THESIS

Medium Access Control Protocols for Ad Hoc Networks Using Directional Antennas

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Contents

Chapter 1

Introduction

With the rapid advancements in communication technologies and the proliferation of devices, ubiquitous computing, also known as pervasive computing, has attracted special interest recently. The concept of ubiquitous computing is proposed by Mark Weiser [1]. Ubiquitous computing has as its goal the nonintrusive availability of computers throughout the physical environment, virtually, if not effectively, invisible to the user. In the inside of the ubiquitous computing, ubiquitous networks provide an information environment accessible from anywhere, at any time, and with any device [2]. In ubiquitous networks, there are enormous numbers of computers, such as Personal Computers (PCs), laptop computers (note PCs), Personal Digital Assistants (PDAs), mobile phones, electrical home appliances, devices imbedded in walls, chairs, clothing, light switches, vehicles and everything around the world. Therefore, the central control of these devices is impossible to achieve the ubiquitous networking. It requires the distributed control on the ubiquitous networks.

A key enabling technology for such networks is ad hoc networks [3, 4, 5]. Ad hoc networks are the autonomous system of mobile terminals and can be rapidly and flexibly deployed without any established infrastructure or centralized control facilities like base stations. Each mobile terminal operates not only as a host but also as a router, forwarding packets for other mobile terminals that may not be within direct transmission range of each other. Ad hoc networks are suited for use in situations where infrastructure is either not available, not trusted, not cost effective, or should not be relied on in times of emergency. A few examples include: wireless sensor networks [6, 7, 8, 9]; wireless mesh networks [10]; disaster recovery (search-and-rescue) [11, 12], where the entire communication infrastructure is destroyed and resorting communication quickly is crucial; inter-vehicle communication in Intelligent Transportation Systems (ITS) [13, 14]; an infrastructure-less network in a conference or meeting; the forestry or lumber industry; animal tracking; space exploration; undersea operations; law enforcement; and military applications.

However, there are several problems to be solved for ad hoc networking, from the physical layer to the application layer as follows.

1. The physical layer must adapt to rapid changes in link characteristics due to the unique properties of the wireless medium.

2. The Medium Access Control (MAC) layer needs to minimize collisions, allow fair access among nodes, and semi-reliably transport data over the shared wireless channels.

3. The network layer needs to determine and distribute information used to calculate the multi-hop paths in a way that maintains efficiency when links change frequently because of the mobility of nodes.

4. The transport layer must be able to handle delay and packet loss statistics that are very different than wired networks.

5. Applications need to be designed to handle frequent disconnection and reconnection with peer applications. Also, security is an important issue, especially for security-sensitive applications [15].

Among these problems of ad hoc networks, this thesis addresses the issues of the MAC layer. In most of the previous works on ad hoc networks, omni-directional antennas are usually used at the physical layer. These antennas radiate or receive power equally well in all directions. Traditional MAC protocols, such as IEEE

802.11 [16], have been intrinsically designed for omni-directional antennas and these protocols lead to inefficient use of the wireless channel and consequently deteriorate the throughput in ad hoc networks as discussed in [17, 18, 19].

On the other hand, directional antennas can transmit or receive in a desired direction, and thus have the following benefits when used in ad hoc networks.

- High link quality due to high SINR (signal to interference and noise ratio)
- Spatial reuse of the wireless channel
- Range extension obtained by the higher antenna gain
- Reduction of power consumption

However these potentials directional antennas may have, they require a sophisticated MAC protocol to take advantage of these benefits. Therefore, several MAC protocols using directional antennas, typically referred to as directional MAC protocols, have been proposed recently. Directional MAC protocols, however, introduce new kinds of problems arising from directivity. The major problems of directional MAC protocols are as follows:

1. Determination of neighbors' location
2. Deafness
3. Directional hidden-terminal problem
4. Directional exposed-terminal problem

The main goal of this thesis is to address these issues in directional MAC protocols for ad hoc networks. The main contributions of this thesis are summarized as follows:

1. This thesis identifies the benefits of directional antennas for ad hoc networks.

2. We define the issues of directional MAC protocols, i.e., determination of neighbors' location, deafness, and directional hidden- and exposed-terminal problems.

3. In this thesis, the issue of the determination of neighbors' location is addressed and SWAMP (Smart antennas based Wider-range Access MAC Protocol) is proposed.

4. The deafness problem is deeply discussed and two directional MAC protocols, DMAC/DA (Directional MAC with Deafness Avoidance) and RI-DMAC (Receiver-Initiated Directional MAC), are proposed to handle the problem.

The rest of this thesis is organized as follows: Chapter 2 presents the classification and issues of wireless MAC protocols, and reviews the traditional MAC protocols for ad hoc networks. Chapter 3 discusses the directional MAC protocols. The concept and different types of directional antennas, benefits of directional antennas in ad hoc networks, and issues of directional MAC protocols are described in the chapter followed by the review of the related directional MAC protocols. In Chapter 4, we propose SWAMP to solve the determination of neighbors' location and evaluate the performance of SWAMP through extensive simulation study. The deafness problem is discussed in depth, and DMAC/DA and RI-DMAC are proposed to handle the problem in Chapter 5. We summarize and conclude this thesis in Chapter 6.

Chapter 2

Wireless Medium Access Control Protocols

2.1 Introduction

This chapter presents wireless medium access control protocols. Medium Access Control (MAC) protocols control access to the shared medium by defining rules that allow nodes to communicate with each other in an orderly and efficient manner. One essential issue in wireless networks is to improve the channel utilization of a wireless channel and increase the network throughput, and thus a wireless MAC protocol plays an important role in sharing of wireless channel among terminals.

In Section 2.2, we first classify wireless MAC protocols and point the scope of this thesis. Section 2.3 summarizes the problems of wireless MAC protocols such as the hidden-terminal and exposed-terminal problems. We then review the conventional MAC protocols in Section 2.4 followed by the summary in Section 2.5.

2.2 Classification of Wireless MAC Protocols

There are currently two variations of wireless networks: distributed and centralized. Distributed wireless networks consist of a collection of geographically distributed devices that communicate with one another over a wireless medium. The devices are referred to as nodes or terminals in this thesis. A typical example of distributed wireless networks is illustrated in Fig. 2.1. There is no pre-existing

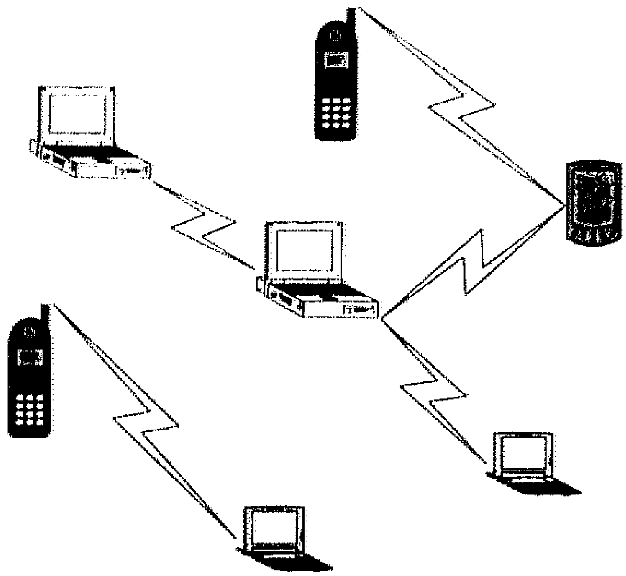


Figure 2.1: Distributed wireless networks.

infrastructure and no central administration in distributed wireless networks. Wireless nodes have a wireless interface and exchange information between one another in a distributed manner. This type of networks is also called ad hoc networks or infrastructure-less networks. This thesis usually uses the term "ad hoc networks" instead of distributed wireless networks or infrastructure-less network.

Centralized wireless networks, to the contrary, have a base station that acts as the coordinator, and wireless terminals connect to and communicate with the base station. An example of centralized networks is shown in Fig. 2.2. The base station is connected with backbone networks, which is usually wireline networks. In centralized networks, while downlink transmissions (from base station to terminals) are broadcast, the up link (from terminals to the base station) is shared by all the nodes. The base station can control the uplink transmissions by allowing access according to some rules. Cellular networks and wireless local area networks (WLANs) are categorized into this type of networks.

In both types of network, wireless medium is a broadcast medium and shared by all nodes in a network. If more than two nodes access the medium and transmit signals at the same time, this simultaneous transmission results in a collision, and

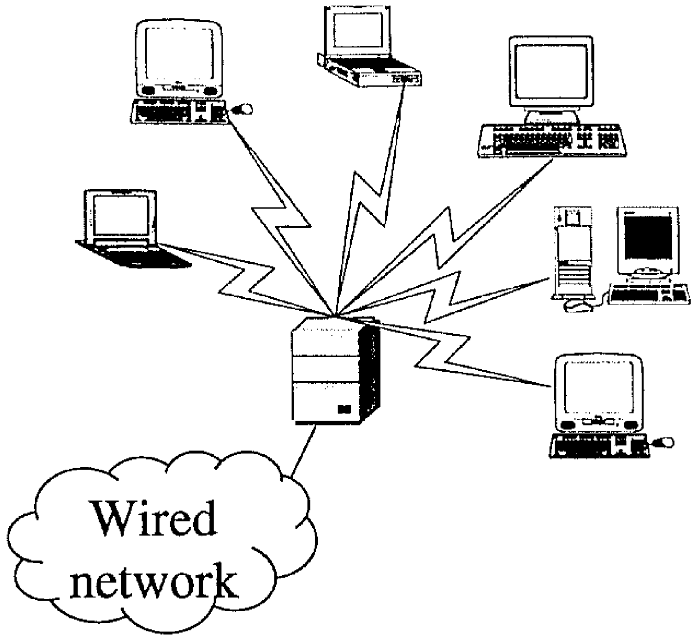


Figure 2.2: Centralized wireless networks.

the receiver nodes cannot decode the signals. Therefore, Medium Access Control (MAC) protocols control access to the shared medium by defining rules that allow these nodes to communicate with each other in an orderly and efficient manner. The MAC sub-layer is the part of the seven-layer OSI model data link layer (layer 2). One essential issue in wireless networks is to improve the channel utilization of a wireless channel and increase the network throughput, and thus a wireless MAC protocol plays an important role in sharing of wireless channel among terminals so that these terminals can communicate with each other.

In [20], Gummalla and Limb classify existing wireless MAC protocols. A classification of wireless MAC protocols is shown in Fig. 2.3. Distributed MAC protocols are designed for ad hoc networks, and centralized MAC protocols are designed for centralized wireless networks.

Protocols used in ad hoc networks are random access protocols, in which all nodes in a network randomly access the medium in a distributed manner according to the protocol. In other words, all nodes contend for access to the channel, and

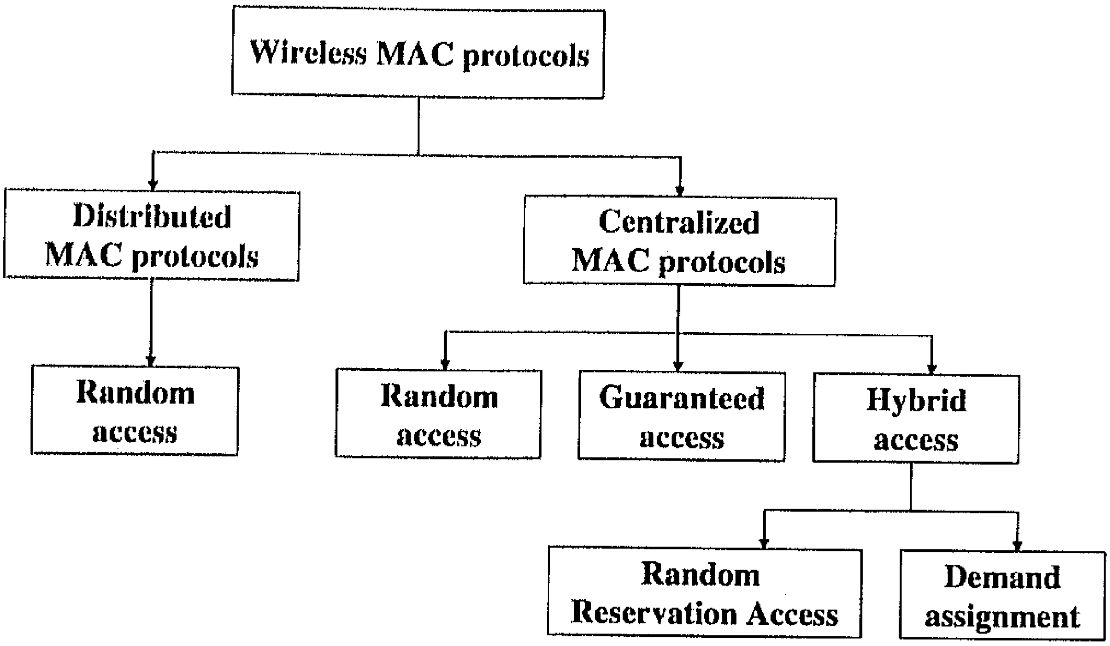


Figure 2.3: Classification of wireless MAC protocols.

thus random access protocols are also called contention-based protocols.

There are three types of protocols in centralized MAC protocols: random access protocols, guaranteed access protocols, and hybrid access protocols. In a guaranteed access protocol, nodes access the medium in an orderly manner, usually in a round-robin fashion. One guaranteed access protocol is a polling protocol. It uses a master-slave configuration, where the master polls each node and the polled node sends data in response to the poll. IEEE 802.11 PCF (Point Coordination Function) [16] and IEEE 802.15.1 [22], also known as Bluetooth [23], are polling protocols. The other guaranteed access protocol is token-passing protocol [24, 25], in which a token is exchanged in a network and only a node which have the token is allowed to access the medium. In hybrid access protocols, each node sends a request to the base station over a control channel using a random access protocol, and then the base station allocates bandwidth for the actual data transmission over a data channel using a guaranteed access protocol. Cellular networks are a typical example of hybrid access protocols. The hybrid access protocols can be classified into random reservation access protocols and demand assignment protocols. In a random reservation protocol, the base station has implicit rules for reserving upstream bandwidth. On the other hand, in a demand assignment protocol, the base station controls upstream data transmissions according to QoS (Quality of Service) requirements of nodes. It collects all the requests from the nodes and uses scheduling algorithms to make bandwidth allocations.

This thesis focuses on the contention-based MAC protocols in ad hoc networks. Guaranteed access protocols and hybrid access protocols require the base station and these are only used in centralized networks, and therefore these are out of the scope of this thesis.

2.3 Problems of Wireless MAC Protocols

This section summarizes four problems of wireless MAC protocols to be considered when designing protocols.

1. Half-Duplex Operation

It is almost impossible to receive data from another node while transmitting signals in wireless networks. This is because when a node is transmitting data, a large fraction of the signal energy leaks into the receive path. This is referred to as self-interference. Therefore, transmission and reception cannot be carried out simultaneously at each node. It also implies that collision detection is not possible while sending data, and that MAC protocols used in wired networks such as CSMA/CD (Carrier Sense Multiple Access with Collision Detection) [26] do not work well. As collisions cannot be detected by the sender, the contention-based MAC protocols should handle collisions using collision avoidance techniques.

2. Time Varying Channel and Channel Errors

Radio signals propagate through air according to three mechanisms: reflection, diffraction, and scattering. The received signal power varies as a function of time due to multipath and fading. Multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths. Fading refers to the time variation of the received signal power caused by changes in the transmission

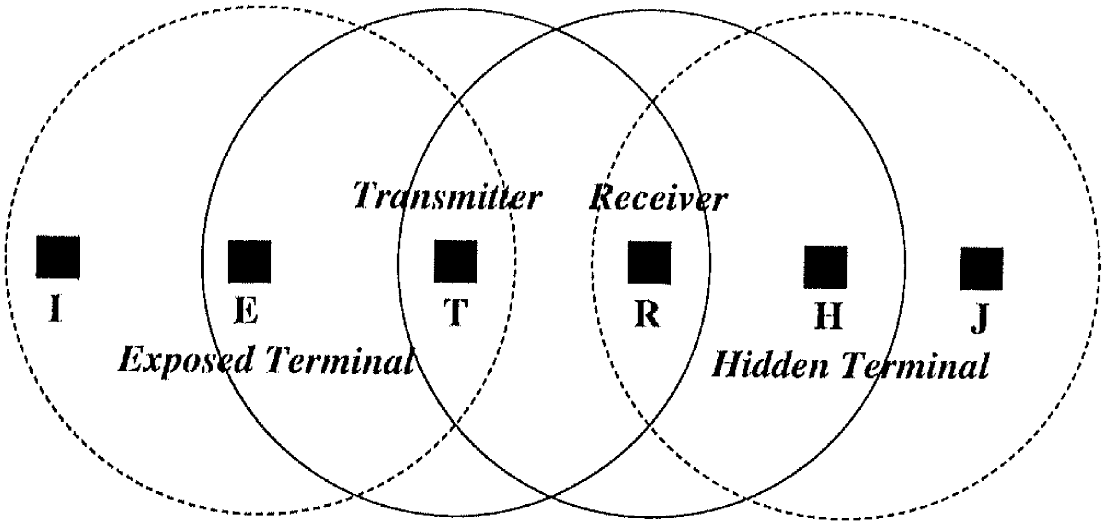


Figure 2.4: Hidden-terminal and exposed-terminal problems.

medium or path. As a result, time-varying wireless channel introduces large bit errors. In wired networks, the bit error rates are typically less than 10^{-6}, and the probability of a packet error is small. In wireless networks, on the other hand, the bit error rates are 10^{-3} or higher, resulting in a higher probability of packet errors. To overcome high bit error rates, most wireless MAC protocols use link-level acknowledgments (ACK) and retransmissions.

