國立交通大學

電信工程學系碩士班
碩士論文

適用於具指向性天線與功率控制無線隨意網路之跨層設計

Cross-Layer Design for Wireless Ad-hoc Networks with Directional Antennas and Power Control

研 究 生：蕭昆苑 Student: Kun-Yuan Hsiao

指導教授：李大嵩 博士 Advisor: Dr. Ta-Sung Lee

中華民國九十四年六月

適用於具指向性天線與功率控制
無線隨意網路之跨層設計

Cross-Layer Design for Wireless Ad-hoc Networks with Directional Antennas and Power Control

研究生：蕭昆苑　　Student: Kun-Yuan Hsiao

指導教授：李大嵩 博士　　Advisor: Dr. Ta-Sung Lee

國立交通大學
電信工程學系碩士班
碩士論文

A Thesis
Submitted to Institute of Communication Engineering
College of Electrical Engineering and Computer Science
National Chiao Tung University
in Partial Fulfillment of the Requirements
for the Degree of
Master of Science
in
Communication Engineering
June 2005
Hsinchu, Taiwan, Republic of China

中華民國九十四年六月

適用於具指向性天線與功率控制
無線隨意網路之跨層設計

學生：蕭昆苑　　　　　　　　　　指導教授：李大嵩 博士

國立交通大學電信工程學系碩士班

摘要

無線隨意網路 (wireless ad hoc network) 是由多個可任意移動位置之行動主機所組成，相較於有基礎結構之網路，無線隨意網路擁有較靈活之傳輸方式，然而傳統使用全方向性天線之無線隨意網路傳輸易造成網路擁擠。將指向性天線應用在無線隨意網路中能夠顯著地提升空間再使用的可能性而減緩網路擁擠程度，進而提昇網路整體資料流量。為了能完全發揮指向性天線的特性，許多指向性媒介接取控制 (directional medium access control) 協定被提出。然而這些指向性媒介接取控制協定卻引起了新類型的隱藏節點 (hidden node) 和封鎖問題，導致資料流量隨之下降。在本論文中，吾人針對使用指向性天線的實體、媒介接取控制與路由協定提出一整合性的設計。吾人提出之 M-null 指向性天線模型搭配指向性媒介接取控制不只能夠指向性地傳送封包，也能形成 M 個波束形成之零點 (beamforming null) 以消除來自其他方向的干擾。如此一來隨意節點不只能充份地達到空間再使用，也能透過解決隱藏節點和封鎖問題而明顯地增加資料流量。此外為了有效處理指向性天線強增益對遠方通訊之干擾，吾人提出了功率控制之跨層設計。透過控制傳送功率，能使得在鄰近範圍內的二組或以上的節點可同時進行資料傳輸，因而大大地提昇網路整體資料流量，此外也可降低功率消耗。最後，相較於使用全向性天線和基本指向性天線的系統，吾人藉由電腦模擬驗證本論文所提的系統架構可大幅度地改進網路的整體效能。

Cross-Layer Design for Wireless Ad-hoc Networks with Directional Antennas and Power Control

Student: Kun-Yuan Hsiao Advisor: Dr. Ta-Sung Lee

Institute of Communication Engineering
National Chiao Tung University

Abstract

A wireless ad hoc network is a collection of wireless mobile hosts that are dynamically and arbitrarily located in a certain area. Compared with infrastructure networks, ad hoc network has more flexible ways of communication. However, the conventional ad hoc network uses omnidirectional antennas, which may result in network congestion. Using directional antennas can increase the potential for spatial reuse to alleviate network congestion significantly, leading to higher total network throughput. In order to exploit the benefit of directional antenna, many directional MAC (DMAC) protocols are proposed. However, these DMAC protocols induce new types of hidden terminal and blocking problems, which decrease the network throughput performance drastically. In this thesis, we propose an integrated design of physical, MAC and routing protocols with the use of directional antennas. An M-null directional antenna model with DMAC is proposed to transmit packets directionally and form M beamforming nulls to eliminate interference from other direction. Therefore, ad hoc nodes can adequately achieve spatial reuse, and the throughput performance is improved significantly due to addressing the hidden terminal as well as blocking problems. Furthermore, to deal with the high directional antenna gain which may potentially interfere with communications taking place far away, we propose a cross-layer design of power control protocol. Through controlling transmission power, simultaneous data transmissions of two or more pairs of nodes located in each other's vicinity may be allowed and thus the network total throughput is enhanced drastically. In addition, power consumption is reduced. Finally, we evaluate the performance of the proposed system architecture by computer simulations, and confirm that the throughput performance is improved greatly over omnidirectional and basic directional antenna communications in ad hoc networks.

Acknowledgement

I would like to express my deepest gratitude to my advisor, Dr. Ta-Sung Lee, for his enthusiastic guidance and great patience. I learn a lot from his positive attitude in many areas. Heartfelt thanks are also offered to all members in the Communication Signal Processing (CSP) Lab for their constant encouragement. Finally, I would like to show my sincere thanks to my parents and friends for their invaluable love.

Contents

List of Figures

List of Tables

Acronym Glossary

ABR	associativity based routing
ACK	acknowledgment
AODV	ad hoc on-demand distance vector
CGSR	clusterhead gateway switching routing
CSMA	carrier sense multiple access
CTS	clear to send
DACK	directional acknowledgment
DBF	distributed bellman-ford
DCF	distributed coordination function
DCTS	directional clear to send
DIFS	distributed inter frame space
DMAC	directional medium access control
DMAP	directional medium access protocol with power control
DNAV	directional network allocation vector
DOA	direction of arrival
DRTS	directional request to send
DSDV	destination sequence distance vector
DSR	dynamic source routing
DST	dynamic source tracing
DVCS	directional virtual carrier sensing
ESPAR	electronically steerable passive array radiator
FSR	fisheye state routing
GPS	global positioning system
GSR	global state routing
MAC	medium access control
MACA	multiple-access with collision avoidance
MCMV	multiply constrained minimum variance
NAV	network allocation vector
PCF	point coordination function
PHY	physical
RTS	request to send
SIFS	short inter frame space

SSA	signal stability-based adaptive
TORA	temporally ordered routing algorithm
WRP	wireless routing protocol
ZRP	zone routing protocol

Chapter 1

Introduction

There has been a growing interest in wireless mobile ad hoc networks in recent years. A wireless ad hoc network is a collection of wireless mobile nodes that are dynamically and arbitrarily located in a certain area, and is very distinctive from cellular-based networks mainly because of their lack of centralized control. Moreover, a wireless ad hoc network may consist of many partially overlapping radio coverage areas where a single transmission channel is shared by all of its nodes. In this case, nodes interfere with each other, and without an effective medium access control (MAC) protocol, packet collisions occur frequently. However, the medium reservation policy in recently proposed MAC protocols that aims to solve the collision problem limits network capacity greatly [1].

Directional antennas can provide a higher gain and reduce interference by focusing energy towards an intended direction. Spatial reuse of wireless medium can thus be achieved, and network capacity is increased accordingly. However, the problem of utilizing directional antennas to improve the performance of ad hoc networks is non-trivial. Current directional MAC (DMAC) protocols modified from IEEE 802.11 standard [2], such as [3]-[10], do not benefit by using directional antennas, because these protocols induce new types of hidden terminal [3] and blocking problems, which result in collisions and inhibiting transmission respectively. Directional antennas, due to its greater transmission range, may potentially interfere with communications taking place far away. It is clear that the problems must be addressed to exploit the benefits of directional antennas.

Another important issue in wireless ad hoc networks is power awareness. The high directional antenna gain will be paramount importance to interfere with communications occurring far away. Power control is a critical factor to limit multiuser interference and increase the number of simultaneous data transmissions. In addition, power is a precious resource in wireless networks. It is a marvelous advantage of reducing power consumption, since the power energy is precious for all ad hoc nodes which are mobile terminals of limited size. Many different power control protocols in wireless ad hoc networks are proposed [11][12][13].

In this thesis, we propose an integrated design of physical, MAC, and routing protocols with the use of directional antennas. We assume that each node has an electrically steerable directional antenna system. With DOA information available, RTS/CTS packets can be transmitted directionally. Upon receiving these control packets, the corresponding direction and duration of the incoming data transmission can be recorded. Therefore, only those nodes located within the direction of transmission are blocked, and these nodes are not blocked in all directions. Spatial reuse can thus be achieved, and the throughput performance is improved significantly. Furthermore, to address problems with DMAC protocols, we propose an *M*-null directional antennas model which can form *M* beamforming nulls to eliminate neighbor interference from any other directions except transmission direction. The DOA information helps a node to identify the relative directions of its neighbors; therefore, we can set *M* null angles in neighbor nodes' directions. Moreover, our MAC protocol which uses power control on control packets can not only provide an excellent throughput but also reduce the power consumption. The experimental results show that compared with omni-directional and basic directional approach, the proposed system architecture improves network performance significantly.

This thesis is organized as follows. In Chapter 2, we address issues of medium access control in wireless ad hoc networks. A congestion problem under heavy traffic loading is also discussed. In Chapter 3, we give a detailed description of the proposed system architecture including physical, MAC, and routing layer. We will propose the power control strategy in Chapter 4. Afterwards, computer simulations are presented in the later part of Chapters 3 and 4. Finally, we conclude this thesis and propose some potential future works in Chapter 5.

Chapter 2

Issues in Wireless Ad Hoc Networks

One of the most important key points of wireless ad hoc networks is medium access control (MAC) mechanism. Though there have been lots of MAC protocols proposed and designed for wireless ad hoc networks, the IEEE 802.11 MAC protocol [2] is widely used as the standard of wireless local area networks. However, this protocol does not function well in multihop ad hoc environments. In Section 2.1, we will discuss some limitations induced from the IEEE 802.11 MAC protocol.

To deal with congestion problems in IEEE 802.11 MAC protocol, many research results on directional antenna MAC protocol are proposed. Nevertheless, the existing directional antenna MAC will lead to new MAC problems, which is introduced in Section 2.2.

2.1 Medium Reservation

In a wireless ad hoc network, a single transmission channel is shared by all of the stations. Therefore the network contains many partially overlapping radio coverage areas where stations interfere with each other. A collision occurs when the receiving end hears two or more signals at the same time, which is mainly induced from interference. Obviously, collisions can result in poor network performance. In order to meet the network performance requirements, MAC protocols with collision avoidance must be well designed.

Due to lack of fixed infrastructure, the interoperability between stations in an ad hoc network becomes much harder. Most proposed MAC protocols are based on the carrier sense multiple access (CSMA) mechanism. The basic idea of CSMA is to reserve the radio channel for the source of a certain on-going transmission by carrier sensing. Any station wishing to transmit must sense the medium first. If some other nodes are already transmitting, the node sets a random timer and then waits for this period of time to try again. On the other hand, if the medium is currently idle, the node begins its transmission. However, the simple CSMA mechanism is susceptible to the hidden node problem, especially in wireless ad hoc networks. We begin our discussion by giving a specific description of hidden node problem.

2.1.1 Hidden Node Problem

In a wireless ad hoc network, a node can communicate with every other node in a certain range directly or use other nodes as relays. Due to lack of fixed infrastructure, it is hard for a node to be aware of other on-going transmissions. Hidden nodes are those out of range of other nodes or a collection of nodes. Thus if some neighbor nodes are already transmitting, a hidden node could send out a signal unintentionally at the same time. The signal from the hidden node collides with the transmitting signal at the receiving end and information will be lost.

As depicted in Figure 2.1, node A is out of the transmission range of node C. If node C is transmitting signal to node B, node A will not know that node B is receiving signal from node C. In the meanwhile, collision could occur at node B if node A decides to send out signal. In this case, node A is known as a hidden node. As mentioned before, hidden nodes can cause costly packet collisions and significantly reduce network performance. When a collision of data packet occurs, the data packet will be discarded, and the system must waste time on retransmissions. Therefore, many MAC protocols have been proposed to eliminate the hidden node problem.

2.1.2 RTS/CTS Exchanging Mechanism

In order to solve the hidden node problem, and thus achieve high throughput, a mechanism known as RTS/CTS exchanging is widely used. The RTS/CTS exchanging mechanism was initially proposed in a protocol called multiple-access with collision avoidance (MACA) [14]. A node wishing to send a data packet must firstly broadcast a request-to-send (RTS) control packet which contains the length of the data packet that will be sent. After receiving the RTS packet, the receiver responses by sending out a clear-to-send (CTS) control packet which also contains the length of the upcoming data packet. According to the data length information, any node hearing either RTS or CTS packet must set a timer to record the end of upcoming data transmission. Thus all the neighbors of the transmitting end and the receiving end will be informed about the data transmission by RTS and CTS control packets respectively. These nodes remain silent until the data transmission is completed, and therefore collisions are avoided. As shown in Figure 2.2, node B wants to communicate with node C. Node B first sends out an RTS control packet and waits for response from node C. At the same time, node A is blocked by this RTS packet and remains silent until the end of the following data transmission. Upon receiving the RTS packet, node C sends out a CTS packet to show that it is ready for receiving data from node B. Node D also receives this CTS packet and will not send out any signal. After exchanging RTS/CTS packets, node B can start transmit data packet to node C without been interfered. This example clearly shows how the hidden node problem is eliminated by RTS/CTS exchanging mechanism, and thus collisions are avoided. Via this control packet exchanging process, all the hidden nodes won’t transmit during the period of data transmission, and the effect of hidden node problem is eliminated.

However, in an ad hoc network with heavy load, there could be lots of nodes wishing to transmit data packets at the same time. This could result in the flood of RTS packets, and the flooded control packets could prohibit a large number of nodes from transmitting any packet. Consequently, the throughput of the network goes to zero as the load increases. Before giving a further description of this problem, the most widely used MAC protocol, IEEE 802.11 MAC protocol, will be introduced in the following section.

2.1.3 IEEE 802.11 DCF protocol

The IEEE 802.11 protocol covers the MAC and physical (PHY) layer. The MAC layer defines two different access methods, the distributed coordination function (DCF) and point coordination function (PCF). Since the PCF cannot be used in ad hoc networks, the following discussion will focus on the DCF protocol.

IEEE 802.11 DCF protocol is basically a carrier sense multiple access with collision avoidance mechanism which is implemented by RTS/CTS exchanging. All other nodes receiving either the RTS or CTS packet set their virtual carrier sensing indicator, called a network allocation vector (NAV). The NAV is a counter counts down to zero at a constant rate, which is updated according to the duration field in the control packet. Before the NAV counts down to zero, the virtual carrier is sensed busy. Thus the area covered by the transmission range of the sender and the receiver is reserved for data transmission. In addition to the RTS/CTS packets, IEEE 802.11 DCF protocol requires an acknowledgment (ACK) packet transmitted by the receiver after the successful reception of data packet. The sender ascertains the success of data transmission by receiving the ACK packet. If no ACK packet is received, data retransmission can be initiated immediately.

IEEE 802.11 DCF protocol also employs a congestion control mechanism based on random backoff. When a node has data to transmit, it detects the wireless medium first. If the medium has been idle for more than a time interval called distributed inter frame space (DIFS), this node can transmit the data packet immediately. Otherwise, it waits until the medium becomes idle, and then defers for another DIFS interval. If the medium remains idle after this DIFS interval, the random backoff mechanism is started. Without the backoff mechanism, collisions may occur just at the moment because there may be more than one node waiting for the medium to become free. The node sets a backoff time that is randomly selected from interval $[0\ CW]$, where CW is the contention window value maintained in every node. At the first transmission attempt, CW is set as CW_{min}, and it is doubled at each retransmission up to CW_{max}. Once CW is set to CW_{max}, it remains at the value of CW_{max} until it is reset. The backoff timer counts down as the channel is sensed idle, pauses during data transmission, and reactivates when the medium is sensed idle again. When the backoff timer expires for more than a DIFS and the medium is still idle, the node starts transmission. If data is transmitted successfully, or maximum retry limit is reached, CW will be reset to CW_{min}. Figure 2.3 shows a complete packet exchanging timing diagram of an IEEE 802.11-based wireless ad hoc network, where SIFS stands for short inter frame space. SIFS is the smallest time interval defined in the IEEE 802.11 MAC protocol. After a SIFS, only acknowledgements, CTS or data frames may be sent. At the end of a defer process, every node starts a backoff process to avoid collision at this very moment.

As mentioned before, the RTS/CTS exchanging mechanism could result in poor throughput performance, especially in heavy load networks. The following section will give a thorough explanation of this RTS/CTS-induced congestion problem.

2.1.4 Blocking Problem

In the RTS/CTS exchanging mechanism, any node receiving either an RTS or CTS packet will be blocked for a certain period of time to ensure not to interfere with on-going transmissions. Since nodes in an ad hoc network share a single transmission channel, only one node is allowed to transmit at any time within the range of a receiver, and all the other nodes may be blocked. As for the neighbors of a blocked node, these nodes will not be aware of the fact that this node is blocked. Therefore, communication with the blocked node may still be initiated by its neighbors. In this situation, the sender sends out an RTS packet and waits for response. However, the blocked destination will not respond to this RTS packet. Since the sender does not get any response to its RTS packet, it enters into an exponential backoff mode. Furthermore, this RTS packet forces every other node that receives it to inhibit any transmission even though the blocked destination does not respond. Without a CTS response, data transmission will not be ignited. It’s a waste of medium that stations been inhibited from transmitting while no data transmission takes place actually.

Figure 2.4 explains the problem. In this figure, data packets are transmitting between node A and node B, and node C is blocked by the RTS/CTS packets from nodes A and B. In the period that node C is blocked, node D sends out an RTS packet to node C and won't get CTS response back. Meanwhile, node E is blocked due to the RTS packet from node D. However, node E is unnecessarily blocked because it is out of the transmission range of nodes A and B. This blocking situation could propagate through the network and result in a severe problem that the throughput of the network goes to zero. If node F sends an RTS packet to node E while node E is blocked, not only node F enters into backoff mode, but also node G is unnecessarily blocked due to the RTS packet from node F. Only nodes in the gray area are required to be blocked. However, node E and node G are blocked as well. As for node D and node F, they are forced to enter backoff mode. Neither nodes in backoff mode nor nodes been blocked can transmit data, which wastes lots of radio resource. This is how blocking problem propagates and it may affect network performance severely as the load increases. From this example, we clearly show how the RTS/CTS-induced blocking problem affects the network performance. The most significant drawback is the poor throughput performance. As the load of network increases, more RTS packets are sent out, and thus more nodes are blocked. Since no node transmits data, the throughput is drastically reduced.

2.2 Directional Antenna for Wireless Ad Hoc Networks

Directional antennas offer tremendous potential for improving the performance of wireless communication systems. In this section, we introduce recent topics about directional antenna for wireless ad hoc network.

2.2.1 Classification of MAC Protocols for Directional Antenna Models

Directional antenna models using for wireless ad hoc networks can be classified into two groups: steered beam and switched beam antenna systems and there have been several MAC protocols for different directional antenna models proposed for wireless ad hoc networks. A steered beam system can steer the main lobe of the beam, which is sectorized in simulation, in the direction of the desired user. Each node is equipped with M antennas whose orientations can be maintained at any time, regardless of the node’s movement. In this model, it is assumed that nodes have directional reception capability, i.e., they can activate the antenna pointing to the direction of the desired destination while deactivating antennas in all other directions. Thus, the receiving node is not influenced by simultaneous transmissions from other nodes as long as it is not received at the antenna low beam when the receiver is currently listening to. Many recent researches adopt this antenna model [3]-[5].

The first MAC protocol using steered beam system uses omnidirectional RTS as well as CTS packets [5]. DATA and ACK packets are transmitted and received in the sector antennas facing the receiver and transmitter, respectively. The second MAC protocol sends a directional RTS and an omni directional CTS [6]. These MAC protocols employ at least one omnidirectional transmission of a control packet that leads to several inefficiencies. First, they do not fully exploit the potential benefits of directional antennas because omnidirectional RTS/CTS block neighbor nodes in all directions, and spatial reuse cannot be obtained. Second, omnidirectional transmission of a control packet causes to limit the coverage area. The presence of omnidirectional transmissions of either RTS or CTS limits the range of directional transmissions, which is now defined by the smaller coverage range between any of these packets. They do not exploit the increased coverage range provided by directional transmissions. In other words, given a particular transmit energy, an array of M antenna beams provides an increased antenna gain in comparison with the omni mode of the order of M [5][6][10]. This gain is doubled if there is directivity in both transmission and reception. Thus, a directional communication between two stations may significantly increase the distance between them as compared to the equivalent omni communication, a benefit that has not been explored by the above schemes.

In [3], the directional MAC (DMAC) protocol is proposed that RTS/CTS and DATA packets transmit directionally. Since DMAC has more spatial reuse, DMAC can have better performance, but it will increase instances of hidden terminal problem.

Another directional antenna model is a switched beam system which consists of a set of predefined beams, of which the one that best receives the signal from a particular desired user is selected [4]. As we can see in Figure 2.5, the area around the node is covered by M beams. The beams are numbered from 1 to M starting at the three o’clock position and running counter clockwise. The node can transmit its signal to anyone of the M beams, increasing the coverage range of the transmission towards a specific direction. In idle mode the node hears omnidirectional. In the reception of a signal the node uses selection diversity, which means that it uses the signal from the antenna that is receiving the maximum power of the desired signal. With this mechanism the receiver can extend the communication area.

A scheme of circular directional transmission of RTS is carried out by the transmitter which ensures that the RTS packet will eventually reach the intended destination [4]. The destination then sends back a single directional CTS packet towards the source. This scheme can be referred as Circular RTS MAC (CRM).A more serious problem with CRM is in the design of its RTS/CTS handshake. For example, if the destination node does not reply back with a CTS (due to a collision), nodes in the neighborhood of the transmitter which correctly receive the circular RTS will not be able to initiate any transmission as their Directional Network Allocation Vector (DNAV) is set. Clearly, this degrades the network capacity. Another limitation in CRM is transmission of circular directional RTS through “empty” sectors which do not have any neighbor nodes. In [15], Directional Antenna Medium Access (DAMA) protocol is proposed and performs more effectively than CRM. However, DAMA and CRM is inferior to IEEE 802.11 in few antenna beams in grid topology, because they cannot benefit much from spatial reuse when the load is low as it spends a considerable amount of time performing the circular transmissions of RTS.

