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PERFORMANCE IMPROVEMENT OF AD HOC NETWORKS USING DIRECTIONAL ANTENNAS AND POWER CONTROL

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LIST OF ACRONYMS

4G	The Fourth Generation wireless communications technology
ACK	Acknowledge
ADC	Analog to Digital Converter
AOA	Angle of Arrival
AODV	Ad Hoc On-Demand Distance Vector Routing
AP	Access Point
BER	Bit Error Rate
BFN	Beamforming Network
BM	Butler Matrix
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CMA	Constant Modulus Algorithm
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Multiple Sense Access with Collision Avoidance
CTS	Clear To Send
DCF	Distributed Coordination Function
DCTS	Directional CTS
DES	Discrete Event Simulator
DIFS	DCF IFS
DRTS	Directional RTS

DSP	Digital Signal Processing
DSSS	Direct Sequence Spread Spectrum
DVCS	Directional Virtual Carrier Sensing
EIFS	Extended Inter-Frame Spacing
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
GloMoSim	Global Mobile Information System Simulator
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
IFS	Inter-Frame Spacing
IR	Infrared
ISM	Industrial-Science-Medical
LAN	Local Area Network
LLC	Logical Link Control
LMS	Least Mean Square algorithm,
MAC	Media Access Control
NAV	Network Allocation Vector
NS2	Network Simulator 2
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PCF	Point Coordination Function

PCS	Physical Carrier Sensing
PDA	Personal Digital Assistant
PPS	Packet Per Second
QoS	Quality of Service
RF	Radio Frequency
RLS	Recursive Least Square algorithm
RTS	Ready To Send
Rx	Receive
SDMA	Space Division Multiple Access
SIFS	Short IFS
SINR	Signal to Interference and Noise Ratio
SIR	Signal-to-Interference Ratio
SMI	Sample Matrix Inversion algorithm
SNT	Scalable Network Technologies
TCP/IP	Transport Control Protocol/Internet Protocol
TDMA	Time Division Multiple Access
Tx	Transmit
VCS	Virtual Carrier Sensing
WiFi	Wireless Fidelity
WLAN	Wireless local area network

RÉSUMÉ

Au cours de la dernière décennie, un intérêt remarquable a été éprouvé en matière des réseaux ad hoc sans fil capables de s'organiser sans soutien des infrastructures. L'utilisation potentielle d'un tel réseau existe dans de nombreux scénarios, qui vont du génie civil et secours en cas de catastrophes aux réseaux de capteurs et applications militaires. La Fonction de coordination distribuée (DCF) du standard IEEE 802.11 est le protocole dominant des réseaux ad hoc sans fil. Cependant, la méthode DCF n'aide pas à profiter efficacement du canal partagé et éprouve de divers problèmes tels que le problème de terminal exposé et de terminal caché. Par conséquent, au cours des dernières années, de différentes méthodes ont été développées en vue de régler ces problèmes, ce qui a entraîné la croissance de débits d'ensemble des réseaux. Ces méthodes englobent essentiellement la mise au point de seuil de détecteur de porteuse, le remplacement des antennes omnidirectionnelles par des antennes directionnelles et le contrôle de puissance pour émettre des paquets adéquatement. Comparées avec les antennes omnidirectionnelles, les antennes directionnelles ont de nombreux avantages et peuvent améliorer la performance des réseaux ad hoc. Ces antennes ne fixent leurs énergies qu'envers la direction cible et ont une portée d'émission et de réception plus large avec la même somme de puissance. Cette particularité peut être exploitée pour ajuster la puissance d'un transmetteur en cas d'utilisation d'une antenne directionnelle. Certains protocoles de contrôle de puissance directionnel MAC ont été proposés dans les documentations. La majorité de ces suggestions prennent seulement la transmission directionnelle en considération et, dans leurs résultats de simulation, ces études ont l'habitude de supposer que la portée de transmission des antennes omnidirectionnelles et directionnelles est la même. Apparemment, cette supposition n'est pas toujours vraie dans les situations réelles. De surcroît, les recherches prenant l'hétérogénéité en compte dans les réseaux ad hoc ne sont pas suffisantes. Le présent mémoire est dédié à proposer un protocole de contrôle de puissance MAC pour les réseaux ad hoc avec des antennes directionnelles en prenant tous ces problèmes en considération.

Mots clés: Réseaux ad hoc, antennes directives, contrôle de puissance

ABSTRACT

The past decade has witnessed a remarkable interest in wireless ad hoc networks that operate without any infrastructure support. The potential for deployment of such networks exists in many scenarios ranging from civil and construction engineering, and disaster relief to sensor networks and military applications. The IEEE 802.11 Distributed Coordination Function (DCF) is the dominant MAC protocol for wireless ad hoc network. However, the DCF method could not utilize shared channel efficiently and suffers from various problems such as exposed and hidden terminal problems. Therefore, in recent years, various methods have been developed to address these problems and accordingly increase the overall network throughput, which mainly involves adjusting the carrier sensing threshold, replacing the omnidirectional antennas by directional antennas and controlling packet transmission power adequately. Directional antennas offer numerous advantages over omnidirectional antennas and thus could enhance the performance of ad hoc networks. They focus energy only in the target direction and offer longer transmission and reception ranges for the same amount of power. This feature could be used to adjust the power of the transmitter when a directional antenna is in use. Some power controlled directional MAC protocols have been proposed in the literature. Most of these proposals consider only directional transmission and, in their simulation studies, they usually assume the communication range of omni and directional antennas are the same. Apparently this assumption is not supported in any realistic situation. Moreover, there is a lack of work that considers the heterogeneity in ad hoc networks. In this thesis, we propose a suitable power controlled MAC protocol for ad hoc network with directional antennas by taking all of these issues into consideration.

Keywords: Ad hoc networks, directional antennas, power control

CHAPTER I

INTRODUCTION

1.1 General concept of ad hoc networks

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

From the perspective of the fourth Generation (4G) communication, support of ad hoc networking (MANET) is one of the requirements for 4G system [1]. Each terminal having ad hoc capability could behave as a router, forwarding traffic to other terminals and the base station. In the scenario in which terminals are out of the range of a base station, or do not have enough network interfaces, terminals could still reach the operator's infrastructure via other terminals. Thus the 4G networks could increase their coverage to a shadow region where it would be prohibitively costly or unfeasible to have radio coverage provided by base stations [2].

The phrase "ad hoc" comes from the Latin which literally means "for this purpose"[3]. The nodes in ad hoc networks are autonomous; they could be laptop computers, Personal Digital Assistants (PDAs), sensors, or mobile phones. The autonomous nodes can self-organize and self-manage the network without requiring fixed infrastructure such as a base station or central controller. Nodes in an ad hoc network are free to join, move around, and leave the network without any restriction. Ad hoc networks are able to recover and continue to be functional in the case of link breakages. For instance, when nodes leave the network or nodes' hardware breaks down, the nodes that lost their links could simply ask for new routes, then the new routes can be established and the network can maintain connectivity and reachability. Each individual node in ad hoc network is not only a host with responsibility for sending or receiving packets but a router that takes charge of forwarding packets to other nodes. If the source and the destination are not in one hop range, they use the intermediate nodes to forward the packets. In this case, the intermediate node would act as a router.

1.2 Application and usage scenarios

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

In military scenarios, aircraft are able to form an ad hoc network in the sky to communicate with one another and present a backbone for land platforms to communicate with them. The infantry can establish an ad hoc network immediately when they arrive at a battlefield to achieve communication requirements like voice, telemetry, and video. For mobile objects including warships, tanks, vehicle, and aircraft, an ad hoc network can be formed by requiring only that each object to be within the range of its closest neighbours while traditional radio technology requires a range which covers the entire topology of the network [4].

In the disaster recovery field, for example an earthquake where the supporting structures are damaged, ad hoc networks can be set up within hours to address the need of organizing and managing different search and rescue groups to work efficiently. Wireless sensor networks are another application of ad hoc networks in which sensor devices are connected in open peer-to-peer ad hoc network architecture to offer various utilizations such as monitoring traffic congestion in a city, detecting a biological weapon in the battle field and border intrusion.

Wireless mesh networks could be considered as a type of wireless ad hoc networks. Compared with mobile ad hoc networks in which routing nodes are mobile, the routing nodes in mesh networks are stationary. These mesh nodes together establish the backbone of the network. The clients' non-routing mobile nodes connect to the mesh nodes in order to use the backbone to communicate with one another and with the Internet-connected nodes to obtain Internet access. Mesh networks extend the reach of wireless networks and are ideally suited for many environments such as commercial zones, neighborhood communities and university campuses [5] [6].

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

1.3 Research problem and goals

Traditional work on ad hoc networks assumes that each device is equipped with omnidirectional antennas. With the continuing reductions in the size and cost of directional antenna in recent years, it has become feasible to use directional antennas for ad hoc networks. However, the use of directional antennas in ad hoc networks introduces some new problems, which include the deafness problem, hidden terminal problem, and higher directional interference problem. The IEEE 802.11 MAC protocol is designed to exploit omnidirectional antennas and could not work well in directional antenna based ad hoc networks. Therefore, several modified MAC protocols have been proposed to exploit directional antennas, enhance the spatial reuse, and increase network capacity.

On the other hand, integrating transmission power control algorithms into directional MAC protocols is another method to improve the performance of ad hoc networks and has received increasing interest in recent years. Some power controlled based directional MAC protocols have been proposed. To my knowledge, most of these works consider only directional transmission and they ignore the heterogeneity of ad hoc networks which means nodes in ad hoc networks could be equipped with different network facilities (some with directional antennas and some with omnidirectional antennas). In this thesis, we take heterogeneity into consideration and propose a power control mechanism in a purely directional MAC protocol which enables both directional transmission and reception of all control and data packets.

The objectives of this master's thesis are to:

- Present a general understanding of ad hoc networks.
- Present the important concepts of the MAC layer and the physical layer of the conventional IEEE 802.11 standard that are widely used in ad hoc networks as well as an overview of smart antenna technology ranging from very

fundamental elements to detailed discussion of switched beam and adaptive antennas.

- Analyze the MAC layer problems and challenges when using directional antennas in ad hoc networks. Study and compare several recently proposed MAC protocols that aim to better exploit the benefits of directional antennas.

- Illustrate the effects of transmission power control in ad hoc networks as well as review the current proposals concerning power control schemes in the context of both omnidirectional and directional antenna-based MAC protocols. Propose a suitable power controlled directional MAC protocol.

- Introduce the concept of QualNet simulator, its architecture and directory structure, its implementation of various protocols and its operation. Implement our proposed protocol in QualNet and compare it with other protocols so as to evaluate the performance improvement of ad hoc networks.

1.4 Thesis organization

The rest of the thesis is organized as follows. In Chapter 2, we describe the conventional IEEE 802.11 protocol used for ad hoc networks when terminals are equipped with omnidirectional antennas, including Distributed Coordinate Function (DCF), Carrier Multiple Sense Access with Collision Avoidance (CSMA/CA) and virtual carrier sense mechanisms; we also present the concepts of smart antennas from a technical point of view. In Chapter 3, we firstly present the MAC layer challenges of using directional antennas in ad hoc networks, then we discuss and compare several directional antenna-based MAC protocols that have been proposed in the literature in recent years. Chapter 4 presents several power control schemes in wireless ad hoc networks, which includes the power control schemes using both omnidirectional antennas and directional antennas. Our proposed power controlled MAC protocol, which is based on DVSC (Directional Virtual Carrier Sensing) protocol, is also described in this chapter. In Chapter 5, the simulation results for the proposed protocol are presented and compared to the IEEE 802.11 protocol and conventional DVCS protocol that do not include an integrated power control scheme. The simulation software is also discussed in this chapter. Finally, Chapter 6 provides a summary of the thesis and some directions for further work.

CHAPTER II

TECHNICAL BACKGROUND

2.1 Introduction

In this chapter, we present an overview of the conventional IEEE 802.11 standard that is widely used in ad hoc networks, as well as the concepts of smart antenna technology. Section 2.2 focuses on IEEE 802.11 architecture and protocols. The IEEE 802.11 distributed coordinate function, CSMA/CA and VCS (Virtual Carrier Sensing) mechanism are presented in detail. In section 2.3, we discuss two kinds of smart antenna: switched beam and adaptive array.

2.2 The IEEE 802.11 standard

2.2.1 IEEE 802.11 architecture and protocols

IEEE 802.11, or WiFi, is a set of WLAN standards developed by Working Group 11 of the IEEE LAN/MAN Standards Committee (IEEE 802). It supports two operation modes: the ad hoc mode which allows peer-to-peer communication between mobile terminals and the infrastructure mode in which mobile terminals communicate through the supporting structure such as a base station or an access point. The operating frequencies of IEEE 802.11 contain two Industrial-Science-Medical (ISM) frequency bands: 2.4GHz and 5.8GHz. The original 802.11 WLAN specification was published in 1997 and clarified in 1999. Moreover, there are still some 802.11

standard amendments being used, such as 802.11d for scanning scheme, 802.11k for Quality of Service (QoS), 802.11i for enhanced security, 802.11r for fast roaming and 802.11s for mesh networking. The most popular and widely used amendments are the 802.11a, 802.11b and 802.11g protocols.

IEEE 802.11a uses the same core protocols as the original standard and operates in the unlicensed 5GHz band. It utilizes the 52-subcarrier orthogonal frequency division multiplexing (OFDM) as physical transmission scheme and has a maximum raw data rate of 54Mbit/s.

IEEE 802.11b uses another unlicensed 2.4GHz band and employs the same CSMA/CA media access method defined in the original standard. Due to CSMA/CA protocol overhead and channel conditions, IEEE 802.11b has a lower maximum raw data rate (11Mbit/s) when compared with IEEE 802.11a.

IEEE 802.11g works in the same frequency band as 802.11b (2.4GHz) and uses the same physical layer protocol as 802.11a (OFDM). It supports a raw data rate up to 54 Mbit/s.

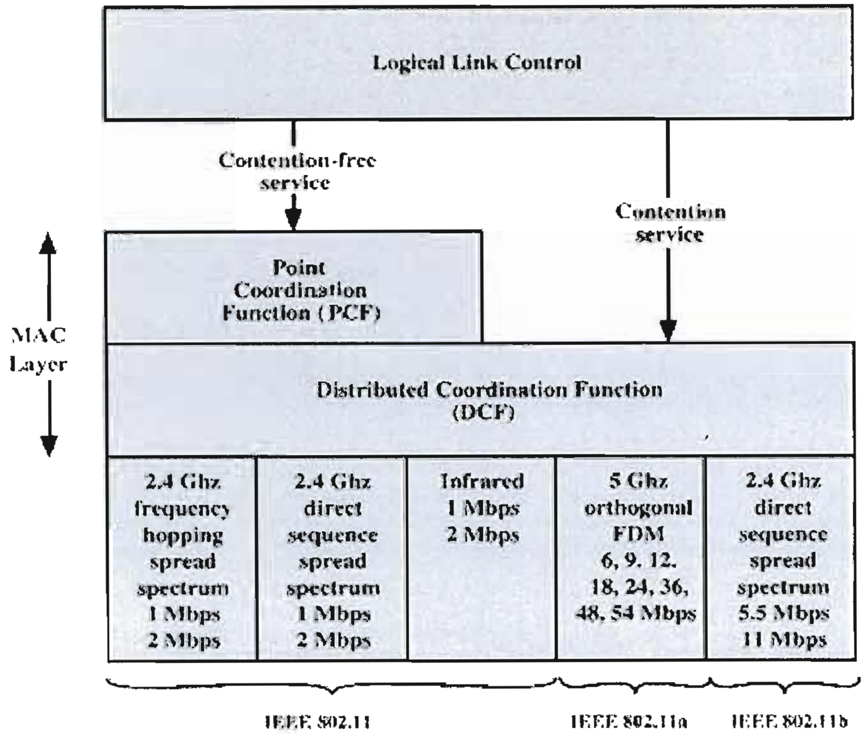

Figure 2.1: IEEE 802.11 protocol architecture

The IEEE 802.11 family specifies both the MAC layer and the PHY (physical) layer of the OSI (Open Systems Interconnection) model for wireless networks. Figure 2.1 illustrates the IEEE 802.11 protocol architecture. The PHY layer describes the specifications concerning different choices of RF technologies to use, such as Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), infrared (IR), and Orthogonal Frequency Division Multiplexing (OFDM). The purpose of the MAC layer is to provide a control mechanism that allows multiple users to use the shared channel efficiently. The data link layer is divided into two layers: the logical link control (LLC) layer and the MAC layer. The MAC layer provides two different types of service: the contention-based service offered by the Distributed Coordination Function, and the contention-free service offered by the Point Coordination Function (PCF). The DCF service is based on the CSMA/CA scheme and offers the basic access method of the 802.11 MAC protocol. The PCF is implemented on top of DCF service to support infrastructure-based wireless communication where terminals communicate via access points. Note that, the PCF service is not available for use in ad hoc mode.