3. Hidden-Terminal Problem

In free space, signal strength attenuates with the square of the distance [27]. Therefore, only nodes within a specific radius of the transmitter can detect the carrier on the channel. This introduces hidden-terminal problem in carrier sense protocols [28]. Fig. 2.4 illustrates the hidden terminal problem. Suppose that node T is a transmitter and that node R is its intended receiver. While node T is transmitting to node R, node H senses the channel to communicate with node J. However, node H cannot hear any transmission because it is out of range of node T, and recognizes that channel is idle. If node H transmits the signal, it interferes with the communication between T and R, and results in a collision at node R. Node H is referred to as a hidden terminal of node T in Fig. 2.4. Hidden terminals are located within the range of the intended receiver of the on-going communication but out of range of its transmitter.

4. Exposed-Terminal Problem

The other problem in carrier sense protocols is exposed-terminal problem [35]. In Fig. 2.4, assume that node E is intending to communicate with node I while nodes T and R are communicating. When node E is ready to transmit, it senses the channel and detects carrier, and therefore defers its transmission. However, any transmission of node E does not reach node R, and hence does not interfere with data reception at node R. It is possible to communicate concurrently although node E detects carrier. Node E's carrier sense does not provide the necessary information since it was exposed to node T. Node E is referred to as an exposed terminal of node T in this case.

2.4 Conventional Contention-Based MAC Protocols

Wireless MAC protocols have been extensively studied since the 1970s and a large number of protocols have been proposed [20, 21]. This section introduces typical contention-based MAC protocols.

2.4.1 ALOHA

ALOHA is the first wireless MAC protocol proposed by Abramson for packet radio networks [29, 30]. The protocol is simple and operates as follows:

- A node that has data to send transmits it.
- If the transmission collides with another transmission, it retries after waiting for a random period.

Slotted version of ALOHA is called slotted ALOHA [31]. In slotted ALOHA, time is slotted and transmission attempts are made at the beginning of the slot. The transmission time of a packet is equal to one slot. Slotted ALOHA reduces the probability of collisions and also the collision periods.

The theoretical throughput of ALOHA and slotted ALOHA is calculated as follows [33]. Assume that the infinite population of nodes generates new frames according to a Poisson distribution with mean S frames per frame time. In addition to the new frames, the nodes generate retransmissions of frames that previously suffered collisions. Let us further assume that the probability of k transmission attempts per frame time, i.e., the arrival rate of new and rescheduled frames, is also Poisson, with mean G per frame time. The throughput is calculated by

$$S = GP_o, \tag{2.1}$$

where P_o is the probability that a frame does not suffer a collision.

A frame will not suffer a collision if no other frames are sent within the vulnerable period. The vulnerable period of ALOHA is 2× frame time. The probability that k frames are generated during a given frame time is given by the Poisson distribution:

$$P_r[k] = \frac{G^k \times e^{-G}}{k!} \tag{2.2}$$

so the probability of zero frames is just e^{-G}.

In an interval two frame times long, the mean number of frames generated is $2G$. The probability of no other traffic being initiated during the entire vulnerable period is thus given by $P_o = e^{-2G}$. Using $S = GP_o$, we get

$$S = Ge^{-2G}. \tag{2.3}$$

The maximum throughput occurs at $G = 0.5$, with $S = 1/2e$, which is about 0.184

In slotted ALOHA, since the vulnerable period is halved that of ALOHA, the probability of no other traffic during the same slot as our test frame is e^{-G} which leads to

$$S = Ge^{-G}. \tag{2.4}$$

The throughput of slotted ALOHA peaks at $G = 1$, with a throughput of $S = 1/e$, which is about 0.368.

2.4.2 CSMA

In CSMA (Carrier Sense Multiple Access) [32], each node senses the carrier before transmitting. If the node detects carrier then it defers transmission; otherwise it transmits. Carrier sense attempts to avoid collisions by confirming the signal strength in the vicinity of the transmitter. However, collisions occur at the receiver when it receives more than two signals at the same time. There are several variants derived from CSMA: Non-persistent CSMA, 1-persistent CSMA, and p-persistent CSMA. In all variants, a node senses the channel before sending. In non-persistent CSMA, if a node detects an idle medium, it transmits immediately. If the medium is busy, it waits a random amount of time and start carrier sense again. In 1-persistent CSMA, a node transmit if the medium is idle. Otherwise it continues to listen until the medium becomes idle, and then transmits immediately. If a collision occurs, the node waits a random amount of time and start all over again. P-persistent CSMA applies to slotted channels and works as follows; When a node becomes ready to send, it senses the channel. If it is idle, it transmits with a probability p. With a probability $q = 1 - p$ it defers until the next slot. If that slot is also idle, it either transmits or defers again, with a probabilities p and q. The process is repeated until the frame is transmitted.

Kleinrock and Tobagi [32] have analyzed several CSMA protocols in detail. Table 2.1 shows the maximum normalized throughput of these protocols obtained from [32] when the normalized propagation delay is 0.01.

Table 2.1: Maximum throughput of ALOHA and CSMA.

Protocol	Maximum throughput
Pure-ALOHA	0.184
Slotted-ALOHA	0.368
1-persistent CSMA	0.529
Non-persistent CSMA	0.815
P(0.03)-persistent CSMA	0.827

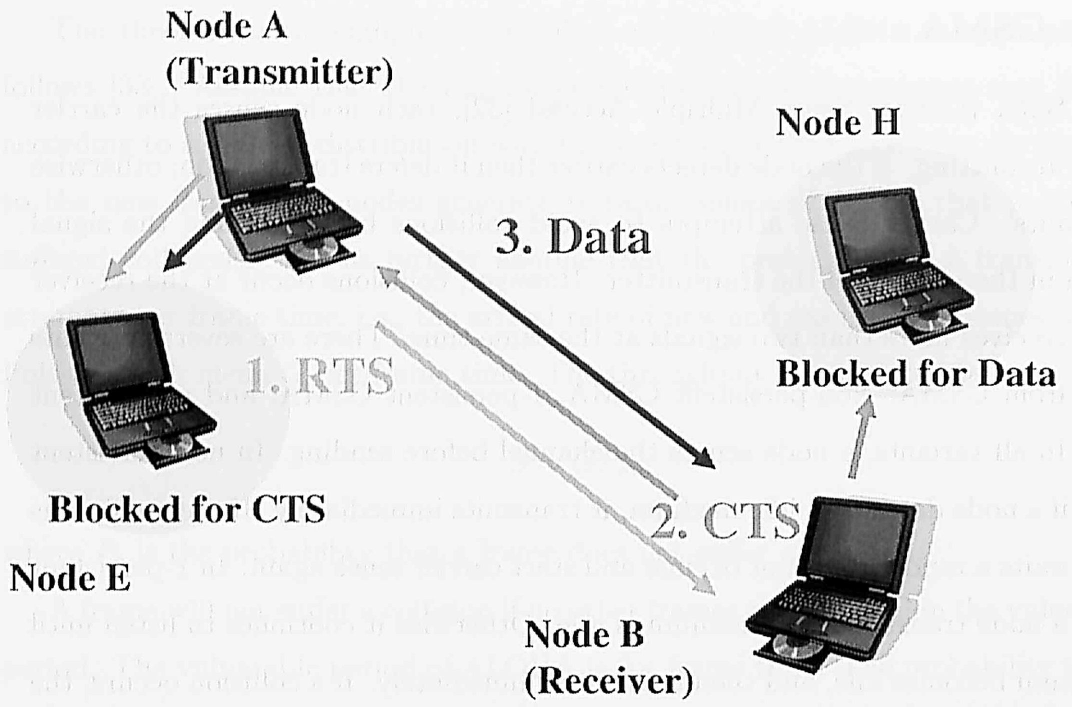


Figure 2.5: MACA.

2.4.3 MACA

Karn proposed MACA (Multiple Access with Collision Avoidance) to address the hidden-terminal and exposed-terminal problems [34]. Carrier sense is not performed at each node in MACA. Instead, the three-way handshake is used for collision avoidance. Fig. 2.5 illustrates the handshake mechanism used in MACA. When node A wishes to transmit to node B, it sends a Request To Send (RTS) frame to B; this RTS frame contains the length of the imminent data transmission. If node B receives the RTS, it immediately replies with a Clear To Send (CTS) frame; this CTS also contains the length of the imminent data transmission. Upon receiving the CTS, node A immediately sends its Data frame. Any node overhearing an RTS defers all transmissions until the associated CTS frame would have finished. On the other hand, any node overhearing a CTS frame defers for the length of the expected data transmission. Nodes that receive an RTS but not a CTS (e.g., node E in Fig. 2.5) can commence transmission without interference with the on-going communication between nodes A and B after the CTS has been sent because they are in range of the transmitter but out of range of the receiver. This mitigates the exposed-terminal problem. The hidden-terminal problem is solved by CTS. A hidden terminal (e.g., node H in Fig. 2.5) defers from transmitting during A's data transmission after receiving the CTS. If node A does not receive the CTS in response from node B, it assumes a collision occurred, and then schedules the packet for retransmission. MACA uses the binary exponential backoff (BEB) algorithm to select the next retransmission time, which is illustrated in Section 2.4.5.

In [35], MACA is enhanced by Bharghavan, Demers, Shenker and Zhang, and MACAW (Multiple Access with Collision Avoidance for Wireless LAN) is proposed. In MACAW, the MILD (Multiplicative Increase Linear Decrease) backoff algorithm is used and the CW (Contention Window) size, which is discussed in Section 2.4.5, is shared by neighbors to improve fairness. In [36], Fuller and Garcia-Luna-Aceves propose FAMA-NTR (Floor Acquisition Multiple Access Non-persistent Transmit Request). FAMA-NTR enhances MACA by using non-persistent CSMA.

2.4.4 MACA-BI

In [39], Talucci and Gerla propose MACA-BI (By Invitation), a simplified version of MACA with the two-way handshake and a first receiver-initiated MAC protocol for ad hoc networks. Fig. 2.6 illustrates the handshake mechanism used in MACA-BI. In MACA-BI, RTS frames are omitted and all transmissions are triggered by receivers using the RTR (Ready To Receive) frame, which is transmitted by the receiver node for inviting the transmitter node to transmit its packet. This reduces the number of control frames and also reduces the Tx-Rx turn-around time. Because each node does not have the exact knowledge of the packet arrivals at neighbor nodes, the traffic estimator at each node predicts the packet arrivals of neighbor nodes based on the previous history. If the polled node has no packet for the polling node, the transmission of the RTR frame degrades the network performance. Therefore, MACA-BI needs the good traffic estimator at each node to perform well.

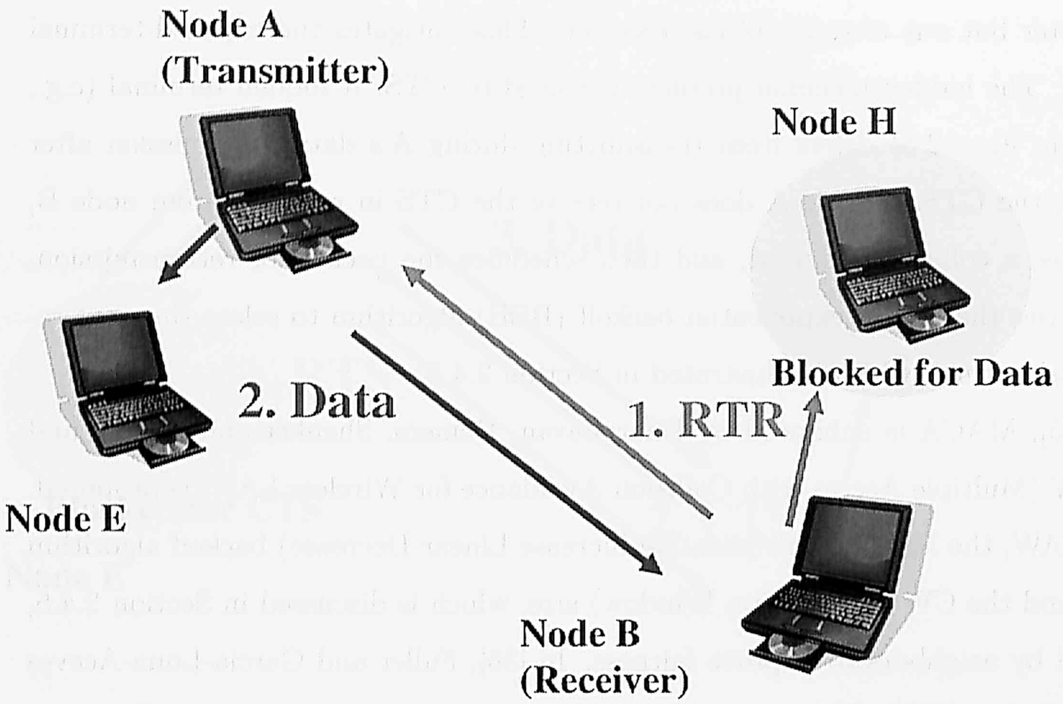


Figure 2.6: MACA-BI.

2.4.5 IEEE 802.11

Currently, the IEEE 802.11 [16] is the de facto standard for wireless local area networks (WLAN) and also for ad hoc networks. It specifies both the medium access control (MAC) and the physical (PHY) layers. The physical layer specification includes transmission techniques (e.g., DSSS (Direct Sequence Spread Spectrum), FH (Frequency Hopping), IR (infrared), and OFDM (Orthogonal Frequency Division Multiplexing)), data modulations (e.g., BPSK, QPSK, and QAM), and other physical layer functionalities. Concerning the physical layer, three IEEE 802.11 standards are currently available: IEEE 802.11b [40], IEEE 802.11a [41], and IEEE 802.11g [42]. The physical layer specifications are out of the scope and thus are not discussed in this thesis. This subsection reviews the MAC layer specification.

IEEE 802.11 Architecture

There are two modes in IEEE 802.11: ad hoc and infrastructure modes. The infrastructure mode consists of an access point (AP) acting as a coordinator for the network and mobile nodes communicating through it. Ad hoc mode essentially

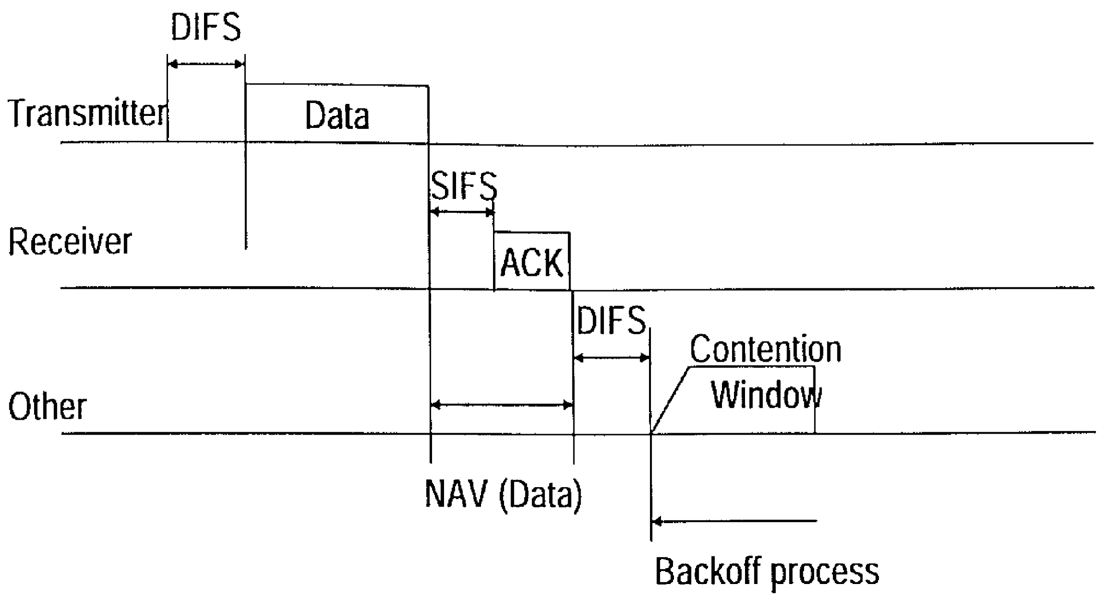


Figure 2.7: Basic access method in DCF.

eliminates the need for an access point, and the mobile nodes can be connected dynamically in an arbitrary manner. As discussed in Section 2.2, these two modes are corresponding to the distributed wireless networks and centralized wireless networks, respectively.