In these MAC protocols for directional antenna models aforementioned, the directional antenna models use simple but impractical models in their simulation. In steered beam and switched beam system, the main lobe beam is simulated as sector beam which antenna pattern is flat-topped within the width of the main lobe beam. They approximate the radiation pattern of the low beams into a sphere with the node at its center and the gain of the low beams is assumed to be very low. There is not an antenna array can formulate an antenna pattern which has a flat-topped main lobe beam and low beams with very low gain. In many adaptive beamforming arrays, the gain of low beams is approximately one-tenth of gain of the main lobe. We will propose a practical directional antenna model and show that the influence of the gain of low beams is very greatly in wireless ad hoc networks.

2.2.2 Problems of Existing Directional Medium Access Control (DMAC) Protocols

In this section, we discuss some channel access problems of existing directional MAC protocols in wireless ad hoc networks. These problems can be classified in hidden terminal and blocking problems.

A. Hidden Terminal Problems

In section 2.1.1, we have discussed the well-known hidden terminal problem in multi hop wireless networks can be resolved by the exchange of RTS/CTS control packets. However, the RTS/CTS exchange assumes that these packets are transmitted omnidirectionally. If directional antenna adopts DMAC protocol, directional transmission of RTS/CTS introduces new kinds of hidden terminal problems, which are discussed below.

(1) Hidden terminal due to asymmetric gains in omnidirectional and directional modes:

Assume that all nodes in this figure are currently idle in Figure 2.7. Nodes have an omnidirectional gain of G_o. The protocols in [9][16] use equal directional gain of G_d for directional RTS/CTS (DRTS/DCTS) and data packets. G_d is greater than G_o. In Figure 2.7, assume that node C sends a DRTS to node D and node D replies with a

DCTS. Nodes C and D form their transmission and reception beams in each other's direction, and node C starts transmitting DATA to node D. At the same time, node A is in the idle mode listening omnidirectionally and is distant from node D, so it does not hear the DCTS and cannot sense this transmission. While this transmission is in progress, assume that node A has a data packet to send to node B, and thus sends a DRTS to node B with a directional gain of G_d. Since node A and node D now also form beams in each other's direction, node D possibly receives DRTS/DATA from node C and A simultaneously, and then a collision is occurred. This problem is identified in their protocol but is not addressed [3]. The DMAC protocols proposed in [9][16] do not also resolve this problem.

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

Suppose that in Figure 2.7, node B is transmitting to node A. While this transmission is in progress, node C exchanges RTS/CTS packets with node D and is sending data to node D. Since node B forms a beam in the direction of node A, it cannot receive the DCTS from node D. In this scenario, node B is unaware of the ongoing transmission in its neighborhood, although B is within the transmission range of node D. Assume after node B finishes transmitting to node A, and now intends to transmit packets to node D. Consequently, node B sends a DRTS packet to node D and a collision is occurred at node D. The MAC protocols proposed in [3][9][16] suffer from this problem.

(3) Hidden terminal due to low beams:

Low beams represent the power radiated/received in directions other than the intended direction. Consider Figure 2.7 again, if node A intends to send data to node B, it first sends a DRTS to node B. When B replies with a DCTS, node A starts sending the data packet. Node H does not hear the DCTS since it is not located in the direction of the main lobe of node B. Furthermore, assume that the gain of the low beams of node B is comparatively small, and node H is listening omnidirectionally. Meanwhile, node H has data for node B, and thus, points its main lobe towards node B. Even though node B has only a low beam in the direction of node H, the high antenna gain of the main lobe of node H could result in a collision at node B. However, in this case, the interferer is sending the signal towards the low beams of the receiver. This problem remains unresolved in the protocols in [3][9][16].

(4) Hidden terminal due to vulnerable transmitter:

Assume that node H sends a DRTS to node G in Figure 2.7, and node G replies with a DCTS. After receiving the DCTS, node H commences data transmission. This DRTS/DCTS exchange is heard by node C, which sets its DNAV accordingly. Meanwhile, node C intends to send a data packet to node B. Node C’s DNAV in the direction of node B is not set, and thus it sends a DRTS to node B and waits for a DCTS. However, node H points its main beam towards node C, and node C has finite low beam gain in node H’s direction. Therefore, the received power from node H at node C may be significant. In the meanwhile, if node B replies with a DCTS, this causes a collision at the node C. Thus, nodes in the vicinity of a transmitter may not be able to initiate data transmission even in the free DNAV directions while a neighbor transmitter is sending data. A similar problem can be occurred when a transmitter is expecting an acknowledgement (ACK) following a data packet transmission.

B. Blocking problems

(1) Blocking problem due to low beams:

In Figure 2.7, assume that node G and I are close to node C. Node C has packets to send to D, so it sends a DRTS to D first. Although the gain of the low beams is one-tenth of gain of the main beam approximately, nodes G and I which are in omnidirectional mode can still sense the DRTS from node C. Consequently, nodes G and I are blocked, so they cannot communicate with each other. However, node G cannot transmit to nodes C and D in this scenario, which implies that collisions are not occurred. This apparently implies a potential tradeoff between spatial reuse and collisions when using directional antennas.

(2) Blocking problem due to high gain:

Suppose that in Figure 2.7, node A has packets to send to node B. Since node A sends DRTS to node B with high directional gain of G_d, node D can receive the DRTS packet from node A, even D locating out of the omnidirectional transmission range of node A. Then, node D is blocked in the direction of node A. In the period that node D is blocked, node C sends out an DRTS packet to node D and will not get DCTS response back. Meanwhile, node E is blocked due to the DRTS packet from node C. However, node D will not be blocked when it operates in IEEE 802.11 omnidirectional mode. Node E is also unnecessarily blocked because it is out of the transmission range of nodes A and B. This blocking situation could propagate through the linear topology, which nodes are arranged into a line, and result in a severe problem that the throughput of the network reduces drastically. As for node C, it is forced to enter backoff mode. Neither nodes in backoff mode nor nodes been blocked can transmit data, which wastes lots of radio resource. As the load of linear topology increases, more RTS packets are sent out, and more nodes are blocked.

Therefore, no node transmits packets, and then the throughput decreases greatly.

2.3 Summary

In a wireless ad hoc network, a single transmission channel is shared by all of the stations. The main function of MAC layer is to manage the use of the shared medium. IEEE 802.11 MAC protocol is the most widely used protocol in the current implementation of wireless ad hoc network. This protocol is basically based on the CSMA protocol. In order to solve the hidden node problem, IEEE 802.11 MAC protocol exploits the RTS/CTS exchanging mechanism. The RTS/CTS exchanging mechanism is widely used in wireless ad hoc networks to avoid collisions caused by hidden nodes. Any node that receives an RTS or CTS packet inhibits itself from transmitting. Therefore, data transmission can be completed without the occurrence of collisions.

However, the RTS/CTS exchanging mechanism could lead to blocking problem where a node could be blocked even though there is no nearby node transmitting. Moreover, the blocking problem may propagate through the network, and the throughput goes down as the load increases. From a network point of view, the blocking problem reveals the tricky point of MAC functionality. On the one hand, MAC protocols must manage the shared medium to ensure successful data transmission, but on the other hand the medium reservation policy induces congestion in the network, like the blocking problem. Directional antennas have been suggested to be used in wireless ad hoc networks to reduce interference outside the intended direction, which increases spatial reuse of the transmission medium. However, from the previous sections we know that the throughput reduction results from the limitation of medium reservation. Features of directional antenna with

DMAC protocol can alleviate the network congestion.

We have shown that previous research results on DMAC for wireless ad hoc network using directional antenna introduce new types of problems (such as hidden terminal problems, and blocking problem), and the directional antenna models used at network simulation engine (ex. NS2) are too simple to be practical. In the following chapters, we will present our system architecture and computer simulations to show that the proposed scheme overcomes the shortcomings in DMAC and achieves better throughput than IEEE 802.11 and basic directional antenna model with few antenna elements in wireless ad hoc networks.

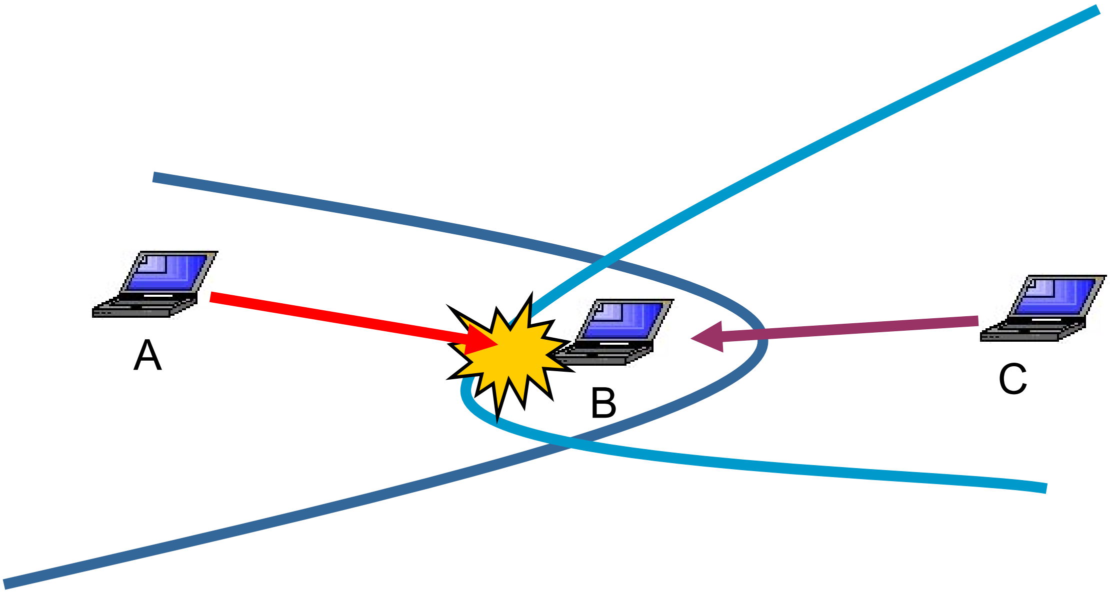


Figure 2.1: Hidden node problem: Node C is sending data packet to node B. Node A is out of radio range of node C, and thus is a hidden node. Collision occurs at node B when node A initiates transmission.

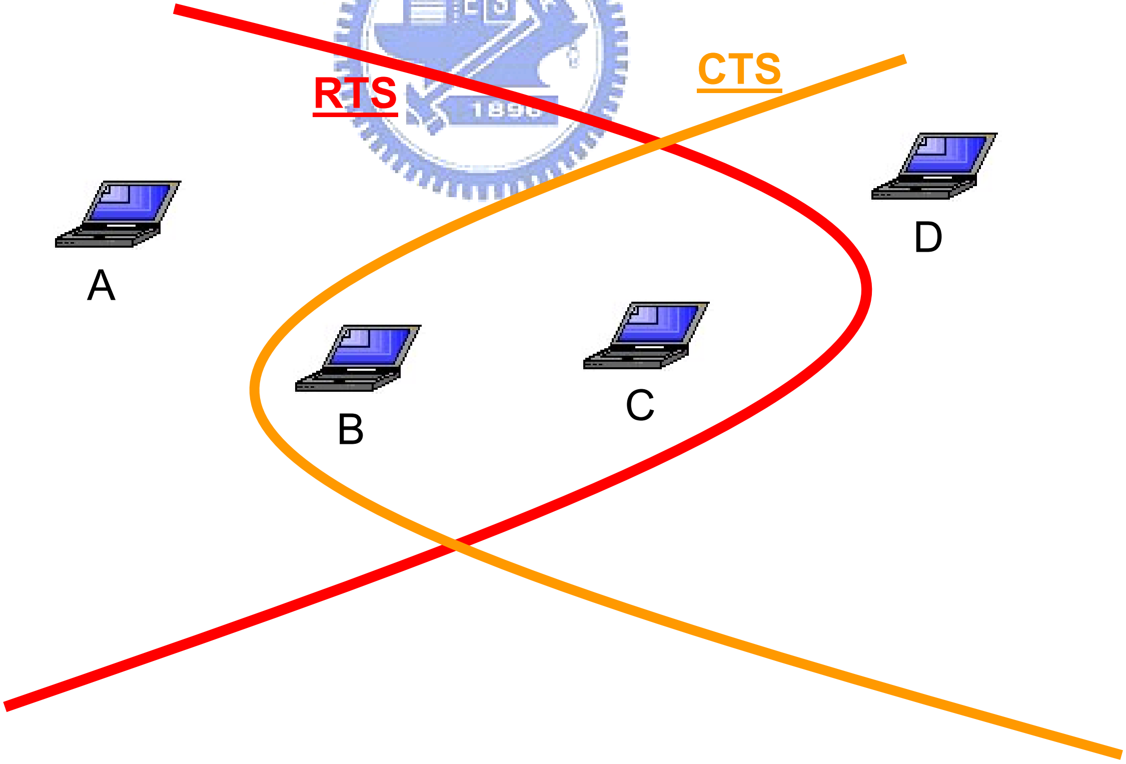


Figure 2.2: Node B and node C do the RTS/CTS exchanging before data transmission. Node A and node D are blocked by the RTS packet and the CTS packet, respectively.

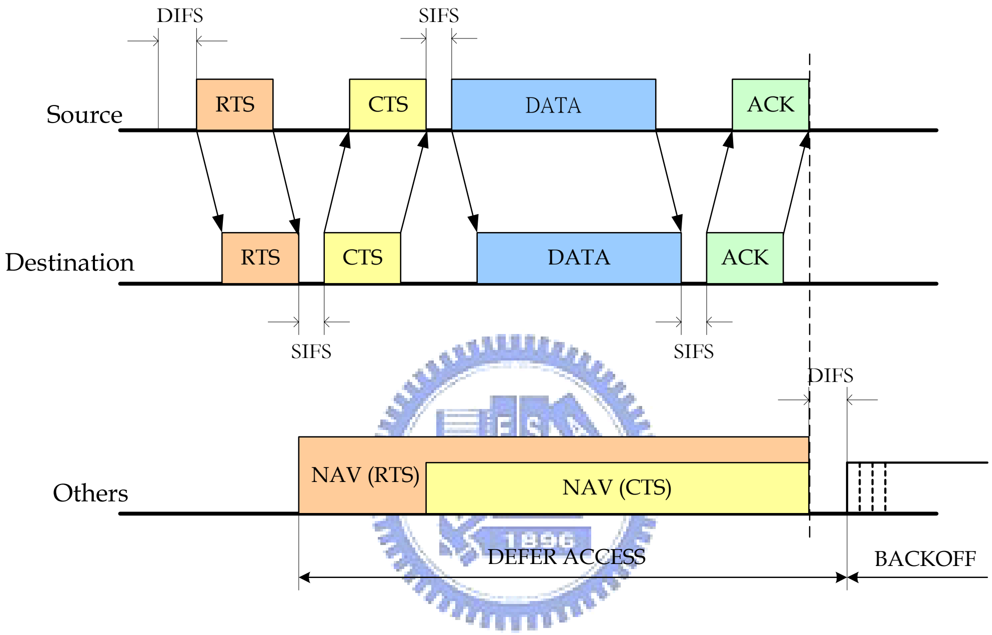


Figure 2.3: Packet transmission timing based on IEEE 802.11 MAC protocol.

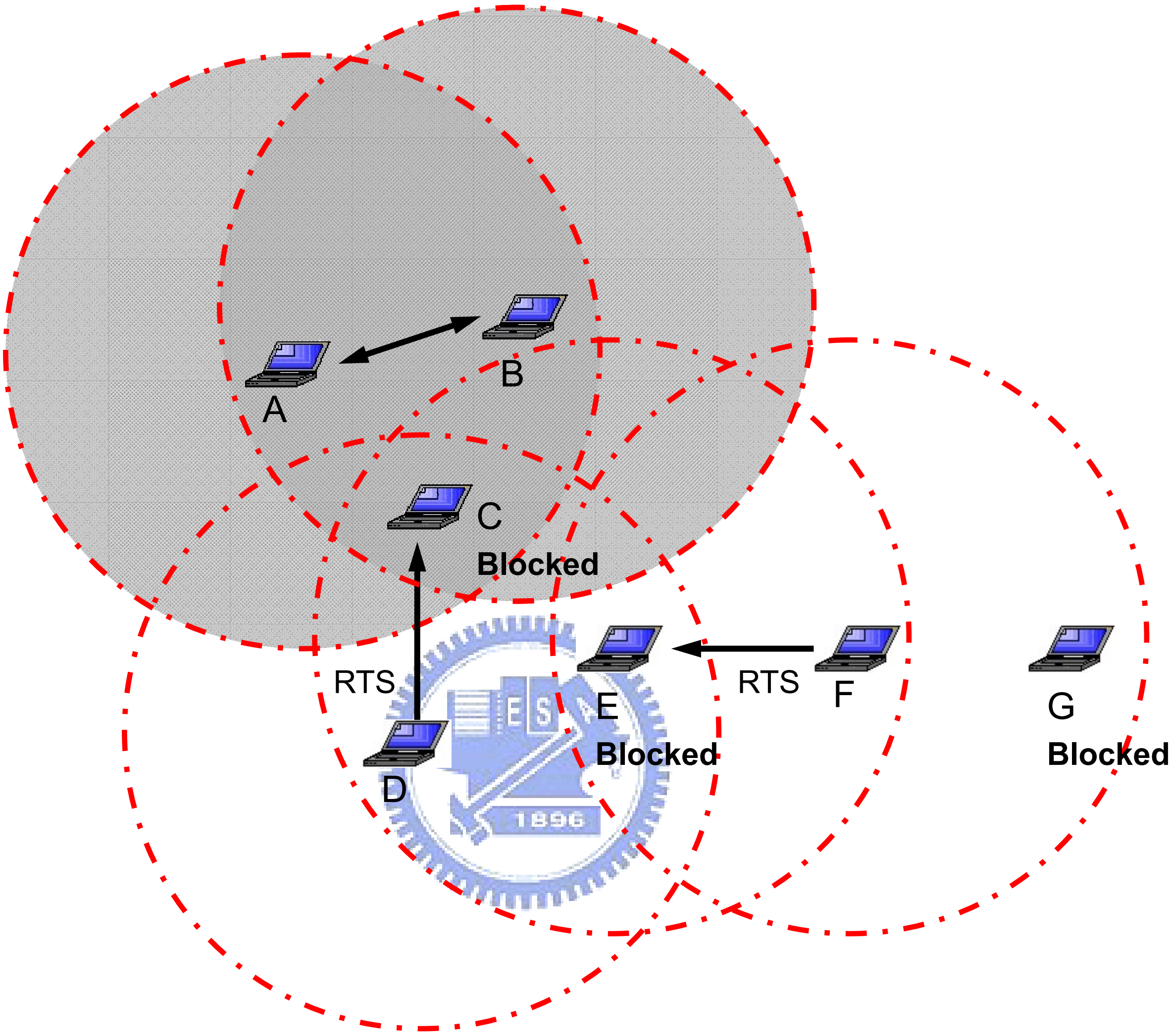


Figure 2.4: Blocking problem: Node A and node B are transmitting data packets. Only nodes in the gray area are required to be blocked. Node E and node G are unnecessarily blocked. This figure also shows how blocking problem propagates.

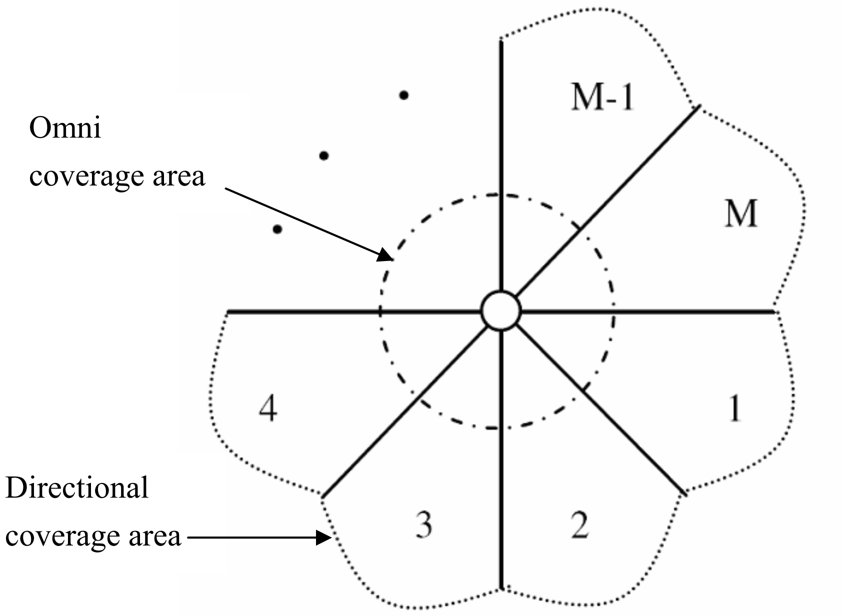


Figure 2.5: The sectorized antennas model [4]

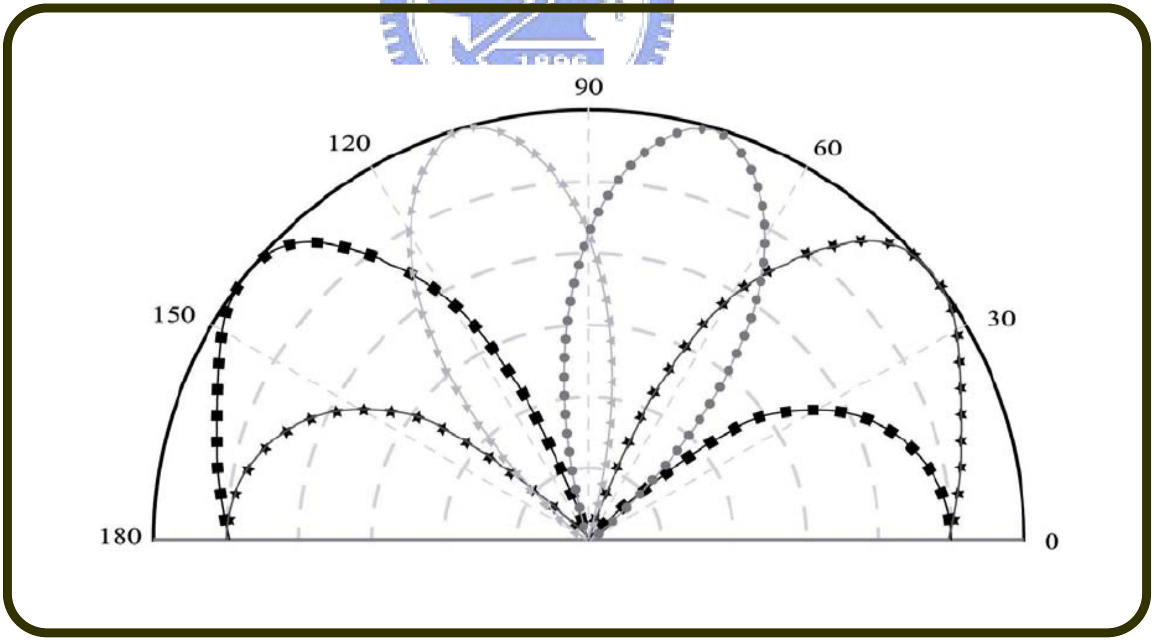


Figure 2.6: The switched beam antenna system

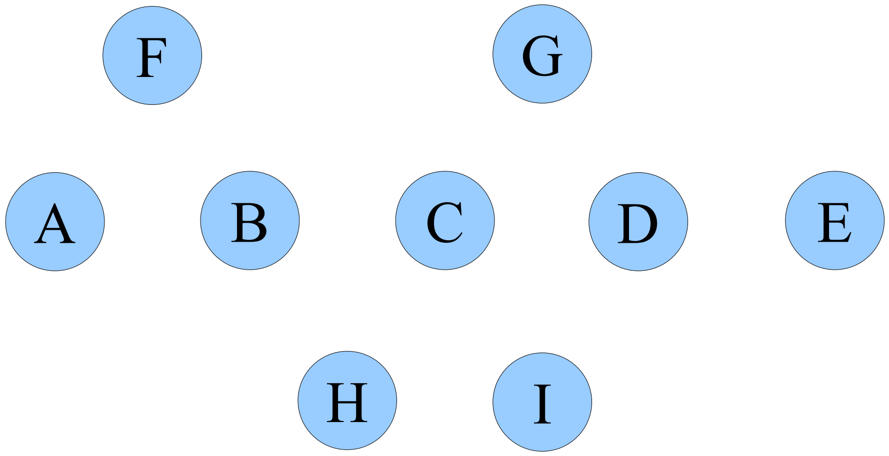


Figure 2.7: A topology used to demonstrate the hidden terminal and blocking problems in existing MAC protocols

Chapter 3

Performance Enhancement via Directional antennas

Directional antennas offer tremendous potential for improving the performance of wireless communication systems. Continuing reductions in the cost and size of antenna arrays make it feasible for wireless mobile ad hoc networks. By using directional antennas, radio interference can be reduced effectively, thereby improving the utilization of wireless medium. With directional antennas, simultaneous data transmissions of two or more pairs of nodes located in each other's vicinity may be allowed. However, we have shown that the throughput reduction results from the new types of hidden terminal and blocking problems in existing DMAC protocols. Therefore the merits of directional antennas may not be fully exploited without the modification. In this chapter, we present an integrated physical, MAC, and routing layers design of new directional antennas model, *M*-null directional antennas model, to utilize the advantages of directional antennas and address the problems in existing DMAC protocols.