2.2.2 The distributed coordinate function (DCF)

The basic 802.11 MAC layer uses Distributed Coordinate Function to allow communications between multiple mobile node pairs in the absence of an access point or base station. DCF is based on the mandatory CSMA/CA mechanism and the optional 802.11 RTS/CTS (Ready to Send/ Clear to Send) handshaking mechanism. According to DCF, a station must monitor the channel to determine whether there is any other station transmitting data before starting data transmission. If the channel is busy, the stations wait until the medium becomes idle. If any two stations are permitted to transmit by the protocol simultaneously immediately after the medium becomes idle, then collisions occur. In order to solve this problem, CSMA/CA defines various kinds of backoff time named "inter-frame spacing." A station intending to access the medium utilizes the inter-frame spacing (IFS) to prevent collisions from happening. In addition, the RTS/CTS handshaking mechanism is used with the aim of solving the hidden terminal problem.

2.2.3 Carrier sense multiple access with collision avoidance (CSMA/CA)

CSMA could be considered as a Time Division Multiple Access (TDMA) mechanism due to the fact that it allows multiple mobile stations to compete for use of the shared medium at different time slots in order to avoid the occurrence of collisions. On the other hand, CSMA could also be considered as a kind of Space Division Multiple Access (SDMA) mechanism because transmissions among several mobile node pairs are permitted to take place simultaneously without interfering with each other when mobile stations are equipped with directional antennas. According the CSMA/CA mechanism, all stations are obliged to remain silent for IFS. Various IFS are specified in the IEEE standard [7] with the objective of prioritizing different frame transmissions. High priority frames only wait for the short IFS (SIFS) period before they compete for channel access. The DCF IFS (DIFS) is adopted to transmit data frame. Extended inter-frame spacing (EIFS) is used when source station detects the Data Corruption.

CSMA/CA mechanism works as illustrated in Figure 2.2. A source node wishing to transmit senses the channel to determine the status of the medium. If no activity is detected for a period of DIFS, the source node can use the channel to transmit. If activity is detected during the period of DIFS, the backoff timer is activated. In this case, the source node waits until the medium becomes idle and then continues to sense the medium for a period of DIFS together with an additional, randomly selected backoff time. If the medium is always idle during the sensing duration, the source node could start transmitting data. If the source node senses that the medium has become busy again within the sensing duration, it stop downcounting the backoff timer and waits until the medium becomes idle and then senses the medium again for a new DIFS and the remaining backoff time. If the medium remains idle during this sensing duration, the source node begins to transmit data; otherwise it repeats this procedure until the backoff timer reaches the value zero.

Upon reception of data frame, if the bit error rate (BER) of the received data frame is under the threshold limit, the receiving node initiates the transmission of an acknowledgement frame (ACK) after a SIFS time period. On the reception of this ACK, the source node knows that this process is completed. On the other hand, the receiving node will not issue an ACK frame if the data frame is corrupted. The receiving node use the cyclic redundancy check (CRC) algorithm for error detection.

If the ACK is not received by the source node, the data frame is assumed to have been corrupted or lost, and the data packet will be scheduled to be retransmitted later.

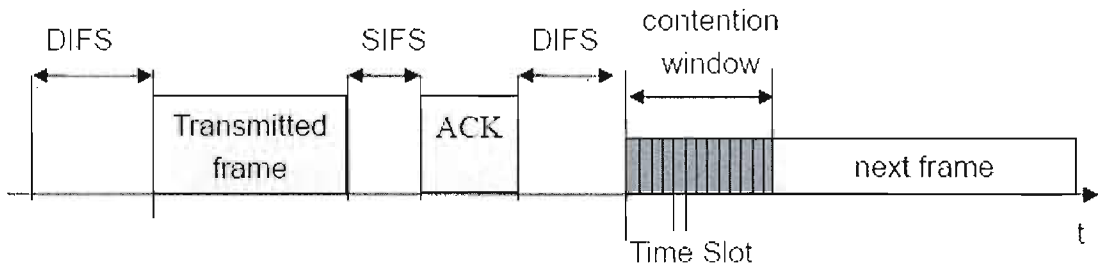

Figure 2.2: Basic operation of CSMA/CA

2.2.4 Virtual carrier sense

In the IEEE 802.11 standard, two kinds of carrier sensing mechanisms are defined, aiming at avoiding collisions in a channel. They are Physical Carrier Sensing (PCS) and Virtual Carrier Sense (VCS). PCS works in physical layer by determining the signal strength to detect collisions. However, its RF hardware is expensive to build. Another PCS issue is that it is not able to solve the well known hidden terminal problem which will be demonstrated in detail in the next paragraph.

The hidden terminal problem happens when two source stations send packets to the same destination station simultaneously due to lack of awareness of each others existence. As an example, in the following scenario, shown in Figure 2.3, source station "A" is sending packets to "B". Another source "C" also intends to send packets to "B" because C is out of the transmission range of A and hence can not physical carrier sense the ongoing transmission of A. In other words, A is "hidden" for C. So, source "C" starts to send packet to "B". Thus, a collision occurs and consequently reduces the network throughput significantly.

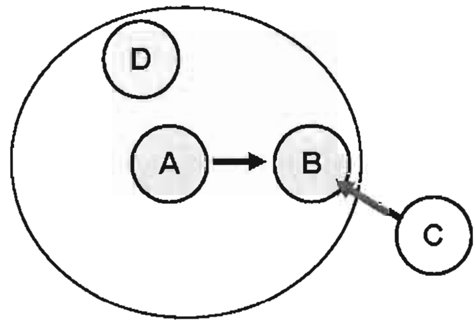

Figure 2.3: Hidden terminal problem [8]

Virtual Carrier Sense works in the MAC layer and offers a good solution to the hidden terminal problem by using Network Allocation Vector (NAV) and RTS/CTS handshaking mechanism. NAV is a timer that specifies the time period during which the station is not allowed to transmit. Figure 2.4 illustrates how the VCS works. At first, a source station wishing to transmit broadcasts an RTS packet which includes the information of the source address, destination address, and the duration of the transmission to follow. By receiving the RTS packet, the destination station responds with a CTS packet if the medium is idle after an SIFS time. The CTS packet includes the same information as the RTS packet. The neighbors of both source station and destination station overhear the RTS and/or the CTS and set their VCS timer according to the duration info specified in RTS/CTS packets. The surrounding stations then use this information to schedule the time for the next medium sensing. This process guarantees a station which did not receive the RTS is able to hear the CTS and set its VCS accordingly. RTS and CTS frames are very small in size when compared with the data frame. As a result, if any collision happens during the RTS/CTS handshaking, the bandwidth waste is very small compared to the case where collision happens during the data frame transmission (when not employing RTS/CTS mechanism).

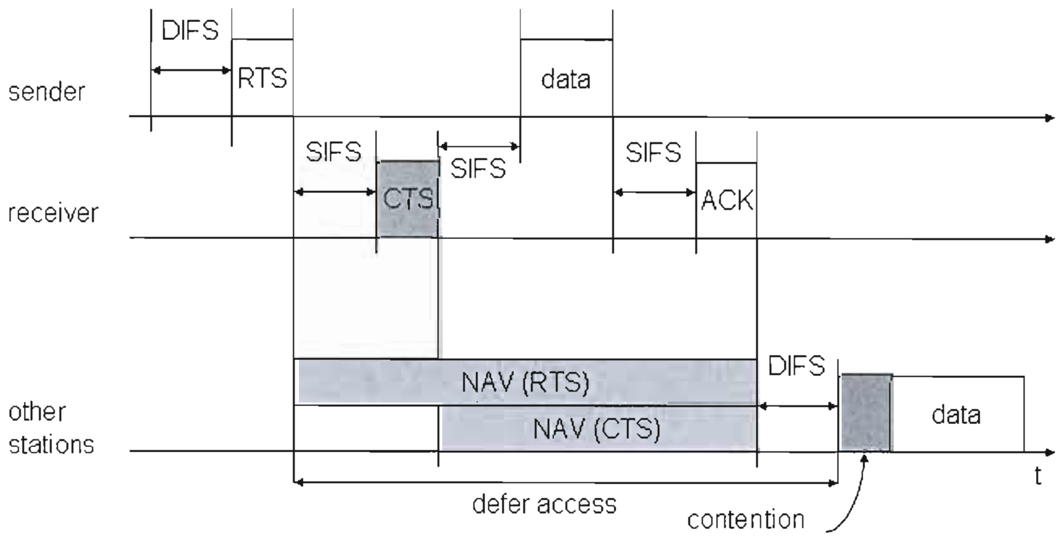

Figure 2.4: Virtual carrier sense [8]

An example of VCS is explained below as shown in Figure 2.5. First, source station A broadcasts an RTS to its neighbors: B and D. Upon receipt of the RTS, Node D finds the RTS is not for itself, so it defers its transmission. And the destination station B then sends back a CTS to A. It is obvious that node C can hear this CTS packet because it is within the transmission range of station B. thus station C also updates its NAV according to the duration information that encapsulated in CTS and defers its transmission. Thus, this process solves the hidden terminal problem and prevents interferences during data transmission between station A and B.

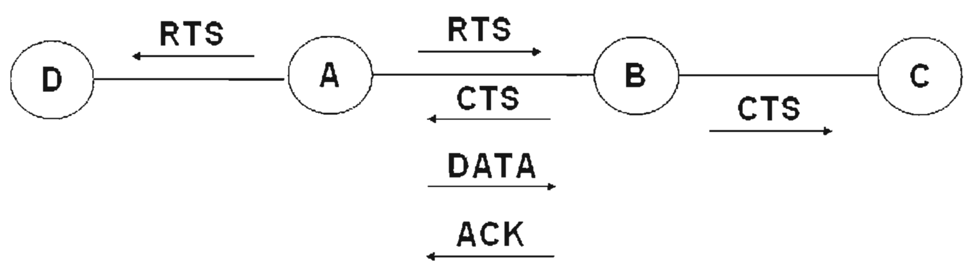

Figure 2.5: Solution for hidden terminal [8]

2.3 Smart antennas technologies

2.3.1 Background of smart antennas

In contrast to the enormous bandwidth available in optical fiber networks, the electromagnetic spectrum resources in wireless communication systems are limited. In order to maximize the efficient use of spectrum, some multiple access technologies have been developed. The first generation (1G) system for mobile telephony was analog and it employed the Frequency Division Multiple Access (FDMA) technique to allow different subscribers to communicate at the same time by using different frequencies. An example of a second generation (2G) system is the digital Global System for Mobile Communications (GSM) standard and it adopted the Time Division Multiple Access (TDMA) technique to allow different subscribers to use the same frequency in different time slots. Third generation (3G) systems utilized the Code Division Multiple Access (CDMA) technique and enabled different subscribers to communicate simultaneously on the same frequency through the use of unique spreading codes. Smart antenna technology born in 1960s introduces a new multiple access method: Spatial Division Multiple Access (SDMA). The SDMA mechanism enables different subscribers who are separated in space to communicate simultaneously using the same frequency and same spreading codes [9] [10]. Smart antennas have been widely deployed in various communication systems to improve wireless network capacity and resolve performance challenges.

An antenna in a communications system is a kind of the port through which Radio Frequency (RF) energy is radiated from the transmitter to the outside space for transmission purposes, and in reverse, from the outside space to the receiver for reception purposes. An omnidirectional antenna (also known as an isotropic antenna) radiates or receives RF energy equally in all directions. Smart antennas actually should be referred to as smart antenna systems because the antenna is not smart. It is the antenna system that can control the antenna array intelligently to form a directional radiation pattern. The smart antenna can be considered a pattern controllable antenna. It consists of a number of antenna elements arranged spatially and interconnected electrically through complex weights. The radiation pattern of the antenna array is determined by the weights based on Digital Signal Processing (DSP). Smart antenna systems could be classified into two categories: switched beam antenna and adaptive array antenna [11] [12] [13].

2.3.2 Switched beam antennas

The switched beam smart antenna system is a simple and cheap technology. It merely employs a basic switching function for selecting among separate antennas or predefined array beams. Figure 2.6 presents a basic switched beam antenna architecture which contains a control logic unit for beam selection, a switch unit for activating the right beam and a BeamForming Network (BFN).

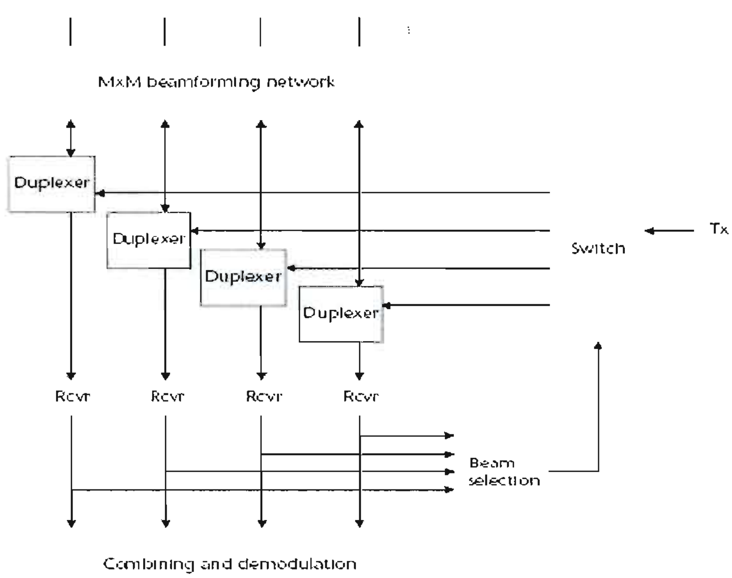

Figure 2.6: Block diagram of switched beam antennas [15]

As an example in a cellular communication system, a base station equipped with the switched beam system could detect the signal strength and choose the beam that offers the highest SINR (Signal to Interference and Noise Ratio). As the cellular phone moves throughout the sector, the base station would switch from one beam to another to achieve the best performance if required, as illustrated in Fig. 2.7. Only a single beam pattern could be used at any given time. Such an antenna system could increase coverage range up to 200 percent over conventional sector cells depending on the propagation environment, hardware and software used. It could also suppress interference arriving from directions away from the active beam's center. However, from Figure 2.7 we should notice one shortcoming of the switched beam system is that the limited predefined main beams are only available for certain prefixed directions. In the case that the user is located between two predefined main beams, the base station is not able to achieve any directional gain from the antenna system although we could increase the number of beams to mitigate this problem [14].

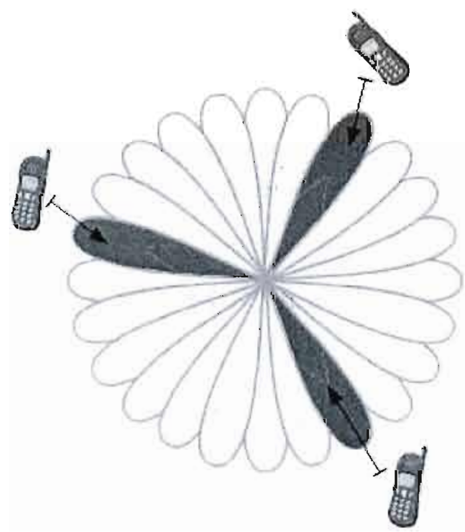

Figure 2.7: Switched beam coverage pattern [85]

Switched beam smart antenna systems work well in clean areas with low or no interference. However, in high interference environments, switched beam antennas are further limited due to their predefined fixed beam characteristic and the fact that they lack the ability to reject interference.

2.3.3 Adaptive array smart antenna systems

Compared with switched beam which only allows base stations to switch among several fixed beams in predetermined directions, the adaptive antenna is capable of steering main beams dynamically towards desired users and null toward interfering signals by using advanced signal processing techniques. In other words, by employing advanced signal processing functionality, the adaptive array has the ability to adapt to radio environment changes such as a user's movement. When a user is moving, the adaptive array system changes its antenna pattern smoothly to follow the user, always providing highest gain in the user's direction. Figure 2.8 illustrates the pattern of an adaptive antenna system. It shows the main lobe coverage extension toward the target user and nulls directed toward two interferers. The core idea of adaptive beamforming is to change the complex weight value of each element according to the changing radio environment. By multiplying these complex weight values to the output of each element, the system is able to generate the desired radiation pattern that matches the traffic conditions and offers the highest beam gain in the desired direction. Many adaptive algorithms have been developed aiming to compute the optimal complex weight which contains amplitude and phase information used for beam steer. Note that the direction of the main beam is determined by amplitudes and phases of the antenna elements of the adaptive array system.

