The performance of the DtD MAC protocol is significantly affected by the number of sectors M (as can be observed from the previous two sections). This is because the sender needs to send M DRTS packets in each direction on average. If we can improve this sector scanning mechanism, there is a possibility of improving the efficiency, and hence, throughput.

One example of improving the efficiency of the protocol is to synchronize all nodes in the network. If this is possible, we can reduce the maximum number a sender needs to retry DRTS transmissions. This in turn would require less DRTS packets to be sent on average.

To fully utilize the benefits of directional antennae, directional MAC protocols need to support directional-to-directional transmission. To this end, we have taken a first step in this direction and proposed a directional MAC protocol that supports directional-only transmission and reception. We have showed that the DtD MAC protocol can improve network throughput and fairness. However, many future opportunities for improvement still exist. We outlined a few key issues in this chapter in hope of inspiring further research in this direction.

Bibliography

[1] Y. Wang and J. Garcia-Luna-Aceves, "Spatial reuse and collision avoidance in ad hoc networks with directional antennas," in *Proc. of GLOBECOM'02*, November 2002, pp. 112–116.

[2] T. Issariyakul, H. Ekram, and K. Dong, "Medium access control protocols for wireless mobile ad hoc networks: issues and approaches," *Wireless Communications and Mobile Computing*, vol. 3, no. 8, pp. 935–958, November 2003.

[3] L. X. Cai, L. Cai, X. Shen, and J. Mark, "Efficient resource management for mmWave WPANs," in *Proc. of WCNC'07*, March 2007, pp. 3816–3821.

[4] A. Nasipuri, S. Ye, J. You, and R. Hiromoto, "A MAC protocol for mobile ad hoc networks using directional antennas," in *Proc. of WCNC'00*, September 2000, pp. 1214–1219.

[5] Y. Ko, V. Shankarkumar, and N. Vaidya, "Medium access control protocols using directional antennas in ad hoc networks," in *Proc. of INFOCOM'00*, March 2000, pp. 13–21.

[6] M. Takai, J. Martin, A. Ren, and R. Bagrodia, "Directional virtual carrier sensing for directional antennas in mobile ad hoc networks," in *Proc. of MobiHoc'02*, June 2002, pp. 183–193.

[7] R. Ramanathan, J. Redi, C. Santivanez, D. Wiggins, and S. Polit, “Ad hoc networking with directional antennas: A complete system solution,” *IEEE Journal on Selected Areas in Comm.*, vol. 23, no. 3, pp. 496–506, March 2005.

[8] R. Choudhury, X. Yang, R. Ramanathan, and N. Vaidya, “Using directional antennas for medium access control in ad hoc networks,” in *Proc. of MOBICOM’02*, March 2002, pp. 59–70.

[9] H. Gossain, C. Cordeiro, D. Cavalcanti, and D. P. Agrawal, “The deafness problems and solutions in wireless ad hoc networks using directional antennas,” in *Proc. of GLOBECOM’04*, Nov.-Dec. 2004, pp. 108–113.

[10] G. Jakllari, I. Broustis, T. Korakis, S. V. Krishnamurthy, and L. Tassiulas, “Handling asymmetry in gain in directional antenna equipped ad hoc networks,” in *Proc. of PIMRC’05*, September 2005, pp. 1284–1288.

[11] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, “MACAW: A media access protocol for wireless LAN’s,” in *Proc. of SIGCOMM*, Aug.-Sept. 1994, pp. 212–225.

[12] S. Kumar, V. Raghavan, and J.Deng, “Medium access control protocols for ad hoc wireless networks: A survey,” *Elsevier Ad Hoc Networks*, vol. 4, no. 3, pp. 326–358, May 2006.

[13] T. Rappaport, *Wireless Communications: Principles and practice.* Prentice Hall PTR, 2002.

[14] P. H. Moose, “A technique for orthogonal frequency division multiplexing frequency offset correction,” *IEEE Transactions on Communications*, vol. 42, no. 10, pp. 2908–2914, October 1994.