DCF (Distributed Coordination Function)

IEEE 802.11 MAC layer provides the Distributed Coordination Function (DCF) for contention services and the Point Coordination Function (PCF) for contention free services. The DCF is the basic medium access mechanism of IEEE 802.11, which uses CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) to mediate the access to the shared medium. On the other hand, the PCF is a centralized, polling-based access mechanism which requires the presence of a base station that acts as an access point. This paper focuses on the DCF. The DCF protocol in IEEE 802.11 standard defines how the medium is shared among nodes. It includes a basic access method and an optional channel access method with RTS and CTS exchanged as shown in Fig. 2.7 and Fig. 2.8 respectively.

Basic Access Method: For a node to transmit, it should sense the medium to determine if another node is transmitting. If the medium is not determined to

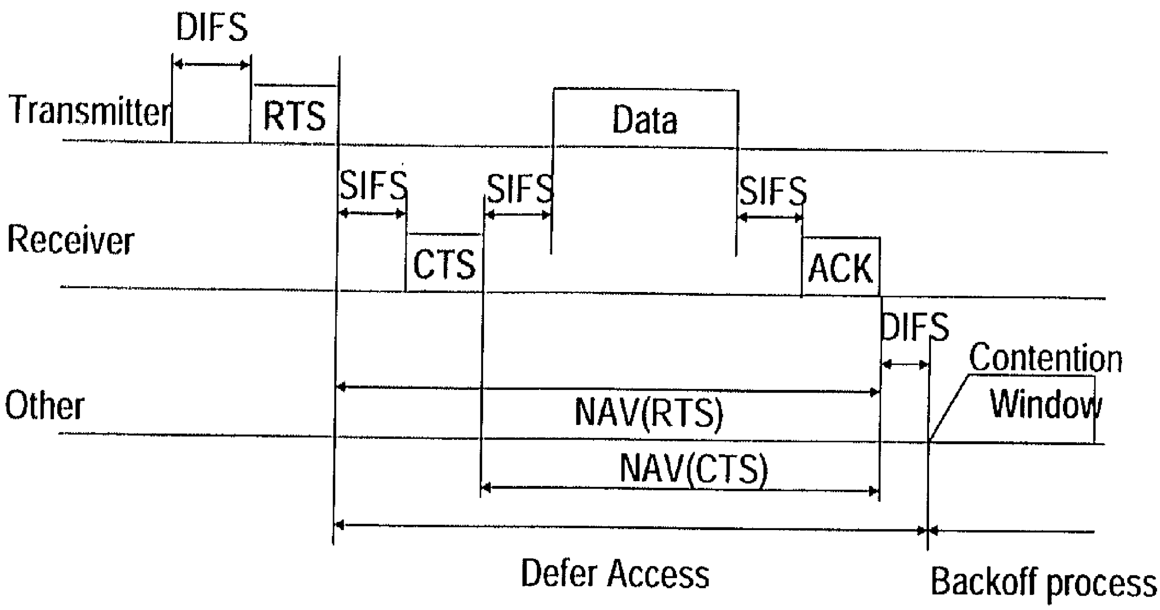


Figure 2.8: Access method with RTS/CTS in DCF.

be busy for the DIFS (DCF interframe space), the transmission may proceed. If the channel is busy for the node, a backoff time (measured in slot times) is chosen randomly in the interval $[0, CW]$, where CW is called the contention window. This timer is decremented by one as long as the channel is sensed idle. It stops when the channel is busy and resumes when the channel is idle again for at least the DIFS period. CW is an integer whose range is determined by the PHY layer characteristics: CW_{min} and CW_{max}. CW is doubled after each unsuccessful transmission, up to the maximum value which is determined by CW_{max}. When the backoff timer reaches zero, the node transmits the Data frame. This backoff algorithm is called a binary exponential backoff (BEB). The ACK is transmitted by the receiver immediately after a period of time called SIFS (Short Interframe Space), which is shorter than DIFS ($DIFS = SIFS + 2 \times SlotTime$).

When the Data frame is transmitted, all other nodes hearing this transmission adjust their network allocation vector (NAV), which is used for virtual carrier sense at the MAC layer. The NAV maintains a prediction of future traffic on the medium based on the duration information that is announced in Data frames. In addition, whenever a node detects an erroneous frame, the node defers its transmission by a fixed duration indicated by EIFS (Extended Interframe Space). This time is equal to the SIFS + ACKtime + DIFS.

Table 2.2 shows the values of the slot time, inter frame space, and CW for different PHY layer specifications. IEEE 802.11b use the same values as the legacy IEEE 802.11 (DSSS). IEEE 802.11b standard is the most widely deployed in WLANs nowadays. Therefore, this thesis uses the slot time of 20 (μ s), SIFS interval of 10 (μ s), DIFS interval of 50 (μ s), CW_{min} of 31 and CW_{max} of 1023 for simulation study.

Table 2.2: Slot time, inter frame space, and CW for different PHY layers.

Parameters	802.11 (DSSS)	802.11 (FH)	802.11 (IR)	802.11a	802.11g
Slot time (μ s)	20	50	8	9	20 or 9
SIFS (μ s)	10	28	10	16	10
DIFS (μ s)	50	128	26	34	50
CW_{min}	31	15	63	15	31 or 15
CW_{max}	1023	1023	1023	1023	1023

Access Method with RTS/CTS: If the optional access method is used, the RTS frame should be transmitted by the transmitter and the receiver should accept the data transmission by sending the CTS frame prior to the transmission of the actual data packet.

Nodes located within the transmitter's range that hear the RTS should update their NAVs and defer their transmissions for the duration specified by the RTS. Nodes that overhear the CTS frame update their NAVs and refrain from transmitting. Therefore, the hidden-terminal problem is relieved, but the exposed-terminal problem remains.

2.5 Summary

This chapter presented wireless MAC protocols. First we classified wireless networks into distributed and centralized, and focused on the distributed wireless network, a collection of nodes that communicate with one another. We then summarized the classification of wireless MAC protocols. Among the categories, contention-based MAC protocols are used in ad hoc networks. This chapter also explained the major problems in wireless MAC protocols. The unique properties of the wireless medium make the design of MAC protocols very different from, and more challenging than, wired networks. Especially, to the best of our knowledge, the hidden-terminal and the exposed-terminal problems have not been solved completely in ad hoc networks even when using RTS/CTS solution. Finally, we reviewed the typical examples of contention-based wireless MAC protocols; ALOHA, CSMA, MACA, MACA-BI, and IEEE 802.11. These protocols attempt to mitigate collisions caused by simultaneous transmissions and/or hidden-terminal problems. In the next chapter, we summarize directional MAC protocols.

Chapter 3

Directional MAC Protocols

3.1 Introduction

Wireless MAC protocols described in Chapter 2 assume that each node is equipped with an omni-directional antennas, which radiate or receive power equally well in all directions. These protocols usually reserve the wireless channel over a large area using RTS/CTS to avoid collision caused by the hidden-terminal problem, and it wastes a large portion of the network capacity. To deal with this problem, the use of directional antennas in ad hoc networks has attracted special interest recently. Directional antennas can transmit or receive in a certain direction, and it has great potential in improving the channel utilization and network capacity. However these potentials directional antennas may have, they require a sophisticated MAC protocol to take advantage of these benefits. Therefore, several MAC protocols using directional antennas, typically referred to as directional MAC protocols, have been proposed recently. Directional MAC protocols, however, introduce new kinds of problems arising from directivity.

The rest of this chapter is organized as follows: In Section 3.2, we first explain the concept and different types of directional antennas compared with omni-directional antennas. The potential benefits of directional antennas such as high spatial reuse and range extension are summarized in Section 3.3. Section 3.4 then defines the conditions of the directional communication used throughout this thesis. In Section 3.5, we identify the issues of directional MAC protocols, caused by the directional transmissions. Section 3.6 reviews and discusses the existing directional MAC protocols, followed by the summary in Section 3.7.

3.2 Directional Antennas

In this section, we describe the types and operation of directional antennas.

3.2.1 Concept of Directional Antennas

In most of the previous works on ad hoc networks, omni-directional antennas are usually used at the physical layer. These antennas radiate or receive power equally well in all directions resulting in a circular transmission/reception pattern as shown in Fig. 3.1 (A). Therefore, the signal is received by all the neighbor nodes within the transmission range. Since a packet is usually intended for a specific receiver (i.e., unicast), it is not necessary for all the surrounding nodes to receive the signal. The electromagnetic energy of the signal in omni-directional transmission is spread over a large region of space, while only a small portion of it is received by the intended receiver. This reduces the potential transmission range of each node. In addition, the wasted energy possibly interferes with other on-going transmissions. Because of antenna reciprocity, the signal is also received omni-directionally as well as transmission. Antenna reciprocity is possible because antenna characteristics are essentially the same for sending and receiving electromagnetic energy.

On the other hand, directional antennas, also called smart antennas, have the ability to direct the beam in a particular direction as well as the ability of the omni-directional transmission/reception [43, 44, 45]. Fig. 3.1 (B) shows the typical radiation pattern of directional antennas. As it can be shown from the figure, the radiation pattern consists of a main lobe of peak gain, which is pointed towards the intended receiver, and side- and back-lobes. These undesirable side lobes and back lobes are generated by the physical limitation. Directional antennas are broadly divided into two types: Switched beam antennas and Steered beam antennas.

The utility of directional antennas has already been demonstrated in cellular

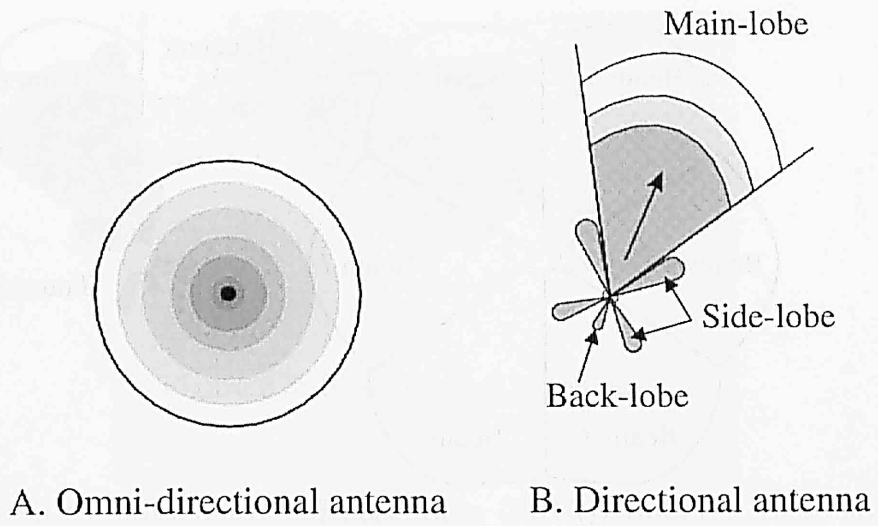


Figure 3.1: Omni-directional (A) and directional (B) antennas.

networks via its deployment at base stations [46, 47]. The first generation of analog cellular systems, such as Advanced Mobile Telephone System (AMPS), used omni-directional antennas at the base stations, which was made available in 1983. From the later AMPS implementation, three sectored directional antennas are used to increase the signal-to-interference ratio (SIR). Today mobile terminals are equipped with omni-directional antennas due to the cost and size of antennas. However, continuing reductions in the cost and size of antennas will soon make it feasible to use this technology in mobile stations and other types of wireless network systems.

3.2.2 Switched Beam Antennas

Switched beam antennas are also called sectored antennas. In switched beam antennas, the area around the antenna system is divided into a fixed number of sectors. Each antenna element transmits a beam such that covers one sector. Hence for an M-sectored switch beam antenna system, there are M antenna elements covering $(2\pi/M)$ for each. An example of a 6-sectored switched beam antenna and its coverage pattern for a single beam is shown in Fig. 3.2. In practice, multiple fixed beams are formed by shifting the phase of each element's signal by a predetermined amount, and the transceiver can then choose one beam for transmitting or receiving.

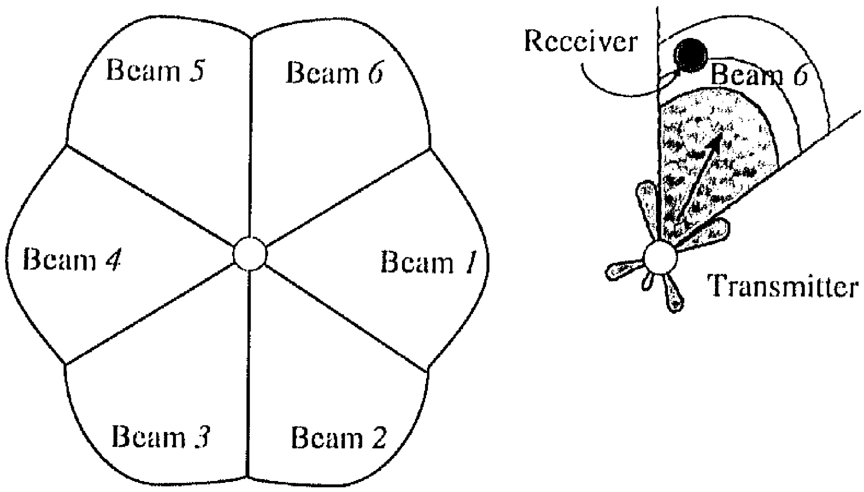


Figure 3.2: Switched beam antenna with 6 beams.

It can propagate a beam in one of the given lobes but cannot steer the angle of the lobe dynamically. Switched beam antennas are cheaper and require less complexity than the steered beam antennas.

3.2.3 Steered Beam Antennas

In a steered beam system, the main lobe can be pointed virtually in any direction, and therefore it can be focused to the precise angle of the intended receiver as illustrated in Fig. 3.3. This is achieved by including a direction of arrival (DoA) algorithm for the signal received from the node in phased array antenna systems. MUSIC (multiple signal classification) [48], ESPRIT (estimation of signal parameters via rotational invariance techniques) [49], and SAGE (space alternating generalized expectation maximization) [50] are methods for estimating the DoA. When adaptive array antennas are used, a DoA algorithm for determining the direction towards interference sources (e.g., other nodes) is added for suppressing the signal from interference sources. The radiation pattern can then be adjusted to null out the interferers. In addition, by using special algorithms and space diversity techniques, the radiation pattern can be adapted to receive multipath signals which can be combined. These techniques will maximize the signal to interference ratio

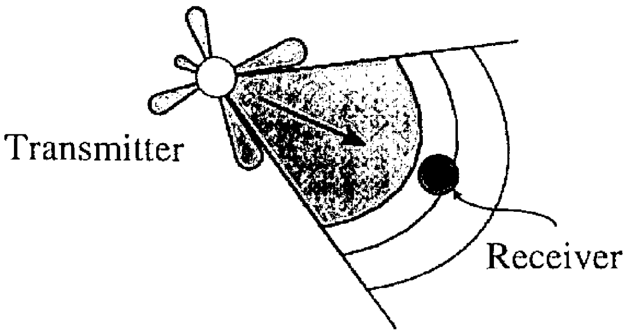


Figure 3.3: Steered beam antenna.

(SIR) (or signal to interference and noise ratio (SINR)) However, these antennas are complex and involve the higher cost compared with switched beam antennas. Directional MAC protocols with cooperative nulling are proposed in [51, 52] to take advantage of null steering in adaptive array antenna systems.

Recently, small, low cost and low power array antennas have been developed for user terminals such as in ad hoc networks. One example is ESPAR (Electronically Steerable Passive Array Radiator) antenna [53, 54, 55] (Fig. 3.4). Adaptive array antennas are normally digital beamforing antennas. On the other hand, ESPAR antenna relies on RF beamforming which drastically reduces the circuit complexity. The ESPAR antenna consists of one center element connected to the main radiator and several surrounded parasitic elements in a circle (Fig. 3.5). Each parasitic element (the passive radiator) is reactively terminated to ground. Adjusting the value of the reactance, which terminates the parasitic elements, forms the antenna array radiation pattern into different shapes. The features of ESPAR antenna are: controlling beam direction, multiple beams formation, steerable beam and controlling null steering. ESPAR antenna can also be used as a switched beam antenna, by selecting the predefined value of reactance for one specific directional beam among multiple directional beam patterns.

Some researchers attempted to compare with efficiency of various smart antennas technology (i.e., switched type and steered type) for MAC protocols [45, 56]. The purpose of this thesis is not the comparison of the antenna technology but

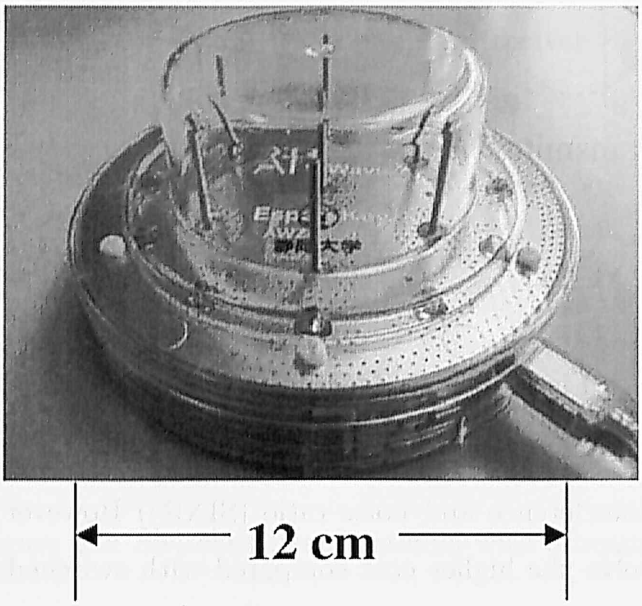


Figure 3.4: ESPAR antenna.

development of effective access method.