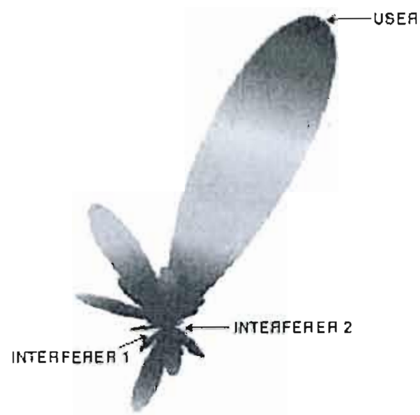

Figure 2.8: Adaptive array antenna pattern [16]

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

Figure 2.9 presents a typical adaptive array antenna system. From this figure, it is obvious that Digital Signal Processing is the key technology. This is because numbers of dynamic adjusting functionality of adaptive antenna system rely on DSP. Before the digital signal processor is able to work, the received analog signal must first be downconverted to baseband frequency. Next, the Analog to Digital Converter (ADC) will take charge of converting it to digital format.

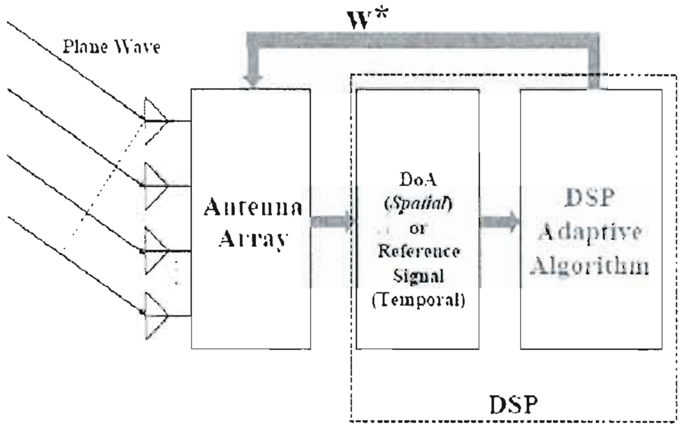

Figure 2.9: Typical adaptive array smart antenna system [18]

2.3.4 Need for smart antennas

There are many motivations to utilize the smart antenna technique in a wireless system. As an example of a cellular communication system where the capacity has become a critical issue, the use of conventional omni-directional antennas not only causes huge waste of signal energy because only a small part is transmitted to desired receiver but also generates serious interference to neighboring base stations and terminals. Therefore, the sectorization mechanism which divides one cell into several sectors and uses a directional antenna for transmission was developed with the goal of reducing the interference level. Sectorized systems have shown ability to increase frequency spectrum utilization and therefore support more capacity benefits from the sectorization gain. However, sectorized systems lack the ability to change the antenna's beamwidth or orientation in response to a changing propagation environment and traffic condition. This shortcoming results in large capacity waste in sparse traffic sectors and traffic blocks in dense traffic sectors [13]. The adaptive array smart antenna system which can intelligently control its radiation pattern based on signal processing provides an excellent solution to these problems. As we have mentioned before, its feature of focusing a narrow beam towards the target receiver increases coverage of the base station and allows the base station to decrease the transmission power to save battery power. Its feature of generating null towards interferers results in higher frequency spectrum utilization and thus increases the system capacity. And its feature of multipath rejection helps to alleviate the negative effect of multipath and diminish the effective channel's delay spread, hence results in less power loss, higher bit rate, and better QoS.

The smart antenna technique is applicable for almost all current major wireless protocols and industrial standards to achieve larger network coverage and higher system capacity. Examples of these standards could be FDMA employed in AMPS, TACS and NMT; TDMA employed in GSM and IS-136; CDMA employed in IS-95, WCDMA and TD-SCDMA; FDD and TDD [13]. As its costs continue to decline, the smart antenna offers a practical, economical solution to address wireless network capacity and performance challenges for different communication systems, including RFID, WiMax, Ultrawideband (UWB), and even WiFi.

2.4 Summary

In this chapter, important concepts of the MAC layer and physical layer of IEEE 802.11 standards and concepts of smart antenna technology have been presented. The mechanisms of CSMA/CA, VCS are discussed in detail. The 802.11 MAC protocol addresses the hidden terminal problem by using the RTS/CTS mechanism and works well when nodes in the network are equipped with traditional omnidirectional antennas. Furthermore, two main kinds of smart antenna, switched beam and adaptive array antenna are discussed in detail. We present the need for using smart antennas. Smart antennas could be used in many different communication systems including WiFi.

CHAPTER III

AD HOC MAC PROTOCOL WITH DIRECTIONAL ANTENNAS

In the previous chapter, we have presented the conventional IEEE 802.11 standard and smart antenna technologies. Smart antenna technology offers many benefits and plays a key role in 3G and 4G systems. It has been broadly used in various communication systems. However, to simply use directional antenna with the conventional IEEE 802.11 standard for ad hoc network could not bring substantial network improvements and sometimes even deteriorates network performance. This motivates many research groups to develop new MAC protocols which could fully exploit the advantages of directional antennas. This chapter first presents the challenges introduced by using directional antennas in ad hoc networks, followed by a discussion of several new MAC protocols which have been proposed in recent years to better exploit the capability of directional antennas.

The purpose of the Medium Access Control (MAC) is to achieve efficient sharing of a common wireless channel between multiple nodes, which means to allow as many simultaneous communications as possible [19]. Medium access control mechanisms could be classified into two types: contention-based and contention-free. The most used contention-based mechanism for ad hoc networks is CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance), and the most used contention-free MAC mechanism for ad hoc networks is TDMA. In this chapter, we focus exclusively on contention-based new MAC protocols that are designed for directional antennas.

Using directional antennas in ad hoc networks could enable us to achieve numerous advantages over omni-directional antennas. A transmitter equipped with directional antennas can radiate RF energy towards its intended receiver and the receiver can also radiate RF energy towards the sender, hence providing very high antenna gain. The nodes are also capable of selectively receiving signals only from a wanted direction, thus avoiding interference from undesired directions and hence resulting in high SINR. The use of directional antennas makes it possible that more simultaneous transmissions could take place. In the scenario, shown in Figure 3.1, communications between C and D node pair and between X and Y node pair are allow to occur simultaneously. This is impossible when using omnidirectional antennas. The combined effect is to help improve system throughput and capacity.

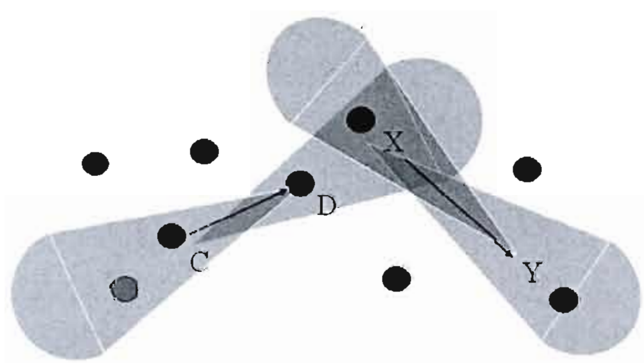

Figure 3.1: Simultaneous transmission when using directional antennas

3.1 Several issues arising from directional communication

Conventional IEEE 802.11 is designed with the assumption that omnidirectional antennas are used at the physical layer. Although the 802.11 MAC protocol could still operate correctly when nodes are equipped with directional antennas, network performance may deteriorate due to several problems, including the hidden terminals problem and the deafness problem. These problems depend on the topology and pattern flow. In the following subsections, we will first present some major problems in the directional MAC design. Then, there will also be a discussion and comparison of various new MAC schemes that have been proposed to alleviate these problems.

3.1.1 The well known hidden terminal problem

To be general, a hidden terminal can be defined as a terminal that is not aware of the ongoing communication between transmitter/receiver pairs and whose intended transmission could lead to the failure of the ongoing transmitter/receiver pair's communication. Conventional MAC protocols for ad hoc networks (the IEEE 802.11 operated in ad hoc mode) address the hidden terminal problem by employing the RTS/CTS handshaking mechanism before data transmission. However, this is under the assumption that RTS/CTS packets are sent omnidirectionally. With the use of directional antenna in physical layer, RTS/CTS packets are transmitted in the directional manner (such as protocols proposed in [20], [21]), thus two new types of hidden terminal problems arise. We explain them respectively below.

(1) Hidden terminal problem due to unequal gains in omni and directional modes

This type of hidden terminal problem is identified in [20] and can be depicted as follows. Suppose in Figure 3.2 that node D sends a DRTS (Directional RTS) and node G responds with a DCTS (Directional CTS), thus Nodes D and G beamform towards each other. Then node D starts transmitting data to G. Meanwhile, suppose that node B is in idle and listening omnidirectionally. Node B is distant enough from node G, so it is unable to hear the DCTS from G (in omni listening mode) since an omnidirectional antenna has lower gain than a directional antenna. While data transmission from node D to G is in progress, assume that node B intends to communicate with C, and thus transmit a DRTS to node C using a directional antenna. It is very possible that this DRTS from B will interfere with node G because node B and node G are now directed towards each other.

To put it simply, this type of hidden terminal problem results from the fact that transmit and receive nodes might be out of each other's range when they are operated in omnidirectional mode and directional mode respectively. However, when they are both in directional mode, they may be within each other's range.

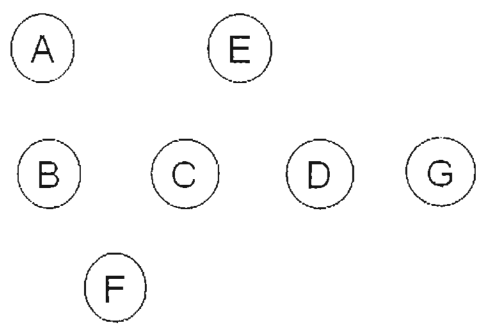

Figure 3.2: A common example scenario

(2) Hidden terminal problem due to unheard RTS/CTS

This type of hidden terminal problem results from the feature of a directional antenna that its antenna gain towards a desired direction is larger than the gain towards other directions. Consider the scenario of Figure 3.2. Assume that node B is beamformed in the direction of node A and is transmitting packets to A. In the meantime, node C transmits a DRTS to node D and node D responds with a DCTS. On receiving DCTS from D, node C starts sending data to D. In this scenario, node B is not able to hear the RTC/CTS exchange between C and D since it is beamformed in the direction of A. In other words, node B is unaware of the ongoing transmission in its neighborhood. While transmission between C and D is going on, suppose that B finishes its transmitting to A and now has intention to transmit a packet to D (or other node in the direction of D, like Node G). Node B sends a DRTS to node D. This leads to a collision at D because D's receiving beam is directed towards B. This type of hidden terminal problem could occur frequently when a directional antenna is used in the physical layer.

3.1.2 Minor lobes problem

Minor lobes represent a term used in radio engineering fields to mean any lobe except the main lobe of an antenna radiation pattern. In short, this problem arises in the case that the interferer is unaware of the ongoing transmission, and sending packets towards the minor lobes of the receiver node.

This minor lobes problem could be presents as follows. Consider the scenario of Figure 3.2 again, suppose that node B wants to transmit data to C, after a DRTS/ DCTS exchange between node B and C, node B starts transmitting data packets to node C. In the meantime, node A cannot sense the DCTS from C because it is out of the direction of the main lobe of node C. Now assume that node A intends to send data to node C and hence beamforms its main lobe towards node C. Although node C has only a minor lobe pointing in the direction of A, collision could happen at node C due to the high gain of the main lobe of node A.

3.1.3 Deafness problem

The deafness problem [22] occurs in the case that a transmit node fails to send packets to a target receiver which is pointing in another direction for an ongoing transmission. We explain the deafness problem using the same scenario in Figure 3.2. Assume that node C has packets to send to node D. Node C transmits a DRTS to D and node D responses with a DCTS. Then node C starts transmitting data to D. While this transmission is in progress, node F intends to transmit to C. Note that node F is unable to hear the DRTS/ DCTS between C and D, which means, F is unaware of the transmission between C and D. Therefore, node F sends a DRTS to node C. Because node C is facing node D, node C does not receive this DRTS from node F and therefore does not reply with DCTS. On receiving no reply from C, node F increases its contention window, chooses a backoff time, and starts counting down. When the countdown reaches zero value, Node F will retransmit the DRTS. Retransmissions could continue over and over again until C finishes its transmission and returns to the omni listening mode. This leads to huge wastage of system capacity and unfairness because the backoff time of node F would be increased after every failed attempt.

3.1.4 Higher directional interference problem

The use of a directional antenna could increase the transmission range and hence make it possible to communicate directly with distant nodes. On the other hand, this increased transmission range could also cause interference to distant nodes. To deal with these problems, some proposals simply suppose that the transmission range of directional antennas is identical to the transmission range of omnidirectional antennas. However, this is not correct in actual practice.

3.2 The directional MAC (DMAC) scheme

In [23], Young-Bae Ko proposed two Directional MAC (DMAC) schemes where each node is equipped with a Global Positioning System (GPS) receiver in order to know the physical location of each node, one transceiver, and several directional antennas. Note that a node is unable to send two packets at the same time by using different directional antennas since there is only one transceiver. This proposal could be considered a per-antenna basis 802.11 protocol. It is similar to the 802.11 DCF protocol in many ways except it transmits RTS, DATA and ACK directionally and alternatively transmits CTS omnidirectionally depending on whether the antenna pattern of the transmitter is blocked. The author assumes that transmission range of a directional antenna is the same as that of an omnidirectional antenna.

3.2.1 Protocol description: DMAC scheme 1: utilizing DRTS packet

Directional MAC (DMAC) scheme 1 enables a transmit node to use a directional antenna to send RTS packets toward a desired receiver node. After the reception of RTS, the receiver node transmits a CTS packet in all directions.

The operation of DMAC scheme 1 could be depicted using the scenario in Figure 3.3. Suppose that node B intends to send data to C and also suppose that there are no active transmissions within B's neighborhood. Thus, Node B transmits a directional RTS (DRTS) containing the B's physical location information to node C. Node A could not hear the DRTS from node B although node A is located within B's communication range. If C receives the DRTS from B successfully, it replies with an omnidirectional CTS (OCTS) to all its adjacent nodes. This OCTS includes the location of node C and location of node B. After a successful DRTS/OCTS exchange, node B starts transmitting data directionally and receives a directional ACK from

Node B. One advantage of DMAC scheme 1 is that it could enable node D to communicate with node E when communication between B and C is still ongoing.

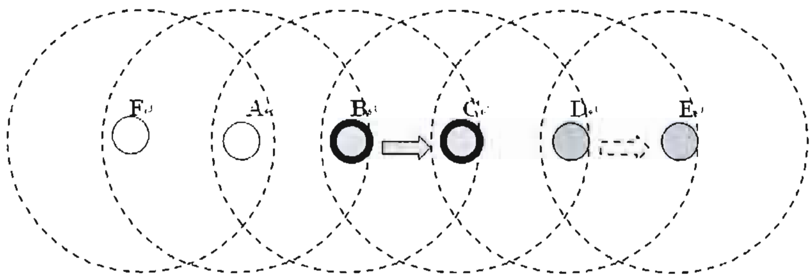

Figure 3.3: DMAC scheme 1&2

3.2.2 The DMAC scheme 2: utilizing both DRTS and ORTS packets

Directional MAC scheme 2 is proposed so as to diminish the probability of collision between control packets. When compared with DMAC scheme 1, the major improvement of DMAC 2 is its use of two types of RTS packet, directional RTS (DRTS) and omnidirectional RTS (ORTS). The node that has data to send would first transmit ORTS or DRTS according to the following two rules:

1) If none of its directional antennas are blocked by the ongoing transmission, an omni-directional RTS packet will be send,

2) Otherwise, if the desired directional antenna is not blocked, a directional RTS (DRTS) packet will be sent. If the desired directional antenna is blocked, the node will defer its transmission until that directional antenna becomes unblocked.

By introducing the combination of DRTS and ORTS packets, DMAC scheme 2 offers a solution which reduces the number of instances of collision between control packets. Except for the two rules mentioned above that are used to determine whether a node should send ORTS or DCTS, DMAC scheme 2 is identical to scheme 1.

3.3 The multihop RTS MAC (MMAC) scheme

A Multihop RTS MAC (MMAC) scheme is introduced in [24] to exploit the higher transmission gain of directional antennas for transmission on multihop paths. The MMAC scheme can be considered an enhancement of the DMAC protocol. MMAC defines two types of neighbor nodes, Direction-Omni (DO) Neighbor and Direction-Direction (DD) Neighbor. DO Neighbor refers to a node that has the ability to receive a directional transmission even if it is in omni mode. Similarly, DD Neighbor refers to a node that can receive the directional transmission only when its directional receiving antenna has been pointed in the direction of the sender node.