[15] R. Scholtz, "Multiple access with time-hopping impulse modulation," in *Proc. of MILCOM'93*, October 1993, pp. 447–450.

[16] A. Viterbi, *CDMA: principles of spread spectrum communication.* Addison Wesley Longman Publishing Co., 1995.

[17] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.* IEEE 802 part 11, 1999.

[18] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, 2000.

[19] A. Spyropoulos and C. Raghavendra, "Energy efficient communications in ad hoc networks using directional antennas," in *Proc. of INFOCOM'02*, June 2002, pp. 220–228.

[20] I. Akyildiz and X. Wang, "A survey on wireless mesh networks," *IEEE Communications Magazine*, vol. 43, no. 9, pp. S23– S30, September 2005.

[21] S. Yong and C. Chong, "An overview of multigigabit wireless through millimeter wave technology: Potentials and technical challenges," *EURASIP Journal on Wireless Communications and Networking*, vol. 2007, 2007.

[22] "IEEE 802.15.3c task group," http://www.ieee802.org/15/pub/TG3c.html.

[23] S. Bandyopadhyay, K. Gyoda, K. Hasuike, S. Horisawa, Y. Kado, and S. Tawara, "An adaptive MAC protocol for ad hoc networks with directional antenna," *IEICE TRANS. COMMUN.*, vol. E84-B, no. 11, 2001.

[24] H. Dai, K. Ng, and M. Wu, "An overview of MAC protocols with directional antennas in wireless ad hoc networks," in *Proc. of ICWMC'06*, July 2006, pp. 84–91.

[25] S. A. Borbash, A. Ephremides, and M. J. McGlynn, "An asynchronous neighbor discovery algorithm for wireless sensor networks," *Ad Hoc Networks*, vol. 5, no. 7, pp. 998–1016, September 2007.

[26] X. An and R. Hekmat, "Self-adaptive neighbor discovery in ad hoc networks with directional antennas," in *Proc. of IST'07*, July 2007, pp. 1–5.

[27] S. Vasudevan, J. Kurose, and D. Towsley, "On neighbor discovery in wireless networks with directional antennas," in *Proc. of INFOCOM'06*, March 2006, pp. 2502–2512.

[28] R. Choudhury and N. H. Vaidya, "Deafness: a mac problem in ad hoc networks when using directional antennas," in *Proc. of ICNP'04*, October 2004, pp. 283–292.

[29] J. Wang, Y. Fang, and D. Wu, "SYN-DMAC: A directional mac protocol for ad hoc networks with synchronization," in *Proc. of MILCOM'05*, October 2005, pp. 2258–2263.

[30] J. Wang, H. Zhai, P. Li, Y. Fang, and D. Wu, "Directional medium access control for ad hoc networks," *ACM Wireless Networks*, p. to appear, February 2008.

[31] R. Choudhury, X. Yang, R. Ramanathan, and N. Vaidya, "On designing MAC protocols for wireless networking using directional antennas," *IEEE Trans. on Mob. Comp.*, vol. 5, no. 5, pp. 477–491, May 2006.

[32] H. Singh and S. Singh, "Tone based mac protocol for use with adaptive array antennas," in *Proc. of WCNC'04*, March 2004, pp. 1246–1251.

[33] Z. Huang, C. Shen, C. Srisathapornphat, and C. Jaikaeo, “A busy-tone based directional MAC,” in *Proc. of MILCOM’02*, October 2002, pp. 1233–1238.

[34] Z. Zhang, “Pure directional transmission and reception algorithms in wireless ad hoc networks with directional antennas,” in *Proc. of ICC’05*, May 2005, pp. 3386–3390.

[35] Z. Zhang, B. Ryu, G. Nallamothu, and Z. Huang, “Performance of all-directional transmission and reception algorithms in wireless ad hoc networks with directional antennas,” in *Proc. of MILCOM’05*, October 2005, pp. 225–230.