3.1 System Architecture

From the previous chapter, we know that the throughput of a wireless ad hoc network could go to zero as the traffic load increases. The goal is to utilize the features of directional antennas and diminish this situation. Figure 3.1 illustrates a network situation where network capacity is improved by using directional antennas. Node C is allowed to initiate data transmission to node D while nodes A and B are transmitting. Moreover, although node G is located in the middle of nodes E and F, data transmission between nodes G and J will not interfere with nodes E and F. However, transmission between nodes G and H is not allowed, because node G is blocked in the direction of data transmission between nodes E and F. In normal situations where nodes are equipped with omni-directional antennas, most of these nodes are blocked. Data transmission between these nodes must take turns by contention. At most two sessions are allowed to be held simultaneously.

In the following discussion, the main idea is to share the knowledge of the wireless medium at the physical layer with higher layers. In standard wireless ad hoc networks, omni-directional antennas are utilized at the physical layer, which provides only information about received power. More useful information, direction of arrival (DOA) can be gained via the use of directional antennas. The DOA information will be shared with higher layers. From the previous chapter, we know that the fundamental resolution to blocking problem is to modify the MAC protocol. The MAC layer protocol should not block all the other neighbors in all directions. Since directional antennas can focus energy in an intended direction, spatial reuse can be achieved. With DOA information available, nodes can be aware of directions of on-going transmissions. As a result, data transmission may be initiated on the premise that no on-going transmissions will be interfered. In order to fully exploit the advantages of directional antennas, the DOA information can be further utilized at the network layer.

3.2 Physical Layer: Directional antennas

Wireless ad hoc networks are conventionally equipped with omni-directional antennas. However, the technology of directional antennas for wireless mobile communication has received enormous interest in recent years. In this section, we present the implementation of directional antennas at the physical layer.

3.2.1 Features of Directional antennas

Directional antennas have the ability to concentrate the radiation towards the intended direction of transmission or reception. Individual elements on the directional antennas transmit signals omni-directionally, and these signals interfere with each other constructively or destructively. As a result, signal strength increases in one or more directions and eliminates in the others. Consequently, the amount of radiated power to the destined node is reduced, which can largely improve the energy efficiency. However, in the case of omnidirectional antennas, the transmitted power radiates equally well in all directions and only a small percentage of power reaches the destined node. Moreover, because directional antennas have a lower gain outside the intended direction, interference can be minimized. Figure 3.2 shows an example of beam pattern steered by an 8-element circular antenna array [17]. It has a main lobe with about 60° width and gain of 8. The radiated power is concentrated in the range from -30° to 30°, and is suppressed outside the range. In addition to the main lobe, there are also several side lobes which represent the loss of energy. With more elements on the directional antennas, the increased signal strength in the intended direction can be larger, and the control over beamwidth and direction can be more effectively. The communication area can be extended via the use of directional antennas, and the communication link can benefit more by beamforming at both transmitter and receiver.

3.2.2 Multiply Constrained Minimum Variance (MCMV) Beamforming

Before introducing the proposed *M*-null directional antennas model, we introduce Multiply Constrained Minimum Variance (MCMV) beamforming [18], which the proposed *M*-null directional antennas model is based on in this section.

The array data model:

$$\mathbf{x} = \textstyle\sum_{i=1}^{D} s_i \mathbf{a}(\theta_i) + \mathbf{n} = \mathbf{A}\mathbf{s} + \mathbf{n} \qquad (D\times 1) \tag{3.1}$$

where $\mathbf{s} = [s_1, s_2, \ldots, s_D]^T$ is a transmitted symbol vector, $\mathbf{A} = [\mathbf{a}(\theta_1), \mathbf{a}(\theta_2), \cdots, \mathbf{a}(\theta_D)]$: $D\times D$, $\mathbf{a}(\theta_i)$ is an array steering vector: $D\times 1$, θ_i is a DOA of the ith path, and $\mathbf{n}(k)$ is a noise vector.

The design of an MCMV beamforming involves minimizing the output power subject to the constraints that the desired signal receives a unit gain and the coherent interferers get rejected. Assume that we have information about desired source DOA θ_1 as well as interference DOAs θ_i, $i = 2, \ldots, D$. We want to pass desired source distortionlessly while rejecting sources $2 \sim D$ in a “hard” manner that adds auxiliary constraints to put nulls at θ_i, $i = 2, \ldots, D$ to suppress noise and undetected interference with minimum power criterion. Determine the optimum weight vector **w** by solving the following optimization problem:

$$\begin{cases} \min\limits_{\mathbf{w}} \; E\{|\mathbf{w}_{MC}^H\mathbf{x}(k)|^2\} = \mathbf{w}_{MC}^H\mathbf{R}_{xx}\mathbf{w}_{MC} \\ \text{subject to: } \mathbf{w}_{MC}^H\mathbf{a}(\theta_1) = 1 \\ \qquad\qquad\quad \mathbf{w}_{MC}^H\mathbf{a}(\theta_i) = 0 \quad i = 2,\ldots,D \end{cases}$$

where $\mathbf{R}xx = E\{\mathbf{x}(k)\mathbf{x}^H(k)\}$: $D\times D$ is the autocorrelation of $\mathbf{x}(k)$.

Solution by Lagrange Multipliers:

$$\begin{cases} \nabla_{\mathbf{w}_{MC}}(\mathbf{w}_{MC}^H\mathbf{R}_{xx}\mathbf{w}_{MC} - \sum\limits_{i=1}^{D}\lambda_i\{\mathbf{w}_{MC}^H\mathbf{a}(\theta_i) - \delta[1-i]\}) = 0 \\ \mathbf{w}_{MC}^H\mathbf{a}(\theta_i) = \delta[1-i] \quad i = 2,\ldots,D \end{cases}$$

s.t.

$$\begin{cases} \mathbf{R}_{xx}\mathbf{w}_{MC} = \sum\limits_{i=1}^{D}\lambda_i\mathbf{a}(\theta_i) = \mathbf{A}\boldsymbol{\lambda} \\ \mathbf{w}_{MC}^H\mathbf{A} = \mathbf{e}_1^T \end{cases}$$

where $\boldsymbol{\lambda} = [\lambda_1,\ldots,\lambda_D]^T$: $D\times 1$, and $\mathbf{e}_1 = [1, 0,\ldots, 0]^T$: $D\times 1$

With some manipulation:

$$\mathbf{w}_{MC} = \mathbf{R}_{xx}^{-1}\mathbf{A}(\mathbf{A}^H\mathbf{R}_{xx}^{-1}\mathbf{A})^{-1}\mathbf{e}_1 \qquad (D\times 1) \tag{3.2}$$

Check:

$$\mathbf{w}_{MC}^H\mathbf{A} = \mathbf{e}_1^T(\mathbf{A}^H\mathbf{R}_{xx}^{H^{-1}}\mathbf{A})^{-1}\mathbf{A}^H\mathbf{R}_{xx}^{H^{-1}}\mathbf{A} = \mathbf{e}_1^T \tag{3.3}$$

MCMV beamforming approach can be applied to an array of arbitrary geometry for suppressing coherent and in coherent interference. The optimal weights are generated to form beamfroming nulls in the coherent interferers' directions of $\pm 30^\circ$, $\pm 60^\circ$, $\pm 100^\circ$, $\pm 160^\circ$ in Figure 3.3.

If there is an angle error in estimation, the beamforming nulls cannot eliminate coherent interference completely. There are two methods to counteract the angle error. Firstly, using high-order null constraint is very effective in counteracting the angle error in estimation. Secondly, setting two beamforming null constraints near the direction of main interference can have a wide angle range of beamforming null to tolerate large angle error. For example, as shown in Figure 3.4, we set two beamforming null constraints in 59° and 61°, there is a wider angle range of the beamforming null in 60°.

3.2.3 *M*-Null Directional antennas Model

Most studies on wireless ad hoc networks with directional antennas have assumed the use of a small, low-cost adaptive antenna which is known as electronically steerable passive array radiator (ESPAR) antenna [19]. As shown in Figure 3.5, the (M+1)-element ESPAR antenna consists of one center element connected to the main radiator and M surrounded passive parasitical elements in a circle. The main radiator exhibits an omni-directional radiation pattern. Each passive parasitical element is loaded with a variable reactor. The antenna pattern is formed according to the bias voltage on the reactors, and thus the reactance values. The ESPAR antenna is capable of forming either omni-pattern or directional pattern. For omni-pattern forming, the bias voltage on each reactor is set equally on condition that the received power is maximized [20]. For directional pattern forming, an optimized set of bias voltage on reactors is obtained such that the received signal power is maximized in the direction of the source.

According to MCMV beamforming in Section 3.2.2, we can use (M+1)-element antennas to build an M-null directional antennas model, which has one main beam,

M-1 side lobes, and M beamforming nulls. For ad hoc networks, a simple circular antenna array is capable of steering a beam through all 360°. M-null directional antennas can concentrate the radiation towards the intended direction of transmission or reception and null interference in specific direction, so it can completely utilize the potential of spatial reuse, and alleviate the hidden terminal problems and blocking problems. In latter simulations, we will show that M-null directional antennas model achieves outstanding performance over the basic directional antennas communications and IEEE 802.11 omnidirectional antennas.

In the following discussion, the antenna system on each node is assumed to be capable of operating in two modes; omni-mode and directional mode. Both the omni and the directional modes can be used to transmit or receive signals. In omni-mode, a node is capable of receiving or transmitting in all directions with a constant gain of G_o. A node stays in omni-mode while idle. In directional mode, a node can point its antenna beam towards an intended direction with a gain of G_d which is typically larger than that in omni-mode. Consequently, a node in directional mode has a greater transmission range than in omni-mode. The direction in which the main lobe should be steered for a given transmission is specified to the antenna by the upper layer protocol. When a node is in the omni-directional receiving mode, it is susceptible to interference from all directions. Only when the node has formed a beam to a specific direction, it can avoid the interference from other directions.

3.3 MAC Layer: DMAC

Current MAC protocols, such as IEEE 802.11 standard, do not benefit when using directional antennas, because these protocols have been designed for omnidirectional antennas. To best utilize directional antennas, a suitable MAC protocol must be well designed. The use of RTS/CTS exchanging mechanism is optional in the standard, and is assumed to be used in the following sections. The basic idea of directional MAC (DMAC) protocol is to block only those nodes located within the direction of upcoming data transmission. An intuitive way to achieve this goal is to transmit RTS/CTS packets directionally, which can thus largely reduce the number of blocked nodes. Furthermore, those nodes which received RTS/CTS packets are not blocked in all directions. Through the adoption of directional network allocation vector (DNAV) [6], these nodes can initiate data transmissions in some other directions. In the following, a DMAC protocol based on directional virtual carrier sensing (DVCS) [9] will be introduced.

3.3.1 Neighbor Node Location Identification

In order to steer the antenna beam to an accurate direction in its next hop and send out RTS/CTS packets directionally, the sender needs to know the relative locations of its neighbors. Some related works on DMAC protocol assume that the physical location information may be obtained by using the global positioning system (GPS), ultrasound, or multiple orthogonal channels for control packet transmission. However, these additional resource requirements could make the protocol impractical and unrealistic. For nodes equipped with directional antennas, neighbor node locations can be obtained by direction of arrival estimation techniques. Each node caches estimated DOAs from neighbor nodes when it hears any signal, regardless of whether the signal is sent to the node. In a complex environment where lots of scattering, reflection and diffraction could be induced, the result of DOA estimation may not match the physical relative direction which could be obtained by external devices such as GPS. However, the DOA information based on signal strength evaluation may be much more practical than physical location information. In other words, the DOA is the most effective direction to reach the transmitter with the minimum path loss. The DOA information is updated every time the node receives a new signal from the same neighbor. With DOA information available, RTS/CTS packets can be transmitted in an accurate direction. Therefore, only those nodes located within the direction of upcoming data transmission will be blocked. The DOA caching mechanism is implemented at routing layer and will be introduced in Section 3.4.2.1.

3.3.2 Modification of RTS/CTS Exchanging Mechanism

This DMAC protocol is an enhancement to the IEEE 802.11 MAC protocol. As mentioned before, two modes of antenna operation are available; omni-directional mode and directional mode. A node listens to the channel omni-directionally when idle. In the DMAC scheme, the RTS, CTS, DATA, and ACK packets are sent directionally. Firstly, as in the IEEE 802.11 protocol, the sender sends out an RTS packet prior to data transmission. The RTS packet is sent directionally to the receiver according to the DOA information. When the receiver receives this RTS packet, it not only updates the DOA information, but also adapts its beam pattern to maximize the received power and locks the pattern for the CTS transmission. Once the sender receives the CTS packet, it updates the DOA information and adapts its beam pattern for the data transmission as well. This beam pattern adaptation process provides a more reliable data transmission. During the data transmission, beam patterns are locked toward each other for both transmission and reception, and are unlocked after the completion of ACK packet transmission. These locked patterns maximize the signal power at the receiver as long as the channel condition remains the same. Since the period from CTS through ACK transmission is for only a short period of time, the channel response may be assumed to be stable.

Figure 3.6 shows the steps of beam locking and unlocking. Assume that node A has data to be sent to node B. At the first step, node A transmits an RTS packet directionally toward node B according to the last updated DOA from node B. Although this RTS packet may not be sent in an accurate direction due to node movements, the direction of the upcoming data transmission can be corrected in the following steps. Upon receiving the RTS packet, node B updates its DOA information and locks its beam pattern to this newly derived direction for CTS packet transmission. At the second step, node B sends out a CTS packet toward node A. Node A updates its DOA information and locks its beam pattern to node B as well. At the third step, node A starts to transmit data packet. These locked beam patterns provide reliable data transmission at both sides. Eventually, data transmission is completed with an ACK packet replied from node B directionally.

3.3.3 Directional Network Allocation Vector (DNAV)

The value of network allocation vector indicates the duration of the ongoing transmission in the vicinity, and the node must reserve the channel for those acting nodes by deferring its own transmission. Directional NAV is an enhancement of NAV, which reserves the channel only in a certain range of directions. The design of DNAV is to release the medium which is not necessarily reserved, and thus spatial reuse can be achieved. If a node receives an RTS or a CTS packet from its neighbors, a DNAV is set. Each DNAV is tagged with two important values; the direction where the control packet comes from and the duration of the corresponding data transmission. A node cannot transmit any signals whose direction is in the range of unexpired DNAVs. Another important factor is the width of DNAV, which is based on the beamwidth formed by the directional antennas. The DNAV width of a node must be larger than the beamwidth.

Assume that the width of DNAV is $2w$ degrees and the beamwidth is $2b$ degrees. For a node transmitting safely, it must refer to its DNAV table and the difference between the transmitting direction and all the DNAVs must exceed $(w+b)$ degrees. In other words, the antenna beam intended to a certain direction must not overlap with any unexpired DNAVs. In the following discussing, we set that the width of DNAV is 45°; the range of DNAV$_1$ is from 315° to 45°; the range of DNAV$_2$ is from 45° to 135°; the range of DNAV$_3$ is from 135° to 225°, and the range of DNAV$_4$ is from 225° to 315°. Figure 3.7 shows a simple example where spatial reuse is achieved. Node B has data packets to send to node C, and data transmission is initiated after RTS/CTS exchanging. Node A received RTS and CTS packets from nodes B and C, respectively. Two DNAVs with 45° width, DNAV$_1$ and DNAV$_3$, are set upon the reception of these control packets. The numbers in the parentheses represent the relative angles between node A and these two active nodes. If node A has a packet to be sent to node D or node E, it must refer to its DNAV table to check if there is any transmission ongoing in the corresponding direction. Node A cannot transmit any signal to node E until the expiration of DNAV$_3$ which was set upon the reception of the CTS packet from node C. However, transmission to node D is not deferred by any DNAV, and can be ignited. As mentioned in Section 3.3.1, the DOA is always the most effective direction towards the transmitter with the minimum path loss. This also implies that transmissions towards the DOA of the transmitter could cause the most interference. Therefore, the most effective way to avoid collisions is to set DNAV according to the DOA even the signal DOA does not match where the transmitter is physically located. The width of the DNAV can also be adjusted for the control of aggressiveness of a transmitter. A DNAV with a narrower width makes more directions available for transmission, and thus makes the transmitter more aggressive.

To best exploit the advantages of directional antennas, the routing protocols should be modified as well. The relative direction information of neighbor nodes can be further utilized. In the following section, we introduce the basic concepts of routing protocols in ad hoc networks, and achieve our goal by modifying a well-known routing protocol, the DSDV routing protocol.

3.4 Routing Layer

A wireless ad hoc network is a collection of mobile nodes that are free to move arbitrarily in a certain area where interconnections between nodes could change continuously. Moreover, in a wireless ad hoc network, a node can communicate with every other node in a certain range directly or use other nodes as relays. Due to lack of infrastructure, nodes themselves function as routers which discover and maintain routes to other nodes in the network. Discovering a route is to form a path from a source node to a destination node by selecting nodes in the network as relays. Maintaining a route is to take actions to reconstruct a broken route when one of the relays on the route is no longer available. Without an effective construction of routes, packets cannot be delivered reliably from one node to another, especially under a fast changing topology. The design of efficient routing protocols is the important issue in such dynamic wireless networks.

In order to fully exploit the advantages of directional antennas, we want to find a suitable routing protocol. Therefore, our goal is to establish a routing mechanism which can provide the information for physical and MAC layers. Before proceeding with the discussion of the proposed routing protocol, the classification of current routing protocols will be introduced in the following section.

3.4.1 Classification of Current Routing Protocols

There have been several routing protocols proposed for wireless ad hoc networks [21]-[32]. Depending on when the route is computed, these routing protocols may be categorized as: table-driven routing and on-demand routing protocols [33]. Table-driven routing protocols are also called proactive routing or pre-computed routing protocols. As implied by the name, table-driven routing protocols attempt to maintain a table which consists of up-to-date routing information from each node to every other node in the network. In order to maintain a consistent network view, updates of routing information are propagated throughout the network periodically or whenever the link state of the network changes. The advantage of table-driven routing protocols is that a route to the destination is already available when a source wants to send packets to a certain node in the network. However, the propagation of routing information could result in flooding of update packets, which consumes a lot of the wireless network bandwidth. Destination sequence distance vector (DSDV) [21], clusterhead gateway switching routing

(CGSR) [22], wireless routing protocol (WRP) [23], global state routing (GSR) [24], and fisheye state routing (FSR) [25] are examples of table-driven routing.

On-demand routing protocols is also called reactive routing protocols. In this method, routes are created only when they are needed. In other words, the route may not exist in advance and it is computed just before the packet is sent. When a source needs a route to send packets to a destination, it initiates a route discovery process within the network. This process is completed once a route is found, and the route will be maintained by a route maintenance procedure which includes the detecting and rebuilding of a broken route. The major advantage of on-demand routing protocols is that the precious bandwidth of wireless ad hoc networks is greatly saved. The bandwidth consumption due to the exchange of routing information is limited because only those routes that are needed will be maintained. However, the source node must wait until such a route can be discovered. Dynamic source routing (DSR) [26], ad hoc on-demand distance vector (AODV) [27], temporally ordered routing algorithm (TORA) [28], dynamic source tracing (DST) [29], associativity based routing (ABR) [30], and signal stability-based adaptive (SSA) [31] are examples of on-demand routing. Furthermore, hybrid methods make use of both to come up with a more efficient one which minimizes the overhead incurred during route discovery and maintenance. Zone routing protocol (ZRP) [32] is an example of hybrid methods.