MMAC utilizes directional antennas for both transmission and reception. Each node is equipped with an omnidirectional antenna and an adaptive antenna. Since directional antennas provide a higher gain and communication range than omnidirectional antennas, a node could possibly communicate directly with the distant node. For that reason, MMAC utilized multiple hops to send RTS packets in order to establish connection with the node that is far away. The following CTS, data and acknowledgement packets are transmitted in single hop. MMAC could not solve the problems of deafness and hidden terminals, but it could compensate for the negative impact resulting from those problems, and therefore lead to improvement in performance.

3.3.1 Protocol description: multihop RTS MAC (MMAC)

MMAC scheme is presented briefly as follows using the scenario in Figure 3.4. Suppose that node A has data packet for node F. According to the MMAC scheme, the neighbor nodes can be classified into DO neighbors A-B-C-F and DD neighbors

A-F. First a DRTS packet is sent by node A to F. Node D and G located between A<->F pair overhear this DRTS and hence defer transmission accordingly. When F receives the DRTS, in case that node F directs its directional antenna toward the direction of node A, the Direction-Direction (DD) link can be established directly and transmission can commence.

Otherwise, the DO neighbors would participate into the procedure of establishing the Direction-Direction communication between A<->F pair. A special type of RTS packet (called a forwarding-RTS) is used during this process. First node A transmits a forwarding-RTS packet to its DO neighbor-Node B and node B forwards it to node F via node C. Meanwhile, node A directs itself toward the direction of node F to wait for the DCTS from F. Note that node B and C forward this forwarding-RTS packet without using any backoff time and will not update their DNAV tables in order to minimize the forwarding time consumption. Upon the receipt the forwarding-RTS, destination node F initiates a CTS packet and sends it to node A directionally. When node A receives the DCTS through DD route, the Direction-Direction (DD) link could be established successfully.

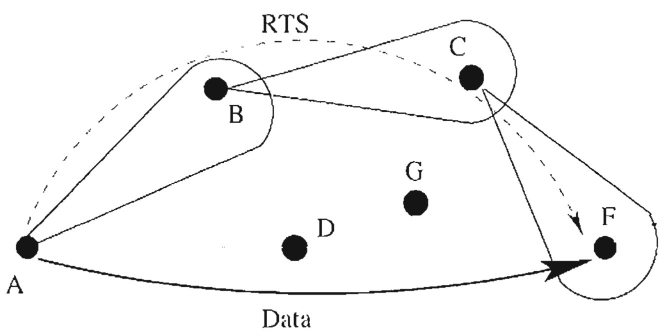

Figure 3.4: Multihop RTS MAC scheme

3.4 The directional virtual carrier sensing (DVCS) scheme

A new carrier sensing mechanism called Directional Virtual Carrier Sensing (DVCS) is designed in [25] for mobile ad hoc networks using directional antennas. DVCS supports not only directional transmission but directional reception. It does not need specific physical configuration of directional antennas and external devices. Instead of relying on additional GPS devices to locate each node, DVCS only needs minimum information on Angle of Arrival (AOA) and antenna gain for each signal from an underlying physical device.

DVCS can work with omnidirectional antennas. It allows nodes equipped with directional antennas to be interoperable with nodes running the original IEEE 802.11 MAC with omnidirectional antennas. The DVCS scheme selectively disables some directions in which the node could interfere with ongoing transmission, and permits the node to transmit towards other directions, which leads to a significant network capacity increase.

3.4.1 Protocol description: DVCS scheme

The DVCS scheme is implemented based on conventional IEEE 802.11 DCF protocol. The difference between DVCS and 802.11 VCS is that DVCS added three new features, as follows:

◆ **AOA caching**

According to DVCS, each node estimates and caches the AOAs (angle of arrivals) from its neighboring nodes when it hears any signal, no matter whether the signal is being transmitted to the node or not. And each node keeps updating the cached AOA every time it receives a newer signal from the same neighboring nodes. When the node intends to send data to one of its neighbors, if the AOA information for the desired neighbor has been cached, it beamforms in the direction of that neighbor to transmit an RTS frame directionally. It will retransmit up to 4 times when it fails to get the CTS response back from the neighbor. Otherwise, RTS frames are retransmitted omnidirectionally up to 3 times before notifying the higher layer of a link failure.

◆ **Beam locking and unlocking**

After the destination node receives the DRTS or RTS frame, it will adapt its main lobe aiming to maximize the received power and then lock the pattern for subsequent directional CTS and directional ACK transmissions. After the source node receives the DCTS sent by destination node correctly, the source node also beamforms its main lobe in the direction of the destination node and locks the pattern for transmitting data and receiving ACK. Please note that the beam patterns at both sides are used for both transmission and reception. Finally, after the source node receives the directional ACK frame successfully, the beam patterns at both sides will be unlocked. These locked patterns could maximize the receiving signal power at both sides provided that channel condition is stable during the entire transmission.

◆ **DNAV setting**

The DVCS scheme uses Directional Network Allocation Vector (DNAV) instead of the Network Allocation Vector (NAV) in the IEEE 802.11 MAC. Unlike NAV, each DNAV consists of a direction and a width to determine which angle range of antennas should be disabled. A node could have multiple DNAVs and maintain a unique timer for each DNAV. The node keeps updating the direction, width and expiration time of every DNAV all the time when the physical layer offers newer information. When a node senses a packet which is not from itself, it will compute the AOA and set its DNAV accordingly. The DVCS selectively excludes the directions included in DNAVs for transmission in order to prevent interference to other ongoing communications, but it allows the node to send packets towards the directions which are not included in DNAVs. In case of omnidirectional transmission, DVCS determines the medium is available to use when no DNAV is set for the node.

In case of directional transmission, it determines the medium is available to use for a desired direction when no DNAV covers that direction.

3.5 Other directional MAC schemes

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

3.6 Summary and comparison

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

These proposed MAC protocols employ various antenna patterns and antenna gains when transmitting RTS/CTS/DATA/ACK. Table 3.1 compared the four discussed schemes with the IEEE 802.11 in terms of antenna pattern and gain used when transmitting different packets. As clearly shown from this table, the DVCS scheme is the only one that supports both directional transmission and reception of both control and data packets (RTS/CTS/DATA/ACK packets).

These directional MAC schemes use various methods to obtain node location information. For example, DMAC simply utilizes the extra GPS device to get the location information. MMAC and DVCS estimate the node location information by running different DOA algorithms. None of these proposals considers the effect of transmit power control. By using power control, the performance could be improved further, as we will discuss in the next chapter.

Table 3.1: Four proposed MAC schemes compare with IEEE 802.11

	RTS		CTS		DATA		ACK	
	Tx	Rx	Tx	Rx	Tx	Rx	Tx	Rx
IEEE 802.11	Om	Om	Om	Om	Om	Om	Om	Om
DMAC Scheme 1	Di	Om	Om	Om	Di	Om	Di	Om
DMAC Scheme 2	Di/Om	Om	Om	Om	Di	Om	Di	Om
MMAC	Di	Om	Di	Di	Di	Di	Di	Di
DVCS	Di/Om	Di	Di	Di	Di	Di	Di	Di

Om = Omnidirectional

Di = Directional

CHAPTER IV

POWER CONTROL IN AD HOC NETWORKS

This chapter presents an overview of several power control mechanisms in ad hoc wireless networks. Power control is the most important issue in cellular networks. As an example of CDMA systems, if power control is not employed, the near-far effect problem will causes unfairness and degrade the capacity of the CDMA system. Therefore, the use of power control mechanisms in cellular systems has been extensively investigated in the literature.

In mobile ad hoc networks, a number of researches have been conducted to incorporate power control mechanisms into the MAC protocols. Several power control mechanisms have been proposed in [27, 28, 29, 30, 38, 39]. However, these power control mechanisms were designed for the MAC protocols that use omnidirectional antennas. As discussed in chapter 4, designing MAC protocols using directional antennas is a topic in recent years, and a small amount of work has been proposed. Based on these different types of directional MAC protocols, the directional antenna-based power control mechanisms have been proposed in only a handful of papers (e.g., [40, 41, 45, 47, 49]). This chapter will first present an overview of power control mechanisms in the context of omni-directional antennas. Second, we will investigate the recent proposed power control schemes in the context of directional antennas and also point out which MAC protocol the power control scheme is built on. Finally, we present our proposed power control scheme for directional antenna-based MAC Protocols.

4.1 Omnidirectional antenna based power control mechanisms

A number of power control algorithms have been investigated in the context of omnidirectional antennas in recent years. The power control scheme proposed in [26] uses RTS/CTS handshake to decide whether to increase or decrease the power level for data packets. It allows the source node to indicate its current transmit power level in the RTS packet, and allows the receiver node to specify a desired transmit power level in the CTS sent back to the source node. When receiving the CTS, the source node transmits DATA using the power level encapsulated in the CTS. A similar power control scheme is employed in [27, 28, 29]. In [27], the RTS and CTS packets are sent at maximum power level, the DATA and ACK are sent with power control. The scheme in [28] maintains a table for the minimum required power that is just enough to overcome interference and communicate with adjacent nodes. Each node is capable of adjusting the transmission power level dynamically according to the table. Proposed power control MAC (PCM) investigated in [30] also uses a similar power control scheme except that it periodically increases the transmit power to maximum level during the DATA packet transmission.

The Power Controlled Multiple Access (PCMA) protocol proposed in [31] uses two separate channels, a first channel for "busy tones" and a second channel for all other packets. Instead of using RTS/CTS handshake, PCMA employs busy tones, to solve the hidden terminal problem. The busy tones mechanism is also utilized in [32, 33, 34, 35].

The author in [36] investigated a power control protocol that utilized multiple channels. One channel is employed to transmit the control packets such as RTS, CTS, RES, and broadcast packets with full transmit power. And multiple channels are employed to transmit DATA and ACK packets using adjusted transmit power. When the source node receives the CTS packet, it sends a RES packet to reserve a channel for the following data transmission. Subsequently, DATA and ACK packets are exchanged on the reserved data channel using a reduced power level that is determined during the RTS/CTS handshake.

The power control mechanism proposed in [37, 38] allows nodes to control the transmit power according to the packet length. A suitable transmit power level is computed based on the size of the MAC packet to be transmitted. The COMPOW protocol introduced in [39] presents a joint solution for power control and routing for ad hoc networks. It maintains routing tables at different power levels and calculates the optimal transmit power level according to the routing information. The smallest common power is selected for all nodes so as to guarantee bidirectional links and the connectivity of network.

4.2 Power control schemes using directional antennas

While there has been a large amount of research on incorporating power control mechanisms into the MAC protocols in the context of omni-directional antennas, only a small amount of research considers the application of power control to the MAC protocols using directional antennas.

In [40], J. Zander first proposed a power control scheme with use of directional antennas for a slotted ALOHA multihop packet radio network in the year 1990. Thenceforth, several researches have been conducted into incorporating power control schemes into the directional MAC protocols.

In [41], a power control scheme that applied to DMAC is proposed. It uses the RTS-CTS handshake to decide what power level to use for transmitting data and acknowledgement packets. According to this scheme, the directionally transmitted RTS is sent with the highest power. On receiving the RTS, the destination node, D, calculates the amount of the difference between the SINR of the received RTS packet and the SIRmin threshold. Destination node, D, encapsulates this difference amount in the CTS packet and sends the CTS packet back omni-directionally. When source node, S, receives this omnidirectional-CTS, it extracts this difference from the CTS packet and reduces the power used to transmit data by this amount and then adds a margin value. The purpose of using margin value is to adapt to the change in communication path due to unexpected interference. In this proposal, the author assumes that the omnidirectional antenna gain is the same as directional antenna gain. However, this assumption is not true in practice. And it is easy to demonstrate the SDMA efficiency enhancement with this assumption.

In [42], a similar power control mechanism was incorporated into a TDMA based MAC protocol named LiSL/D. LiSL/D is a purely directional antenna based protocol that allows both directional transmission and reception while most of the directional MAC protocols only utilized directional transmission. A link budget analysis was performed with the intention of computing the appropriate power level by considering some effects such as path loss, signal-to-noise ratio, transmitter and receiver antenna gain.

The author in [43] evaluates the performance of ad hoc networks with beamforming antennas where a CSMA/CA based channel access protocol is used and there are no RTS/CTS packets actually sent. An abstract power control model is considered for power control purposes. The nodes monitor the received power and change their transmission power using a "back-door" mechanism.

The author in [44] incorporated a correlative power control scheme into DMAC protocol. This DMAC protocol is proposed in [45]. The correlations that exist between the RTS/CTS/DATA/ACK packets are derived. Transmit power is controlled based on the correlations derived as well as the estimation of interference power.

In [46], a distributed power control protocol was proposed for ad hoc networks with smart antennas. According to the proposed power control scheme, RTS/CTS packets are transmitted with full power in omni-directional mode. DATA/ACK packets are transmitted with reduced power in directional mode. SINR estimates are exchanged between source and destination nodes, and a ''power reduction factor'' is calculated and updated iteratively for computing how much power is required for transmitting data packets and acknowledgment. The MAC protocol used for the proposed power control scheme is presented in detail in [47]. It is based on the extensions to the standard IEEE 802.11 distributed coordination function. The author utilized two different values for the IEEE 802.11 Network Allocation Vector (NAV) calling them SHORT NAV and NAV. Figure 4.1 depicts an example of the packet transmission timeline of the MAC protocol. The RTS-CTS handshake in OMNI-Mode makes the source node S and destination node D capable of locking their antenna beams toward each other to form a transmission link in ARRAY-Mode.

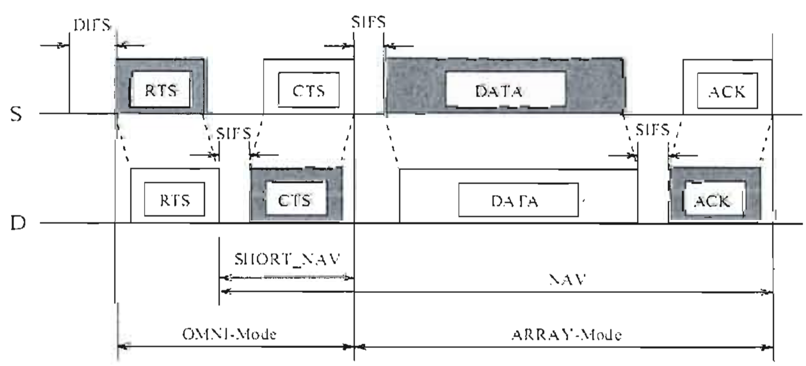

Figure 4.1: An example of packet transmission timeline of the MAC protocol [47]

4.2.1 Power control mechanisms in multi-channel MAC protocols

In [48], a two-level transmit power control mechanism is implemented to improve SDMA efficiency and reduce energy consumption. In this mechanism, Control packets (Beacon, RTS, and CTS) are sent using full power omni-directionally while DATA and ACK packets are sent using reduced power directionally. The node utilized two different power levels for omni-directional transmission and directional transmission in order to obtain the approximate transmission range. As an example of node N, if it transmit packets using the maximum power in omni-directional mode, a reduced power will be used in directional transmission mode because directional transmission consume less power compared to omni-directional transmission for the same distance.

A MAC protocol called LCAP (load-based concurrent access protocol) for MANETs with directional antennas is proposed in [49] by Aman Arora. In LCAP, separate channels are employed for data and control packets. According to this protocol, the transmitter sends RTS packet with maximum power in omni-directional mode. Any node that receives this RTS packet computes an estimate of the path loss value between itself and the transmitter together with the AOA information. The node that wants to receive the DATA packets replies with the CTS packet using adjusted transmission power in directional mode. On receiving the CTS, the transmitter beamforms in the receiver's direction and sends DATA using the power level encapsulated in the CTS packet. The concept of load control is employed to determine the appropriate power level for data in order to find a balance between energy consumption and spatial reuse. A small margin value is also added to tolerate future interference during transmission. The simulation program used to evaluate the performance of LCAP is CSIM; a C language based process-oriented discrete-event simulation package [50]. Simulation results show LCAP can enhance network throughput and reduce transmission energy consumption per packet compared to the RMAC protocol which was the author's previous proposal.

The directional MAC power control protocol (DMAP) [51] proposed by the same author allows the transmitter to increase or decrease the transmission power for data packets dynamically. DMAP uses two channels, one channel for control packets (RTS/CTS/ACK), and the other for data packets. According to DMAP, an omnidirectional-RTS is sent at a fixed power whereas CTS and DATA are sent using the negotiated power level directionally. The transmitter calculates the required transmission power for DATA according to the "power control factor" that is encapsulated within the D-CTS packet. The deafness problem would be solved by adjusting the power assigned to CTS packets. For comparison, DMAP, 802.11b as well as BASIC protocol are simulated using the CSIM simulator. Simulation results demonstrate the performance enhancement offered by DMAP in terms of network throughput and energy consumption.