3.3 Benefits of Directional Antennas

This section discusses the benefits of directional antennas in ad hoc networks. As described in Section 3.2, directional antennas can transmit or receive in a desired direction, and thus have the following benefits when used in ad hoc networks.

1. High link quality due to high SINR
2. Spatial reuse of the wireless channel
3. Range extension obtained by the higher antenna gain
4. Reduction of power consumption

High link quality is achieved by reducing the undesirable signal power and/or by suppressing the signal from interference sources. This benefit contributes to the higher performance at the physical layer. Second and third benefits contribute to

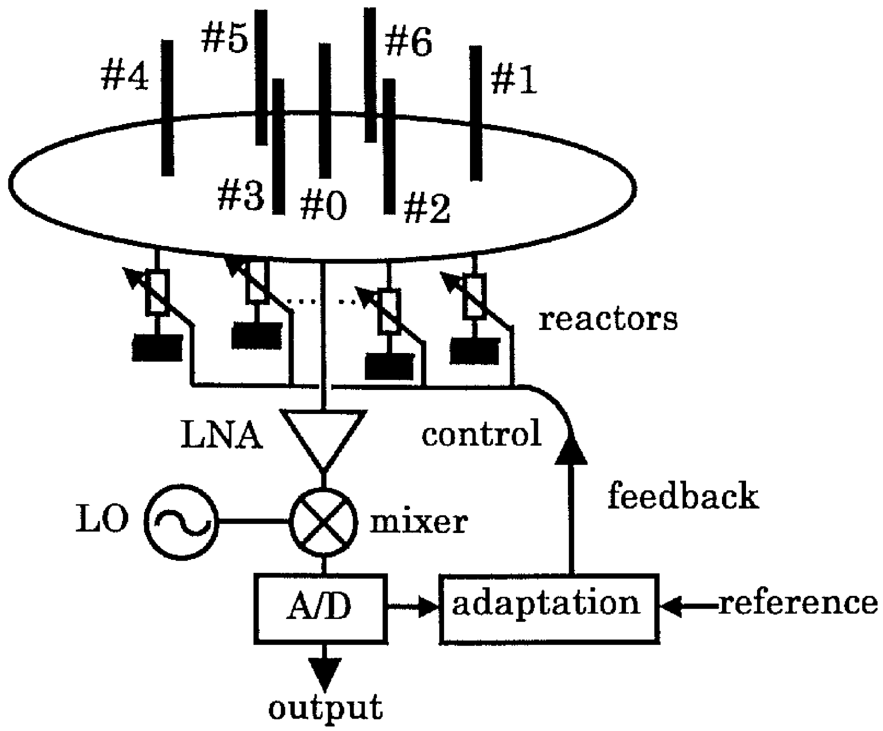


Figure 3.5: Configuration of ESPAR antenna.

the MAC layer performance, which this thesis discusses. Increasing spatial reuse of the wireless channel allows nodes to communicate without interference at the same region, frequency and time. Therefore, the number of simultaneous communications in ad hoc networks is increased, and consequently the high throughput is achieved. Furthermore, the directional transmission concentrates signal power to the receiver, which enlarges the transmission range. Thus, it can potentially establish links between nodes far away from each other, and the number of routing hops can be fewer than that of omni-directional antennas.

Now we illustrate these two potential benefits compared to the omni-directional antennas. Fig. 3.6 shows a communication scenario where there are 12 nodes in a given area and each node is equipped with an omni-directional antenna. In the figure white squares show the communicating nodes and black squares show the idle or blocked nodes. When each node is equipped with an omni-directional antenna, nodes located within the communicating nodes should be silent until the entire data

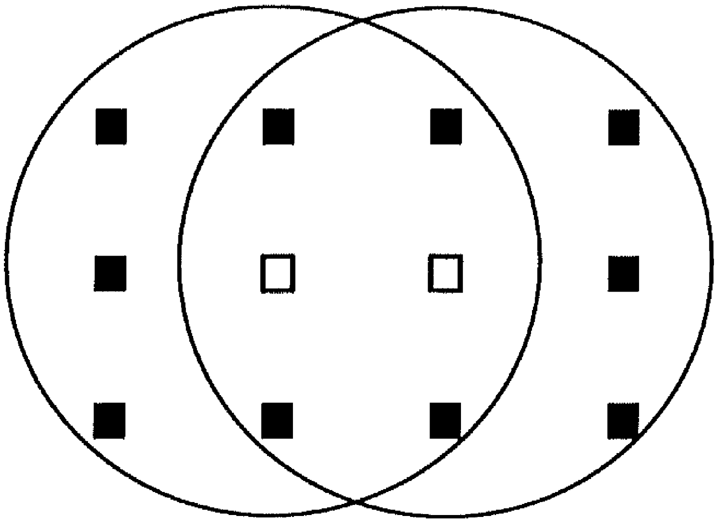


Figure 3.6: Communication scenario of omni-directional case.

transmission completes; otherwise collision occurs. To avoid collisions, traditional MAC protocols introduce the RTS/CTS solution such as in IEEE 802.11 as discussed in Chapter 2. However, it wastes a large portion of the network capacity by reserving the wireless media over a large area as discussed in [17, 18].

Directional antennas can deal with this problem and improve the network performance by spatial reuse of the wireless channel. Fig. 3.7 shows the effect of spatial reuse where each node is equipped with a switched beam antenna system. In the figure, five simultaneous communications are possible without interference when each node points its beam towards the communication partner. This is the scenario when transmission range is kept the same for omni-directional and directional communications.

Fig. 3.8 shows the effect of range extension. Typically, gain of main lobe is higher than that of omni-directional beam. The directional transmission concentrates signal power to the receiver, which enlarges the transmission range with the same input power. Therefore, it can potentially establish links between nodes far away from each other, and it prevents network partitions and the number of routing hops can be fewer than that of omni-directional antennas. This effect can increase the throughput performance and also reduce the end-to-end delay. To the contrary, if

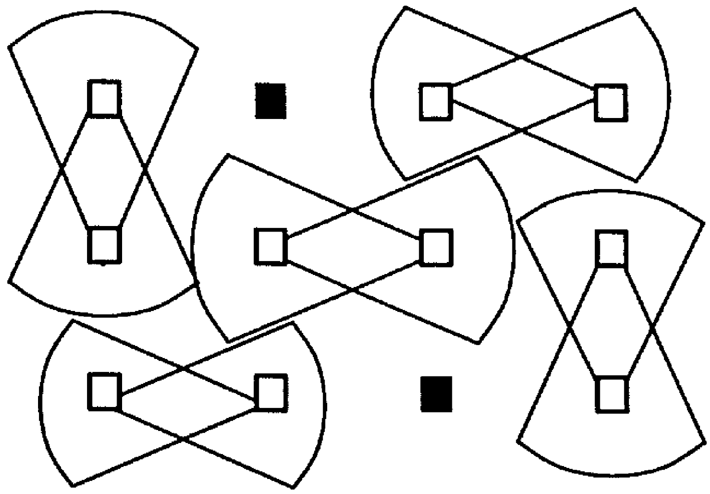


Figure 3.7: Effect of spatial reuse.

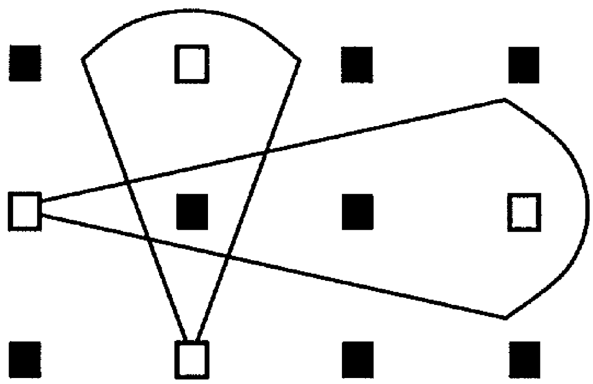


Figure 3.8: Effect of range extension.

each node equalizes its transmission range with omni-directional transmission range, it requires the low power input and power consumption is reduced. This is the fourth effect of directional antennas.

3.4 Definitions of Directional Communication

We define N as a set of nodes in the network area ($N = \{n_1, n_2, \dots, n_K\}$). We define the omni-directional antenna pattern as a circle with radius r^o, and the directional antenna pattern as a circular sector with radius $r^d (\geq r^o)$, angle (boresight of the antenna pattern) α ($0 < \alpha \leq 2\pi$) and beamwidth θ ($0 < \theta \leq 2\pi$).

Omni-directional transmission area and omni-directional reception area of $n_i \in N$ are defined as $T^o_{n_i}$ and $R^o_{n_i}$, respectively. Also, directional transmission area and directional reception area of n_i are defined as $T^d_{n_i}(\alpha, \theta)$ and $R^d_{n_i}(\alpha, \theta)$, respectively.

We assume that node n_t transmits a message with angle α_t and beamwidth θ_t, and node n_r receives it with angle α_r and beamwidth θ_r (Fig. 3.9). When the transmission area T_{n_t} and the reception area R_{n_r} are overlapped, n_r will receive a message transmitted by n_t, which is defined as $\{T_{n_t} \cap R_{n_r} \neq \emptyset\}$. In directional case, in addition, n_r will receive a message transmitted by n_t iff (if and only if) Equations (3.1), (3.2) and (3.3) hold, which is defined as $\{T^d_{n_t}(\alpha_t, \theta_t) \cap R^d_{n_r}(\alpha_r, \theta_r) \neq \emptyset\}$.

$$\frac{\theta_t}{2} \geq \begin{cases} \mid \alpha_t - \delta_t \mid & (\mid \alpha_t - \delta_t \mid \leq \pi) \\ 2\pi - \mid \alpha_t - \delta_t \mid & (\mid \alpha_t - \delta_t \mid > \pi) \end{cases} \tag{3.1}$$

$$\frac{\theta_r}{2} \geq \begin{cases} \mid \alpha_r - \delta_r \mid & (\mid \alpha_r - \delta_r \mid \leq \pi) \\ 2\pi - \mid \alpha_r - \delta_r \mid & (\mid \alpha_r - \delta_r \mid > \pi) \end{cases} \tag{3.2}$$

$$\mid n_t - n_r \mid \leq r^d + r^d \tag{3.3}$$

where δ_t is an angle from n_t to n_r, δ_r is an angle from n_r to n_t, and $\mid n_t - n_r \mid$ is the distance between nodes. Informally speaking, a transmitting beam of n_t should be towards n_r, and vice versa.

3.5 Issues of Directional MAC Protocols

This section summarizes the issues of directional MAC protocols. Directional antennas have great potential to deal with the problem of omni-directional antennas and to improve the network performance, such as high spatial reuse and range extension. On the other hand, traditional MAC protocols, such as IEEE 802.11, do not benefit by using directional antennas because intrinsically these protocols have been designed for omni-directional antennas. For that reason the design of a new

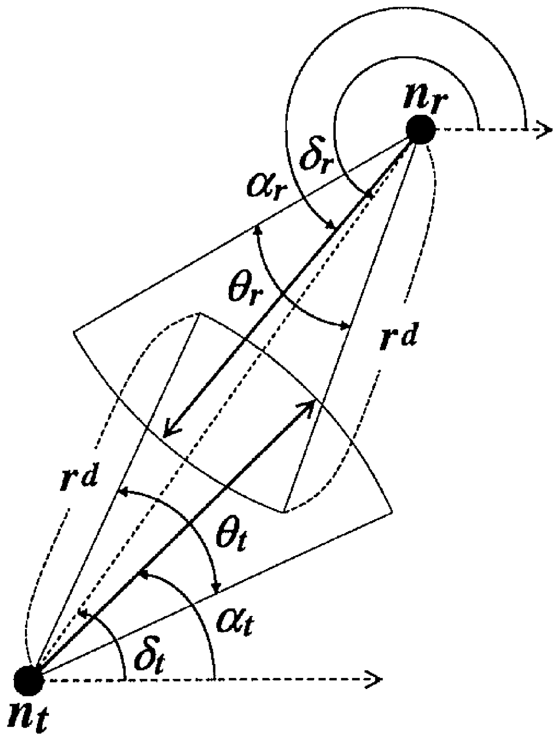


Figure 3.9: Definition of directional communication.

MAC protocol for ad hoc networks using directional antennas is required to take advantage of these benefits that are provided.

Therefore, several MAC protocols using directional antennas for ad hoc networks have been proposed recently. These are typically referred to as directional MAC protocols. However, directional MAC protocols inherently introduce new kinds of problems related to directional transmissions as identified in [58, 59, 60]. We discuss these common problems of directional MAC protocols here.

3.5.1 Determination of Neighbors' Location

In directional MAC protocols, the transmitter must know and maintain the location of the intended receiver to point the beam in the appropriate direction while network topology is dynamically changing. In order to extend the transmission range, it is necessary to obtain the information of the nodes located farther away than the omni-directional transmission range. Therefore, most of directional MAC protocols use the table to maintain the direction of neighbor nodes. When the transmitter uses the table information recorded in advance to point the beam towards the specific node, a gap between the cached location information and the actual location of the neighbor node is arisen due to the lapse of time and the mobility of nodes. This gap deteriorates the reliability of the transmission because the direction of transmission becomes inaccurate due to the out-of-date location information.

We assume n_t attempts to communicate with n_r with angle α_t and beamwidth θ_t based on the cached angle information about n_r. Actual angle from n_t to n_r is δ_t.

When the angle gap becomes larger than the beamwidth, n_t fails to communicate with n_r, which is defined as Equation (3.4). We refer to this phenomenon as location information staleness (Fig. 3.10).

$$\frac{\theta_t}{2} < \begin{cases} \mid \alpha_t - \delta_t \mid & (\mid \alpha_t - \delta_t \mid \leq \pi) \\ 2\pi - \mid \alpha_t - \delta_t \mid & (\mid \alpha_t - \delta_t \mid > \pi) \end{cases} \tag{3.4}$$

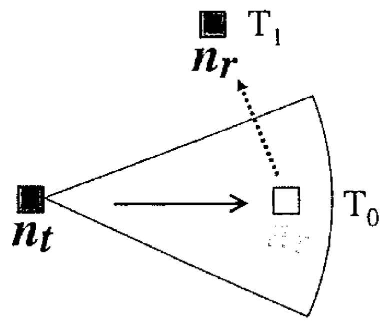


Figure 3.10: Location information staleness.

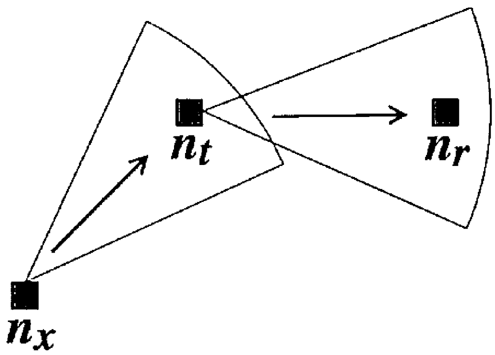


Figure 3.11: Deafness.

3.5.2 Deafness

Directional transmission of RTS/CTS, which is usually used in directional MAC protocols, introduces new kinds of problems. One problem is deafness [58]. In Fig. 3.11, deafness is caused when n_x repeatedly attempts to communicate with n_t, but it fails to communicate because n_t has its beam pointed towards a direction away from n_x and cannot hear the signal from n_x.

A set of deafness nodes $D(n_t, n_r)$ is defined as follows.

$$D = \{n_x | n_x \in N, \{T^d_{n_x} \cap R^d_{n_t} = \emptyset\} \vee \{T^d_{n_x} \cap R^d_{n_r} = \emptyset\}\} \tag{3.5}$$

where n_t is a transmitting node, n_r is a receiving node and n_x is a deafness node, which wants to communicate with n_t or n_r.

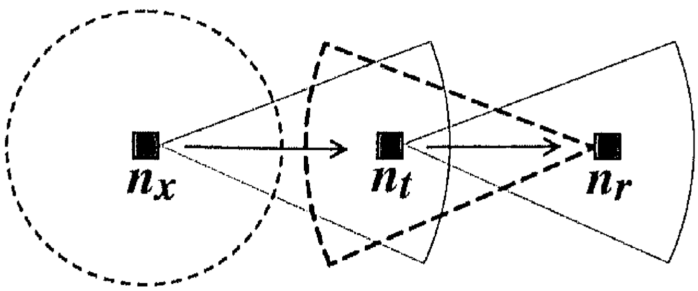


Figure 3.12: Directional hidden-terminal problem.

3.5.3 Directional Hidden-Terminal Problem

The other problem of directional RTS/CTS is hidden-terminal due to asymmetry in gain [58], referred to as the directional hidden-terminal problem in this thesis. Assume that n_t is communicating with n_r (Fig. 3.12). Directional hidden-terminal problem is caused by the neighboring node of the on-going communication, say n_x, which is far enough from n_r not to hear the CTS pointed towards n_t (and also n_x). If n_x transmits the RTS directionally towards the direction of n_r, it may interfere with the on-going communication because n_r is receiving DATA with a higher gain beam pointed towards n_t and n_x.