[36] M. Takata, M. Bandai, and T. Watanabe, “A receiver-initiated directional MAC protocol for handeling deafness in ad hoc networks,” in *Proc. of ICC’06*, June 2006, pp. 4089–4095.

[37] G. Jakllari, W. Luo, and S. V. Krishnamurthy, “An integrated neighbor discovery and MAC protocol for ad hoc network using directional antennas,” *IEEE Transactions on Wireless Communications*, vol. 6, no. 3, pp. 1114–1024, March 2007.

[38] G. Jakllari, W. Luo, and S. V. Krishnamurthy, “An integrated neighbor discovery and MAC protocol for ad hoc networks using directional antennas,” in *Proc. of WoWMoM’05*, June 2005, pp. 11–21.

[39] A. Spyropoulos and C. Raghavendra, “Asympotic capacity bounds for ad-hoc networks revisited: The directional and smart antenna cases,” in *Proc. of GLOBECOM’03*, December 2003, pp. 1216–1220.

[40] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” *IEEE Trans. on Info. Theo.*, vol. 46, no. 2, pp. 388–404, March 2000.

[41] S. Yi, Y. Pei, and S. Kalyanaraman, "On the capacity improvments of ad hoc wireless networks using directional antennae," in *Proc. of Mobhoc'03*, June 2003, pp. 108–116.

[42] J. Hsu and I. Rubin, "Performance analysis of directional random access scheme for multiple access mobile ad-hoc wireless networks," in *Proc. of MILCOM'05*, October 2005, pp. 45–51.

[43] J. Hsu and I. Rubin, "Performance analysis of directional CSMA/CA MAC protocol in mobile ad hoc networks," in *Proc. of ICC'06*, June 2006, pp. 3657–3662.

[44] R. Ramanathan, J. Redi, C. Santivanez, D. Wiggins, and S. Polit, "Ad hoc networking with directional antennas: A complete system solution," *J. Selected Areas in Comm.*, vol. 23, no. 3, pp. 496– 506, Jan. 2005.

[45] R. Choudhury, T. Ueda, and J. Bordim, "Ad hoc networking using beamforming antennas: A testbed experience," Univ. of Illinois at Urbana-Champaign," technical report, Sept. 2004.

[46] P. Bhagwat, B. Raman, and D. Sanghi, "Turning 802.11 inside-out," *Computer Communication Review*, vol. 34, no. 1, pp. 33–38, 2004.

[47] *Qualnet v4.0*, www.scalable-networks.com.

[48] C. Balanis, *Antenna Theory: Analysis and Design.* John Wiley and Sons, 1997.

[49] S. N. Muthaiah, A. Iyer, A. Karnik, and C. Rosenberg, "Design of high throughput scheduled mesh networks: A case for directional antennas," in *Proc. of GLOBECOM'07*, November 2007, pp. 5080–5085.

[50] W. X. Sheng, J. Zhou, D. G. Fang, and Y. C. Gu, “Super-resolution DOA estimation in switch beam smart antenna,” in *Proc. of ISAPE’00*, August 2000, pp. 603–606.

[51] N. Karmakar and M. Bialkowski, “Electronically steerable array antennas for mobile satellite communications-a review,” in *Proc. of ICPAST’00*, May 2000, pp. 81–84.

[52] E. Shihab, “DtD MAC Qualnet source code,” www.ece.uvic.ca/~emads/code.html.

[53] N. Ehsan and R. L. Cruz, “Optimal rate and beam-width control in wireless ad-hoc networks with directional antennas,” in *Proc. of ICC’07*, June 2007, pp. 4943–4948.

[54] *Merged proposal: New PHY Layer and Enhancement of MAC for mmWave System Proposal.* IEEE 802.15 WPAN Millimeter Wave Alternative PHY Task Group 3c (TG3c), November 2007.

[55] R. Jain, *The Art of Computer Systems Performance Evaluation.* New York: Wiley, 1991.