In [52], the authors proposed BT-DMACP, a three channels power control protocol for ad hoc networks with directional antennas. The BT-DMACP protocol uses three channels for data packets, control packets, and busy tone respectively. The Busy tone channel is utilized to solve the deafness problem. According to the proposed power control scheme, the source node sends an RTS packet at maximum power. On receiving the RTS, the destination node calculates the desired power for data packets based on the interference around the receiver, received RTS power level and SIR threshold. The desired power to use for data transmissions is sent back with the CTS packet. Finally, ACK packets are always sent at maximum power. NS2 (Network Simulator 2) simulation results show the proposed protocol can enhance the channel utilization and decrease power consumption when compared with IEEE 802.11 DCF protocol.

4.3 The proposed power controlled directional MAC protocol

We incorporate power control into DVCS protocol aiming to conserve energy, reduce interference as well as increase throughput and we name our protocol Power Controlled Directional Virtual Carrier Sensing protocol (PCDVCS). The power control algorithm to be incorporated is similar to [41, 42]. We choose DVCS because it provides high performance in heterogeneous ad hoc networks. The power control mechanism is on a per-packet basis, which means power remains the same throughout a packet transmission. The purpose here is to adjust the transmit power so that it is adequate to overcome interference. When a source sends a packet, it encapsulates transmit power inside this packet. When receiver node gets the packet from a sender, it measures the received power of the packet. Based on the transmit power, received power and some other parameters such as receiver's receiving power threshold, interference-plus-noise power, the receiver node computes a recommended power and reduces its transmission power accordingly and also informs the sender whether it should adjust its transmitting power.

4.3.1 Unique points of our work

Our work is unique in several ways:

- Heterogeneity is inherent in wireless ad hoc networks, which means each node could have different characteristics and different network facilities. In terms of antennas, it is general configuration that not all nodes are equipped with directional antennas [53]. Current power control proposal is evaluated without taking heterogeneity into account. We will evaluate the performance of PCDVCS in this general situation where a directional antenna is partially deployed and demonstrate that the proposed PCDVCS works well in such a network configuration.

- Most previous power control schemes are based on the MAC protocols that support only directional transmission, while directional antennas could be used for both transmitting and receiving. Our work is based on a purely directional antenna-based MAC protocol that supports both directional transmission and reception of RTS/CTS/DATA/ACK packets.

- By employing the QualNet simulation program, our work is evaluated with a more actual directional antenna model and full IP protocols. Most of other work was evaluated by using NS2 with much simpler directional antenna model [54].

- In order to demonstrate the improvement in SDMA efficiency when using directional antennas in ad hoc networks, most of the power control schemes usually suppose that directional antennas have the same communication range as omnidirectional antennas. However, in practice, this assumption is not true. In our simulation study, we use different values for the gain of omni and directional antennas so as to recognize that directional antennas have longer communication ranges than omnidirectional antennas.

- Our work allows transmitting CTS, DATA and ACK with power control while most of the previous research work supports power control only for data packet and/or ACK. This enables both transmitter node and receiver node to reduce energy consumption significantly as well as reducing interference to their neighbor nodes and hence leads to improvement of system throughput.

4.3.2 Operation of PCDVCS protocol

We now present an overview of the operation of the PCDVCS protocol, explaining how the power control mechanism is implemented. Our power control mechanism allows for adjustment of the transmitting power for CTS, DATA and ACK packets. In order to explain the operation of the PCDVCS protocol clearly, we use a simple scenario with only two nodes in the system as illustrated in Figure 4.2.

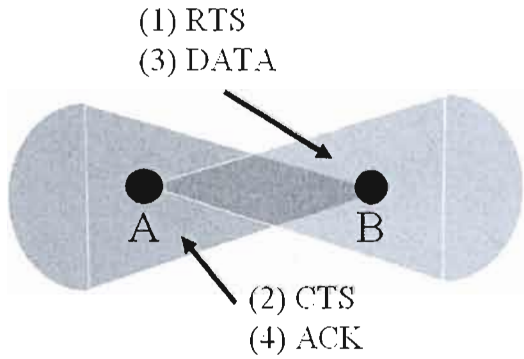

Figure 4.2: Packets transmission using PCDVCS

We assume that node A intends to send data to Node B, and it finds an estimated AOA for node B in its cache. The first step is: Node A adjusts its antenna pattern towards the direction of the cached AOA, which may be a little different than the exact direction of node B since node A or B probably changed their relative locations due to mobility. Following this, node A sends the Directional RTS (DRTS) to node B at a maximum power and encapsulates this transmission power Tx_Power_dBm (noted T_p) inside the DRTS packet. To do this, the format of DRTS packet has to be modified.

Node B senses the DRTS packet and adjusts its antenna pattern to maximize the receiving power. Upon successful reception of DRTS, node B locks the pattern for further transmission and checks the received RTS power Rx_Power_dBm (noted R_p) and must use it to extract Tx_Power_dBm from the DRTS packet. Note that in order for node B to receive the packet, the received power must be greater than Rx_Sensitivity (noted R_s), which represents the minimum power threshold required to receive the packet correctly.

$$R_p = T_p + T_g - P_{PL} + R_g - R_N - P_{fm} \qquad (1)$$

where T_g, P_{PL}, R_g, R_N and P_{fm} denote the transmit antenna gain, the power lost due to the path-loss, the receive antenna gain, the power lost due to the noise at the receiver and the fading margin respectively.

Then, node B computes the difference between the received power and its threshold. We denote this value as γ. So, $\gamma = R_p - R_s$. Node B then encapsulates γ into its DCTS packet and transmits this DCTS back to node A using a reduced power Power_CTS (P_{CTS}).

During the second step, when node A receives the DCTS packet, it re-adjusts its antenna pattern to maximize the receiving power and then locks it until the completion of the transmission of the ACK packet. The AOA of node B stored in node A will also be updated. The operation of beamforming on both sides correctly adjusts the directional antennas. Following this, node A extracts the value of γ from DCTS packet and computes the appropriate power for transmitting data packets (denoted Power_data, P_{data}) using (2).

$$P_{data} = \mathrm{dBTomW}(T_p - \gamma) A_{data} \qquad (2)$$

where dBTomW represents a function used to transfer dB value to mW value, dBTomW(x) = 10(x/10), and where A_{data} denotes the amplified coefficient used for data transmission. The intention of using amplified coefficients is to take account of various negative effects, which include unexpected interference, fading and mobility.

Node B then starts data transmission using P_{data}. The same method is used as mentioned in the second step for computing the required power for CTS and ACK transmissions except that we used a larger value for the amplified coefficients (A_{CTS} and A_{ACK}) when calculating the required power for CTS and ACK (P_{CTS} and P_{ACK} respectively) aiming to decrease the probability of CTS and ACK corruption.

The third step comes after the completion of the ACK transmission, when both transmitter and receiver sides unlock their beam patterns.

4.3.3 Interoperability with omnidirectional antennas

In PCDVCS, a node with omnidirectional antennas could be interoperable with nodes with directional antennas. In the event that node A is unable to find the angle of node B in its AOA cache, node A will transmit ORTS with omnidirectional antenna. If node B is equipped with directional antennas, node B beamforms its radiation pattern in the direction of node A and responds with a DCTS. If node B is only equipped with an omnidirectional antenna, upon the successful reception of ORTS, node B sends back OCTS to node A by omnidirectional antenna and node A could receive it with its directional antenna. By doing so, PCDVCS can work well in heterogeneous ad hoc networks.

4.4 Summary

In this chapter, the power control mechanisms for ad hoc networks using omnidirectional antennas are reviewed first. We then investigate the recent proposed power control schemes using directional antennas. We proposed our power control scheme which is based on the DVCS protocol and explained it in detail.

CHAPTER V

SIMULATION RESULTS

Because ad hoc networks have not been massively deployed, research in this field has relied mainly on computer simulation. This chapter firstly looks at the simulation software used in this thesis. The purpose is to produce a platform to simulate the proposed DVCS-based power control mechanism in a wireless ad hoc network. Thereafter, this chapter focuses on evaluating the improvement of network performance in ad hoc networks when the proposed power control scheme is in use and terminals are equipped with directional antennas. In the simulations, we simulate and compare the performance of the conventional IEEE 802.11 protocol, the DVCS protocol (without power control) and our proposed power controlled DVCS protocol for different scenarios in terms of power consumption and network throughput.

5.1 Introduction to QualNet simulator

Simulation software used in this thesis is QualNet 4.5.1 [55] which is distributed by Scalable Network Technologies, Inc. (SNT). QualNet itself is based on C++. All protocols are implemented as a set of C++ files and called by the simulation kernel. It is a discrete event simulator (DES) and runs based on an event scheduler. This is to say, simulation is not carried out in a continuous time flow, but at each specific time point as events occur. Events are instantaneous occurrences that trigger the system to change its state or to execute a specific action. Examples of specific actions are:

sending a packet to a neighboring layer, changing state variables, starting or restarting a timer, etc.

5.1.1 QualNet GUI

QualNet is a commercial version of Global Mobile Information System Simulator (GloMoSim) which was developed in the Parallel Computing Laboratory of the University of California, Los Angeles (UCLA).Although GloMoSim is free to use for education, academic research purpose, it does not provide good documentations for users and developers and lacks of a series of convenient tools to observe the network behavior and to analyze the results of experiments. QualNet relieves these drawbacks and adds many great features including the powerful Graphical User Interface (GUI) for scenario design and performance analysis, a fast simulation speed, multi-platforms support (UNIX, Windows, Mac OS X and Linux) and scalability up to many thousands of nodes with heavy traffic. A screenshot of QualNet can be seen in Figure 5.1.

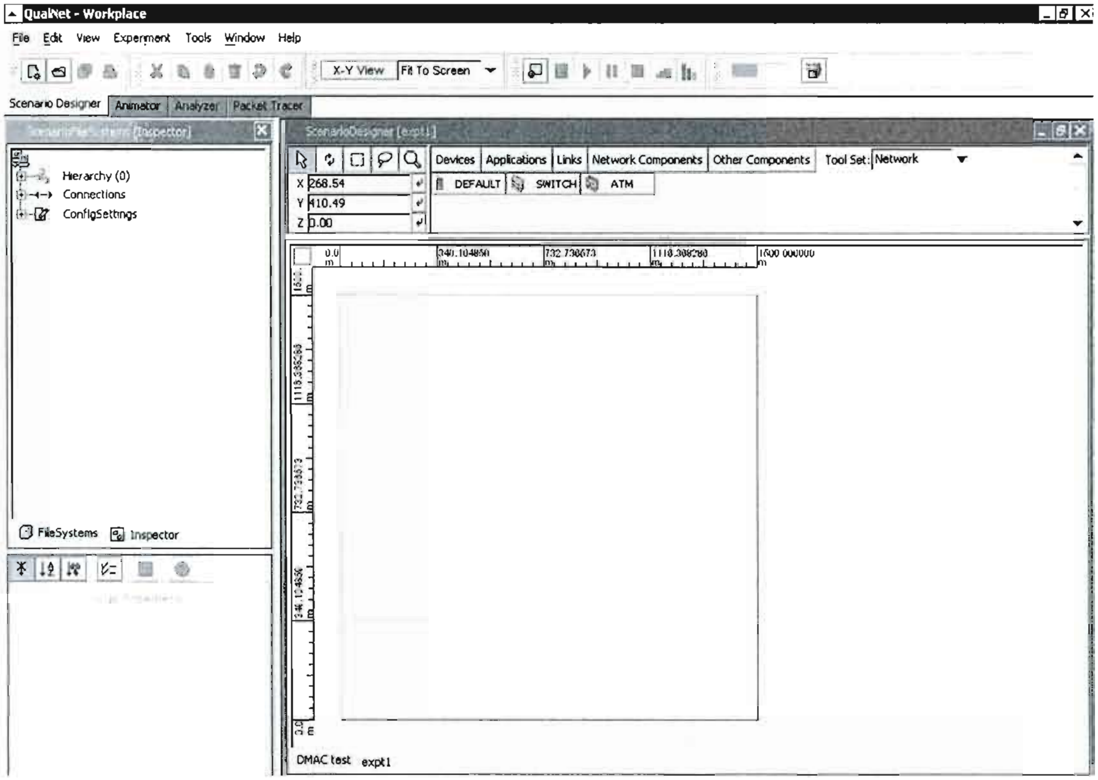

Figure 5.1: QualNet GUI screenshot

QualNet's java based graphical user interface provides four tools for modeling and analyzing the communication system. They are scenario designer, animator, analyzer, and packet tracer. Users create simulation scenarios and configure all the simulation parameters such as radio type, mobility, terrain and MAC, network, transport and application layer protocols via scenario designer. Animator allows the user to clearly observe the traffic flow and dynamic animation of various network events during the simulation. Analyzer enables graphical analyses of simulation results. The packet tracer enables the user to do per-packet analyses and track the path of a specified packet through the communication network.

5.1.2 QualNet protocol stack

QualNet is implemented using a layered architecture similar to the TCP/IP network model. From top to bottom, the protocol stack of QualNet includes five layers: Application Layer, Transport Layer, Network Layer, Link (MAC) Layer and Physical Layer. The neighboring layers communicate by using well-defined APIs. At each layer in the stack, several protocols are implemented as described in Figure 5.2 [55]:

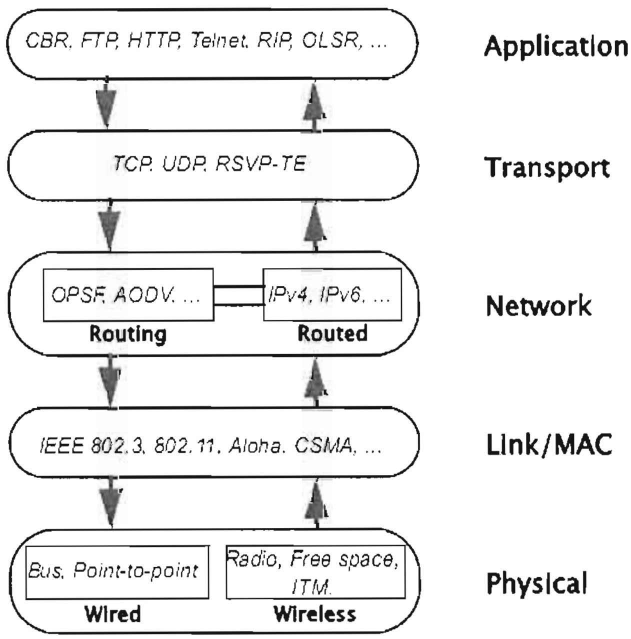

Figure 5.2: Implemented protocols in QualNet

The application layer takes charge of traffic generation and application level routing. Several traffic generator models and application level routing protocols have been implemented in QualNet. Traffic generators supported include CBR, FTP, HTTP, TELNET, VBR, VoIP, MCBR, etc. CBR (Constant Bit Rate) is often used to simulate fixed-rate uncompressed multimedia traffic. FTP (File Transfer Protocol) is often used to simulate transferring files between server and client. Some examples of application level routing protocols supported by QualNet consist of RIP, Bellman-Ford, and BGP.

In the network layer, QualNet support three types of routing protocols: proactive protocols, reactive protocols, and static routing protocols. Examples of proactive protocols are Bellman-Ford algorithm, Routing Information Protocol (RIPv2), and OLSR. Examples of reactive protocols consist of Ad Hoc On-Demand Distance Vector Routing (AODV), Dynamic Source Routing (DSR) and Location-Aided Routing (LAR1). The static routing method forwards packets according to the manually edited routing table.

In the MAC layer, QualNet implemented Aloha, CSMA, MACA (Multiple Access Collision Avoidance), IEEE 802.11, IEEE 802.3, TDMA, and SATCOM (Satellite Communication) protocols.

In the physical layer, physical layer protocols are implemented for IEEE 802.11, IEEE 802.3 and an abstract physical layer. The most important strength of QualNet is its implementation of the physical communication medium. It offers several powerful and detailed models for simulating physical channels including path loss, fading and shadowing models. Three path loss models exist: free space, two ray and irregular terrain models. Two fading models are supported: Rayleigh and Ricean fading models. And the two supported shadowing models are constant and lognormal. In addition to these, three very-well implemented antenna models are also provided: omni-directional antenna, switched-beam antenna and steerable antenna.

In QualNet, each node runs a protocol stack. Each protocol operates at one specific layer of the stack. The operation of protocols in QualNet can be described as a finite state machine. The transition in the finite state machine represents an occurrence of an event. Figure 5.3 depicts the finite state machine corresponding to a protocol in

QualNet. In the beginning, every protocol will call an initialization function that is responsible for reading the external input and configuring the protocol accordingly. Then the event dispatcher takes charge of handling. An event dispatcher consists of a "Wait For Event" state and one or several "Event Handler" states. The protocol waits for an event to occur in the "Wait for Event" state. If an event for that protocol happens, the protocol transitions to the "Event Handler" state. The event dispatcher checks the type of event and calls the appropriate event handler to perform the actions corresponding to the event. Examples of actions performed consist of updating the protocol state, scheduling other events or both. In the end, the transition to the "Finalization" state happens automatically in order to print out the collected statistics.