A set of directional hidden terminals $H(n_t, n_r)$ is defined as follows.

$$H = \{n_x | n_x \in N, \{T^d_{n_t} \cap R^o_{n_x} = \emptyset\} \wedge \{T^d_{n_r} \cap R^o_{n_x} = \emptyset\} \wedge \{T^d_{n_x} \cap R^d_{n_r} \neq \emptyset\}\} \quad (3.6)$$

where n_t is a transmitting node, n_r is a receiving node and n_x is a directional hidden terminal of n_r.

3.5.4 Directional Exposed-Terminal Problem

In most of directional MAC protocols, each node waits for signals with the omni-directional mode in an idle state. Therefore, in Fig. 3.13, during the data transmission between n_t and n_r, n_x gets engaged in receiving signals between n_t and n_r. If n_y sends RTS to n_x, it will result in collision at n_x. We refer to this type of exposed-terminal problem as the directional exposed-terminal problem.

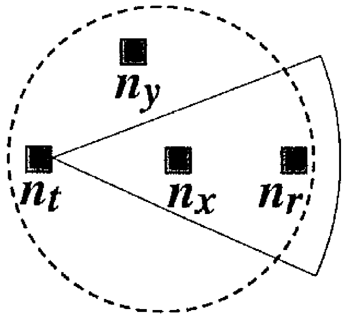


Figure 3.13: Directional exposed-terminal problem.

A set of directional exposed terminals $E(n_t, n_r)$ is defined as follows.

$$E = \{n_x | n_x \in N, \{T^d_{n_t} \cap R^o_{n_x} \neq \emptyset\}\} \tag{3.7}$$

where n_t is a transmitting node, n_r is a receiving node and n_x is a directional exposed-terminal of n_t.

3.6 Conventional Directional MAC Protocols

Recently, several directional MAC protocols for ad hoc networks have been proposed to take advantage of benefits that directional antennas provide. These are usually modifications of IEEE 802.11 DCF. This section reviews and discusses the existing directional MAC protocols in the literature.

3.6.1 Omni-directional RTS/CTS MAC

In [61], Nasipuri, Ye, You and Hiromoto propose a simple modification of IEEE 802.11 DCF. In the protocol, the RTS and CTS frames are transmitted omni-directionally for each Data frame. After exchanging location information each other using omni-directional RTS/CTS, directional capabilities are utilized only for Data/ACK frames.

In [62], Nasipuri, Li and Sappidi propose DMACP (Directional antenna based MAC protocol with Power control). DMACP reduces power consumption by optimization of the transmission power due to estimating the SINR. In [63], Fahmy, Todd and Kozys also propose a similar approach as DMACP.

Adaptive MAC is proposed by Bandyopadhyay, Gyoda, Hasuike, Horisawa, Kado and Tawara in [64, 65]. Omni-directional RTS/CTS is also used in adaptive MAC. In [66], Ueda, Tanaka, Saha, Roy and Bandyopodhyay propose a receiver-oriented rotational-sector based directional MAC protocol. If each node senses some signal, it rotates its directional antenna sequentially and senses the received signal at each direction. Then, it sets its beam to the direction with maximum received signal strength and receives the signal. To track the best possible direction of receiving signal, each control frame is transmitted with a preceding tone. In the protocol, the RTS and CTS frames are transmitted omni-directionally and directional capabilities are utilized only for Data/ACK frames.

These schemes are only available for communications within the omni-directional transmission range because RTS/CTS are transmitted omni-directionally. These schemes cannot exploit one of the main benefits of directional antennas, i.e., the increase of the transmission range. Although omni-directional RTS/CTS is one simple solution for determination of neighbors' location and for avoiding deafness by notifying the on-going communication to all neighbors, it cannot initiate any transmissions until the whole area around the transmitter and the receiver becomes idle. This may reduce the benefits of spatial reuse, a key advantage of directional antennas.

3.6.2 DMAC

Ko, Shankarkumar and Vaidya [57] proposed a first MAC protocol for ad hoc networks using directional antennas in which CTS frames are always transmitted omni-directionally, while RTS control frames are transmitted directionally (scheme 1) or omni-directionally if the channel is clear for all directions (scheme 2).

Choudhury, Yang, Ramanathan and Vaidya propose DMAC (Directional MAC) in which all frames are transmitted and received directionally, and physical and

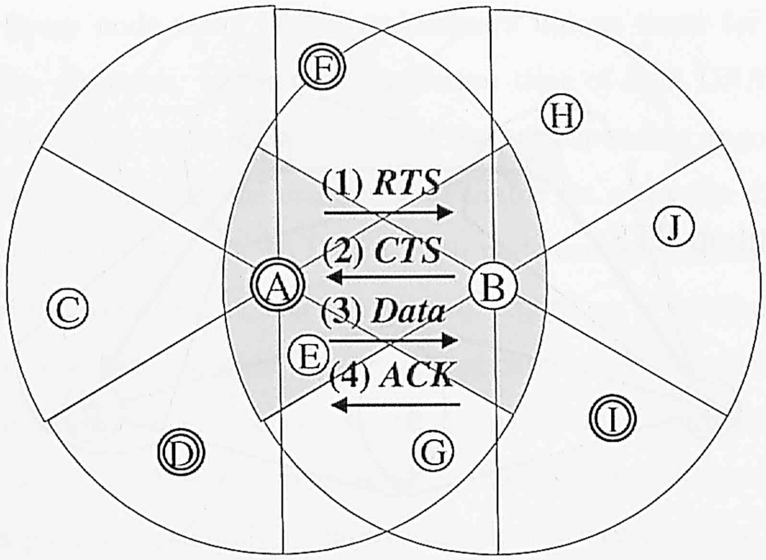


Figure 3.14: DMAC.

virtual carrier sense functions are also performed directionally. Fig. 3.14 shows the communication between node A and node B in DMAC. In this thesis, we refer to this protocol as DMAC with DPCS (Directional Physical Carrier Sensing). Directional virtual carrier sensing is realized by DNAV (Directional NAV), a directional version of NAV. This is also proposed in [67] and we explain DNAV in Section 3.6.4. It is assumed that each node knows exact locations of other network nodes by means of additional hardware such as GPS, and each node transmits signals based on the direction derived from such physical location information.

3.6.3 MMAC

In [58, 59], Choudhury, Yang, Ramanathan and Vaidya propose Multihop RTS MAC (MMAC) to take advantage of the higher antenna gain obtained by directional antenna. MMAC uses multihop RTSs to establish links between distant nodes and then transmits CTS, DATA, and ACK over a single hop (Fig. 3.15). They, however, assume that each node knows the location of other nodes a priori. Therefore, MMAC also needs various additional mechanisms to provide the location information and to forward the RTS. In [58, 59], the issues of directional MAC protocols including

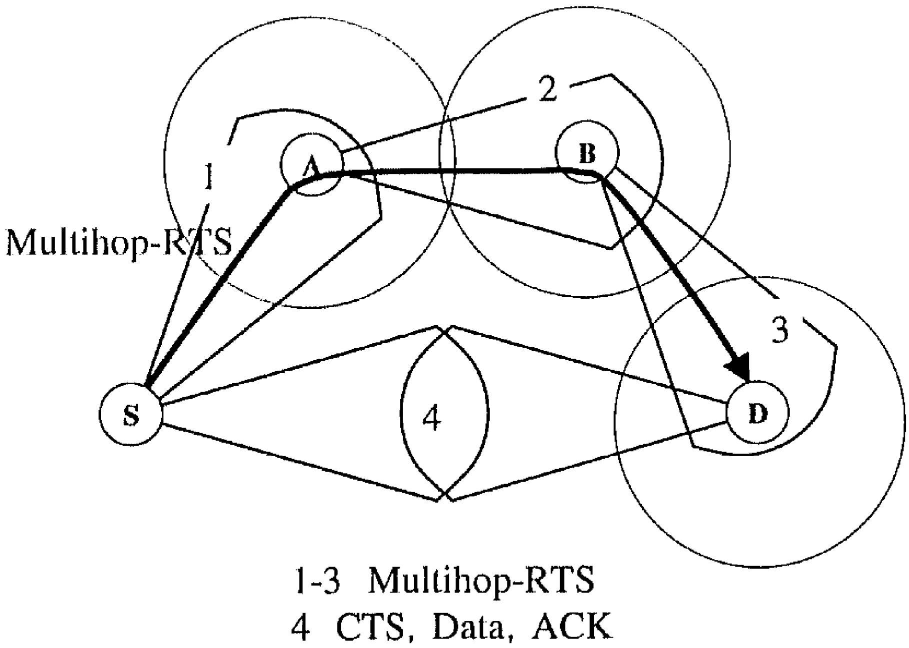


Figure 3.15: MMAC.

deafness and hidden-terminal problems are discussed but no solution is provided.

3.6.4 DVCS

Directional Virtual Carrier Sensing (DVCS) is proposed by Takai, Martin, Ren and Bagrodia [67]. The main idea behind DVCS is to allow contention-based MAC protocols to determine direction-specific channel availability. For that, DVCS uses the directional network allocation vector (DNAV), a directional version of the network allocation vector (NAV) of the IEEE 802.11, which contains information about the total duration of a transaction that is about to happen over the channel. During this time, the node cannot transmit any frame to the channel, reserving it for others do it. In DVCS, the DNAV reserves the channel for others only in a range of directions. To accomplish this, DVCS requires minimal information from the underlying physical device, such as the angle of arrival (AOA) and the antenna gain for each signal, features that can be readily available at the physical layer. Multiple DNAVs can be set for a node, and each DNAV is associated with a direction and a width

(Fig. 3.16). Every node using DVCS maintains a unique timer for each DNAV, and updates the direction, width, and expiration time of each DNAV every time the physical layer gives newer information on the corresponding ongoing transmission. DVCS determines that the channel is available for a specific direction when no DNAV covers that direction. In DVCS, each node caches estimated AOAs from neighboring nodes every time it hears any signal, regardless of whether the signal is addressed to it. If a node has data to send, it first checks if AOA information for the particular neighbor has been cached. If yes, it beamforms the directional antenna towards the cached AOA direction to send an RTS frame. Otherwise, the frame is transmitted omni-directionally. Updates are done every time the node receives a newer signal from the neighbor, and it invalidates the cache if it fails to get the CTS back from the neighbor after 4 failed directional transmissions of RTS frames. Subsequent RTS frames are sent omni-directionally. When the node receives an RTS frame from a neighbor, it adapts its beam pattern to maximize the received power and locks the pattern for the CTS transmission. If the node transmitted an RTS frame to a neighbor, it locks the beam pattern after it receives the CTS frame from the neighbor. The beam patterns at both sides are used for both transmission and reception, and are unlocked after the ACK frame is transmitted.

3.6.5 UDAAN

In [68, 69], Ramanathan, Redi, Santivanez, Wiggins and Polit present utilizing directional antennas for ad hoc networking (UDAAN). UDAAN consists of several mechanisms: a directional power-controlled MAC, neighbor discovery with beamforming, link characterization for directional antennas, proactive routing and forwarding.

Proposed MAC protocols in [57, 61, 62, 63, 64, 65, 66, 67] use at least one omni-directional control frame transmission and thus limits the coverage range in this of omni mode transmission. To fully exploit the increase in coverage range with the use of directional antennas, it must use only directional transmissions.

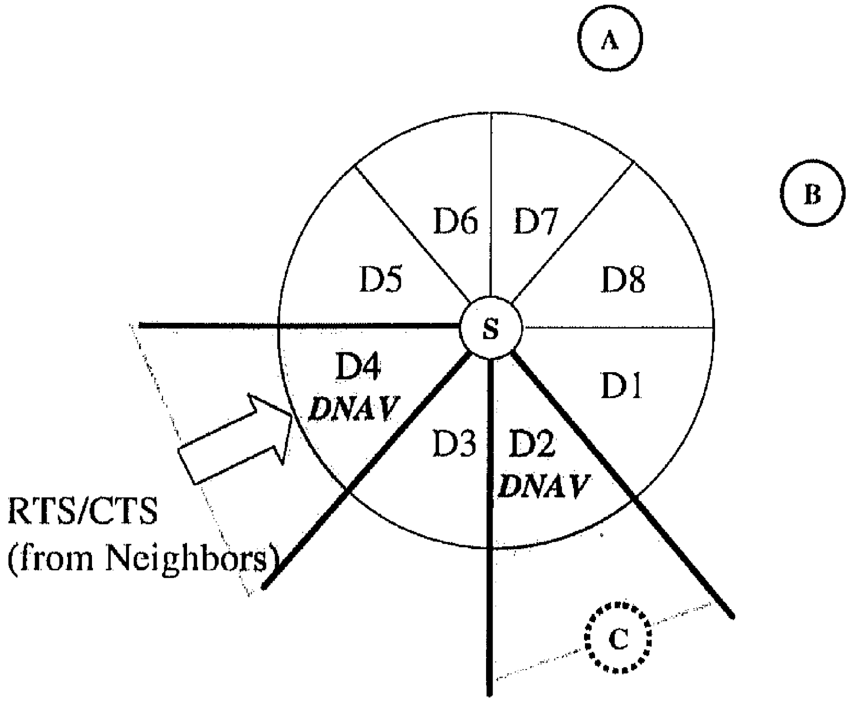


Figure 3.16: DNAV

In order to exploit the longer range advantage of directional antennas, UDAAN incorporates directional neighbor discovery, that is, the ability to discover neighbors that can only be reached if one or both of the nodes use beamforming. Each node periodically sends the Hello message for every beam, and the neighbor nodes determine the direction of the sender by tracking the received AOA. Certainly, this mechanism can provide the longer range, but circular transmission increases delay. This is one factor that causes the throughput decline. Moreover, the overhead of periodical Hello messages increases with high node density. The results in [45] show the degradation of the network performance.

3.6.6 CRM

Korakis, Jakllari and Tassiulas propose Circular RTS MAC (CRM) [72]. In CRM, multiple directional RTS frames are transmitted consecutively in a circular way to scan all the area around the transmitter to find the addressed receiver

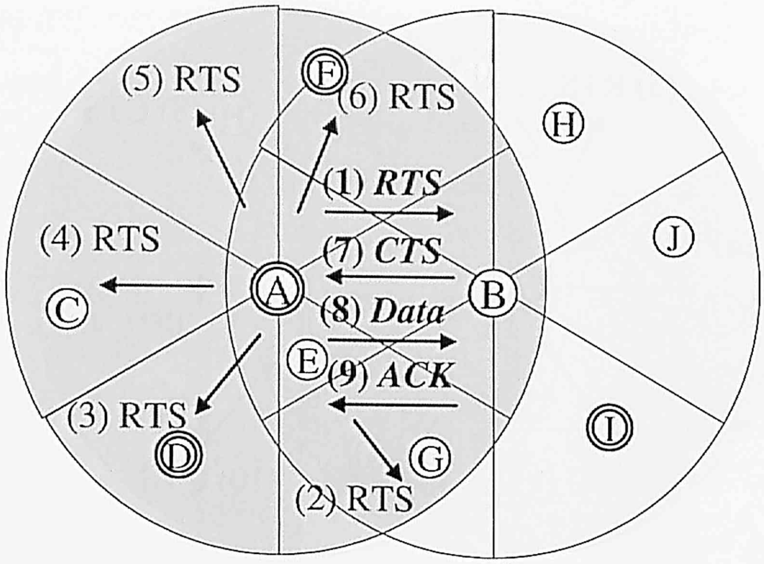


Figure 3.17: Circular RTS MAC.

and to tackle the deafness and the hidden-terminal problem arisen from directional transmissions. Fig. 3.17 illustrates an example sequence of CRM, where node A is the transmitter and node B is the receiver. It prevents deafness by notifying the on-going communication to neighbor nodes. While it prevents deafness at the transmitter side, deafness at the receiver side may appear when node I attempts to communicate with node B. Moreover, if node B does not reply with CTS and node A cannot transmit Data frame, the neighboring nodes of A, which receive RTS and set DNAV, also cannot initiate their own transmissions for the reserved entire duration, and it results in serious wastage of the wireless channel.