3.4.2 Modification of DSDV Routing Protocol

In order to establish a routing mechanism which provides information for physical and MAC layers, routing protocols must be redesigned for this purpose. The DSDV routing protocol is a well-designed routing protocol with completed routing functionality. To provide provides information for physical and MAC layers, we propose some modifications to this routing protocol. The DSDV routing protocol described in [21] is a table-driven routing algorithm. In distance vector routing algorithms, every node maintains for each destination a set of distance vectors, each of which includes destination ID, next hop, distance, and so on. In order to keep the distance estimates up-to-date, each node exchanges distance vectors with its neighbors periodically. When a node receives distance vectors from its neighbors, it updates its distance vectors and the shortest distance to every other node is computed. By combining the next hop of nodes on the path from the source to the destination, a route with the shortest distance is completed in a distributed manner. The distance vector algorithm described above is the classical distributed Bellman-Ford (DBF) algorithm [34]. A significant problem with the DBF algorithm is slow convergence. A node could take a very long time to build a path to a certain destination, especially after significant changes under the network topology. Another major performance problem with DBF algorithm is that the algorithm could cause routing loops. The primary cause of the routing loops is that nodes choose their next hops in a completely distributed fashion based on information which can possibly be stale, and therefore incorrect. One approach to the routing loop problem is to tag each routing table entry with a sequence number so that nodes can quickly distinguish stale routes from the new ones and thus avoid formation of routing loops.

In the DSDV routing protocol, each node must maintain a routing table containing the next hop information for all of the possible destinations within the network. Each entry of the routing table is tagged with a sequence number assigned by the destination. As mentioned before, the sequence numbers enable the mobile nodes to distinguish stale routes from new ones, which can avoid the formation of routing loops. Update packets of routing table are periodically transmitted throughout the network to maintain table consistency. An entry with a newer sequence number is always preferred. As for those entries with the same sequence number, the one with a smaller hop count is chosen as the next hop. In other words, DSDV selects the shortest path based on the number of hops to the destination. Routing functionality is completed by exchanging routing table information throughout the network. To alleviate the potentially large amount of bandwidth required by update packets, two types of route update are defined. The first is known as a full dump which carries all the available routing information. The other one is called an incremental. An incremental routing update carries information which has changed since the last full dump. The full dump routing update can be transmitted relatively infrequently when mobile nodes move slowly. Routing information exchanging can be completed by merely incremental routing updates. When movement becomes frequent, and the size of an incremental routing update increases, a full dump can be scheduled. After a full dump broadcast, the size of the following incremental routing update will be smaller. By employing these two types of update packets, the network traffic can be largely reduced.

Detailed description of the proposed modification to the DSDV routing protocol is introduced in the following sections. The DOA information from the physical layer is utilized here to determine the neighbor distribution in each direction. A neighborhood table records the relative directions to each reachable neighbor of a node, and the omnidirectional received power P_{ro} and thus the M-null directional antennas with DMAC protocol as well as power control strategy can be implemented.

3.4.2.1 Route Discovery

As in the DSDV routing protocol, the proposed modification requires each mobile node to maintain a routing table which lists all the possible destinations within the network. As shown in Table. 3.1, each entry is tagged with some important routing information such as a sequence number, the metric and the next hop to each destination, and the install time of each entry. The sequence number, as mentioned before, provides a judgment on the freshness of a route. Every time a destination node advertises its routing table, the corresponding sequence number is increased. Upon receiving the routing information, a route with a more recent sequence number is always preferred. For those candidates with the same sequence number, a route with the smallest metric is selected, and the corresponding node is chosen as the next hop. In a multi-hop environment, the next hop succeeds the data packets and relays forward the destination. The metric represents the hop count of each route all the way to the destination. The install time field indicates when the entry is installed in the routing table. Examining the install time of each route helps to determine when to delete stale routes. In fact, not all of the information in the routing table is exchanged through the network. As shown in Table. 3.2, update packets contains only information about reachable destinations and the corresponding metrics and sequence numbers.

In addition to the routing table, we add a neighborhood table is maintained in each mobile node in DSDV routing protocol. As shown in Table. 3.3, a neighborhood table lists all the reachable neighbors, the corresponding directional angles, and the omnidirectional received power P_{ro}. Each entry in the neighborhood table is also tagged with the install time as in routing tables. Every time a node hears a signal from one of its adjacent nodes, the DOA and the power receiving of this signal are estimated at the physical layer. Since the signal can be received by this node, the sender of the signal represents a reachable neighbor of this node. If this neighbor is never heard before, it is added into the neighborhood table along with the DOA. If this neighbor is already recorded in the neighborhood table, the DOA is updated. Therefore, a node can be aware of all its reachable neighbors and the corresponding direction to each. The use of the omnidirectional received power parameter P_{ro} is to calculate the power control factor β. We will discuss the cross-layer power control exhaustively in Chapter 4.

The neighborhood table not only helps to guides the antenna beam to the right direction, but also provides neighbor angles to form M beamforming nulls in physical layer. Recall that at the MAC layer, a DRTS packet requires a DOA caching mechanism to be sent directionally toward an intended node. That is, when relaying a data packet, a node must check its routing table for the next hop. After making sure that it has a route to the destination, a DRTS packet is sent directionally toward the next hop according to the DOA information recorded in the neighborhood table. While forming the directional mode, the antennas can also form M beamforming nulls to suppress the neighbor interference as described in Section 3.2.3.

3.4.2.2 Route Maintenance

The mobility of nodes and some other reasons may cause broken links. The broken link may be detected by the MAC layer protocol, or it may also be inferred if no broadcasts have been received for a while from a former neighbor. Since a broken link could result in serious transmission error, a broadcast routing update containing this information should be arranged immediately. In the routing table, a broken link is described by a metric of ∞. Once a node detects a broken link, i.e. an unreachable next hop, it immediately assigns an ∞ metric to any route through that next hop and generates an updated sequence number. This is the only situation when the sequence number is generated by any mobile node other than the destination node. Sequence numbers defined by the originating mobile nodes are generated as even numbers, and sequence numbers generated to indicate ∞ metrics are odd numbers. Upon receiving the notification of a broken link, a node updates its routing table and continues to advertise the broken link. When a node receives an ∞ metric, and it has a later sequence number with a finite metric, it triggers a route update broadcast to disseminate the important news about that destination.

In summary, the amount of overhead required for the proposed routing strategy is the extra memory for neighborhood table which includes neighbor DOAs and omnidirectional received power P_{ro}. Consequently, all the physical, MAC, and routing functionality can benefit from the establishment of neighborhood table. Furthermore, the directional antenna adopted at the physical layer has no effect on the amount of overhead. In other words, a smaller sector size or beamwidth of the directional antennas does not result in more overhead.

3.5 Operation of the Cross-Layer *M*-Null Directional antennas System

In Sections 3.2, 3.3, and 3.4, we have introduced the *M*-null directional antennas model, DMAC, and DSDV in physical, MAC, and routing layers, respectively. Now, we present our directional antennas system operating across these layers. Figure 3.8 shows the flowchart of the procedure of forming *M*-null directional antennas. Before transmission, the first step is that every node broadcasts its routing table. When a node receives the other node's broadcast signals, the DOAs of neighbor nodes are estimated at the physical layer, and the neighborhood table is updated as mentioned before. When a node has a packet to transmit, the second step is to form *M*-null directional antennas upon MCMV beamforming to transmit DRTS directionally. From neighborhood table, the direction of destination and the directions of the other neighbor node which are set to form beamforming nulls are obtained. A node randomly sets *M* beamforming nulls at first. If interference comes from other direction, directional antennas memorize its direction, and a beamforming null is directed to it by replacing a stale beamforming null. While the transmission is in progress, the node can resist new interference by replacing the stale beamforming nulls set in the initial stage.

Figure 3.9 is an example of a transmission which uses the 4-null directional antennas to resolve the hidden terminal and blocking problem mentioned in Section 2.2.2. Assume that in this figure, a node equipped with five antennas can form one main beam, three side lobes, and four beamforming nulls. If node A intends to send data to node B, it first sends a DRTS packet to node B. According to the neighborhood table, node A forms a main beam toward node B, and four beamforming nulls randomly toward nodes C, D, E, and F. After receiving DCTS, node B forms a main beam toward node A, and four beamforming nulls randomly toward node C, D, E, and F. During the transmission, node A will not be interfered by nodes C, D, E, and F, so the hidden terminal problems, discussed in Section 2.2.2, will not occur. In addition, nodes C, D, E, and F will be not blocked by node A, because they do not sense the gain of the side lobes of node A. In this scenario, we use the 4-null directional antennas model to address the hidden terminal and blocking problems and fully utilize the potential of spatial reuse.

Assume that node A does not form a beamforming null to node G, as Figure 3.9 shown. When node A sends DRTS directionally to node B with gain of G_d, it also sends DRTS using side lobes to node G with side lobe gain of $1/10G_d$. In this case, node G cannot sense the DRTS, since node G listens omnidirectionally with gain of G_o in idle state. If node G has packets to send to node C, node G sends DRTS to node C with gain of G_d, then the DRTS interferes with node A, because node A does not form a beamforming null in the direction of node G in the initial stage. Then, node A memorizes the direction of node G, and change the direction of a beamforming null to direct it to node G. Through using the 4-null directional antennas, the two transmission pairs (A⟷B, G⟷C) can survive at the same time. Although node A is interfered by node G at first, it can also avoid the interference by rearranging beamforming nulls.

3.6 Computer Simulation

To evaluate the performance of the proposed system architecture, we use the NCTUns 1.0 network simulator [35]. As NCTUns does not support network environment with directional antennas, we implement the directional antennas model based on the system architecture described in the previous sections. In addition to the 802.11b scheme, we simulate two directional antennas models, the *M*-null directional antennas model and the basic directional antennas model.

In the proposed model, we use five antennas to build the 4-null directional antennas model, which has one main beam and four beamforming nulls in our simulation. To simulate the MCMV beamforming beam pattern, as Figure 3.3 shows, the gain of the main beam is simulated by the quartic function $\mathrm{M}(x)$: $4\cdot(9.7\cdot10^{-7}x^4 + 3.1\cdot10^{-8}x^3 - 0.0019x^2 - 5.4\cdot10^{-6}x + 1)$, where x is an angle error between the pointing direction of transmitter and the real direction of the receiver. We assume that the DOA estimation is perfect in our simulation, so the receiver can get the maximal antenna gain of 4 ($\mathrm{M}(0) = 4$). The gain pattern of the beamforming null is simulated by the quadratic function $\mathrm{N}(x)$: $-0.0008x^2 + 0.0018x + 10^{-6}$. In this function, the gain is 10^{-6} when the angle error is zero and the gain is 0.1 when the angle error is 10°. Note that the beamforming nulls cannot be located within the desired angle range, or the main beam will deviate from the desired angle. In the second model, the basic directional antennas model, the main beam is also simulated by the quartic function $\mathrm{M}(x)$: $4\cdot(9.7\cdot10^{-7}x^4 + 3.1\cdot10^{-8}x^3 - 0.0019x^2 - 5.4\cdot10^{-6}x + 1)$ for the range $[-20^\circ, 20^\circ]$ and has a constant gain 0.1 for all other directions, representing side lobes of the pattern.

The packet length is constant and equal to 1017 bytes. The approximate omni-transmission range is 250 meters. We use the two-ray ground propagation model as the path loss model. The channel model uses the Raileigh fading distribution whose variance is 10 dB. Each simulation run is conducted for 100 seconds, and each data point is obtained by the average of five simulation runs. The following sections present some simulation results that show how the capacity of wireless ad hoc networks depends on these parameters.

3.6.1 Nulling Operation Under 4-Node Topology

In the first part of this section, the 4-node inverted T topology in Figure 3.10 represents the simulation result which discusses the hidden terminal problem. Figure 3.11 shows the throughput performance as a function of the data generation rate under the network topology indicated in Figure 3.10. The dash lines represent only one transmission pair (A⟷B) in the network. In one transmission pair, the 4-null and the basic directional antennas achieve the same throughput due to the same transmission gain of G_d, and they achieve better throughput than the IEEE 802.11 scheme because the greater directional gain has the better packet delivery. The solid lines represent two transmission pairs (A⟷B, C⟷D). In the two transmission pairs, the basic directional antennas and IEEE 802.11 modes induce low throughput compared with 4-null directional antennas mode due to the blocking problem. However, the throughput of two transmission pairs performed by the basic directional antennas is lower than one transmission pair. The reason of that is not only the existence of the blocking problem but also the hidden terminal problem. The 4-null directional antennas mode achieves double throughput in two transmission pairs, because it can achieve spatial reuse and eliminate interference to avoid collisions. Figure 3.11(b) shows the average packet delivery ratio as a function of the data generation rate. The packet delivery ratio is defined as the number of DATA packets received successfully by the destination divided by the number of DATA packets generated by the source nodes. The packet delivery ratio indicates how many DATA packets the data source can deliver to the destination over multiple hops without packet drops due to queue overflow or transmission failure. In Figure 3.11(b), the 4-null directional antennas mode achieves the best packet delivery ratio, and the basic directional antennas performs worse due to collisions, and the IEEE 802.11 scheme obtains the lowest packet delivery ratio due to a low transmission gain.

Figure 3.12 shows a rhombus topology where there are two transmission pairs (A⟷B, C⟷D), and Figure 3.13 indicates the simulation results under this topology. Since the four nodes are so close that nodes C and D can be aware of DRTS/DCTS from the side lobe of node A/B, nodes C and D are blocked. We can also see that the throughput just increases a little over one transmission pair in the basic directional antennas and IEEE 802.11 modes. The 4-null directional antennas mode always achieves double throughput of about 7.6 Mbps compared with one transmission pair in the high data generation rate, which is the same as the simulation shown in Figure 3.11. Figure 3.13(b) is the average packet delivery ratio, which proves that the low throughput of the basic directional antennas is caused by the blocking problem, not hidden terminal problems, and therefore the basic directional antennas performs the same packet delivery ratio as the 4-null directional antennas.

3.6.2 Nulling Operation Under Random Topology

In this section, we simulate a network consisting of 25 static nodes randomly distributed in a 1000 meters × 1000 meters square area. We have simulated a total of five random scenarios and the results presented in Figure 3.14 are the average of their individual results. Figure 3.14(a) shows the throughput performance as a function of the traffic load. The traffic load is defined as the percentage of communicating nodes in the network. From Figure 3.14(a), the throughput of the network operating in the omni-mode goes to zero as the traffic load increases, which implies that the network behaves like a congested network. While in the case of directional mode, the throughput performance is greatly improved under heavy traffic loading, since directional antennas modes can achieve high spatial reuse. In addition, the throughput of the 4-null directional antennas mode achieves a higher throughput of 4.7 Mbps than the basic directional antennas mode, because the 4-null directional antennas model resolves the hidden terminal and blocking problems.

Another important factor, the packet delivery ratio, is also improved in the 4-null directional antennas mode in Figure 3.14(b). The packet delivery ratio decreases as the traffic load increases. The 4-null directional antennas mode has the highest packet delivery ratio, and again nulling interference improves the performance greatly. Figure 3.14(c) shows the average delay of the network as a function of the traffic load. It is observed that the average delay increases as the traffic load increases. Similarly, the 4-null directional mode achieves the best performance.

3.6.3 Effect of Number of Beamforming Nulls

In this section, we study the dependence of the network performance on different numbers of beamforming nulls. The network consists of 25 mobile nodes randomly distributed in a 1000 meters × 1000 meters square area. Figure 3.15 shows the throughput performance versus traffic load. We consider five different numbers of beamforming nulls in this simulation, which are zero, two, four, six, and eight. The larger number of beamforming nulls allows nulling more neighbor interference, and thus the network throughput is increased. Nevertheless, the increase of throughput saturates as the number of beamforming nulls increases, which implies that the effect of the increasing beamforming nulls is less and less as the number of beamforming nulls is large. This suggests that we can choose the most appropriate number of beamforming nulls according to the tradeoff between the throughput performance and the antenna cost.

3.6.4 Effect of Beamforming Null Angle Error

In this section, we discuss the effect of nulling angle error on the throughput performance. The angle error is defined by the difference between the estimated DOA and the real direction of the receiver. We use the topology shown in Figure 3.12. There are two transmission pairs and the transmission distances are both 100 meters. Figure 3.16 shows the total throughput of two transmission pairs (A⟷B, C⟷D) versus the nulling angle error. The transmission maintains a high throughput performance of about 7.6 Mbps within an angle error of 2.2°, because the two transmission pairs do not block each other. However, as the angle error exceeds 2.2°, the throughput decreases drastically but the throughput is still superior to the basic directional antennas mode within the angle error of 3°. Because there exists an acceptable power threshold, CSThreshold (Carrier Sense Threshold), at the physical layer, the throughput looks like a cliff from 2.2° to 3°. When the angle error exceeds 3°, the benefit of the beamforming null is lost, and the 4-null directional antennas mode performs like the basic directional antennas. From this simulation result, it is clear that if we want the *M*-null directional antennas model to offer better performance, a more accurate neighbor node location identification technique is needed, such as GPS.

3.7 Summary

From the previous chapter, we know that the throughput reduction results from the medium reservation policy in MAC protocol, and the new types of hidden terminal and blocking problems due to improper DMAC protocols. In this chapter, we propose an integrated refinement of physical, MAC and routing protocols with the use of directional antennas. A node equipped with directional antennas has the ability to estimate the DOA of an incoming signal and thus can identify the relative directions of its neighbors. Before transmitting data packets, nodes exchange RTS/CTS packets directionally, and therefore, only those nodes located within the direction of transmission are blocked. Moreover, if a node receives an RTS or a CTS packet from its neighbors, a DNAV is set according to the DOA of that control packet, and the duration as well. With the help of DNAV, a node is blocked only for those directions where RTS/CTS packets come from, and spatial reuse can thus be achieved. Furthermore, to fully address the problems of DMAC protocols, we propose an M-null directional antennas model operating across three layers to form M beamforming nulls to eliminate neighbor interference. The DOA information helps a node to form beamforming null in the M interference directions. Therefore, the M-null directional antennas model can address the problems in existing DMAC protocols and improves the throughput performance significantly.

In Section 3.6, we present some computer simulation results to verify the improvements of the proposed 4-null directional antennas over the omnidirectional and the the basic directional antennas approach. From the simulation results of Figures 3.11 and 3.13, the 4-null directional antennas mode achieves outstanding performance over the basic directional antennas and the IEEE 802.11 omnidirectional antenna. We also discuss the effect of the number of beamforming nulls; this suggests choosing the most appropriate number of beamforming nulls according to the throughput performance and antenna cost. The result in the simulation of the effect of the nulling angle error shows that the M-null directional antennas mode performs excellent performance within the beamforming null angle error of 3°.

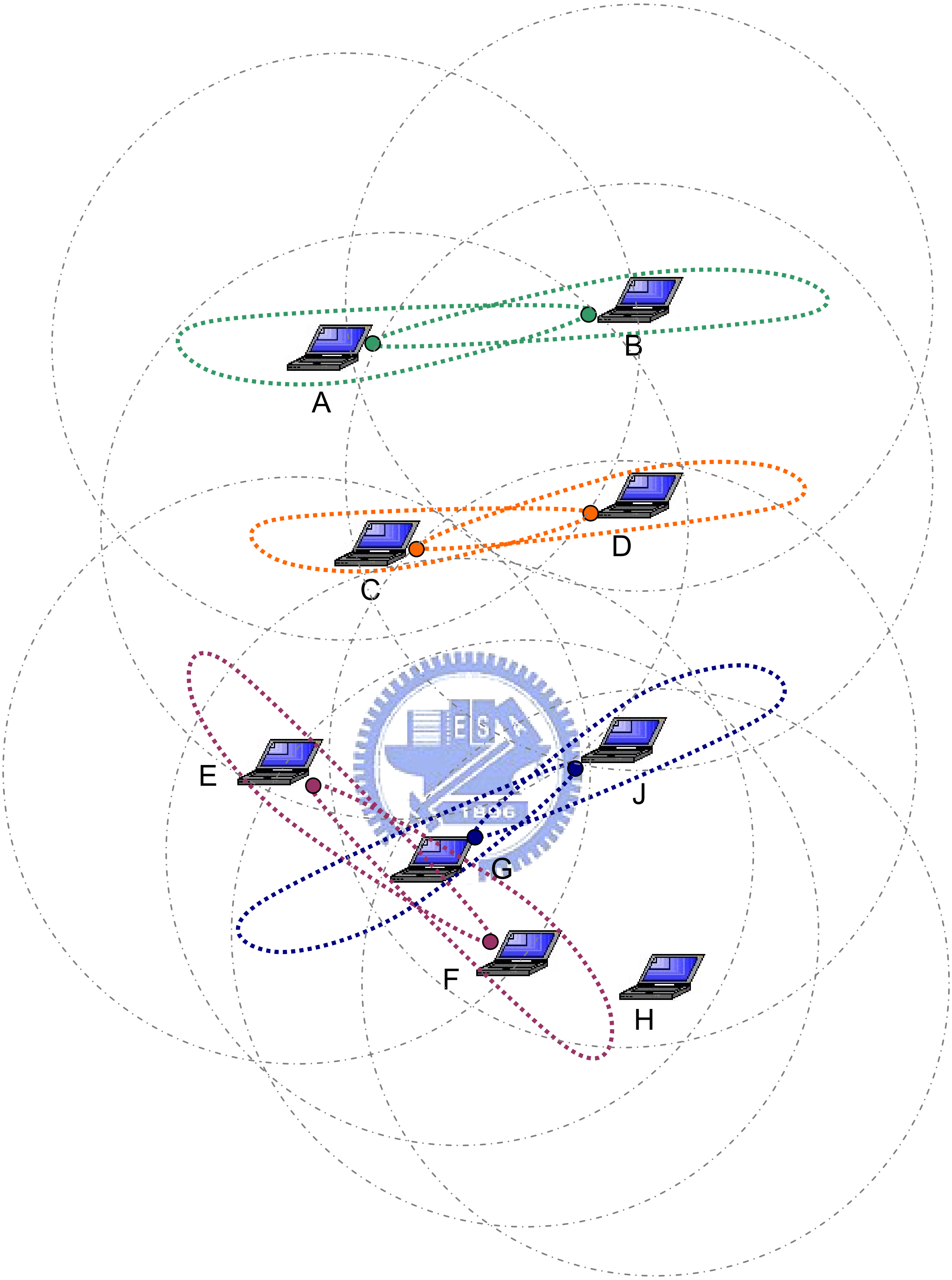


Figure 3.1: Network capacity is improved via directional antennas. Four sessions is allowed to be held simultaneously without interfering with each other. While in the case of omni-directional communication, most nodes are blocked.