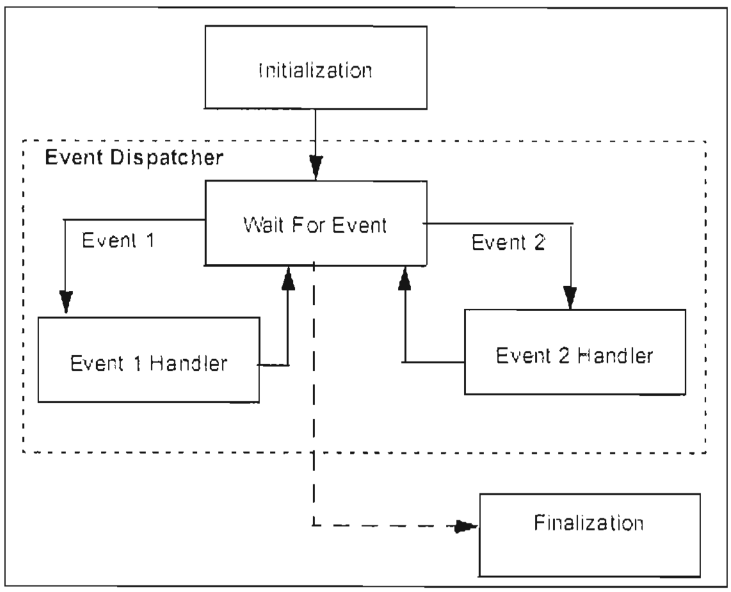

Figure 5.3: Protocol finite state machine

The interface between layers is event based. To send packets to, or request services from a neighbor layer, an event has to be scheduled at that layer. The data structure of an event is called a message that consists of the type of event and the associated data. Two types of messages exist in QualNet: packets which are utilized for communication between layers or between nodes and timers which are utilized to schedule events at a future time. The life cycle of a packet message is shown in Figure 5.4 [56].

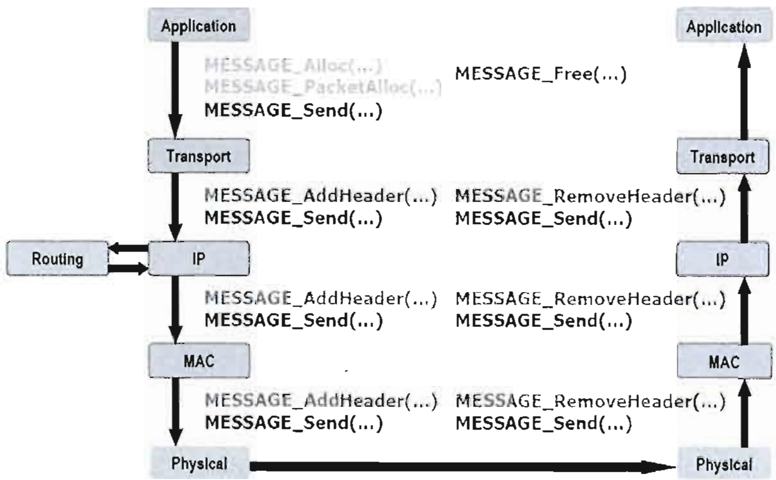

Figure 5.4: Packet life cycle

5.1.3 QualNet simulation approach

A QualNet simulation experiment generally includes three phases as displayed in Figure 5.5.

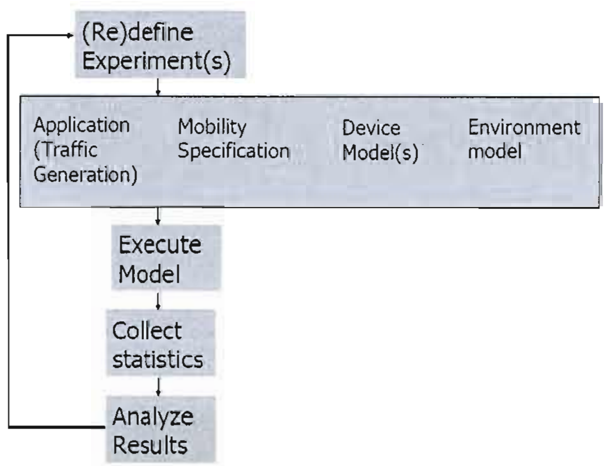

Figure 5.5: Simulation study life cycle for network models

In the startup stage, the simulator reads input files in order to create the simulation scenario, initialize wireless environment, and define traffic flows. There are three major input files: the scenario configuration file, the node placement file, and the application configuration file. The scenario configuration file is the key input file that specifies the network scenario and parameters for the simulation. The node placement file contains the initial position of nodes in the scenario. However, it is not obligatory to use the node placement file, QualNet provides three automatic node allocating methods to allow nodes to be placed uniformly, randomly, or in a grid format. The application file indicates the applications running on each node. In the execution stage, the simulator executes the created scenario and collects simulation results. The output is the statistics file that provides the details of what has happened at each layer. The last stage is to analyze the simulation results. Probably, users need to modify the configuration files in order to adjust the parameters of the experiment for further research.

It is helpful to discuss the structure of the configuration file, which is the major input to the simulation. In the configuration file, the network structure is first defined. This includes informing the program of the number of subnets, their addresses and the number of nodes in each subnet. Next, the parameters of the channel should be set. These consist of channel frequencies, propagation models, and propagation limits. Following this, the physical layer model must be specified, including the transmit power, receiver sensitivity, and all the parameters concerning the antennas. Then, the MAC layer should be declared, followed by the network layer and the used routing protocol. Finally, the type of traffic being sent between two nodes is specified for the application layer.

5.2 Implementation of PCDVCS protocol on QualNet

To evaluate our proposed DVCS based power control scheme, we have to implement it on QualNet. We use Microsoft Visual C++ 2005 IDE for modifying the QualNet source code, adding code, debugging and recompiling QualNet on the Windows platform. After setting all environment variables and configuring Platform SDK correctly, QualNet is able to run and simulate its supported network protocols. However, in order to develop and debug our proposed protocol, the DEBUG option in Makefile must be enabled and QualNet must be recompiled.

5.2.1 QualNet source file organization

The source codes of QualNet are well organized and located in several subdirectories under "QUALNET_HOME" root. The binary object files, configuration files, documentation, and sample scenarios are also stored in these subdirectories. Table 5.1 on the next page depicts these subdirectories in detail

Table 5.1: QualNet source code directories

Subdirectory	Description
QUALNET_HOME/addons	Components developed as custom add-on modules
QUALNET_HOME/bin	Executable and other runtime files, such as DLLs
QUALNET_HOME/contributed	Files related to models contributed by third parties
QUALNET_HOME/data	Data files for the Wireless Model Library, including antenna configurations, modulation schemes, and sample terrain files.
QUALNET_HOME/documentation	Documentation (User's Guide, Release Notes, etc.)
QUALNET_HOME/gui	Graphical components, including icons, Java class files, and GUI configuration files
QUALNET_HOME/include	QualNet kernel header files
QUALNET_HOME/interfaces	Code to interface QualNet with third party tools or external networks, such as HLA, STK, and IP networks
QUALNET_HOME/kernel	QualNet kernel objects used in the build process
QUALNET_HOME/lib	Third party software libraries used in the build process
QUALNET_HOME/libraries	Source code for models in QualNet model libraries, such as Developer, Wireless, and Multimedia & Enterprise.
QUALNET_HOME/license_dir	License files and license libraries required for the build process
QUALNET_HOME/main	Kernel source files and Makefiles
QUALNET_HOME/scenarios	Sample scenarios

5.2.2 Directional antenna model used in QualNet simulator

QualNet offers two kinds of highly detailed realistic directional antenna models, the switched beam antenna model and the electronically steerable antenna model [55]. These two directional antenna radiation patterns are defined in the "default.antenna-azimuth" and "steerable.antenna-azimuth" files respectively. Figure 5.6 presents the switched beam antenna radiation pattern. It is generated by a phase shift algorithm and includes eight antenna elements arranged in the circular form while each element has an omni-directional pattern. The element space is 0.4λ. The beamwidth of each predefined directional beam is 45 degrees. Eight predefined directional beams are utilized to obtain omnidirectional coverage. Figure 5.6 presents the electrically steerable antenna radiation pattern. It includes a circular antenna array with 6 isotropic antenna elements. Each element is also spaced with 0.4λ wavelength of the channel frequency, 2.4 GHz ISM band. This steerable antenna system is able to steer the boresight at one-degree step based on the estimated AOA of the interested signal.

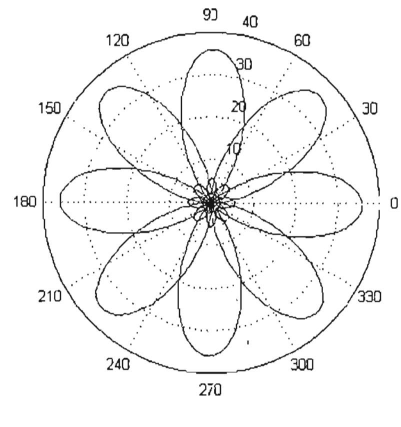

Figure 5.6: Switched beam antenna radiation pattern in QualNet

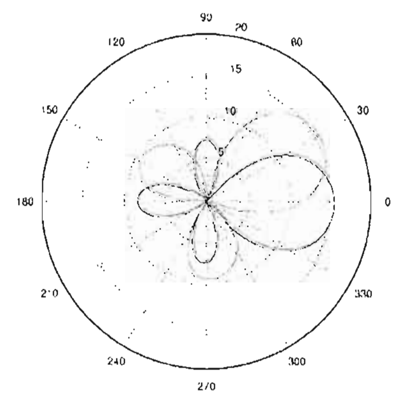

Figure 5.7: Electronically steerable antenna radiation pattern in QualNet

5.3 Simulation scenarios and results

We now evaluate the performance of PCDVCS protocol and contrast it with DVCS protocol and IEEE 802.11b. The results are based on simulation experiments conducted using QualNet. We investigate both the network throughput and the power consumption. Network throughput is defined as the amount of data transferred successfully over the communication channel in a given time period. The throughput is usually measured in kbps, Mbps and Gbps. In our simulation, we measure the average throughput which is the mean value of the throughput of all the traffic flows in the network. For the power consumption, we take into consideration only the power consumed for the purpose of transmission. We also measure the average power consumption which is the mean value of the power consumed for the transmission of RTS/CTS/DATA/ACK packets of all the nodes in the network. For example, if a network has two nodes: node A and node B. Node A wants to send packets to node B. The power consumed by node A to send RTS and DATA packets is 1.25 mJoule. And the power consumed by node B to send CTS and ACK is 0.15 mJoule. Then, the average power consumption for this network is 0.7 mJoule. We conduct simulations under three different scenarios, a simplest two nodes scenario, a randomly generated topology, and a more realistic heterogeneous ad hoc network scenario.

5.3.1 Common parameters

The field temperature is 290K. The two-ray model, also called the plane earth loss model, is used as the path loss model. The value of RTS threshold is set to 0 in order to always turn the RTS/CTS feature on in these three scenarios. The radio type is 802.11b. We don't use auto rate fallback and set data rate to 2Mbps with DBPSK modulation. The height of both omnidirectional antenna and steerable directional antenna are set to 1.5 meters. To simulate power consumption, we select the

GENERIC energy model with the following specification in QualNet: Transmit Circuitry Power Consumption = 100, Receiver Circuitry Power Consumption = 130, Idel Circuitry Power Consumption = 120.

5.3.2 Scenario 1: two nodes scenario

This scenario is simple. The network includes only two nodes. However, this is an important and most used scenario in real life. For example, two users with PDA or cellular phone may want to exchange music or share a movie directly without using any fixed infrastructure. In this case, because the file size of the movie or music is large and therefore takes time to exchange, saving power during the transmission procedure becomes a very important issue, given that PDAs and cellular phones have limited battery power.

In the simulation of this scenario, the geographical area is a 500m x 500m flat terrain. The packet sending rate is set to 100 packets per second for the CBR flows. Data packets are assumed to have a fixed size of 512 Bytes. In the case of 802.11, the two nodes are equipped with omnidirectional antennas. Similarly, in cases of DVCS and PCDVCS, the two nodes are equipped with steerable directional antennas. Other parameters could be found in Table 5.2.

Table 5.2: Simulation parameters of scenario 1

Parameters:	Values:
Area	500m x 500m
Total nodes	2
Propagation channel frequency	2.4 GHz
Path loss model	Two Ray
Data rate	2 Mbps
Packet sending rate	100 pps
TX power	16 dBm
Receiver sensitivity	-89.0 dBm
RTS threshold	0
CBR packet size	512 Bytes
Number of flows	1
Directional antenna model	Steerable directional antenna or Omnidirectional antenna
Directional antenna gain	15 dBi
Directional NAV delta Angel	37 degree
AOA cache expiration time	2s
Directional beamwidth	45 degree

- **Simulation results and discussion:**

From the simulation results, we can clearly see that our protocol is very energy efficient in this simple scenario when compared with IEEE 802.11 and pure DVCS protocols. Figure 5.9 shows the average network throughput. Because there are only two nodes in the network, the interference problem or channel access problem does not exist and therefore these three protocols achieve the same network throughput. In contrast, as shown in Figure 5.10, PCDVCS does decrease power consumption by around 78% compared with 802.11b and DVCS protocols.

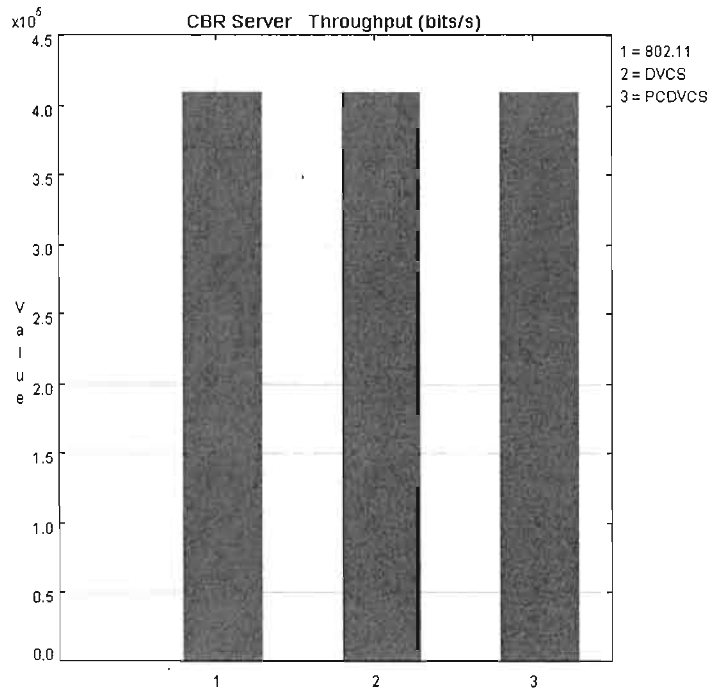

Figure 5.8: Network throughput in scenario 1
(When packet sending rate is 100 packets per second)

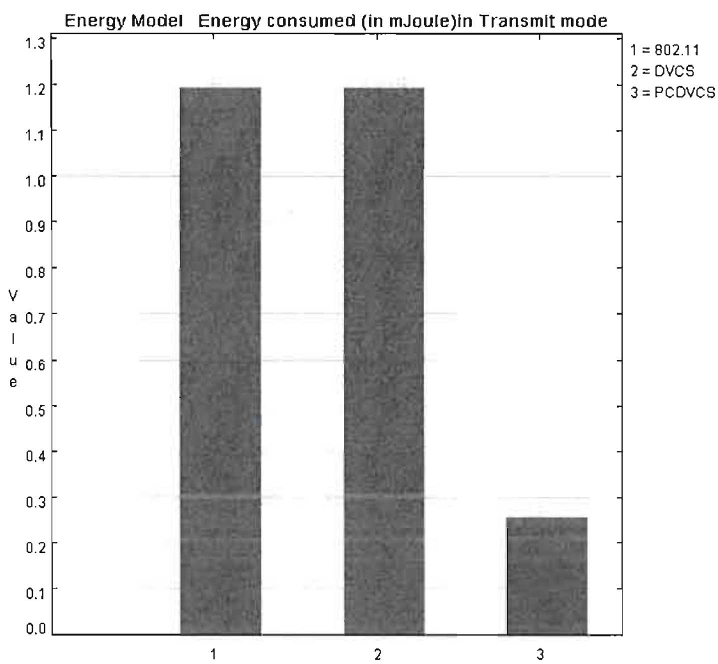

Figure 5.9: Transmission power consumption in scenario 1
(When packet sending rate is 100 packets per second)

5.3.3 Scenario 2: randomly generated topology with CBR

In scenario 2, 45 nodes are randomly placed over a 1500 x 1500 m flat terrain. Ten nodes are randomly selected as the source and each destination node is also randomly selected from 45 nodes. Each node is equipped with a steerable directional antenna. In order to simulate the different communication range of omni and directional antennas, the directional antenna gain is set to 15 dBi. For routing protocol, we use AODV. The transmission power is 16 dBm. For CBR traffic flow, the parameters of the "item to send", 'start time", "end time" are all set to value 0 in order to allow the CBR source keep sending during the period of the entire simulation time. In this set of scenarios, performance is evaluated with varying number of packets per second ranging from 1 pps (packet per second) to 1000 pps. The other main simulation parameters are listed in Table 5.4.