3.6.7 CRCM

To handle deafness at the receiver side, Jakllari, Broustis, Korakis, Krishnamurthy and Tassiulas propose Circular RTS and CTS MAC (CRCM) [73]. CRCM uses the circular CTS frames transmitted towards unaware neighbor nodes as well as the circular RTS frames (Fig. 3.18). Although it can notify the on-going communication to all neighbor nodes around the transmitter and the receiver, the circular transmission of RTS/CTS for each transmitted data packet may incur not only the

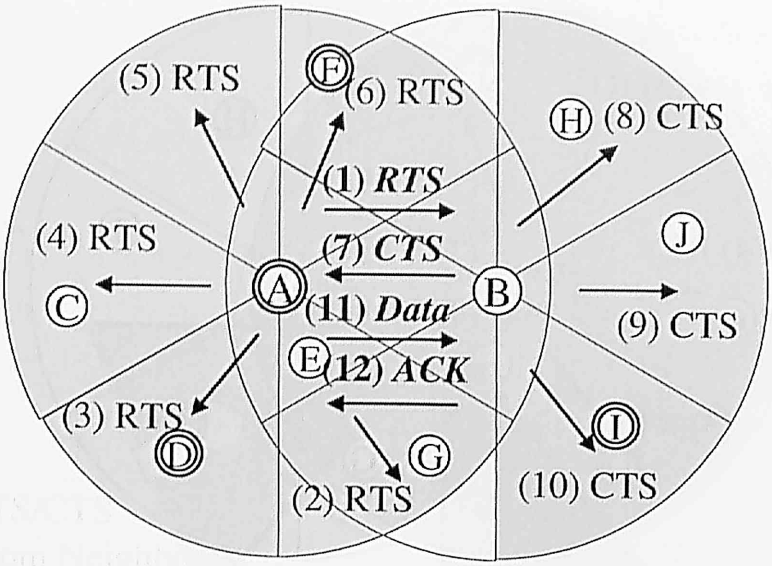


Figure 3.18: Circular RTS and CTS MAC.

delay and large control overhead as the number of beams increases but also collisions between control frames.

3.6.8 MDA

In [74], Gossain, Cordeiro and Agrawal propose MDA (MAC protocol for Directional Antennas). Fig. 3.19 shows the frame exchange of MDA, where active links are A-B, D-A, F-A, and I-B. In MDA, multiple directional RTS and CTS frames are transmitted simultaneously in Diametrically Opposite Directions, called DOD procedure, through the antenna beams with neighbors after the successful exchange of directional RTS and CTS to optimize the circular transmission of control frames. However, it is unnecessary for neighbors, which do not intend to communicate with A or B, to acquire the disjoint node information (e.g., neighbors such as nodes C and J in Fig. 3.19). Furthermore, there is a deafness region not covered by DOD procedure because it is carried out from the next beam to the opposite beam in order to reduce the number of transmitted control frames. Therefore, if node D intends to communicate with A, it may experience deafness.

In [75], Gossain, Cordeiro, Cavalcanti and Agrawal address the issue of deafness

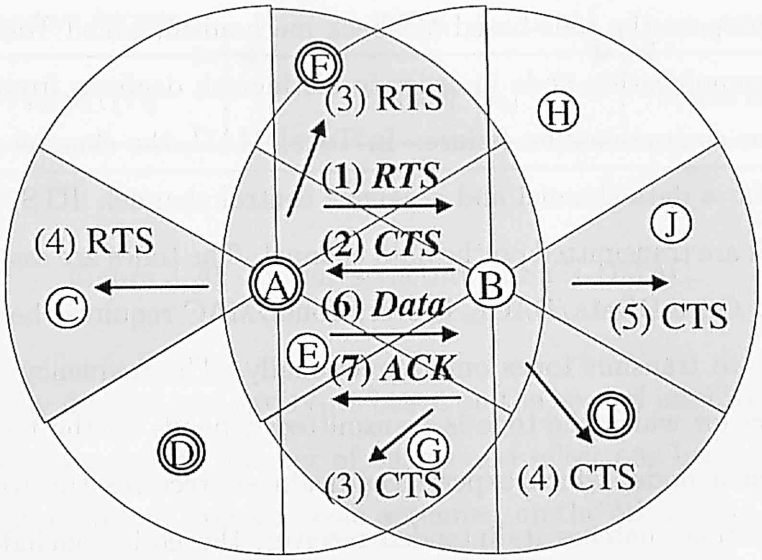


Figure 3.19: MDA.

proactively by estimating the state of the intended receiver. To do this, this scheme requires the circular transmission of RTS/CTS for each transmitted data packet to acquire the on-going transmission information of neighborhoods, which may incur large control overhead.

3.6.9 ToneDMAC

Choudhury and Vaidya [70] propose ToneDMAC, tone-based mechanism to handle deafness reactively. They first propose the omni-directional physical carrier sensing during backoff periods, called omni-directional backing off. Unlike DMAC, each node switches back to the Omni mode during backoff periods. When the node senses a signal in backoff periods, it performs the beam scan to determine the direction of the arriving signal. If the estimated direction is in a different direction from that of the intended receiver, then the transmitter continues backing off; otherwise the transmitter considers that channel is busy. If the transmitter receives RTS addressed to it during backoff periods, the transmitter freezes the backoff timer and replies with CTS. In this thesis, we refer to this variation of DMAC as DMAC with OPCS (Omni-directional Physical Carrier Sensing).

They then propose the tone-based feedback mechanism, called ToneDMAC, to neighbors of communicating node in order to distinguish deafness from congestion as the reason for communication failure. In ToneDMAC, the channel is split into two sub-channels: a data channel and a narrow control channel. RTS, CTS, Data, and ACK frames are transmitted on the data channel. The tones are assigned on the control channel. Once DData/DACK is over, ToneDMAC requires the transmitter and the receiver to transmit tones omni-directionally. The frequency of the tone, and the duration for which the tone is transmitted depends on the transmitter of the tone. When a node, which experiences deafness, receives the tone and the originator of the tone matches its intended receiver, the node concludes that the reason for previous communication failure was deafness. In order to avoid backing off unnecessarily, it preempts its current backoff timer and reselects a new smaller backoff. ToneDMAC needs a dedicated control channel to transmit tones as well as a data channel, and it may be relatively complex.

3.6.10 SYN-DMAC

Wang et al. [71] propose SYN-DMAC to address the issues of directional MAC protocols including deafness for ad hoc networks with clock synchronization. Fig. 3.20 shows the timing structure of SYN-DMAC. Contention and deafness occur during the random access phase (phase I) in a cycle. Therefore, the time that deafness lasts is compressed to the duration T_1. However, this scheme requires that nodes are synchronized to identify the timing structure, which is a challenging task in ad hoc networks. Indeed, it requires GPS receivers or other synchronization schemes (see [71] and references therein).

3.7 Summary

This chapter discussed the existing directional MAC protocols. This chapter first mentioned the concept of directional antennas. Directional antennas have the ability to point the beam in a particular direction using the array of antennas, and

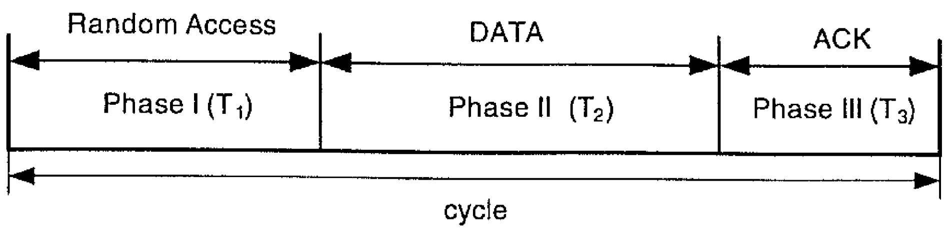


Figure 3.20: Timing structure of SYN-DMAC.

these are broadly divided into two types based on the level of intelligence. Switched beam antennas have a fixed number of beams and select one beam for directional transmission or reception. Steered beam antennas, on the other hand, can point the main lobe in any direction. We then described the benefits of directional antennas in ad hoc networks, such as high spatial reuse and range extension. We discussed the common problems of directional MAC protocols, which should be considered when designing the MAC protocol. The problem of determination of neighbors' location is the fundamental problem to control the directional beam towards the communication partner. The deafness problem and directional hidden-terminal problem are caused by a lack of state information of neighbor nodes. Directional exposed-terminal problem reduces the number of possible concurrent communications due to overhearing unproductive data frame which is not addressed for the node. Finally this chapter presented the conventional directional MAC protocols. In these protocols, the issues of directional MAC protocols identified in Section 3.5 are not well addressed. In the next chapter, we propose a new directional MAC protocol to solve the determination of neighbors' location.

Chapter 4

Solution to the Determination of Neighbors' Location

4.1 Introduction

This paper chapter proposes a new directional MAC protocol called SWAMP (Smart antennas based Wider-range Access MAC Protocol) [77] which consists of two access modes, i.e., the OC-mode (Omni-directional transmission range Communication mode) and EC-mode (Extend omni-directional transmission range Communication mode) in order to combine the spatial reuse of the wireless channel and a wider transmission range, and consequently improve the throughput performance. The OC-mode is mainly designed for spatial reuse and EC-mode is mainly for extension of the transmission range using four beamform patterns. In the OC-mode to achieve the spatial reuse, SWAMP introduces omni-NAV shorter than the conventional NAV, which triggers exposed-terminals to begin an atomic exchange. To provide extension of the transmission range, in the EC-mode, the protocol includes a method of obtaining the neighbors' location information called NHDI (Next Hop Direction Information) by RTS/CTS and additional control frame called SOF (Start of Frame). This enhancement has few overheads compared with the periodical circular probing of neighbors' location. Generally, the OC-mode is used when the pair of a transmitter and a receiver is in the vicinity, while the EC-mode is used when a receiver is out of range of a transmitter's omni-directional beamform pattern.

SWAMP is different from other protocols using directional antennas in the following points; it provides the OC-mode and EC-mode using four beamform patterns, and it provides the low overhead location information collection method in MAC layer.

We then evaluates the performance of SWAMP through computer simulations. This chapter first evaluates the basic performance of SWAMP in terms of the throughput, number of simultaneous communications, overhead, and end-to-end delay. Then, the effects of mobility, density, and retry limits on the throughput performance are evaluated. Furthermore, we analyze the different factors which reduce the probability of successful transmissions, such as location information staleness, deafness and directional hidden- and exposed-terminal problems arisen due to directional transmissions, and confirm its negative impact on the network performance. In addition, we investigate the effects of the different values of parameters related to location information staleness, such as the beamwidth and lifetime of the table information, and the mobility prediction to deal with the issue of location information staleness.

The rest of this chapter is organized as follows: Section 4.2 first proposes a novel neighbor discovery method based on NHDI. Section 4.3 presents our antenna model used in SWAMP. The access method of SWAMP, i.e., OC-mode and EC-mode is proposed in Section 4.4. Frame formats of SWAMP are presented in Section 4.5. Section 4.6 evaluates the performance of SWAMP. Section 4.7 concludes this chapter.

4.2 Neighbor Discovery

As described in Section 3.5, a transmitter must know the location of the intended receiver to point the beam in the appropriate direction. SWAMP assumes that all nodes are equipped with a GPS (Global Positioning System) receiver to determine their own locations. When a transmitter does not know the location of the intended receiver, the transmitter and the receiver exchange each other's location information by omni-directional RTS/CTS handshaking. The transmitter node includes its own location information in RTS so that the receiver node can determine the direction

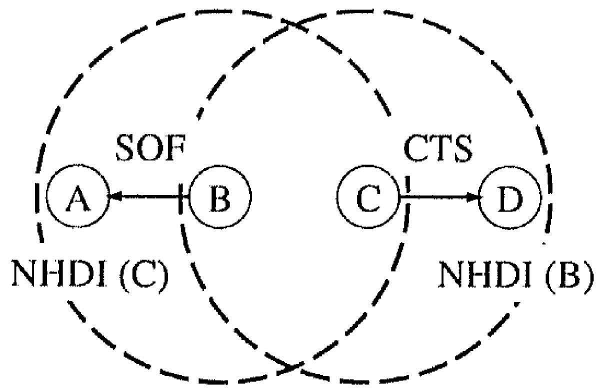


Figure 4.1: NHDI.

Table 4.1: NHDI table.

ID	NHDI	TTL
C	L_c	10
X	L_x	5
Y	L_y	7

to point the beam towards the transmitter node in reference to its own location information. Similarly, the receiver node includes its own location information in CTS. Using an omni-directional beamform is an effective method of inquiring for the address node in ad hoc networks because the nodes move independently. However, the node information, which can be obtained by using omni-directional control frame exchange, is restricted within the omni-directional transmission range. A wider transmission range for communication cannot be performed using this method. Also, though circular transmission control frames using a higher gain directional beamform [64, 45, 68, 69, 72] can obtain the node information that is located further away from the omni-directional transmission range, there are many disadvantages to this as described in Section 3.6.

We thus propose that these nodes forward the location information that is obtained by the reception of the RTS or CTS to neighbors using an omni-directional beam. As a result, neighbors can obtain the location information of nodes located within an area at most two times farther away than that of the omni-directional antenna. We refer to this information that neighbors obtain as NHDI (Next Hop Direction Information).

Control frames should be expanded in order to forward the NHDI to neighbors of both the transmitter and receiver nodes. We add SOF (Start of Frame) which is sent by the transmitter node after receiving CTS. SOF contains the NHDI of the receiver node. Also, the receiver node includes the NHDI of the transmitter node in CTS.

Fig. 4.1 illustrates the propagation of locations with control frames. In the figure, node B is a transmitter and C is the intended receiver. After the RTS/CTS/SOF exchange, D and A can recognize not only locations of B and C, respectively, but also the initiation of communications between B and C. This method does not increase the overhead significantly because of using usual control frames (though only SOF is added).

Each node obtains some NHDI by receiving either CTS or SOF. Every node maintains an NHDI table with one record for every station which receives NHDI. Table 4.1 shows the structure of NHDI table. In every record the node maintains the following information: ID (neighbor's MAC address), NHDI and the TTL (Time To Live). The TTL decreases during the progress of time. If the TTL expires, the corresponding record is deleted. When the NHDI is obtained corresponding to the MAC address that is already registered, it is updated and the TTL is initialized. The NHDI table of a node contains other nodes which the node cannot communicate directly with, which the node can communicate indirectly with by multi-hopping with an omni-directional beam, and which the node can communicate directly with a high gain directional beam to point their direction.

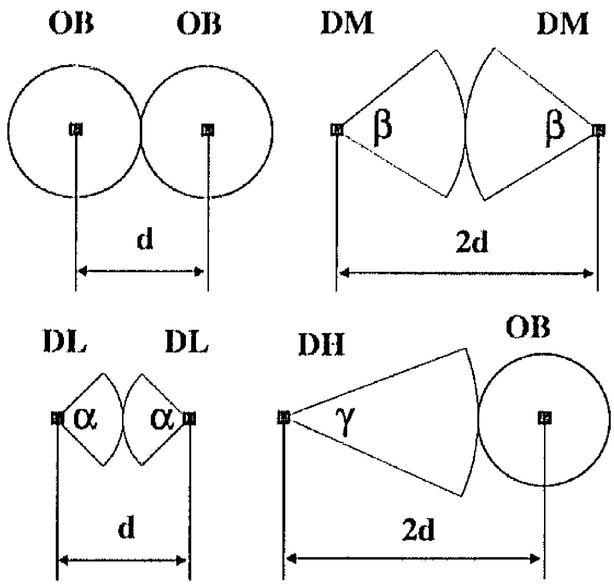


Figure 4.2: Antenna model.

4.3 Antenna Model

SWAMP provides four antenna beam forms. Each antenna beam is assumed to be able to point in any direction and can be formed during a SIFS (Short Interframe Space) interval as with in IEEE 802.11 DCF. Fig. 4.2 illustrates four beam forms and each transmission range. Note that in the figure nodes can communicate when the transmitting beam and the receiving beam are at least tangential to each other. OB and DL are for the regular link communication in OC-mode, while DM and DH for the extended link communication in EC-mode.

- Omni-directional beamform (OB): Gain is G^o (dBi) in whole direction. Transmission range is d (m) between OBs.
- Directional Low gain beamform (DL): Gain is G^o in a specific direction. Transmission range is d between DLs.
- Directional Middle gain beamform (DM): Gain is G^M ($> G^o$) in a specific direction. Tr ansmission range is 2d between DMs.

- Directional High gain beamform (DH): Gain is G^H ($> G^o$) in a specific direction. Transmission range is 2d between DH and OB.

4.4 Access Method

SWAMP is based on IEEE 802.11 DCF [16]. Therefore, several basic functions are maintained, such as physical carrier sensing, virtual carrier sensing, and random backoff procedures. In the IEEE 802.11 standard, the use of RTS and CTS control frames is optional, but SWAMP uses this option all the time for the reason that these control frames can mitigate the influence of the hidden-terminal problem.

SWAMP consists of two access modes, OC-mode (Omni-directional transmission range Communication mode) and EC-mode (Extend omni-directional transmission range Communication mode). OC-mode is selected when the receiver is in the vicinity of the transmitter or when the transmitter does not know the location of the receiver. This mode mainly increases spatial reuse of the wireless channel. EC-mode is selected when a receiver is out of range of a transmitter's omni-directional beam. EC-mode extends the transmission range.

4.4.1 OC-mode

OC-mode is selected when the receiver node is located within the area of omni-directional transmission range or is not registered in the transmitter's NHDI table. Fig. 4.3, Fig. 4.4, Fig. 4.5, Fig. 4.6 and Fig. 4.7 illustrate the OC-mode frame sequence with the corresponding beams. The RTS/CTS handshaking tries to reserve the wireless channel and to exchange the location information between the transmitter and the receiver as shown in Fig. 4.3 and Fig. 4.4. CTS/SOF forwards the NHDI in the neighborhood as shown in Fig. 4.4 and Fig. 4.5. These control frames are sent by an omni-directional beam, whereas Data and ACK frames are sent by DLs that point beams towards each other (Fig. 4.6 and Fig. 4.7).