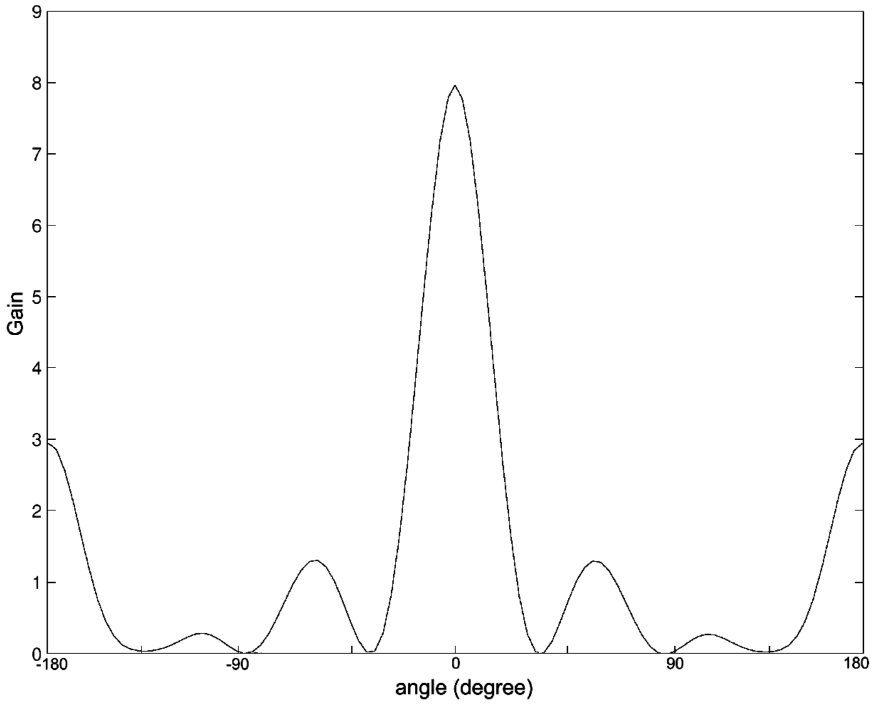


Figure 3.2: Antenna gain pattern of an 8-element circular array.

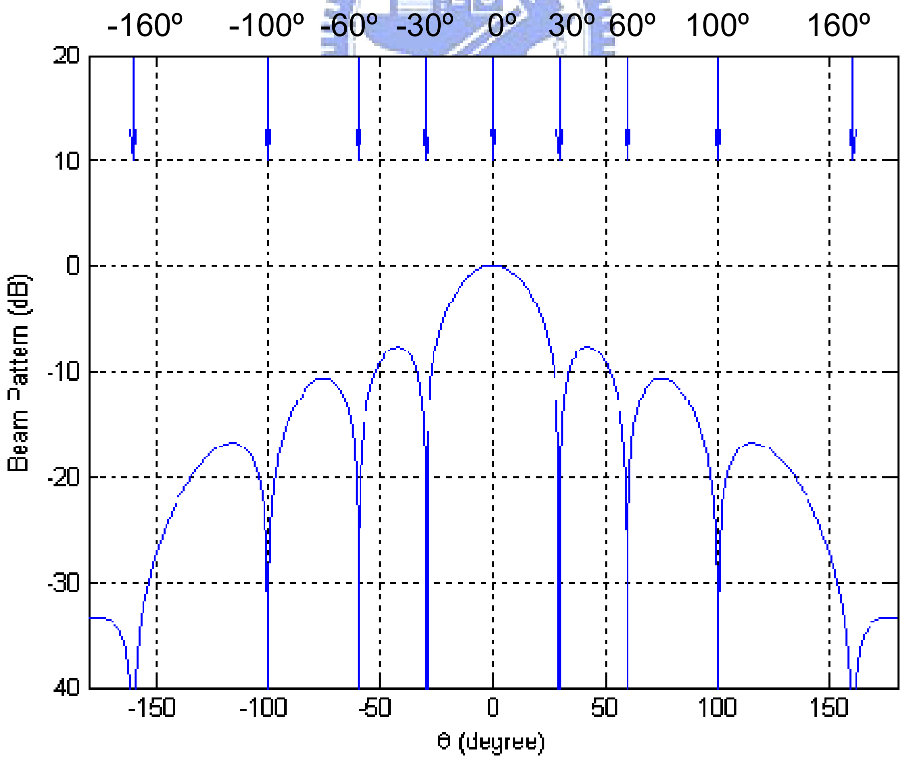


Figure 3.3 : The antenna gain pattern (dB) of an 9-elements MCMV beamforming can form one main beam towards 0° and eight beamforming nulls in ±30°, ±60°, ±100°, ±160°.

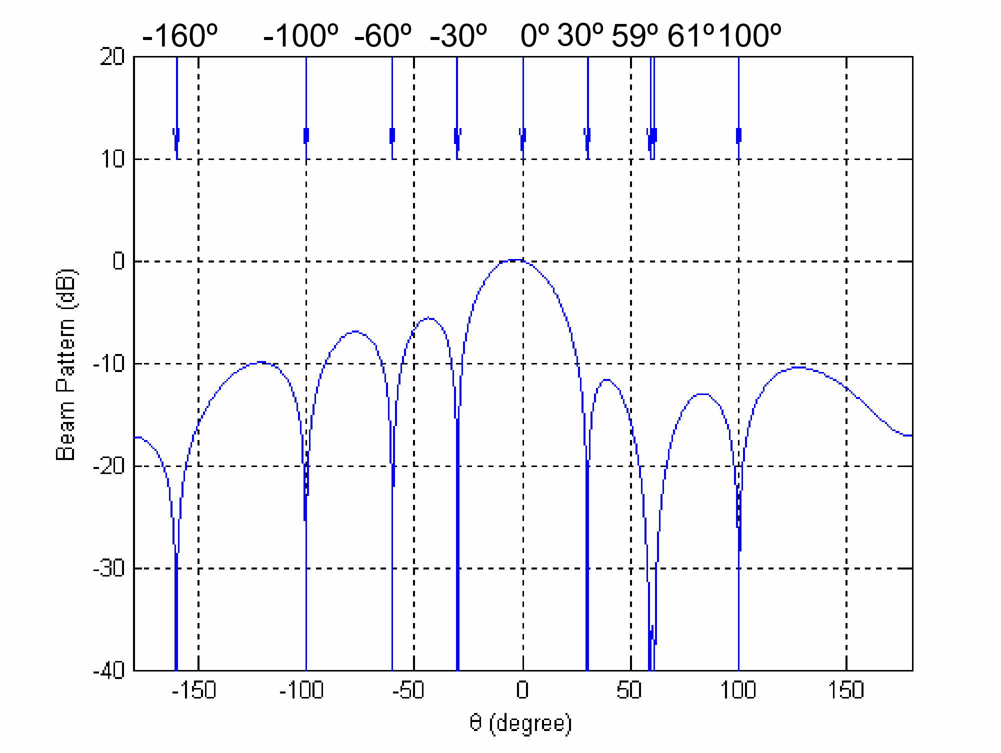


Figure 3.4 : The antenna gain pattern (dB) of an 9-element MCMV beamforming can form one main beam towards 0° and eight beamforming nulls in ±30°, −60°, 59°, 61°, ±100°, −160°.

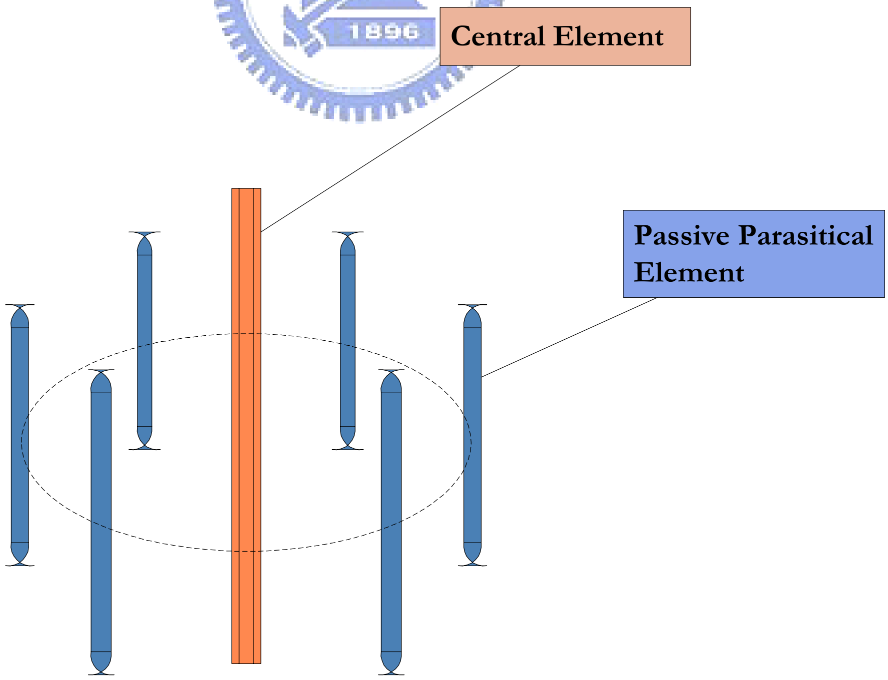


Figure 3.5: A 7-element electronically steerable passive array radiator antenna. The central element is connected to the main RF radiator. Each passive parasitical element is loaded with a variable reactor.

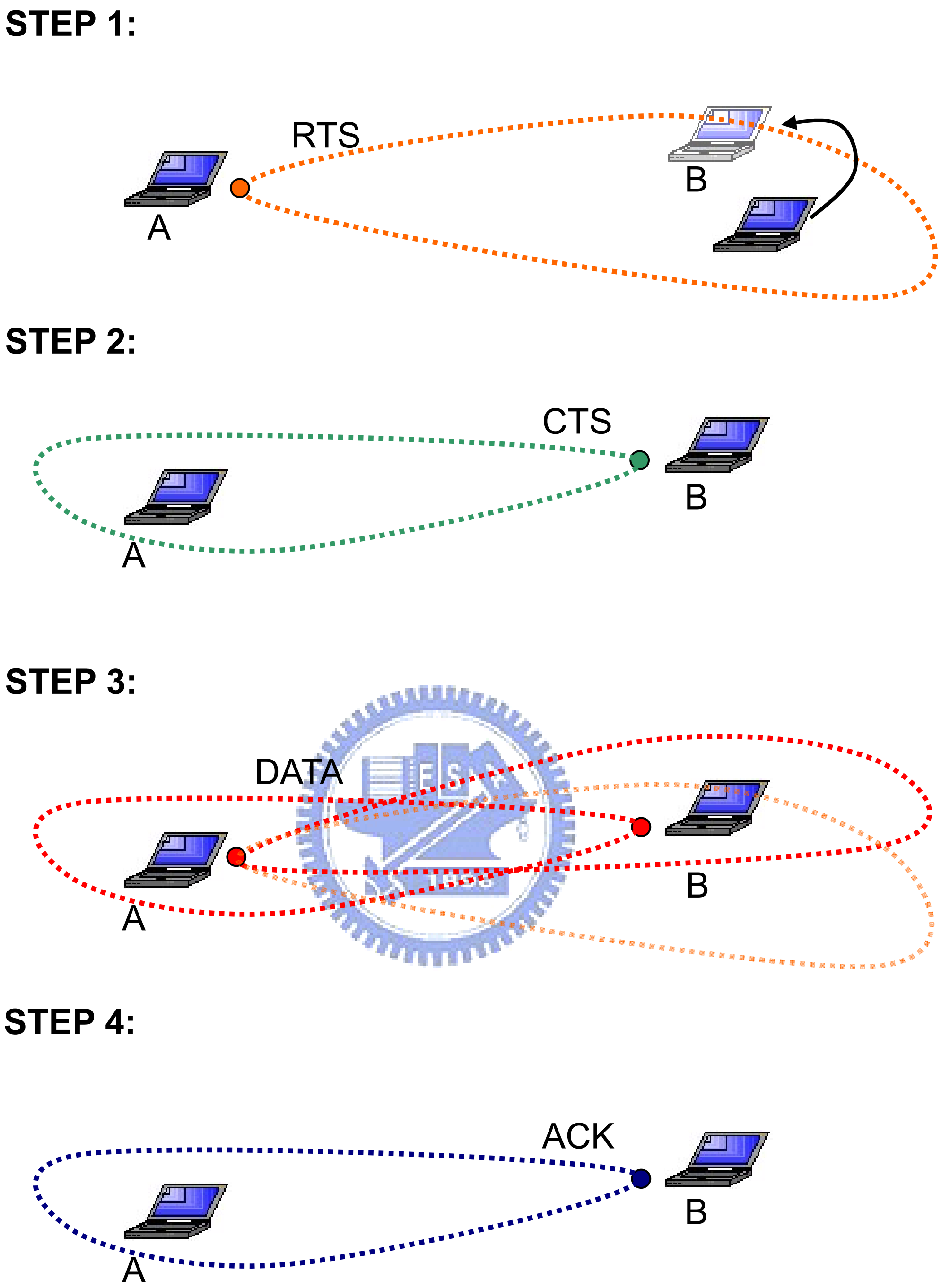


Figure 3.6: A modified RTS/CTS exchanging mechanism using directional antennas. The updates of DOA information are achieved by RTS/CTS exchanging. With the latest DOA information, transmission of data packet can be much more reliable.

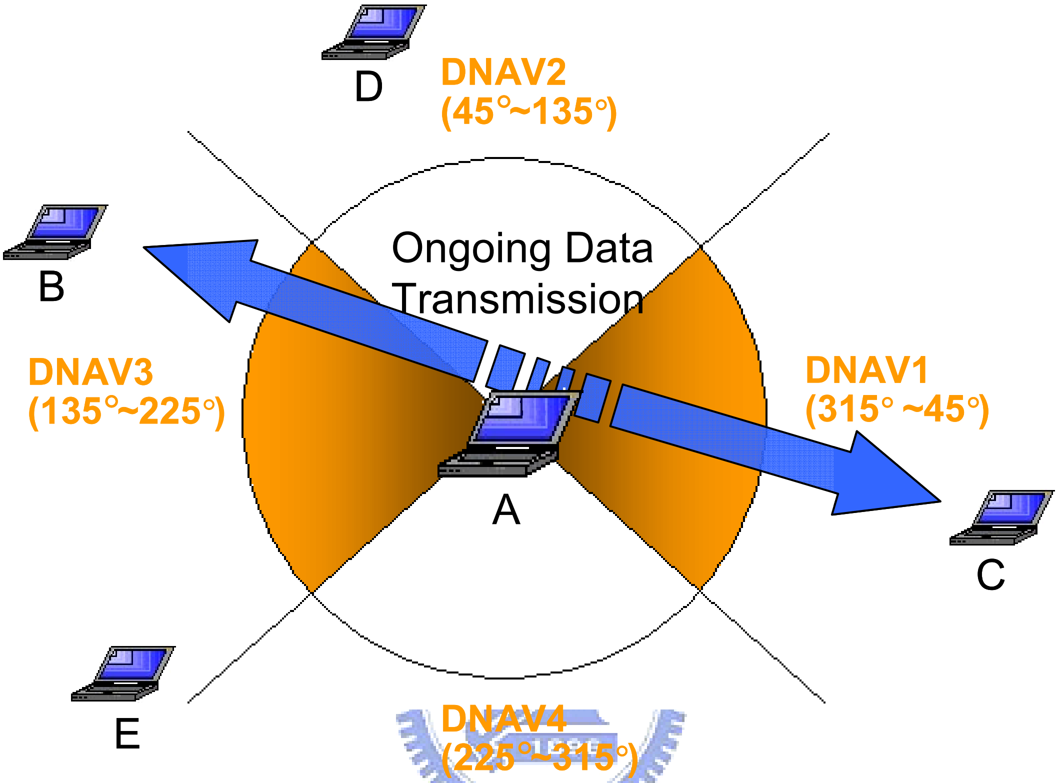


Figure 3.7: Spatial reuse can be achieved by the adoption of DNAV. Two DNAVs, $DNAV_1$ and $DNAV_3$, reserve the wireless medium for nodes B and C. The blank area represents available directions for node A's transmission.

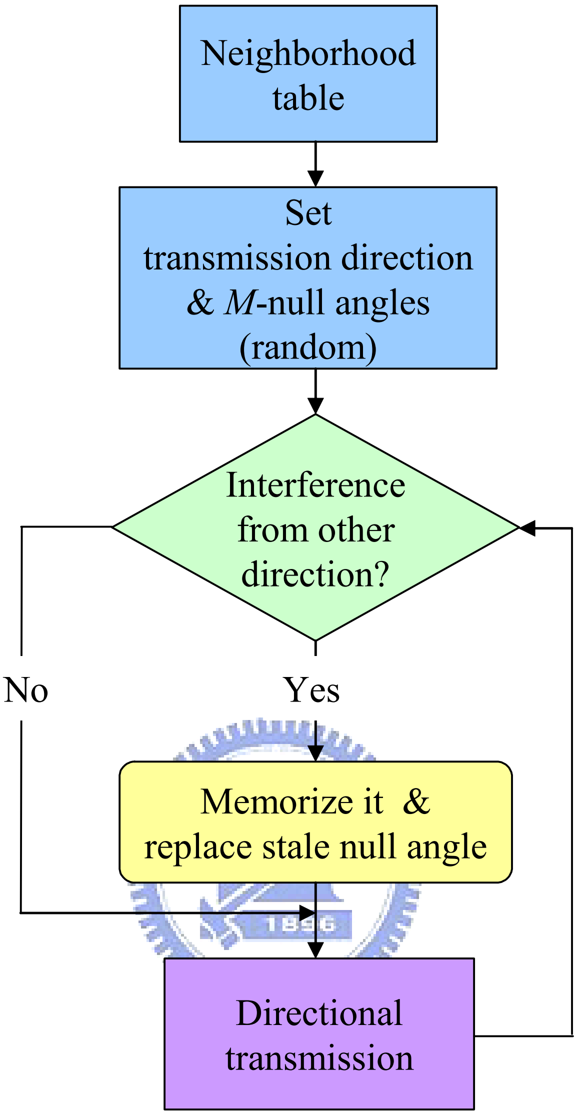


Figure 3.8: Flowchart of operation of the cross-layer *M*-null directional antennas system

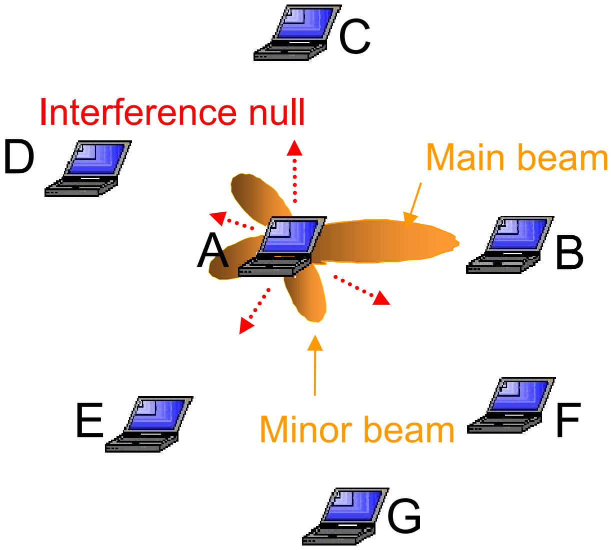


Figure 3.9: An example of transmission using the 4-null directional antennas. Node A equipped with the 4-null directional antennas has packets to transmit to node B. Node A forms a main beam towards B, and four null angles towards nodes C, D, E, and F.