Table 5.3: Simulation parameters of scenario 2

Parameters:	**Values:**
Area	1500m x 1500m
Total nodes	45
Propagation channel frequency	2.4 GHz
Path loss model	Two Ray
Data rate	2 Mbps
Packet sending rate	from 1 pps to 1000 pps
TX power	16 dBm
Receiver sensitivity	-89.0 dBm
RTS threshold	0
CBR packet size	512 Bytes
Number of flows	10
Directional antenna model	Steerable directional antenna
Directional antenna gain	15 dBi
Directional NAV delta Angel	37 degree
AOA cache expiration time	2s
Directional beamwidth	45 degree

● Simulation results and discussion:

The performance comparison for this randomly generated topology is shown in Figure 5.10, 5.11, 5.12 and 5.13. In Figure 5.10 and 5.11, we vary the packet generation rate from 1 pps to 1000 pps. Figure 5.10 depicts the network throughput. It is shown that PCDVCS achieves around 99.3% increase over the throughput of the IEEE 802.11b scheme and up to 36% increase over the throughput of DVCS. This increase is due to the increase in the number of simultaneous transmissions and the largely mitigated interference. At the moderate traffic load of packet generation rate = 500 pps, the throughput of DVCS is even worse than 802.11b. However, as can be seen, the throughput of PCDVCS always outperforms the others. Figure 5.11 depicts the energy consumption versus packet generation rate. It considers only the power consumed for transmission. For all the cases, PCDVCS consumes the least energy compared with 802.11b and DVCS protocols. This power saving is attributed to the gain of the directional antenna and to the power control mechanism. Figure 5.12 and Figure 5.13 highlight the network throughput and power consumption when the packet sending rate is 250 packets per second. As can be seen, PCDVCS achieves about 99.3% increase in throughput over IEEE 802.11b and 16% over DVCS. Meanwhile, the power consumption in PCDVCS is about 36% of that of DVCS and 17% of that of 802.11b scheme.

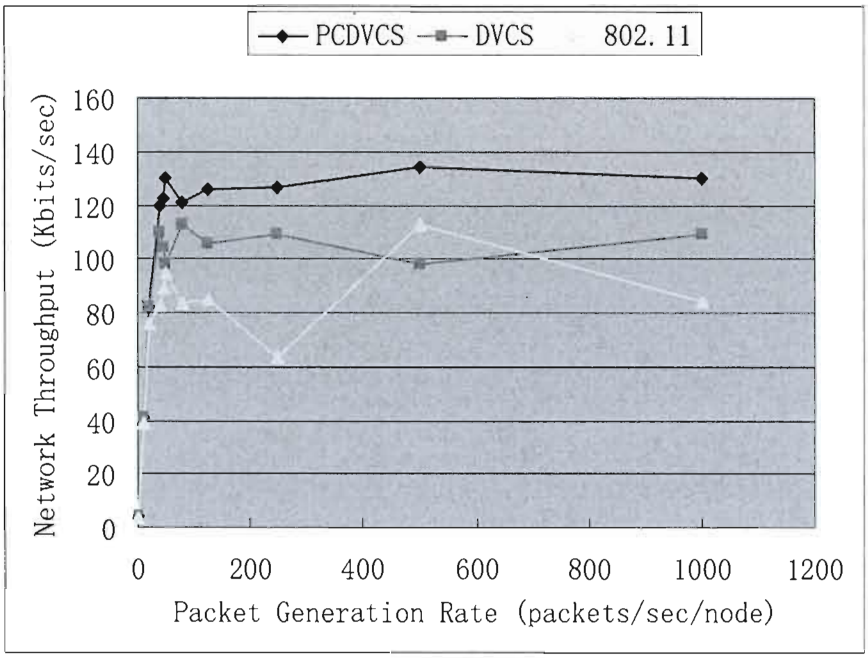

Figure 5.10: Network throughput vs. number of packets
(For randomly generated topology with CBR)

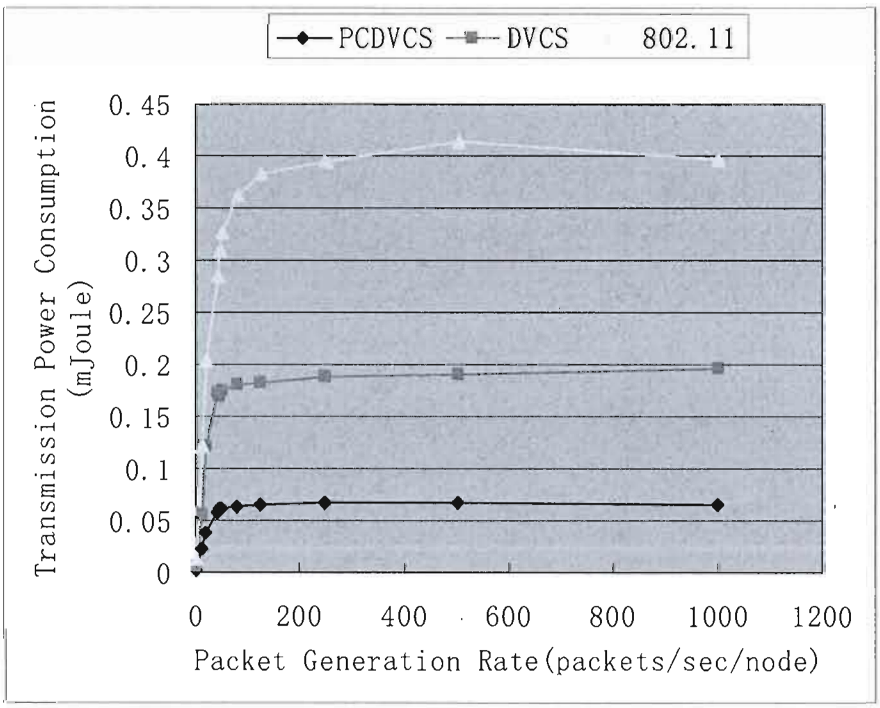

Figure 5.11: Power consumption vs. number of packets
(For randomly generated topology with CBR)

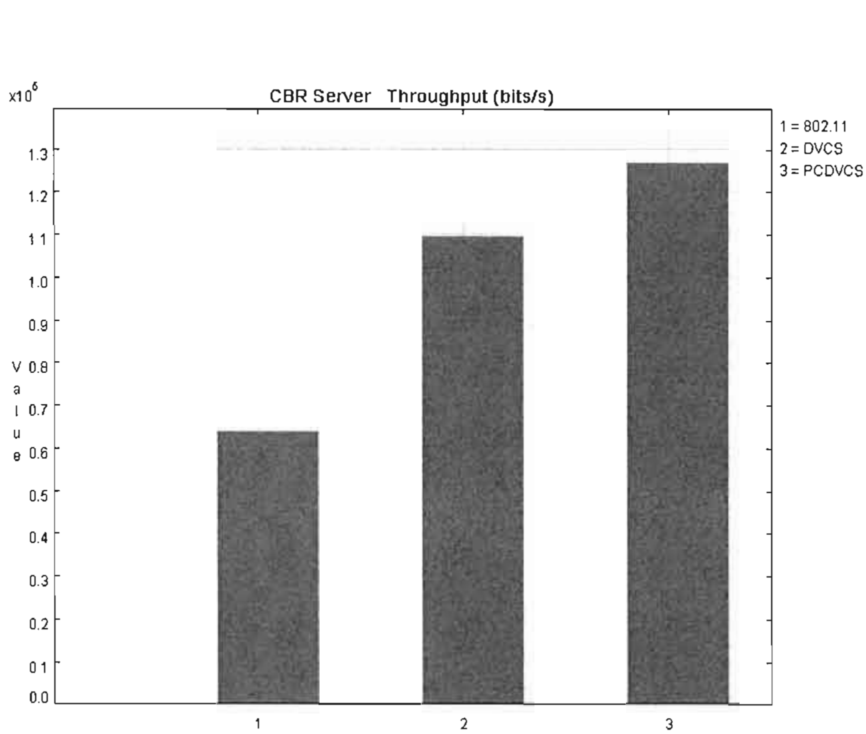

Figure 5.12: Network throughput in scenario 2
(When the packet sending rate is 250 packets per second)

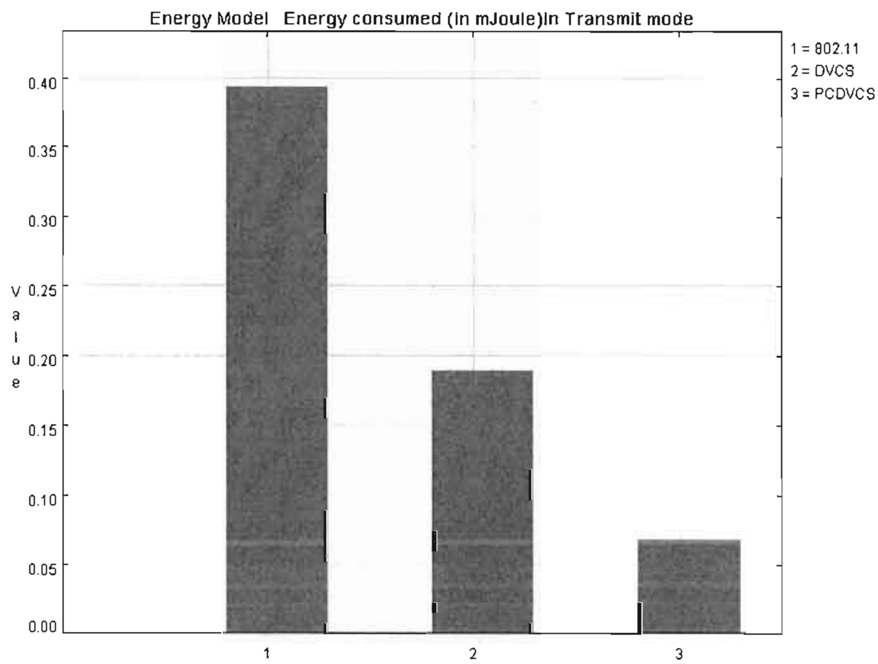

Figure 5.13: Transmission power consumption in scenario 2
(When the packet sending rate is 250 packets per second)

5.2.4 Scenario 3: heterogeneous wireless ad hoc network scenario

Most of the power controlled MAC protocols for directional antennas assume that all nodes in the ad hoc networks are equipped with directional antennas and ignore the issue of interoperability with omnidirectional antennas. However, heterogeneity is inherent in wireless ad hoc networks. It is common that not all nodes in the network are equipped with directional antennas. Therefore, in this scenario, we evaluate the performance of PCDVCS in this more realistic situation.

Fifty(50) nodes are randomly placed over a 1500 x 1500 m flat terrain. 17 nodes are equipped with omnidirectional antennas and run the 802.11 MAC protocol. The other 33 nodes are equipped with directional antennas and run PCDVCS or DVCS protocol. Directional antenna gain is set to 15 dBi. Nine (9) CBR traffic flows are set randomly. The CBR packet size is 512 bytes and the parameters of the "item to send", 'start time", "end time" are all set to value 0 in order to allow the CBR source to keep sending during the entire simulation period. AODV is used as the routing protocol. Performance is evaluated with varying numbers of packets per second ranging from 1 pps to 1250 pps. The other main simulation parameters are in Table 5.5.

Table 5.4: Simulation parameters of scenario 3

Parameters:	Values:
Area	1500m x 1500m
Total nodes	50
Propagation channel frequency	2.4 GHz
Path loss model	Two Ray
Data rate	2 Mbps
Packet sending rate	From 1 pps to 1250 pps
TX power	16 dBm
Receiver sensitivity	-89.0 dBm
RTS threshold	0
CBR packet size	512 Bytes
Number of flows	9
Directional antenna model	Steerable directional antenna
Directional antenna gain	15 dBi
Directional NAV delta Angel	37 degree
AOA cache expiration time	2s
Directional beamwidth	45 degree

- **Simulation results and discussion:**

The performance comparison for this heterogeneous ad hoc network scenario is shown in Figure 5.10, 5.11, 5.12, and 5.13. Figure 5.14 and Figure 5.15 show the network throughput and transmission power consumption versus packet generation rate. Because of power control, the throughput improvement in PCDVCS does not come at the light traffic load of packet generation rate between 1 pps to 50 pps. However, with packet generation rates in excess of 50 pps, the throughput improvement in PCDVCS is obvious. As to power consumption, as shown in Figure 5.15, PCDVCS always consumes less power compared with DVCS. Figure 5.16 and Figure 5.17 highlight the network throughput and power consumption when the packet sending rate is 1000 packets per second. As can be seen, when compared with

DVCS, PCDVCS improves the network throughput by about 35% and, at the same time, achieves a 66.5% reduction in the transmission power consumption.

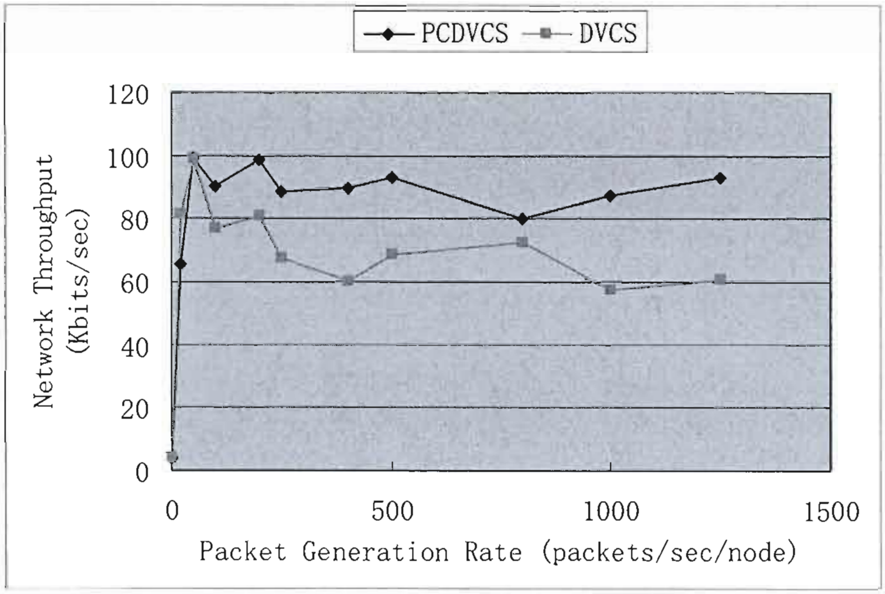

Figure 5.14: Network throughput vs. number of packets
(For heterogeneous ad hoc scenario)

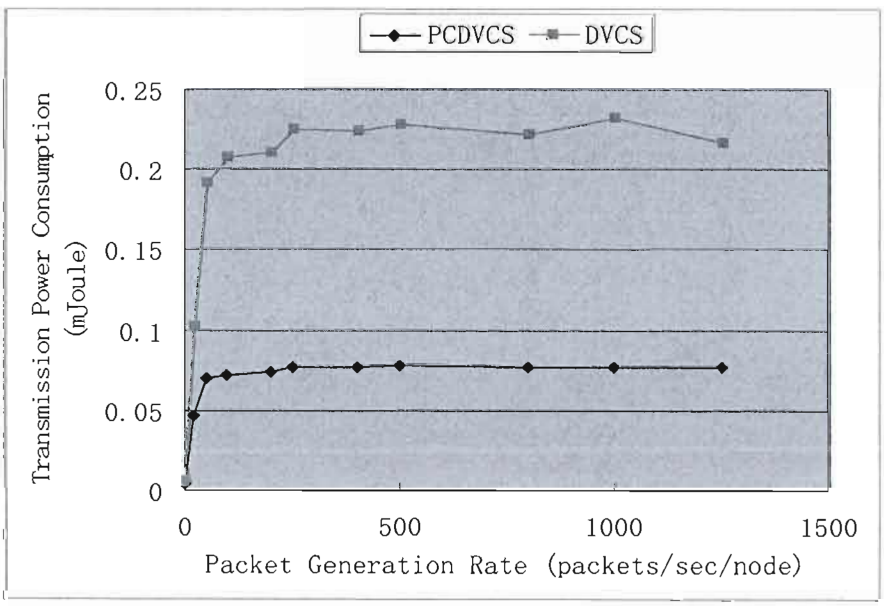

Figure 5.15: Power consumption vs. number of packets
(For heterogeneous ad hoc scenario)