Even if node H or E radiates to the omni-directional transmission range while node S is transmitting the data frame to D, H does not interfere with the on-going

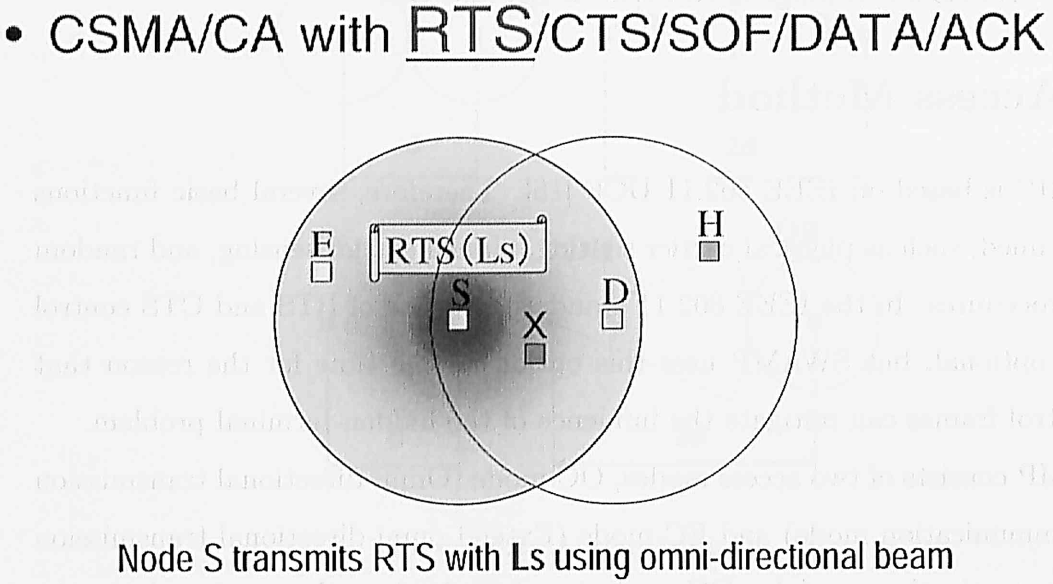


Figure 4.3: OC-mode (RTS).

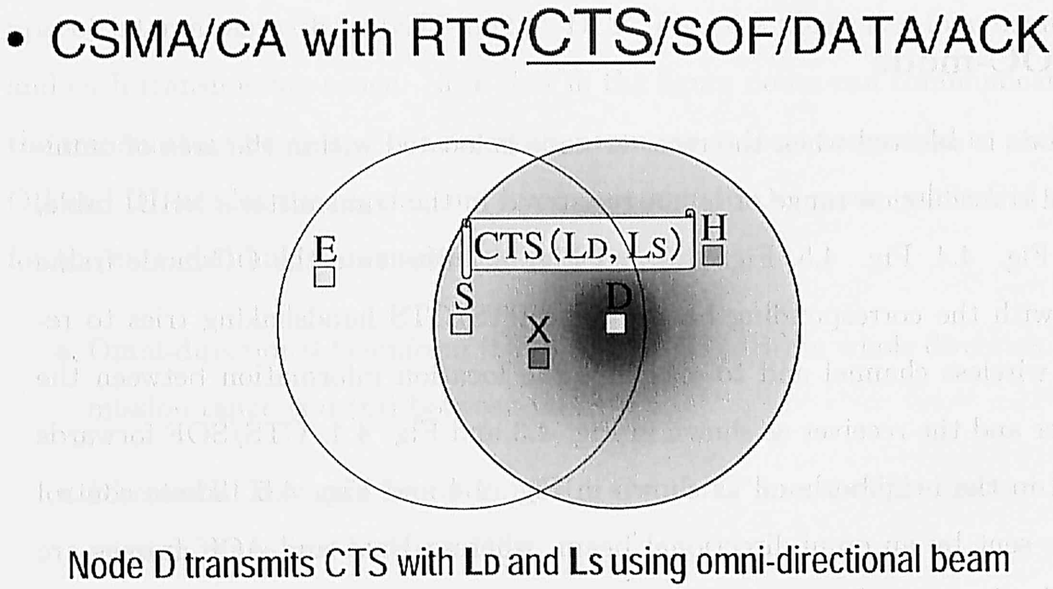


Figure 4.4: OC-mode (CTS).

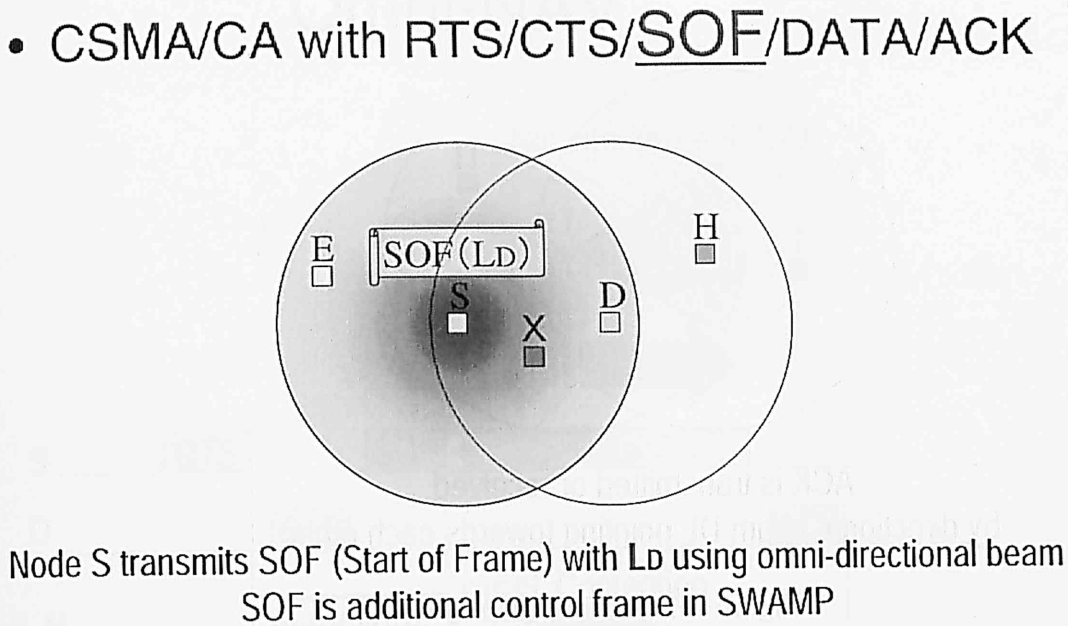


Figure 4.5: OC-mode (SOF).

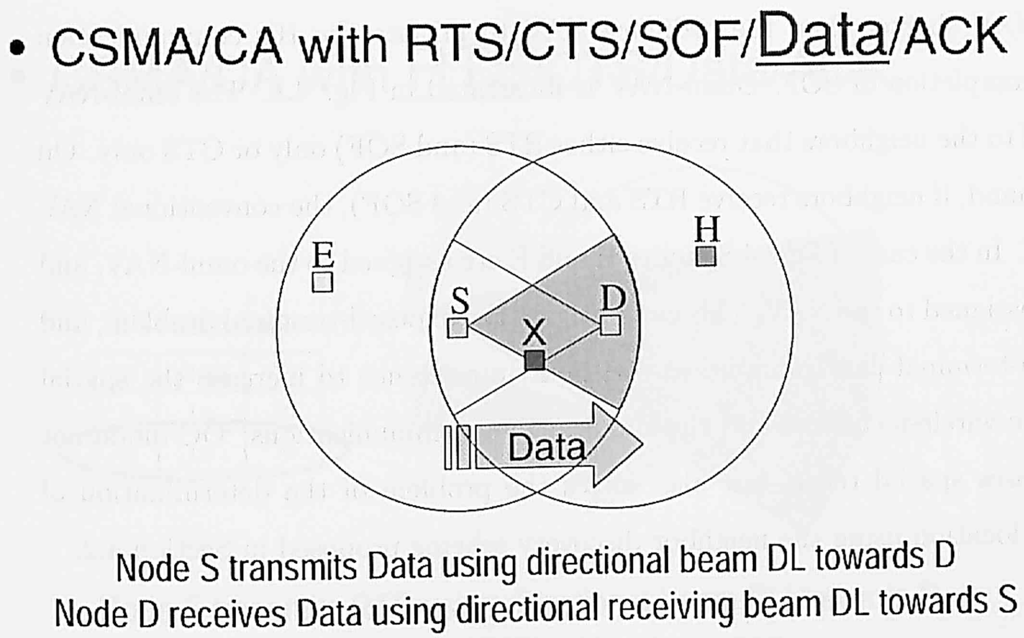
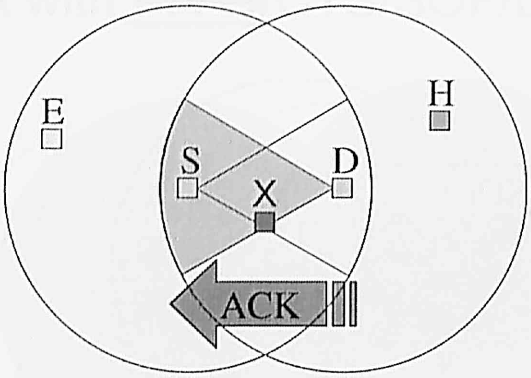


Figure 4.6: OC-mode (Data).

• CSMA/CA with RTS/CTS/SOF/Data/ACK



ACK is transmitted or received
by directional beam DL pointing towards each other

Figure 4.7: OC-mode (ACK).

transmission between S and D because the directional beams of S and D are pointed towards each other. Therefore, H (and even E) does not have to wait for the ordinal NAV if its intended receiver is out of the B-C communication area. SWAMP assigns an omni-NAV shorter than the ordinary NAV to initiate the H's communication after the completion of SOF. Omni-NAV is illustrated in Fig. 4.8. The omni-NAV is assigned to the neighbors that receive either RTS (and SOF) only or CTS only. On the other hand, if neighbors receive RTS and CTS (and SOF), the conventional NAV is assigned. In the case of Fig. 4.8, nodes H and E are assigned to the omni-NAV, and node X is assigned to the NAV. This can mitigate the exposed-terminal problem, and the hidden-terminal can communicate without interference to increase the spatial reuse of the wireless channel and the simultaneous communications. OC-mode not only increases spatial reuse, but also solves the problem of the determination of neighbors' location using the neighbor discovery scheme proposed in Section 4.2.

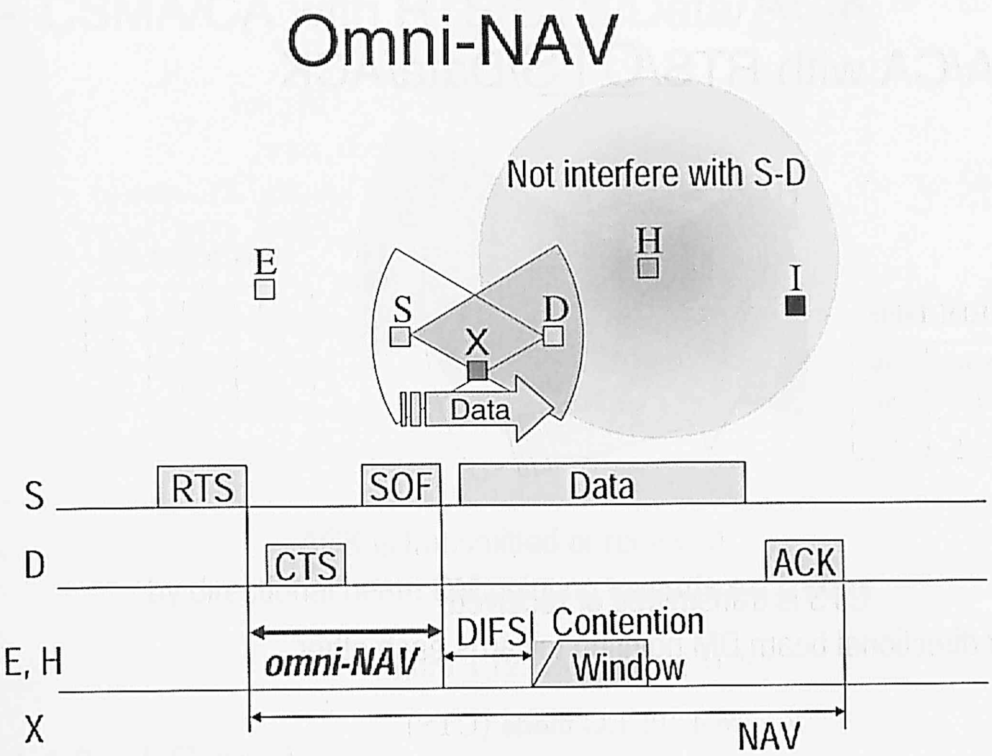


Figure 4.8: Omni-NAV.

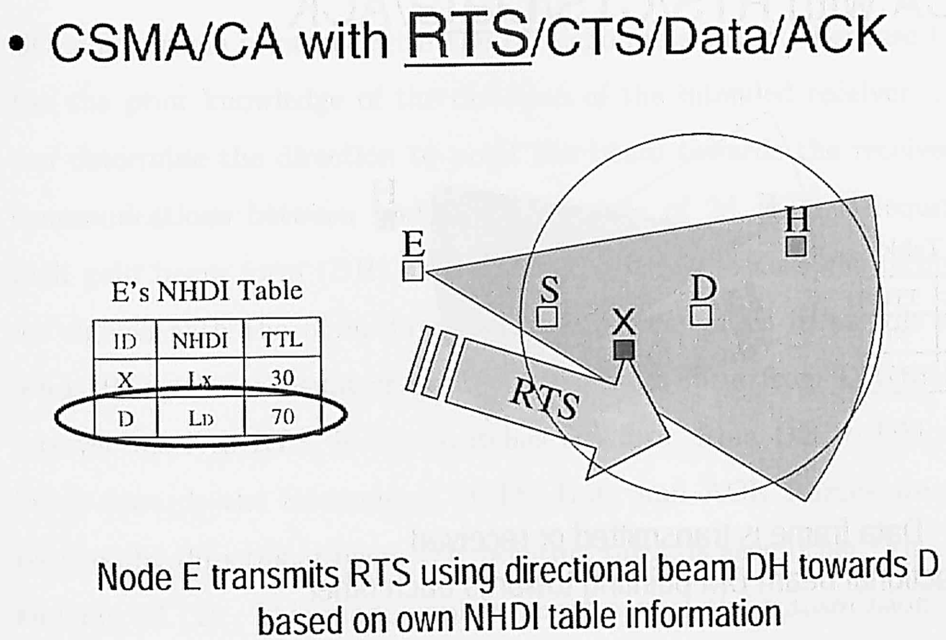


Figure 4.9: EC-mode (RTS).

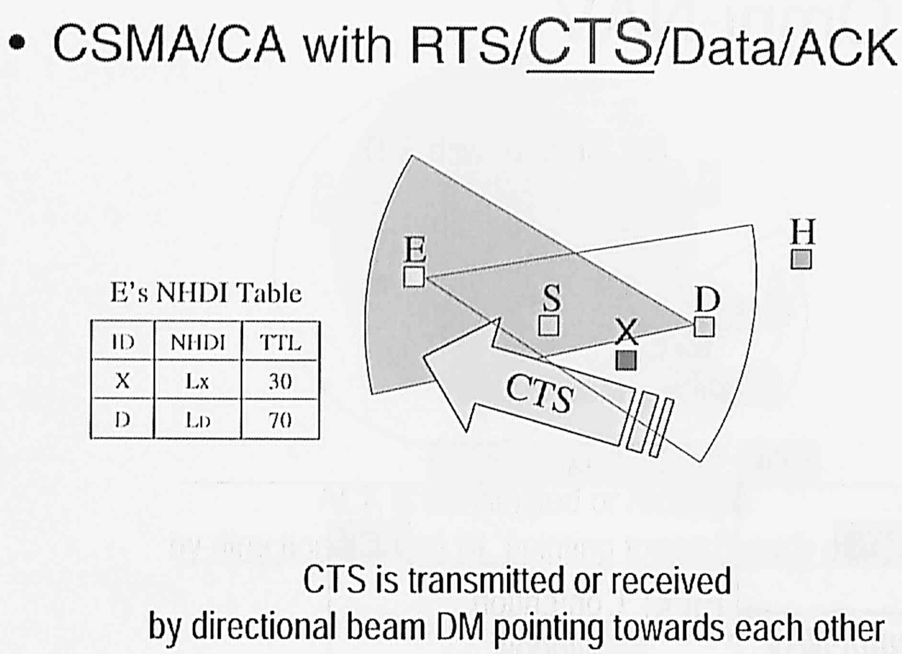


Figure 4.10: EC-mode (CTS).