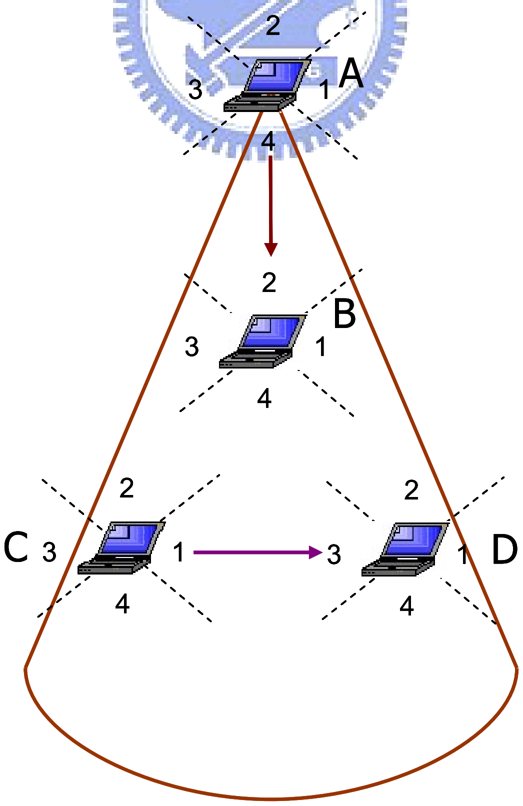
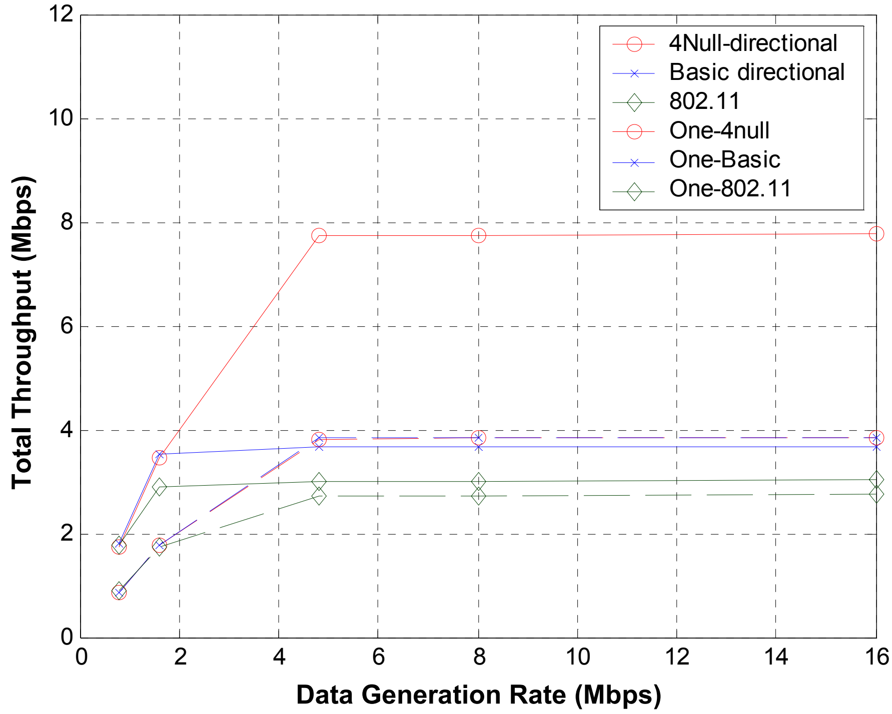
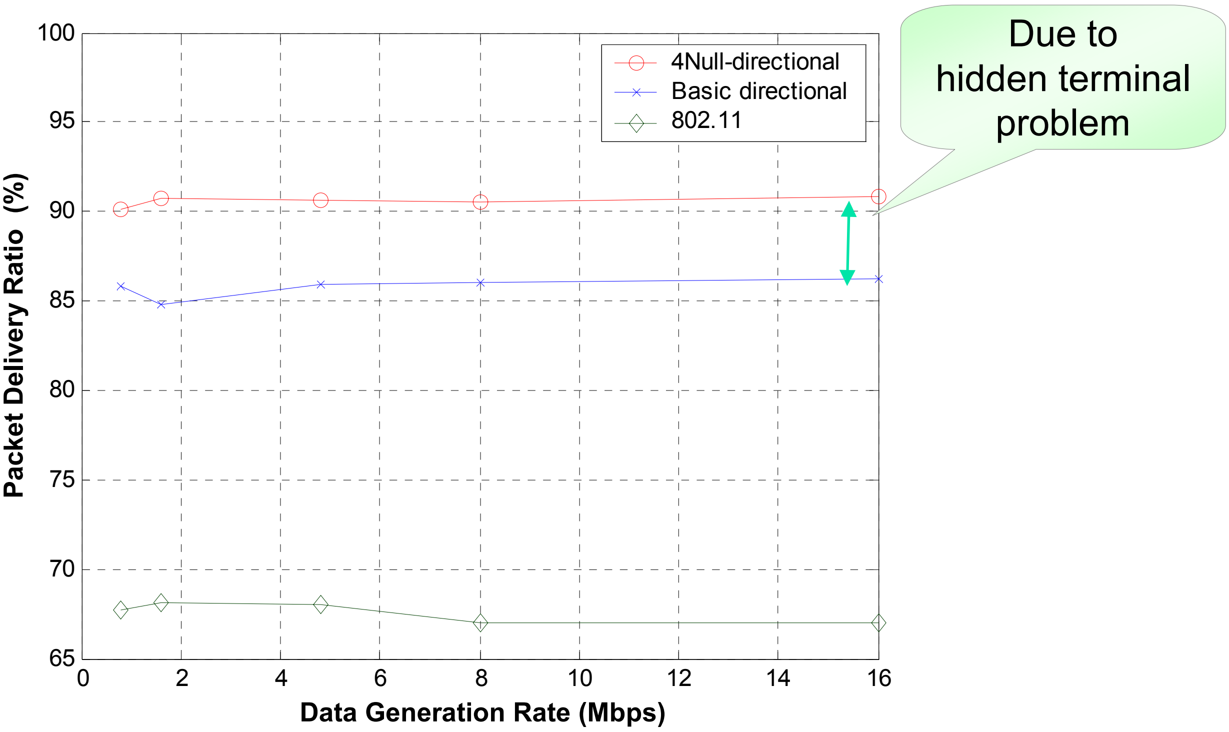


Figure 3.10: The 4-node inverted T topology



(a)



(b)

Figure 3.11: Nulling operation under the 4-Node inverted T topology: (a) Throughput performance versus data generation rate (b) Packet

delivery ratio versus data generation rate

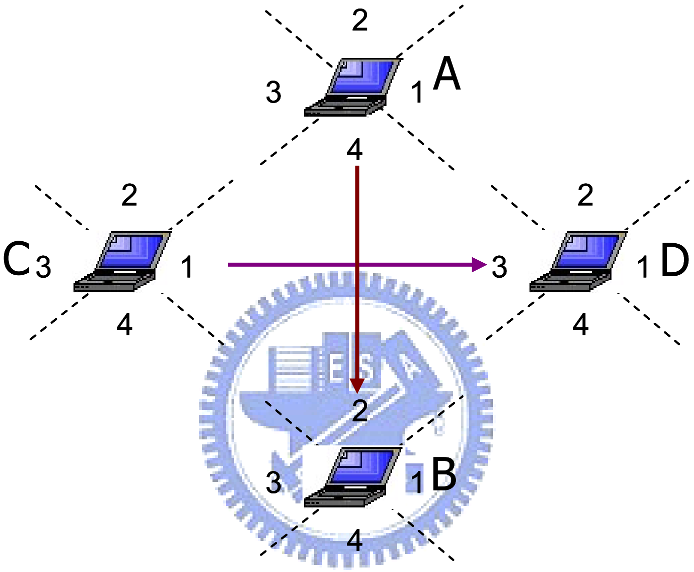
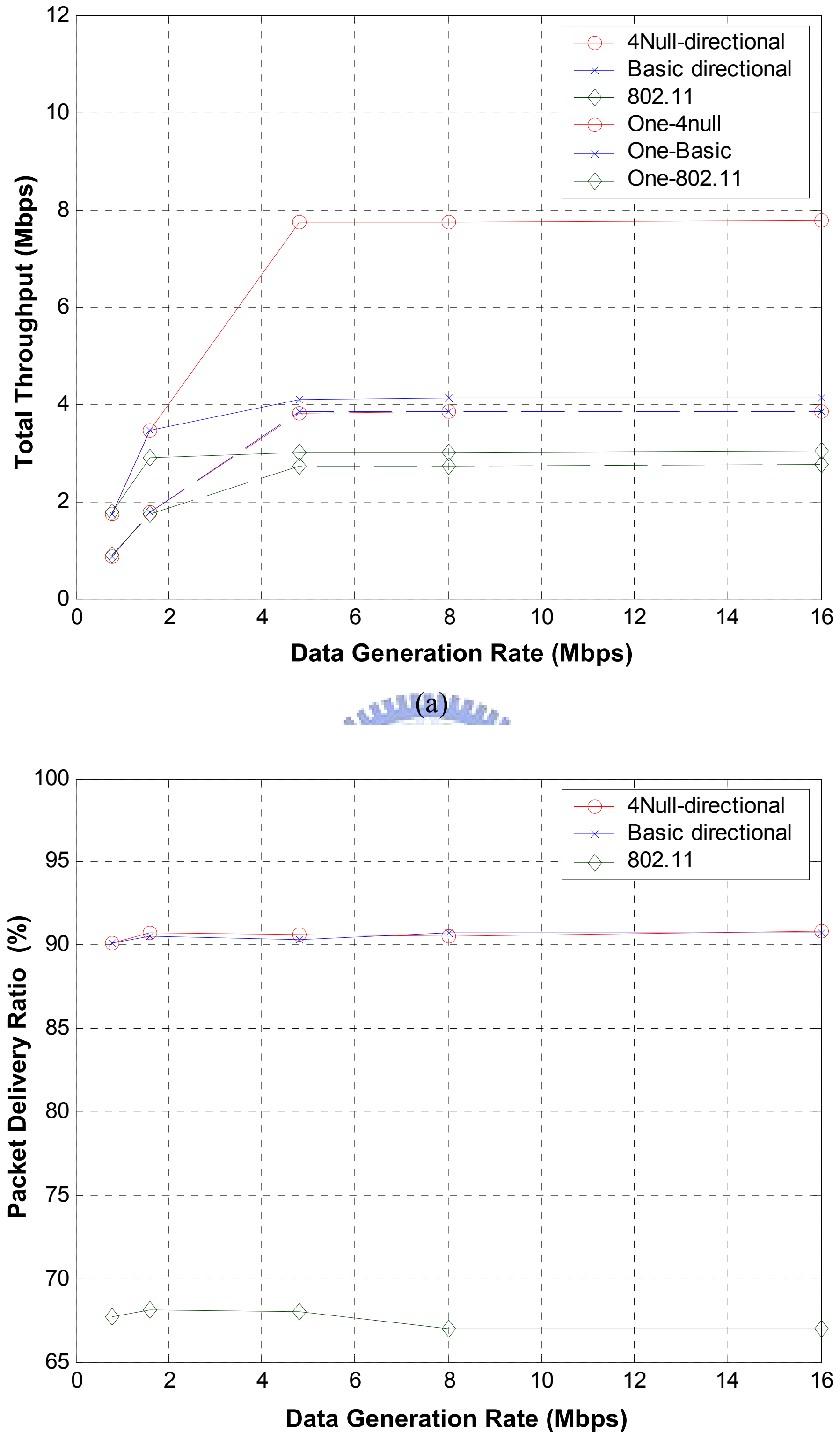


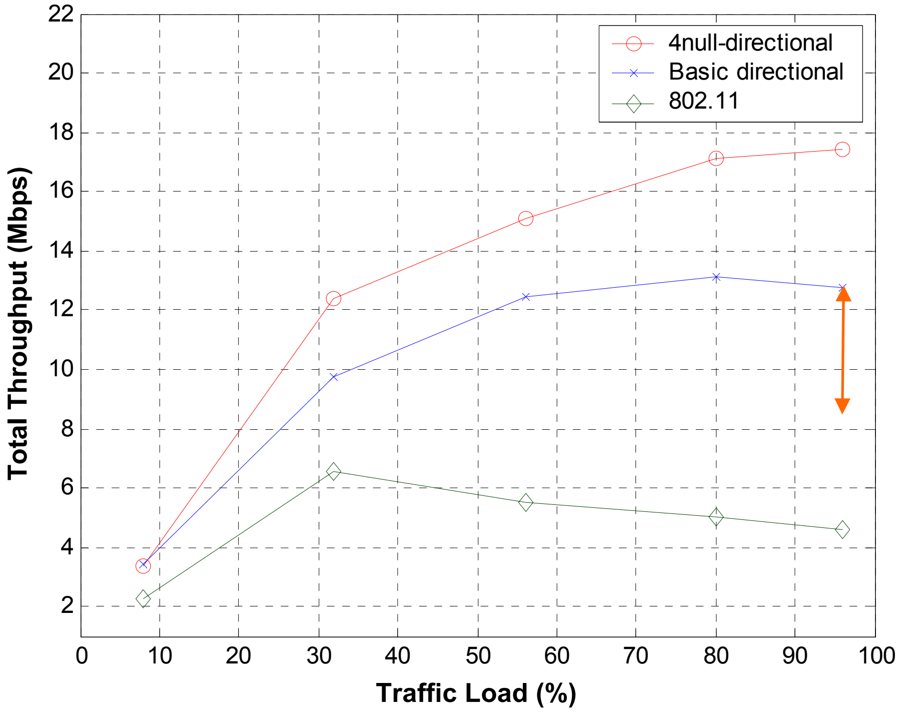
Figure 3.12: The 4-node rhombus topology



(a)

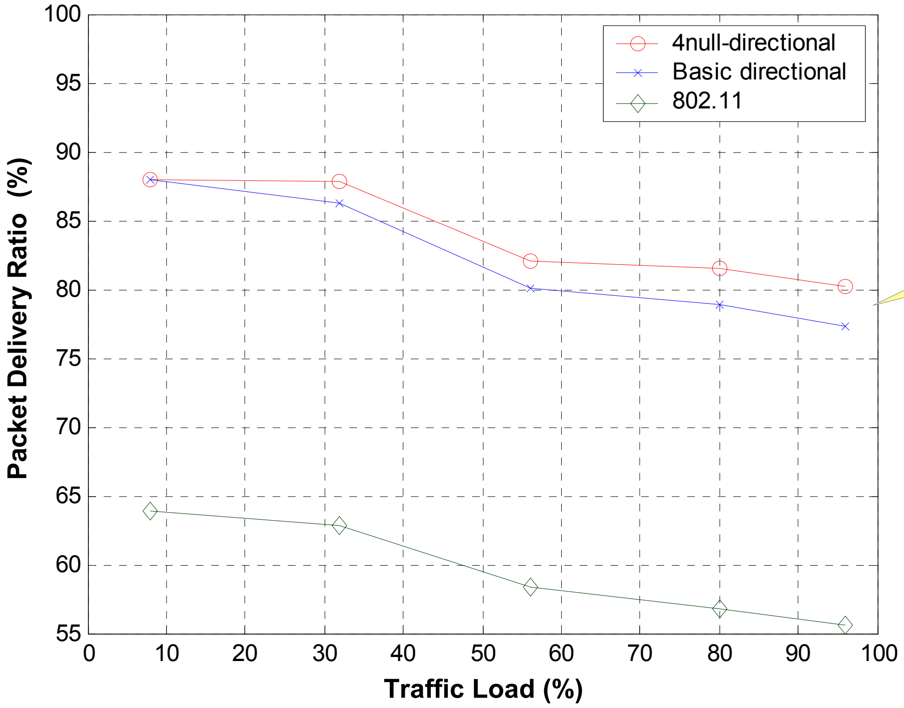
(b)

Figure 3.13: Nulling operation under the 4-Node rhombus topology: (a) Throughput performance versus data generation rate (b) Packet delivery ratio versus data generation rate



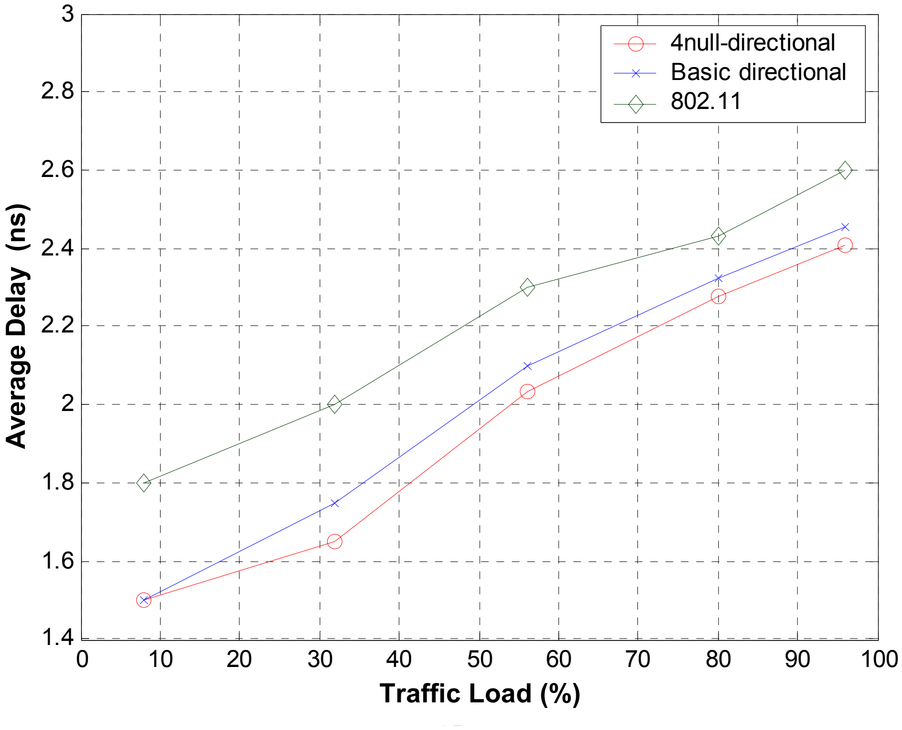
4.7 Mbps
(37%)

(a)



Due to hidden-terminal problems

(b)



(c)

Figure 3.14: Nulling operation under the random topology: (a) Throughput performance versus traffic load (b) Packet delivery ratio versus traffic load (c) Average delay of packet transmission versus traffic load

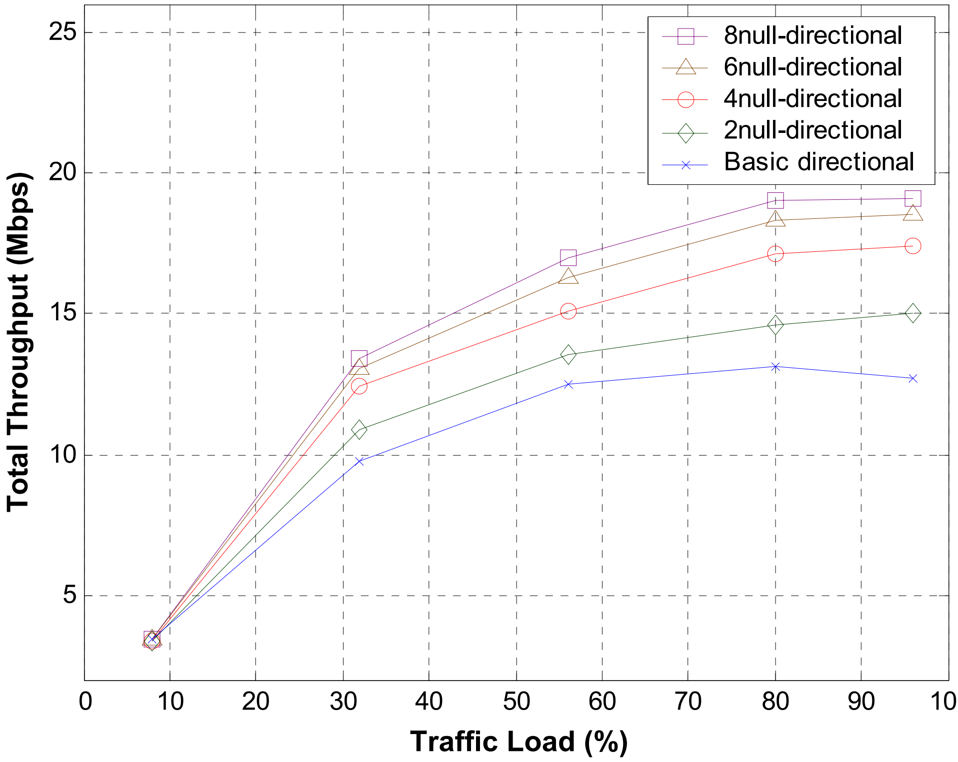
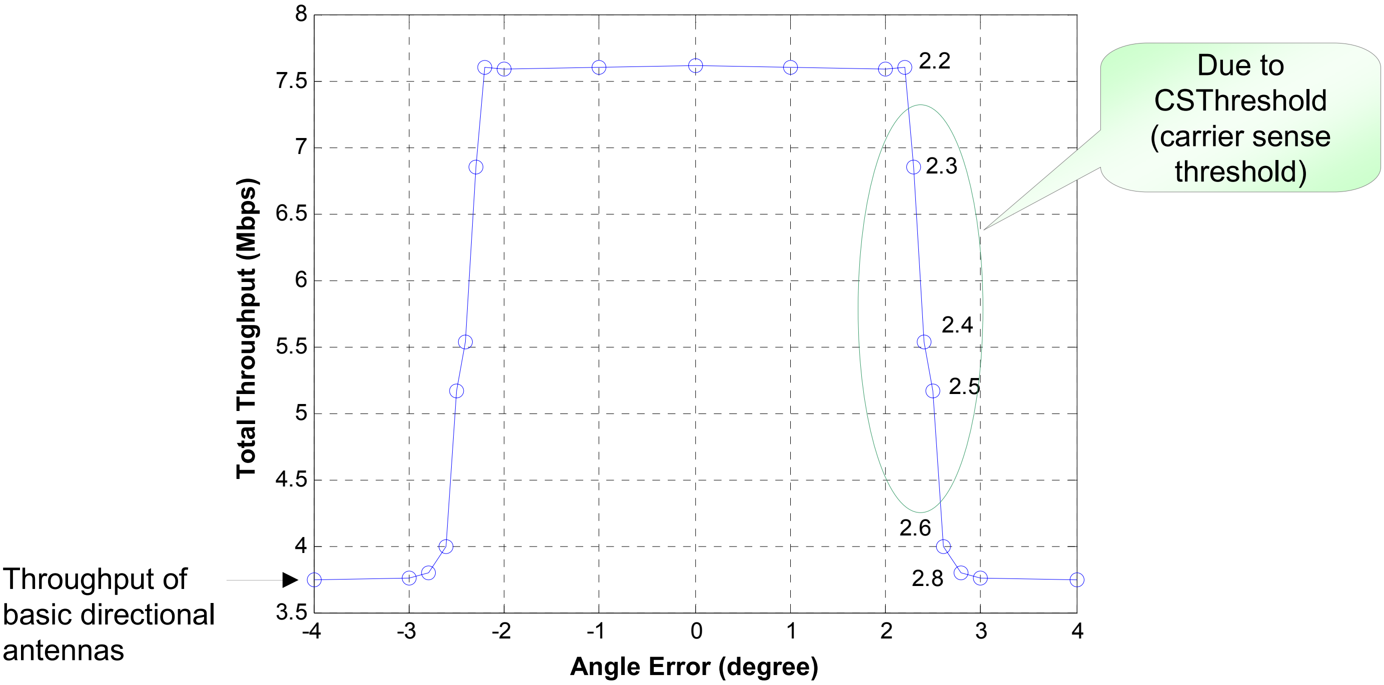


Figure 3.15: Effect of the number of beamforming nulls: the throughput performance simulations which discuss on the cases in which nodes are equipped directional antennas with zero, two, four, six, and eight beamforming nulls.



Throughput of basic directional antennas

Due to CSThreshold (carrier sense threshold)

Figure 3.16: Effect of the beamforming null angle error: throughput performance versus angle error

Table 3.1: The routing table of DSDV protocol

Destination	Metric	Sequence number	Next hop	Install time

Table 3.2: The update packet of DSDV protocol

Destination	Metric	Sequence number

Table 3.3: The neighborhood table of modified DSDV protocol

Neighbor	Angle	Omnidirectional received power P_{ro}	Install time

Table 3.4: Example of routing table update. With the same sequence number, a route with a smaller metric is preferred.

(a) Routing table of node A after receiving the update from node E

Destination	Metric	Sequence number	Next hop	Install time
A	0	S1012	A	T46
D	6	S1000	E	T50
C	7	S962	E	T50
E	5	S850	E	T50

(b) Routing update sent by node B at time T52

Destination	Metric	Sequence number
B	0	S920
A	1	S1012
C	1	S964
D	2	S1000

(c) Routing table of node A after receiving the update from node B

Destination	Metric	Sequence number	Next hop	Install time
A	0	S1012	A	T46
D	3	S1000	B	T52
B	1	S920	B	T52
C	2	S964	B	T52
E	5	S850	E	T50

Chapter 4

DMAC with Cross-Layer Power Control for Wireless Ad Hoc Networks

Power awareness is an important issue in wireless ad hoc networks. Directional antenna achieves high packet delivery due to high transmission gain, but high transmission gain may be viewed as interference by other transmissions. In Section 2.2.2, we have introduced the blocking problem due to a higher gain. An additional advantage of using directional antennas is the higher gain from the directivity of directional antennas, which can be utilized to reduce the transmission power during the directional transmission. Therefore, we should control power to not only maintain the reliability of data link but also reduce the interference for the other nodes. In this chapter, we will completely illustrate the proposed power control protocol which improves throughput performance, and is demonstrated the improvement of the proposed power control protocol by simulation results.