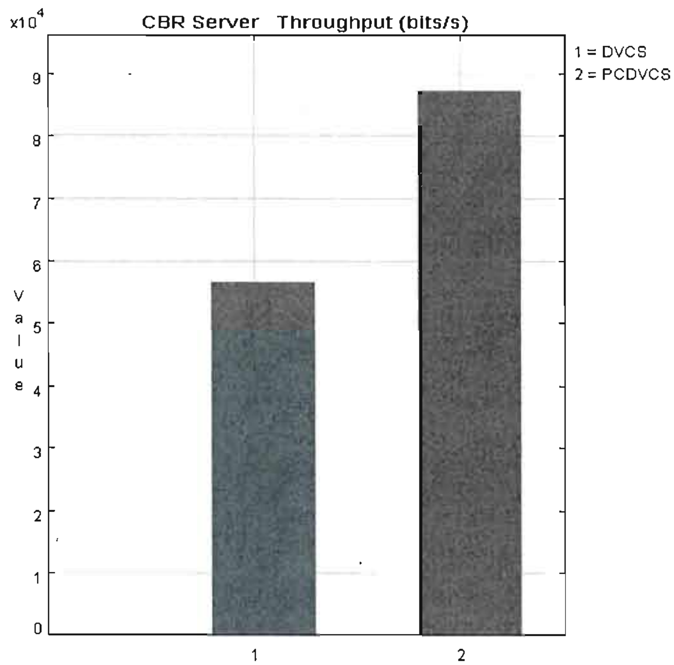

Figure 5.16: Network throughput in scenario 3
(When packet sending rate is 1000 packets per second)

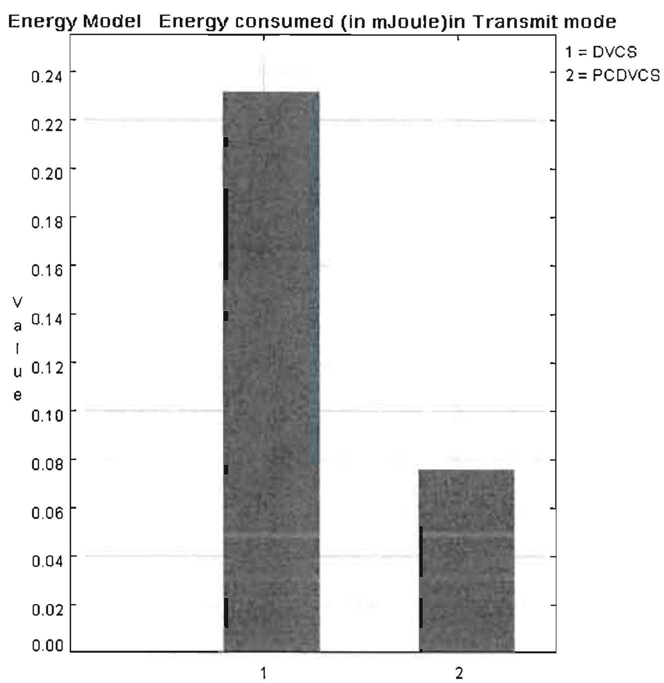

Figure 5.17: Transmission power consumption in scenario 3
(When packet sending rate is 1000 packets per second)

5.4 Summary

In this chapter, the simulation software used in this thesis is introduced in detail. The performance of the proposed PCDVCS protocol is evaluated in three different scenarios. The simulation results were analyzed and compared with the 802.11b protocol and the pure DVCS protocol. We showed that PCDVCS outperforms the 802.11 and DVCS protocols in terms of throughput and power consumption.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

In this chapter, we summarize the main work of this thesis and identify some topics for possible future research.

6.1 Conclusions of the thesis

In this thesis, the concept of the ad hoc network was presented. The conventional IEEE 802.11 protocol used for ad hoc networks and the principles of smart antenna technology were discussed. The MAC layer problems of using directional antennas in ad hoc networks were analyzed and several proposed MAC protocols aimed at addressing these problems were studied. Moreover, the effects of transmission power control in ad hoc networks have been illustrated. A survey of recently proposed power control schemes in the context of both omni-directional and directional antennas was presented. This could be used as reference for researchers in this field. A power controlled directional MAC protocol that could work well in heterogeneous ad hoc networks and enabled both directional transmission and reception of both control and data packets was proposed and implemented in the QualNet simulator. The performance of the proposed protocol was evaluated in realistic situations and compared with different MAC protocols such as the standard IEEE 802.11 MAC protocol and the DVCS protocol. Simulation results showed that the proposed PCDVCS achieves around 99.3% increase over the throughput of the IEEE 802.11b scheme and up to 35% increase over the throughput of DVCS. Meanwhile, it reduces power consumption by up to 83% compared with 802.11b and up to 64% compared with DVCS protocol.

6.2 Future work

Ad hoc networking is a hot research topic. There is much research going on and various problems that remain to be addressed. This thesis only focused on investigating directional antenna based MAC and power control schemes. There are many problems that could be subject to further research, such as:

- Take the effect of routing protocol into consideration when design power controlled MAC protocol.

- Design a new MAC protocol for ad hoc networks when nodes are equipped with MIMO antenna system.

- Integrate power control with topology control.

BIBLIOGRAPHY

[1] J. Liu and Imrich Chlamtac, Chapter 1 of Mobile Ad Hoc Networking, Wiley-Interscience, 2004.

[2] Khaldoun Al Agha, I. Guérin Lassous, G. Pujolle, "Challenges in ad hoc networking", Fourth Annual Mediterranean Ad Hoc Networking Workshop, June 21-24, 2005, Île de orquerolles, France , pp 367- 369

[3] Wikipedia, the Free Encyclopedia, http://en.wikipedia.org/wiki/Ad_hoc

[4] Tim Bauge, Ad hoc networking in military scenarios, White paper, Thales Research and Technology (UK), Issue 1, May 2004

[5] Dr. Victor Bahl, Manager Networking Research, Microsoft Research, "Wireless Mesh Networks: From Theory to Deployed Systems", Slide of ACM SIGCOMM 2006 conference, http://conferences.sigcomm.org/sigcomm/2006/?tutorials

[6] Subir Kumar Sarkar, T.G. Basavaraju, and C. Puttamadappa, "Ad Hoc Mobile Wireless Networks: Principles, Protocols and Applications", Auerbach Publications, US, 2008.

[7] International standard ISO/IEC 8802-11; ANSI/IEEE Std 802.11, 1999 Edn. Part 11: wireless LAN Medium Access Control (MAC) and physical Layer (PHY) specifications.

[8] Sridhar Lyer, "Mobile Computing: Sessions 12, 13, Wireless LANs", Lecture slide, www.it.iitb.ac.in/~it601/dep/Slides/12-13-dot11.ppt

[9] L. C. Godara, "Applications of antenna arrays to mobile communications. Part I: Performance improvement, feasibility, and system considerations," in *Proc. IEEE*, vol. 85, pp. 1031–1060, July 1997.

[10] S. Hara and R. Prasad, "Overview of multicarrier CDMA," *IEEE Commun. Mag.*, vol. 35, pp. 126–133, Dec. 1997.

[11] M. Cooper and M. Goldburg, "Intelligent antennas: Spatial division multiple access." Wireless, *Anual.* Revw. *of Commun.*, pp. 995–1005, 1996, ArrayComm Inc., San Jose, CA

[12] C. A. Balanis, *Antenna Theory: Analysis and Design*, 3rd ed. New York:Wiley, 2005.

[13] "Smart Antenna Systems", Web ProForum Tutorials, The International Engineering Consortium, 2006, http://www.iec.org

[14] T. Thrassyvoulou, "Adaptive beamforming: Using a complex bounding ellipsoid algorithm with gradient projections," Master's thesis, Arizona State University, Aug. 2003.

[15] Ahmed El Zooghby, "Smart Antenna Engineering", Artech House, US, 2005, pp 320-325.

[16] Constantine A. Balanis, Panayiotis I. Ioannides, "Introduction to Smart Antennas", Morgan & Claypool Publishers, 2007, 367 p

[17] J.C Liberti and T.S. Rappaport, Small antennas for wireless communications: IS-95 and third generation CDMA applications, 1st edition, Prentice Hall PTR, April 1999

[18] Anurag Srivastava, Sanjeev Gupta, "Adaptive Array Antenna" ,Lecture slides, Antenna& Microwave Lab of Indian Institute of Technology, Bombay

[19] Antenna Beamforming and Power Control for Ad Hoc Networks, RAM RAMANATHAN, BBN Technologies, Cambridge, Massachusetts

[20] Romit Roy Choudhary, Xue Yang, Ram Ramanathan, and Nitin H Vaidya, "Using directional antennas for media access control in ad-hoc networks," in *Proceedings of the IEEE/ACM MobiCom Conference*, 2002, pp. 59–70.

[21] S. Bandyopadhyay, K. Hasuike, S. Horisawa, and S. Tawara, "An adaptive MAC protocol for wireless ad hoc community network (WACNet) using electronically steerable passive array radiator antenna," in *Proceedings of the IEEE GlobeCom Conference*, 2001, vol. 5, pp. 2896–2900.

[22] R.R. Choudhury and N.H. Vaidya, "Deafness: A MAC Problem in Ad Hoc Networks when Using Directional Antennas," *Proc. IEEE Int'l Conf. Network Protocols (ICNP)*, Oct. 2004.

[23] Y. B. Ko and N. H. Vaidya, "Medium access control protocols using directional antennas in ad hoc networks," in *Proc. IEEE INFOCOM*, Mar. 2000, pp. 13–21.

[24] R. Choudhury, X. Yang, R. Ramanathan and N. Vaidya, "On Designing MAC Protocols for Wireless Networks Using Directional Antennas," *IEEE Transaction on Mobile Computing, Vol. 5, No. 5*, May 2006.

[25] Mineo Takai, Jay Martin, Aifeng Ren, and Rajive Bagrodia, "Directional virtual carrier sensing for directional antennas in mobile ad hoc networks", *MOBIHOC'02*, June 2002

[26] M. B. Pursley, H. B. Russell, and J. S. Wysocarski. Energy-Efficient Transmission and Routing Protocols for Wireless Multiple-hop Networks and Spread-Spectrum Radios. In *EUROCOMM 2000*, pages 1-5, 2000.

[27] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian. Conserving Transmission Power in *Wireless* Ad Hoc Networks. In *ICNP'01*, November 2001.

[28] S. Agarwal, S. Krishnamurthy, R. H. Katz, and S. K. Dao. Distributed Power Control in Ad-hoc Wireless Networks. In *PIMRC01*, 2001.

[29] P. Karn. MACA - A New Channel Access Method for Packet Radio. In *Proc. 9th ARRL Computer Networking Conference*, 1990.

[30] E.-S. Jung and N. Vaidya. A power control MAC protocol for ad hoc networks. In *8th ACM Int.* Conf. *on Mobile Computing and Networking (MobiCom02)*, pages 36–47, Atlanta, GA, September 2002.

[31] J. P. Monks, V. Bharghavan, and W. mei W. Hwu. A Power Controlled Multiple Access Protocol for Wireless Packet Networks. In *INFOCOM 2001*, April 2001.

[32] J. Deng and Z. J. Haas. Dual Busy Tone Multiple Access (DBTMA): A New Medium Access Control for Packet Radio Networks. In *IEEE International Conference on Universal Personal Communications (ICUPC '98)*, volume 2, pages 973-977, 1998.

[33] Z. J. Haas and J. Deng. Dual Busy Tone Multiple Access (DBTMA)-Performance Evaluation. In *VTC'99*, volume 1, pages 314-319, 1999.

[34] S. Singh, M. Woo, and C. S. Raghavendra. Power-aware Routing in Mobile Ad Hoc Networks. In *MOBICOM '98*, October 1998.

[35] S.-L. Wu, Y.-C. Tseng, and J.-P. Sheu. Intelligent Medium Access for Mobile Ad Hoc Networks with *Busy* Tones and Power Control. *IEEE Journal on Selected Areas in Communications*, 18(9):1647-1657, September 2000.

[36] S.-L. Wu, Y.-C. Tseng, C.-Y. Lin, and J.-P. Sheu. A Multi-Channel MAC Protocol with Power Control for Multi-Hop Mobile Ad Hoc Networks. *The Computer Journal (SCI)*, 45(1):101-110, 2002.

[37] J.-P. Ebert, B. Stremmel, E. Wiederhold, and A. Wolisz. An Energy-efficient Power Control Approach for WLANs. *Journal of Communications and Networks (JCN)*, 2(3):197-206, September 2000.

[38] J.-P. Ebert and A. Wolisz. Combined Tuning of RF Power and Medium Access Control for WLANs. In *IEEE International Workshop on Mobile Multimedia Communications (MoMuC'99)*, November 1999.

[39] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. R. Kumar. Power Control in Ad-Hoc Networks: Theory, Architecture, Algorithm and Implementation of the COMPOW protocol. In *European Wireless 2002*, February 2002.

[40] J. Zander. Slotted Aloha Multihop Packet Radio Networks with Directional Antennas. Electronics Letters 26(25), Sep 1990.

[41] Asis Nasipuri, Kai Li, and Uma Reddy Sappidi, "Power Consumption and throughput in Mobile Ad Hoc Networks using Directional Antennas", in *Proceedings of the IEEE International Conference on Computer Communication and Networks (ICCCN2002)*, October 14-16, 2002, Miami, Florida.

[42] Z. Huang, Z. Zhang, and B. Ryu, "Power control for directional antenna-based mobile ad hoc networks," in *Proc., Intl. Conf. on Wireless Comm. and Mobile Computing*, pp. 917–922, 2006.

[43] Ram Ramanathan, "On the performance of ad hoc networks with beamforming antennas", *Proc. of MobiHoc'*2001, pages 95–105, October 2001.

[44] B. Alawieh, C. Assi, W. Ajib, "A Power Control Scheme for Directional MIAC Protocols in MANET", *IEEE Conf., WCNC2007*, pp.258-263, 2007

[45] Y. B. Ko, V. Shankarkumar, and N. H. Vaidya. Medium Access Control Protocols using Directional Antennas in Ad hoc Networks. In *Annual Joint Conference of the IEEE Computer and Communications Societies*, March 2000.

[46] N.S. Fahmy, T.D. Todd, V. Kezys, Distributed power control for ad hoc networks with smart antennas, in: *Proceedings of the IEEE Vehicular Technology Conference*, vol. 4, 2001, pp. 2141–2144.

[47] Nader S. Fahmy, Terence D. Todd, and Vytas Kezys. "Ad Hoc Networks with Smart Antennas Using IEEE 802.11-Based Protocols". In Proceedings of *IEEE International Conference on Communications (ICC)*, April 2002.

[48] D. Saha, S. Roy, S. Bandyopadhyay, T. Ueda, and S. Tanaka. A Power-Efficient MAC Protocol with Two-Level Transmit Power Control in Ad Hoc Network Using Directional Antenna. In *Proceedings of the 5th International Workshop on Distributed Computing (IWDC)*. Calcutta, India, December 2003.

[49] A. Arora and M. Krunz, "Power-Controlled Medium Access for Ad Hoc Networks with Directional Antennas," Elsevier Ad Hoc Networks, 2006.

[50] Mesquite Corporation. Online at http://www.mesquite.com.

[51] A. Arora, M. Krunz, and A. Muqattash. Directional Medium Access Protocol DMAP with Power Control for Wireless Ad Hoc Networks. In *IEEE Global Telecommunications Conference*, Dec 2004.

[52] Z. Xiaodong, L. Jiandong, and Z. Dongfang. A Novel Power Control Multiple Access Protocol for Ad Hoc Networks with Directional Antennas. In *IEEE International Conference on Advanced Information Networking and Applications*, April 2006.

[53] Kagenari Yamamoto Miki Yamamoto, "Performance improvement of Ad Hoc Networks by Deployment of Directional Antenna", *Proceedings of the Third*

International Conference on Mobile Computing and Ubiquitous Networking (ICMU), London, UK, 2006

[54] Young-Bae Ko, Jong-Mu Choi and Nitin H. Vaidya, "MAC protocols using directional antennas in IEEE 802.11 based ad hoc networks," *Wireless Communication and Mobile Computing*, Apr. 2007.

[55] QualNet Simulator Version 4.5.1, Scalable Network Technologies, www.scalable-networks.com

[56] Chaiporn Jaikaero, Chien-Chung Shen, "QualNet Tutorial", Scalable Network Technologies, Inc.