4.1 Power Scaling in DMAC Transmission

As discussed in Section 2.2, the directional high transmission gain will attack or block the nodes which are out of the omnidirectional transmission range. This case is illustrated by an example in Figure 4.1. Considering a linear topology in Figure 4.1(a), assume that every node is idle in the initial state. In Figure 4.1(b), if node A intends to send a DRTS packet to node B, then node D will be blocked in the direction of node A. In this case, the transmission between node C and D is impossible. The same situation occurred in Figure 4.1(c), node A is blocked by node D, when node D transmits to node C. The Figure 4.1(e) shows that if ad hoc nodes can control transmission power, the two transmissions can survive at the same time. However, if a node reduces the power of a DATA packet transmission, the reliability of data link will be decreased, which results in low throughput. Therefore, the proposed power control strategy is only to scale the transmission power of control packets DRTS/DCTS/DACK. The DATA packet still transmits with the high directional gain. In the following, we will illustrate the method of the power scaling in the control packets.

Upon node broadcasting periodically, every node can receive the broadcasting signals from neighbor nodes with the omnidirectional received power P_{ro}:

$$P_{ro} = \frac{P_t G_{to} G_{ro} K}{d^{\alpha}} \tag{4.1}$$

where P_t is the transmission power of node, G_{to} is the omnidirectional transmission gain of node's antenna, G_{ro} is the omnidirectional receiving gain of node's antenna, d is the distance between transmitter and receiver, K depends on the wavelength, and α is a constant that depends on the propagation conditions.

As the transmitter sends DRTS directionally, the receiver receives DRTS omnidirectionally with the received power P_{rdo}:

$$P_{rdo} = \frac{P_t G_{td} G_{ro} K}{d^\alpha} = \frac{P_t \gamma G_{to} G_{ro} K}{d^\alpha} = \gamma P_{ro} \tag{4.2}$$

where G_{td} is the directional transmission gain of node's antenna, and γ is the array gain, which is the ratio of the directional gain G_{td} divided the omnidirectional gain G_{to}.

After discussing the original received power, we want to decide the wanted received power from the scaled transmission power. The simulation engine NCTUns 1.0 defines the carrier sense threshold (CSThreshold). If signal received power is below CSThreshold, the hardware cannot detect this signal. We let $P_t^{'}=\beta P_t$, where β is the power scaling factor, and $P_t^{'}$ is transmission power after scaling. Then, the received power is $P_{rdo}^{'}=\beta P_{rdo}$, and we let $10\log P_{rdo}^{'}$ = CSThreshold + ΔP dB, where ΔP (dB) is the power increment which is the tolerate range of making sure that the receiver can detect the signal power after scaling. If we want to send the DRTS packet, then the scaling factor β_1 is decided by:

$$10\log \beta_1 P_{rdo} = 10\log \beta_1 \gamma P_{ro} = \text{CSThreshold} + \Delta P \quad \text{(dB)} \tag{4.3}$$

$$\beta_1 = \frac{1}{\gamma P_{ro}} 10^{\frac{\text{CSThreshold}+\Delta P}{10}} \tag{4.4}$$

As sending DCTS/DACK, the transmitter and receiver both form directional antennas beamforming, and the directional received power P_{rd} of receiver is:

$$P_{rd} = \frac{P_t G_{td} G_{rd} K}{d^\alpha} = \frac{P_t \gamma G_{to} \gamma G_{ro} K}{d^\alpha} = \gamma^2 P_{ro} \tag{4.5}$$

Then, the scaling factor β_2 is decided by:

$$10\log \beta_2 P_{rd} = 10\log \beta_2 \gamma^2 P_{ro} = \mathrm{CSThreshold} + \Delta P \quad (\mathrm{dB}) \tag{4.6}$$

$$\beta_2 = \frac{1}{\gamma^2 P_{ro}} 10^{\frac{\mathrm{CSThreshold}+\Delta P}{10}} \tag{4.7}$$

Through controlling transmission power by the scaling factors β_1 and β_2, the receiver node catches the control packets with a small but acceptable power, and the power of the control packets will be not strong interference for the other nodes.

4.2 Operation of the Cross-Layer Power Control Protocol

This section presents the DMAC with the power control protocol which is designed with the cross-layer system architecture in Chapter 3. Figure 4.2 shows the procedure of scaling transmission power on control packets. Firstly, as discussed in Section 3.4, every node broadcasts and receives neighbor node's broadcast signal, and then records the omnidirectional received power P_{ro} in the neighborhood table. For an example, assume that transmitter node T has packets to send to receiver node R. According to the neighborhood table, node T gets the received power P_{ro} of node R. Secondly, node T decides the power scaling factor β depending on the type of packets. Node T should send DRTS first, and therefore it chooses the power scaling factor $\beta_1 = \frac{1}{\gamma P_{ro}} 10^{\frac{\mathrm{CSThreshold}+\Delta P}{10}}$, so the scaled transmission power is $P_t' = \beta_1 P_t$. After node R receiving the DRTS packet, it sends DCTS back to node T with the power scaling factor $\beta_2 = \frac{1}{\gamma^2 P_{ro}} 10^{\frac{\mathrm{CSThreshold}+\Delta P}{10}}$, so the scaled transmission power is $P_t^{'}=\beta_2 P_t$. Through the power scaling, the small transmission power of these control packets can be accepted by the receiver and does not interfere or block too many of nodes.

Since the length of the DATA packet, around 1000 bytes, is much larger than the length of control packets, around 30 bytes, we cannot reduce the transmission power of DATA packets, or the reliability of data link will be decreased seriously, which results in low throughput. In the proposed power control protocol, node T transmits the DATA packet with the full transmission power, so the power scaling factor β is 1. Similar to DCTS, node R sends the DACK packet with the power scaling factor β_2 after receiving the DATA packet successively.

4.3 Computer Simulation

The same as Section 3.6, we use the NCTUns 1.0 network simulator [23] to evaluate the performance of the cross-layer power control protocol. In the following simulations, we use the same directional antennas models as indicated in Section 3.6. We assume that the physical layer at the receiver can accurately estimate the DOA of the received signal and record it in the neighborhood table at routing layer. The packet length is constant and equal to 1017 bytes. We use the two-ray ground propagation model as the path loss model. The channel model uses the Raileigh fading distribution which variance is 10 dB. Each simulation run is conducted for 100 seconds, and each data point is the average of five simulation runs. In the NCTUns simulator, the CSThreshold is 87.57 dB, and we set that the directional gain is 4 and omnidirectional gain is 1, as the same with Section 3.6, so the array gain γ is equal to 4. The power increment ΔP is equal to 15 dB. Therefore, the power control factors $\beta_1 = \frac{1}{4P_{ro}} 10^{10.257}$ and $\beta_2 = \frac{1}{16P_{ro}} 10^{10.257}$ are obtained by the Equations 4.4 and 4.7. The following sections will represent some simulation results that compare the performance of the 4-null directional antennas using the power control protocol, with the performances of the 4-Null directional antennas not using the power control protocol and the basic directional antennas mode.

4.3.1 Power Control Under 4-Node Topology

The Figure 4.3 shows a 4-node linear topology, which four nodes are arranged to a line. We assume that node A transmits to B and node C transmits to D. As discussed in Section 2.2, the nodes C and D are in the main beam range of node A, and thus they will be interfered or blocked. Although nodes B and C can null the interference through adapting M-null directional antenna model, nodes A and D still attack or block each other, because they are both in the main beam range of each other.

Figure 4.4 shows the simulation results of the two transmissions (A⟷B, C⟷D) conveying at the same time under linear topology. Figure 4.4(a) shows the throughput performance versus data generation rate. The diamond line, the star line, and the circle line represent the only one transmission (A⟷B), two transmissions without the power control scheme, and two transmissions with the power control scheme, respectively. Obviously, two transmissions achieve higher throughput than one transmission, but only a little performance is improved due to the blocking problem. Through the power control on control packets DRTS/DCTS/DACK, we improve 0.9 Mbps throughput, around 22.5%, over the original protocol in the high data generation rate.

Through controlling power on the control packets, the more simultaneous data transmission pairs are allowed, so the network congestion is alleviated. However, the DATA packet is transmitted with the full power, so the DATA packet may be collided, which induces the low packet delivery. Figure 4.4(b) shows the packet delivery ratio as a function of the data generation rate. The power control scheme achieves a lower packet delivery ratio. In spite of the low packet delivery, the cross-layer power control protocol can really improve outstanding throughput performance and save the power consumption.

4.3.2 Power Control Under Random Topology

We now simulate a network consisted of 25 static nodes randomly distributed in a 1000 meters × 1000 meters square area. We have simulated a total of five random scenarios and the results represented Figure 4.5 are the average of their individual results. In addition to simulating the 4-null directional antenna with the power control, we also simulate another power control protocol, the directional medium access protocol with power control (DMAP), which scales power through DRTS/DCTS exchange [12]. DMAP does not consider the routing layer, so it cannot know the received power from neighbor nodes before sending DRTS. This strategy only can scale the power of DCTS through received power of DRTS. Therefore, the DRTS transmitted with the high directional gain will block many nodes, which results in decreasing total network throughput.

Figure 4.5(a) shows the simulation result of the throughput performances as the traffic load increases. As shown in the Figure 4.5(a), the throughput performances of the power control on DRTS, DCTS, and DACK packets, the power control on DCTS and DACK packets, and the 4-null directional antenna without the power control scheme are approximately the same in the low traffic load, since the nodes are far distant. However, in the high traffic load, the proposed power control protocol enormously outperforms the other protocols. As the power of the DRTS/DCTS/DACK packets is scaled, the throughput has enhancement performance of 7.2 Mbps compared with the 4-null directional antennas not using the power control protocol. The reason is that the network congestion is alleviated. Figure 4.5(b) shows the packet delivery ratio versus traffic load. The proposed power control protocol has the higher packet delivery ratio over the 4-null directional antennas without the power control, since the scaled DCTS and DACK packets have the less probability to interrupt other DATA transmission. However, the proposed power control protocol achieves the lower packet delivery ratio than the power control on DCTS/DACK, since the DRTS with the full directional gain blocks many nodes to avoid collisions. The same performance is represented in Figure 4.5(c), which shows the average delay of the network versus the traffic load. This indicates that the proposed power control protocol excellently enhances the total network throughput over the other protocols, although a little packet delivery ratio is lost.

In addition to considering throughput, we also discuss the issue of the energy efficiency in the following discussion. In order to calculating the power saving, the Equation 4.8 is defined by:

$$\text{Power Saving} = 1 - \frac{\text{Scaled Power}}{\text{Orginal Power}} = 1 - \frac{P_t L_D + P_t^{'}(L_R + L_C + L_A)}{P_t(L_D + L_R + L_C + L_A)} \tag{4.8}$$

where L_D is the DATA packet length, L_R is the DRTS packet length, L_C is the DCTS packet length, and L_A is the DACK packet length. After calculating the average of all simulation results in all the traffic load stages, the proposed power control protocol presents a power saving of 10.71% on average.

4.4 Summary

In this chapter, we proposed the cross layer design of the power control MAC protocol for wireless ad hoc networks. Using the information of routing layer, we can scale the power on the DRTS packet, such that many of the nodes will not be blocked. As a result, the total throughput performance is enhanced significantly. In addition, our protocol uses the power scaling DCTS and DACK packets to prevent collisions due to a high directional antenna gain. The proposed power control protocol also alleviates the network congestion problem introduced by the RTS/CTS exchanging mechanism. Furthermore, we evaluate the performance of the proposed power control protocol using the NCTUns 1.0 network simulator. The simulation result shows that the proposed power control protocol equipped with the 4-null directional antennas improves the network throughput by 194% over the basic directional antennas and 141% over the 4-null directional antenna without the power control protocol. Finally, in addition to enhancing throughput, the proposed power control protocol on average provides a 10.71% power saving, over the directional antennas protocols. The proposed power control protocol can not only provide an excellent throughput but also reduce the power consumption.

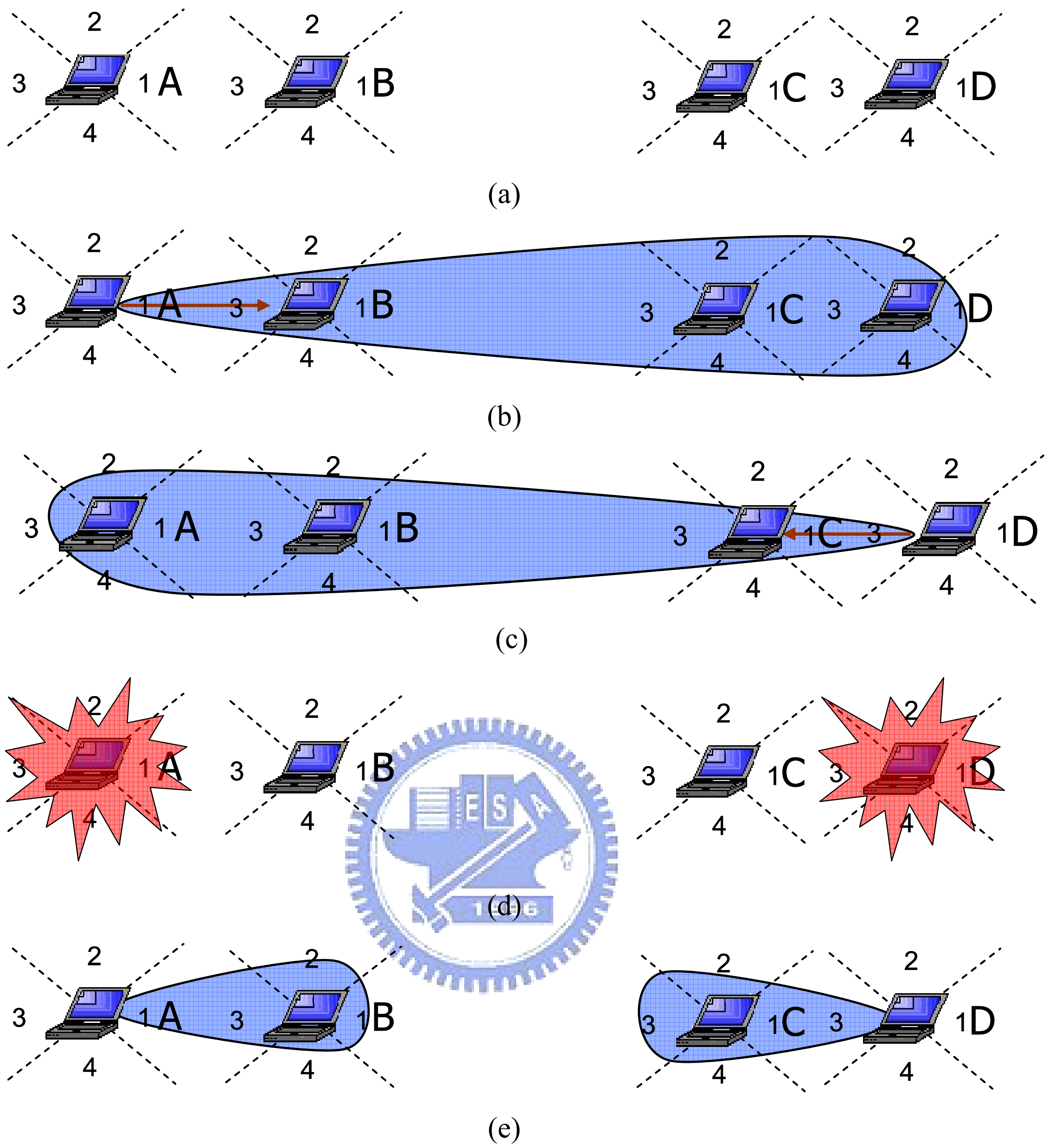


Figure 4.1: An example of the benefit of the power control strategy: (a) The initial state of nodes A, B, C, and D is idle. (b) Node A transmits to node B. (c) Node D transmits to node C. (d) Nodes A and D attack and block each other. (e) Through power control, two transmissions can survive at the same time.

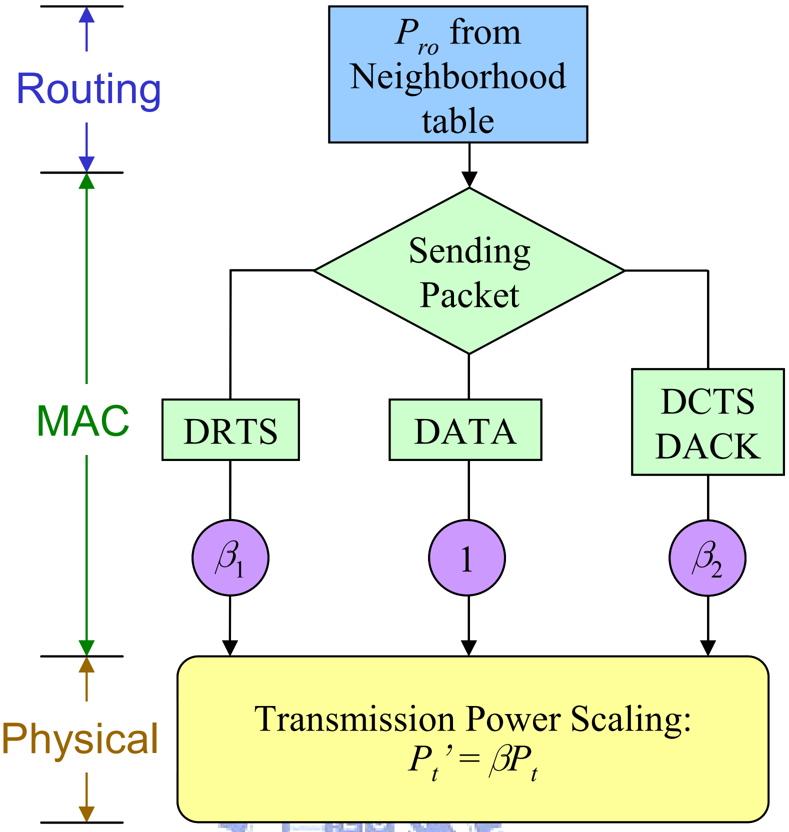


Figure 4.2: Flowchart of operation of the cross-layer power control protocol

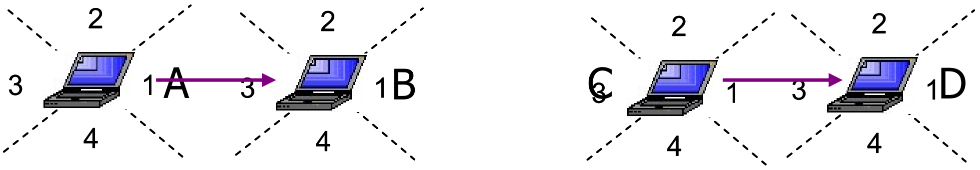
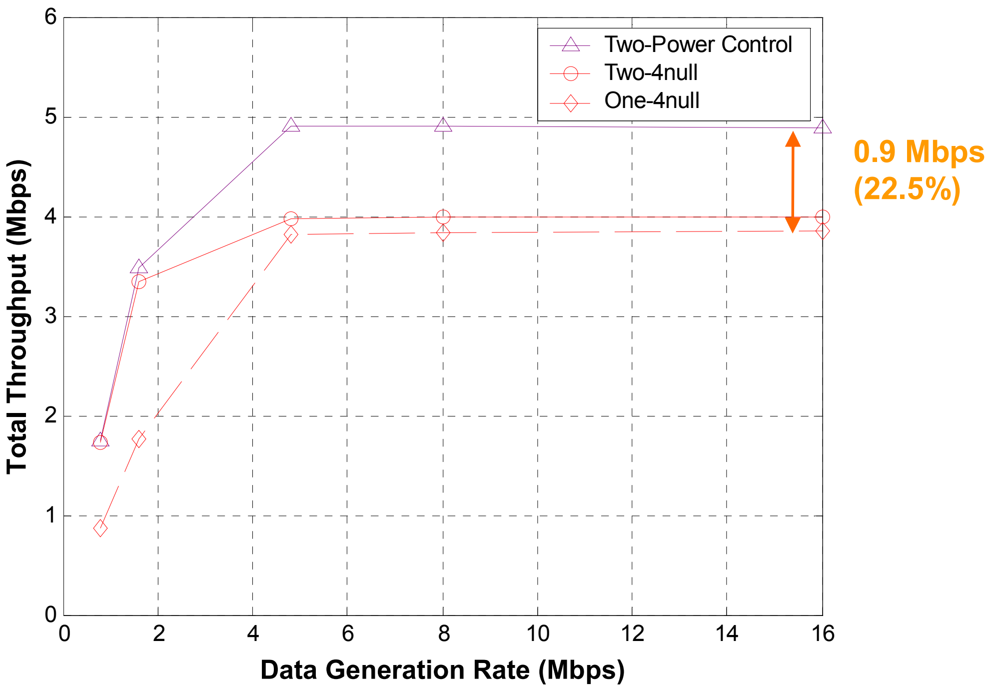
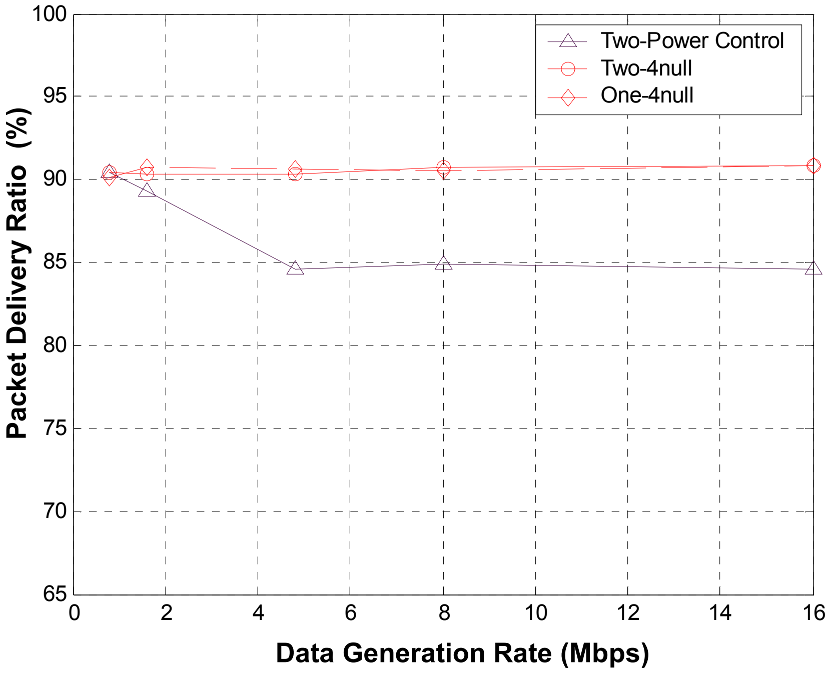


Figure 4.3: The 4-node linear topology: Node A transmits to node B and node C transmits to node D.

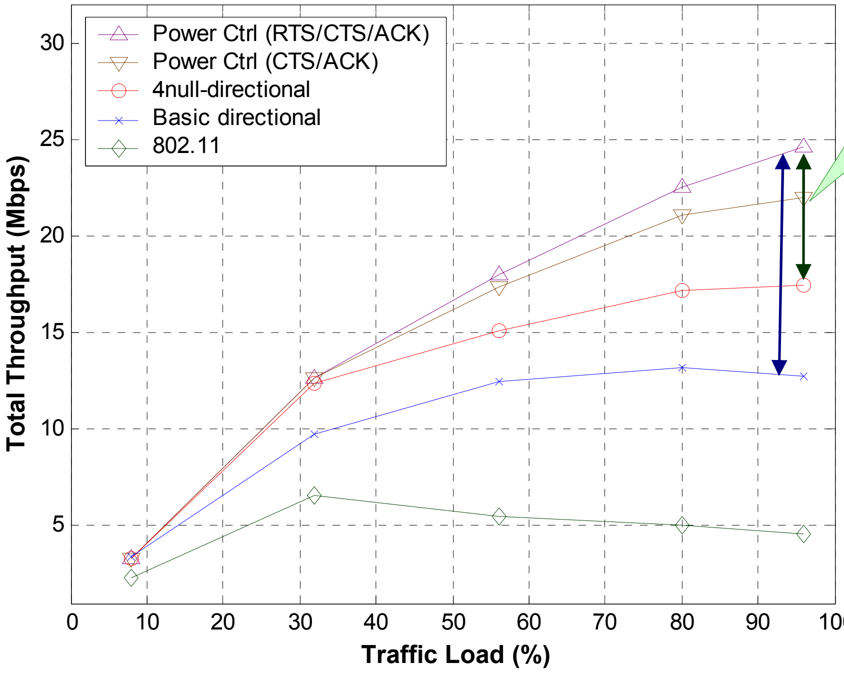


(a)



(b)

Figure 4.4: Performances of the proposed power control scheme under the 4-Node linear topology: (a) Throughput performance versus data generation rate (b) Packet delivery ratio versus data generation rate

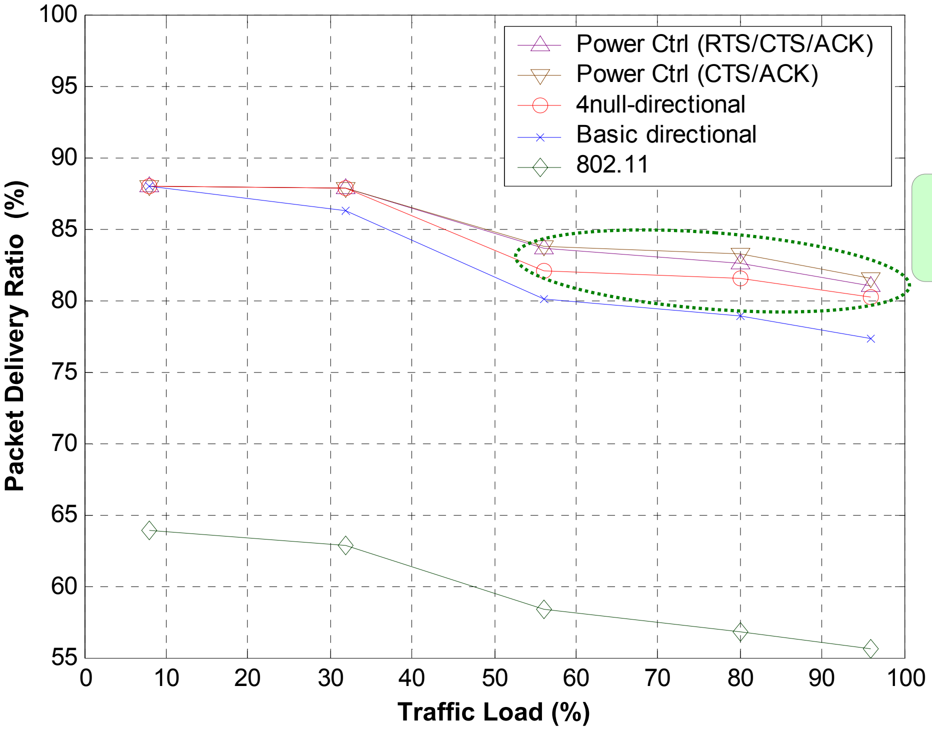


Alleviate the network congestion problem introduced by RTS/CTS exchanging mechanism

7.2 Mbps (41.3%)

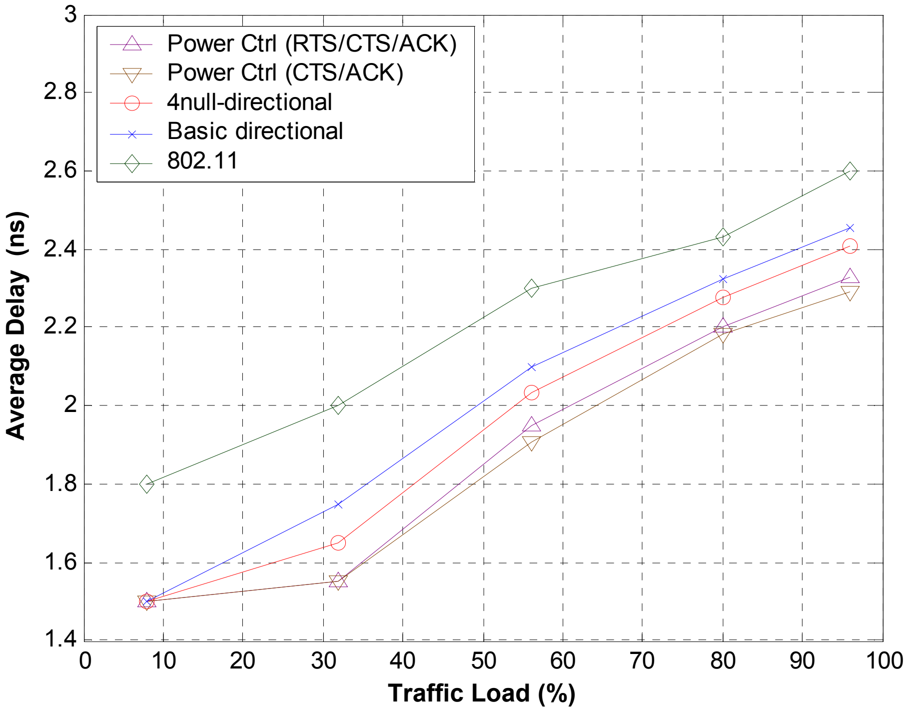
11.9 Mbps (93.5%)

(a)



Smaller power, smaller interference

(b)



(c)

Figure 4.5: Performances of the power control under 4-Node linear topology: (a) Throughput performance versus traffic load (b) Packet delivery ratio versus traffic load (c) Average delay of packet transmission versus traffic load

Chapter 5

Conclusion

In this thesis, we primarily attempt to explore the capabilities of using directional antennas in wireless mobile ad hoc network environments. With the aid of directional antennas, spatial reuse can be achieved, and overall system throughput is improved significantly. We begin our research by discussing problems of directional medium access control (DMAC) protocols in wireless ad hoc networks. Although directional antenna offers a high gain to enhance the throughput performance, this high gain may be a cause of interference to other nodes. In addition, the improper DMAC protocols produce new hidden terminal problems resulting in collisions and blocking problems where a node is prohibited from transmitting any signal even though their transmission will not interrupt the other transmission. These problems enormously limit the performance of a wireless ad hoc network.

Our main contribution in this thesis is the proposal of a cross layer design that integrates physical, MAC and routing protocols to fully exploit the advantages of directional antennas and improve the throughput performance significantly. Figure 5.1 illustrates how the physical, MAC, and routing layers pass the cross layer parameters, DOAs and P_{ro}, and the corresponding utilization of these parameters. In Chapter 3, we propose an integrated refinement of physical, MAC and routing protocols to take advantage of features of directional antennas. At the PHY layer, each node identifies the relative directions of its neighbors. Furthermore, we propose an *M*-null directional antenna model which can form a main beam toward the desired direction and beamforming nulls in the directions of interference. At the MAC layer, RTS/CTS exchanging is executed directionally, and thus the number of blocked nodes is reduced. Moreover, each node maintains a DNAV table in which on-going transmissions in its vicinity and the corresponding duration are recorded. Therefore, only those nodes located within the direction of transmission are blocked, and these nodes are not blocked in all directions. At the routing layer, we propose a modified DSDV routing strategy to discover a route and accomplish the proposed directional antenna protocol.

We evaluate performances of the proposed system architecture using the high-fidelity and extensible network simulator NCTUns in Section 3.6. In the basic 4-node topology, the proposed cross layer protocol, the DMAC protocol equipped *M*-null directional antenna, achieves twice throughput over one transmission due to perfectly resolving hidden terminal and blocking problems. In a heavy load network, the throughput performance of the proposed system architecture is enhanced by 137% over the basic directional antenna MAC and 380% over IEEE 802.11b. The simulation results show that the proposed system architecture significantly improves wireless ad hoc network performance on several aspects, including throughput, delay, and packet delivery ratio. Thus the hidden terminal and blocking problems presented in Chapter 2 is alleviated. Moreover, we present the throughput performance simulations which discuss on the cases in which nodes are equipped directional antennas with zero, two, four, six, and eight beamforming nulls. The outcome shows that the more numbers of beamfroming nulls is, the better throughput performance is achieved. However, the increase in throughput becomes less and less as the number of beamforming nulls increases. Finally, the effect of beamforming nulling angle error on the throughput performance of the *M*-null directional antenna is also investigated. The *M*-null directional antenna model approximately maintains the same high performance within 2.2 degrees angle error. Within the tolerant range of 3 degrees angle error, our model still performs better than the basic directional antenna model. The benefit of beamfoming nulls will be lost as the angle error exceeds 3 degrees.

In Chapter 4, we propose a cross-layer power control protocol at the physical, MAC, and routing layers, which scales power on control packets DRTS/DCTS/DACK. Through choosing different power scaling factors β, transmitter sends control packet with small but acceptable transmission power. Unlike high directional power, the scaled power does not interfere or block excessively the other nodes, so the network throughput is enhanced enormously. The proposed power control protocol also alleviates the congestion problem introduced by the RTS/CTS exchanging mechanism. The simulation results demonstrate that the overall network throughput is improved. Furthermore, the power control protocol reduces transmission power consumption. In summary, the advantage of the proposed power control is twofold, limiting interference to increase throughput and reducing power consumption.

Although the proposed refinement has shown great improvement on network performance, there is room for further exploitation of other features of directional antennas. For example, due to that lower power resulting in poor reliability of data link, the power control mechanism does not scale transmission power of the data packets, and this may result in collisions in some scenarios, as shown in the linear topology in Figure 4.3. Therefore, a potential future work would be the design of a new power control protocol to alleviate the occurrence of collisions.

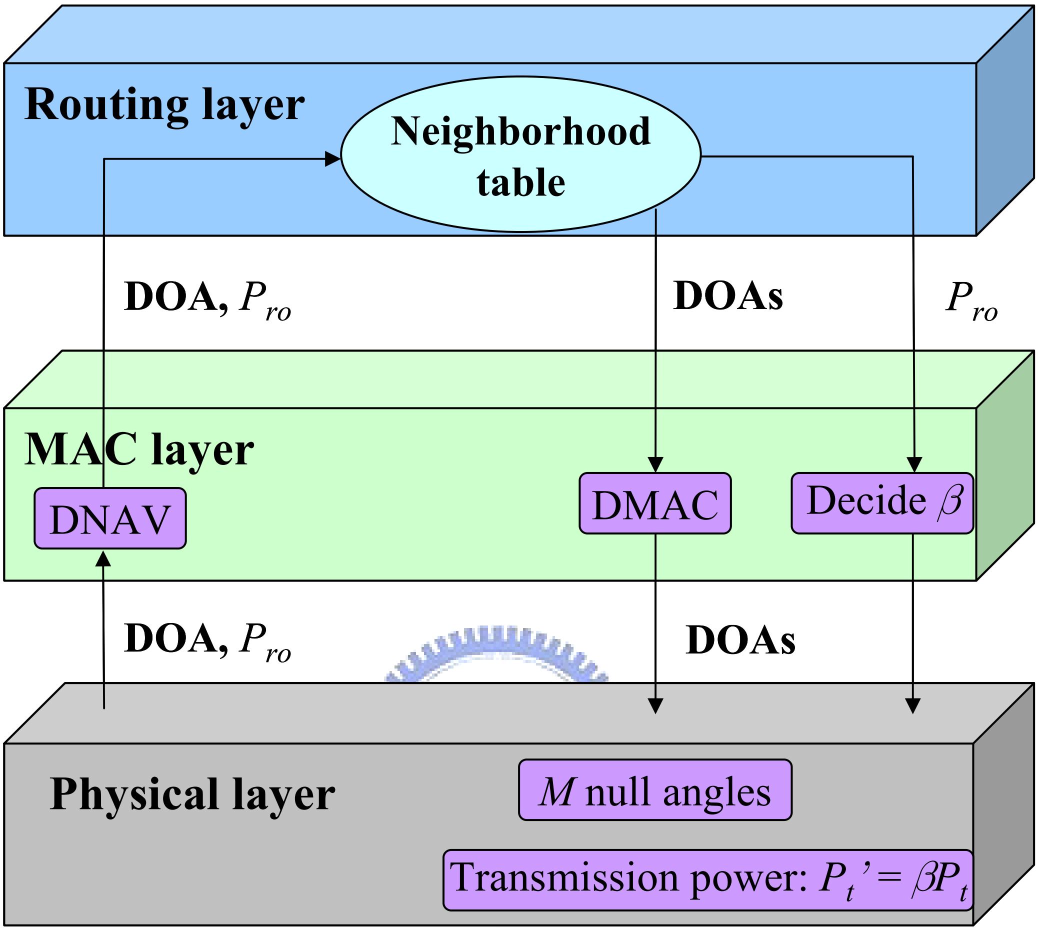


Figure 5.1: Diagram of the cross layer architecture illustrating how the physical, MAC, and routing layers pass the cross layer parameters, DOAs and P_{ro}, and the corresponding utilization of these parameters.

Bibliography

[1] S. Ray, J. B. Carruthers, and D. Starobinski, “RTS/CTS-induced congestion in ad hoc wireless LANs,” in *Proc. IEEE WCNC 2003*, pp. 1516-1521, March 2003.

[2] International Standard ISO/IEC 8802-11: 1999(E), ANSI/IEEE Standard 802.11, 1999 Edition.

[3] R. Choudhury, X. Yang, R. Ramanathan, and N. Vaidya, “Using Directional Antennas for Medium Access Control in Ad Hoc Networks,” in *ACM Mobicom*, September 2002.

[4] T. Korakis, G. Jakllari, L. Tassiulas, “A MAC protocol for full exploitation of Directional Antennas in Ad-hoc Wireless Networks,” in *ACM Mobihoc*, June 2003.

[5] A. Nasipuri, S. Ye, J. You, and R. Hiromoto, “A MAC Protocol for Mobile Ad Hoc Networks using Directional Antennas,” in *Proc. of IEEE WCNC*, September 2000.

[6] Y. B. Ko, V. Shankarkumar, and N. H. Vaidya, “Medium access control protocols using directional antennas in ad hoc networks,” In *Proc. IEEE INFOCOM*, vol. 1(3), pp. 13-21, March 2000.

[7] R. Choudhury, X. Yang, R. Ramanathan, and N. Vaidya, “Using Directional Antennas in Ad Hoc Networks,” *Final report submitted by Texas A&M University to BBN technologies*, July 2001.

[8] Y. Wang and J.J. Garcia-Luna-Aceves, “Spatial Reuse and Collision Avoidance in Ad Hoc Networks with Directional Antennas,” in *IEEE Globecom*, November 2002.

[9] M. Takai, J. Martin, A. Ren, and R. Bagrodia, “Directional virtual carrier sensing for directional antennas in mobile ad hoc network,” in *Proc. MOBIHOC 2002*, Lausanne, Switzerland, June 2002.

[10] R. Ramanathan, "On the performance of Ad Hoc Networks with Beamforming Antennas," in *ACM MobiHoc*, October 2001.

[11] A. Nasipuri, K. Li, and U. R. Sappidi, "Power consumption and throughput in mobile ad hoc networks using directional antennas," *Computer Communications and Networks 2002. Proc. Eleventh International Conference*, pp. 620 - 626 October 2002.

[12] A. Arora, M. Krunz, and A. Muqattash, "Directional medium access protocol (DMAP) with power control for wireless ad hoc networks," *IEEE GLOBECOM '04*, vol. 5, pp. 2797 – 2801, December 2004.

[13] T. ElBatt and A. Ephremides, "Joint scheduling and power control for wireless ad hoc networks," *IEEE Trans. on Wireless Communications*, vol. 3, no. 1, pp. 74 - 85, January 2004

[14] Phil Karn, "MACA – a new channel access method for packet radio," in *ARRL/CRRL Amature Radio 9th Computer Networking Conference*, pp. 134-140, September 1990.

[15] H. Gossain, C. M. Cordeiro, T. Joshi, and D. P. Agrawal, "Cross-Layer Directional Antenna MAC and Routing Protocols for Wireless Ad Hoc Networks", in *Wiley Wireless Communications and Mobile Computing Journal, Special Issue on Ad Hoc Wireless Networks*, to Appear.

[16] 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 *Proc. of the IEEE GlobeCom Conference*, vol. 5, pp. 2896–2900, 2001.

[17] N. S. Fahmy, T. D. Todd, and V. Kezys, "Ad hoc networks with smart antennas using IEEE 802.11-based protocols," In *Proc. IEEE ICC 2002*, vol.6, pp.3144-3148, 2002.

[18] H. L. Van Trees, *Optimun Array Processing*, 2002.

[19] J. Lu, R. Schlub, and T. Ohira, "A performance comparison of smart antenna technology for wireless mobile computing terminals," in *Proc. Asia Pacific Microwave Conference 2001*, pp. 581-584, Taipei, December 2001.

[20] J. Cheng, M. Hashiguchi, K. Ligusa, and T. Ohira, “Electronically steerable parasitic array radiator antenna for omni- and sector pattern forming applications to wireless ad hoc networks,” in *Proc. IEEE Microwaves, Antennas and Propagation*, vol. 150, pp. 203-208, August 2003.

[21] C. E. Perkins and P. Bhagwat, “Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers,” in *Proc. ACM SIGCOMM 1994*, pp. 234-244, October 1994.

[22] C. C. Chiang, H. K. Wu, Liu, and M. Gerla, “Routing in clustered multihop mobile wireless networks with fading channel,” in *Proc. IEEE SICON 1997*, pp. 197-212, April 1997.

[23] S. Murthy and J. J. Garcia-Luna-Aceves, “An efficient routing protocol for wireless networks,” *ACM Mobile Networks Applications. Journal, Special Issue on Routing in Mobile Communications*, vol. 1, no. 2, pp. 183-197, November 1996.

[24] T. W. Chen and M. Gerla, “Global state routing: a new routing scheme for ad hoc wireless networks,” in *Proc. IEEE ICC 1998*, pp. 171-175, August 1998.

[25] A. Iwata, C. C. Chiang, G. Pei, M. Gerla, and T. W. Chen, “Scalable routing strategies for ad hoc wireless networks,” *IEEE JSAC*, vol. 17, no. 8, pp. 1369-1379, August 1999.

[26] D. B. Jonhnson, “Routing in ad hoc networks of mobile hosts,” in *Proc. IEEE Workshop Mobile Computing Systems and Applications*, pp. 158-163, December 1994.

[27] C. Perkins and E. Royer, “Ad hoc on-demand distance vector routing,” in *Proc. IEEE 2nd Mobile Computing Systems and Applications*, pp. 90-100, February 1999.

[28] V. D. Park and M. S. Corson, “A highly adaptive distributed routing algorithm for mobile wireless networks,” in *Proc. IEEE INFOCOM 1997*, pp. 1405-1413, April 1997.

[29] J. Raju and J. J. Garcia-Luna-Aceves, “Efficient on-demand routing using source-tracing,” in *Proc. IEEE Globecom 2000*, no. 1, pp. 577-581, San Francisco, California, November 2000.

[30] C. K. Toh, “Associativity based routing for ad hoc mobile networks,” *Wireless Personal Communication Journal, Special Issue on Mobile Networking and Computing Systems*, vol. 4, no. 2, pp.130-139, March 1997.

[31] R. Dube et al, “Signal stability based adaptive routing (SSA) for ad hoc mobile networks,” *IEEE Personal Communications*, vol. 4, no. 1, pp.36-45, February 1997.

[32] Z. J. Haas and M. R. Perlman, “The performance of a new routing protocol for the reconfigurable wireless networks,” in *Proc. IEEE ICC 1998*, pp. 156-160, August 1998.

[33] X. Zou, B. Tamamurthy, and S. Magliveras, “Routing techniques in wireless ad hoc networks - classification and comparison,” in *Proc. the 6th World Multiconference on Systemics, Cybernetics, and Informatics*, vol. 4, Orlando, Florida, July 2002.

[34] L. R. Ford Jr. and D. R. Fulkerson, “Flows in Networks,” Princeton Univ. Press, 1962.

[35] S. Y. Wang, C. L. Chou, C. H. Huang, C. C. Hwang, Z. M. Yang, C. C. Chiou, and C. C. Lin, “The Design and Implementation of the NCTUns 1.0 Network Simulator,” *Computer Networks*, vol. 42, no. 2, pp.175-197, June 2003.