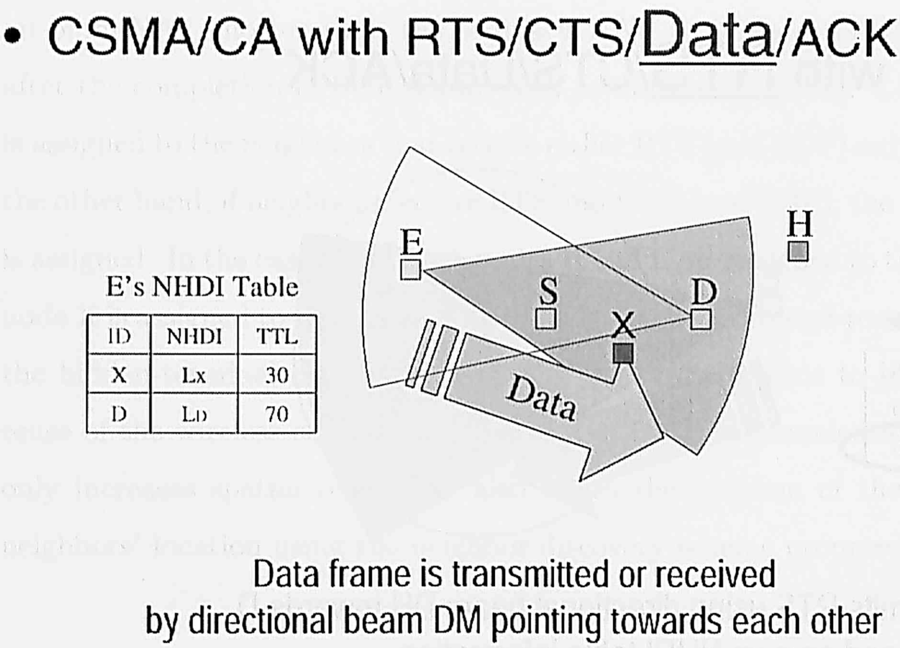


Figure 4.11: EC-mode (Data).

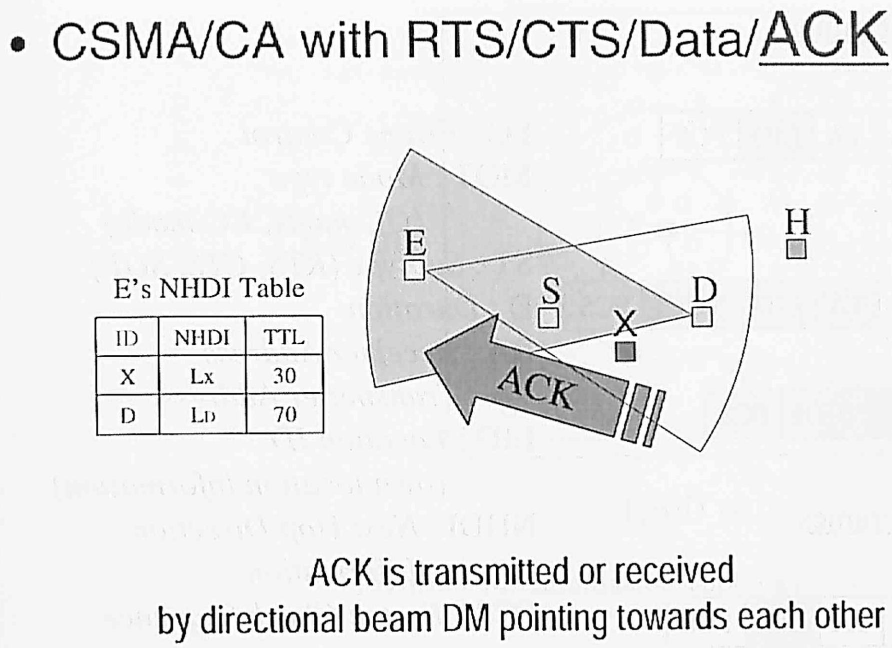


Figure 4.12: EC-mode (ACK).

4.4.2 EC-mode

EC-mode is selected when the receiver node has been already registered in the transmitter's NHDI table. Fig. 4.9, Fig. 4.10, Fig. 4.11 and Fig. 4.12 illustrate the EC-mode frame sequence with the corresponding beam. Because the transmitter has the prior knowledge of the direction of the intended receiver, the transmitter can determine the direction to point the beam towards the receiver. To perform communications between nodes at a distance of 2d, RTS is required to use the high gain beam form (DH) as shown in Fig. 4.9 because the receiver node waits for signals with the omni-directional beam form (OB) in an idle state. After it sends RTS, the transmitter switches the beam form from DH to DM. After the receiver receives RTS, it also switches the form from OB to DM and points the beam towards the transmitter. CTS, Data and ACK frames are transmitted or received by directional beam DM pointing towards each other (Fig. 4.10, Fig. 4.11 and Fig. 4.12). This mode exploits extension of the transmission range with the directional beam for all frames as discussed in [72]. When the transmitter fails EC-mode access over the EC-retry limit, the transmitter deletes the receiver information

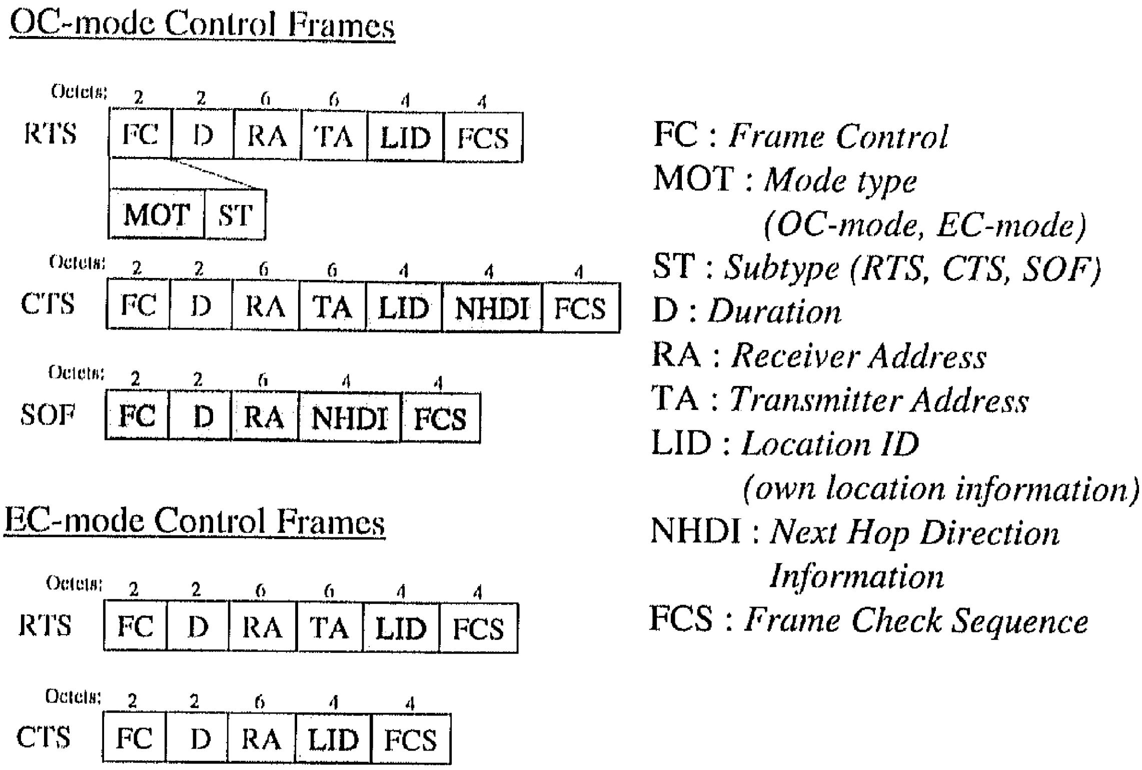


Figure 4.13: Control frame formats.

from its own NHDI table. In EC-mode, DNAV [67] is used instead of NAV for virtual carrier sensing. DNAVs are set up towards the specific directions where on-going communication nodes exist. This allows nodes to initiate an EC-mode transmission if DNAVs are not set in the desired direction and it improves the performance by allowing simultaneous transmissions.

4.5 Frame Formats

Fig. 4.13 illustrates the control frame formats of OC-mode and EC-mode, respectively. The shaded fields show the additional fields introduced in SWAMP compared with the standard IEEE 802.11. Frame formats of Data and ACK frames are the same as that of IEEE 802.11 except for MOT (Mode Type) in the frame control field. Receiver nodes can discriminate the access mode and frame classification by MOT and Subtype in the frame control field. In SWAMP, extension of control frames is

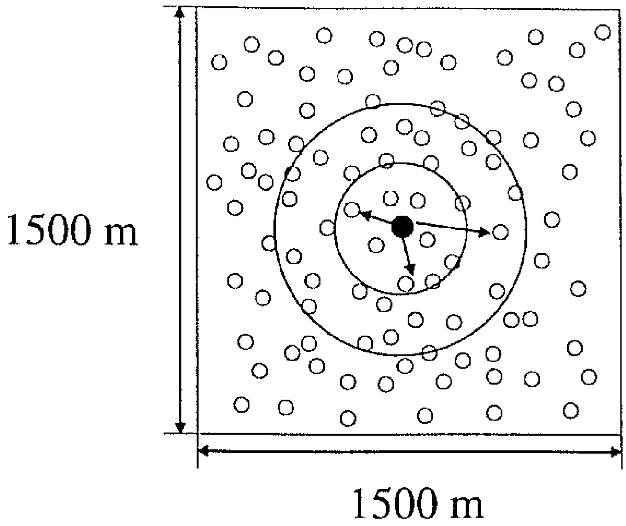


Figure 4.14: Simulation topology.

needed for position information transmission.

4.6 Performance Evaluation

4.6.1 Simulation Model

To evaluate the performance of MAC protocols, we developed an original event driven simulator written in C++. Table 4.2 shows the simulation parameters. We make the following assumptions. A hundred nodes are arranged at random in a square area with dimensions of 1500 m and move independently according to the random way point mobility model [78] with a maximum speed of 40 km/h and a pause time of zero. Packets arrive at every node according to Poisson distribution with mean value of λ (packets/s). Destination node for each packet is chosen at random from two hop neighbors (Fig. 4.14).

A packet size is 512 bytes, location information is 4 bytes and an omni-directional transmission range (d in Fig. 4.2) is 250 m. The beamwidth of DL, DM and DH are 45 degrees. The data rate is 2 Mbps. Other parameters not described in this section, such as the interframe space and the contention window size, follow the IEEE 802.11 (DSSS) specifications [16]. Each result reported is an average of 10 executions with

Table 4.2: Simulation parameters

parameters	value
Area Size	1500m×1500m
Number of Nodes	100
Mobility Model	Random waypoint model
Maximum Speed	40 km/h
Pause Time	0 s
Payload Size	512 byte
Location Information Size	4 byte
Buffer Size	50 packets
Transmission Range (d)	250 m
Beamwidth ($\alpha/\beta/\gamma$)	45 degrees
OC-retry Limit	7
EC-retry Limit	4
Data Rate	2 Mbps

different random seeds. One million application packets are generated for each simulation. In most cases, the 95 percent confidence interval for the measured data is less than 5 percent of the sample mean.

We evaluate the following protocols.

- SWAMP (OC+EC)
- SWAMP (OC)
- IEEE 802.11 DCF [16]

SWAMP (OC+EC) is our proposed MAC protocol and access mode for each packet is selected based on NHDI table. When the destination is registered in the NHDI table, EC-mode is selected; Otherwise OC-mode is selected. SWAMP (OC) is the case using OC-mode only for all communications. If the chosen destination is located out of the omni-directional transmission range, the source node tries to deliver the packet by two-hops in SWAMP (OC). We also evaluate IEEE 802.11 DCF with omni-directional antennas as a benchmark.

Because the area is finite size, there is the boundary problem. The node density in the boundary of the area is lower than that in the center of the area. Furthermore,

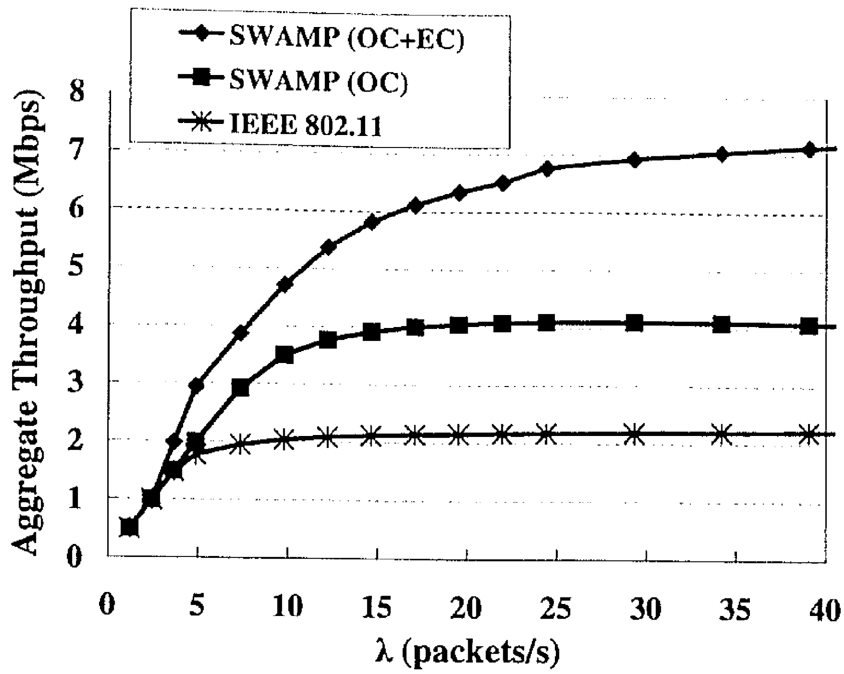


Figure 4.15: End-to-end throughput.

the direction of the intended receiver is not uniform in the boundary, whereas it is uniform in the center. However, the 95 percent confidence interval for throughput per node is less than 8 percent of the sample mean.

4.6.2 Simulation Results

Throughput

The throughput versus the offered load is shown in Fig. 4.15. The throughput of SWAMP (OC), which is the case using OC-mode only for all communications, is roughly 2 times against IEEE 802.11 DCF. This is because OC-mode improves the spatial reuse of the wireless channel due to omni-NAV, and consequently more node pairs can communicate simultaneously. SWAMP (OC+EC) outperforms others because packets are delivered to the destination in fewer hops in EC-mode, and the consumption of the wireless channel and store-and-forward overhead are reduced. In addition, since DNAV is used for virtual carrier sensing in EC-mode, nodes can initiate an EC-mode access if DNAVs are not set in the desired direction and it

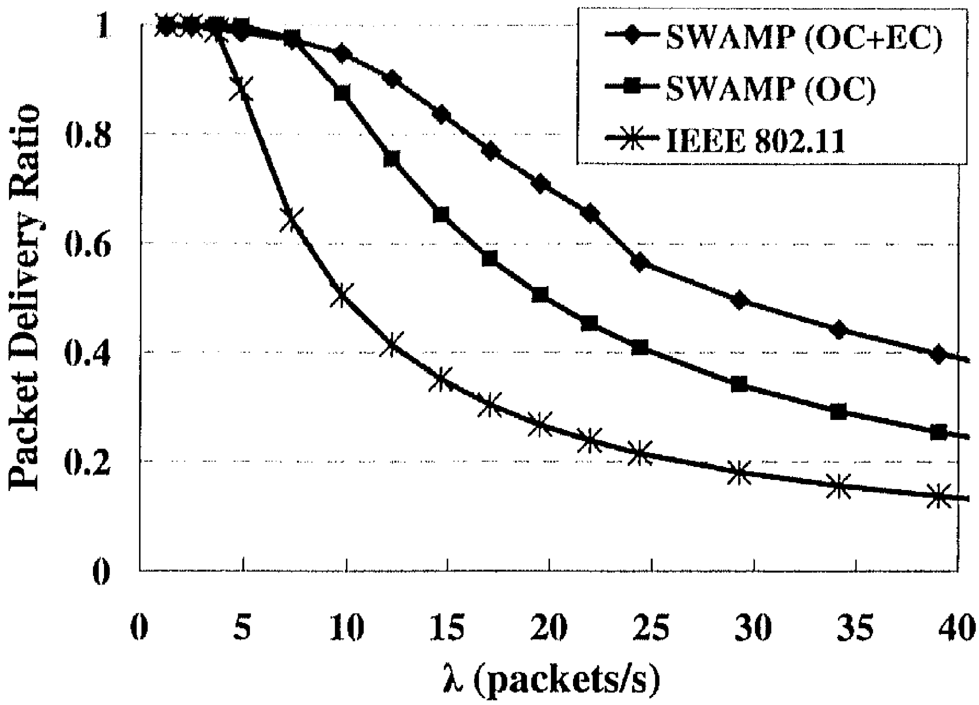


Figure 4.16: Packet delivery ratio.

improves performance by allowing simultaneous transmissions.

Packet Delivery Ratio

The packet delivery ratio versus the offered load is shown in Fig. 4.16. The improvement of both modes is observed in comparison with the IEEE 802.11. Furthermore, SWAMP (OC+EC) has better performance than SWAMP (OC) because the forwarding of NHDI is effective and appropriate to perform the extended transmission range under dynamically changing network topology. Note that the degradation of the packet delivery ratio is mainly caused by the buffer overflow when the offered load is high.

Number of Simultaneous Communications

Fig. 4.17 shows the number of simultaneous communications. It is the amount of bits normally transmitted to 1-bit transmission time in the network. Compared

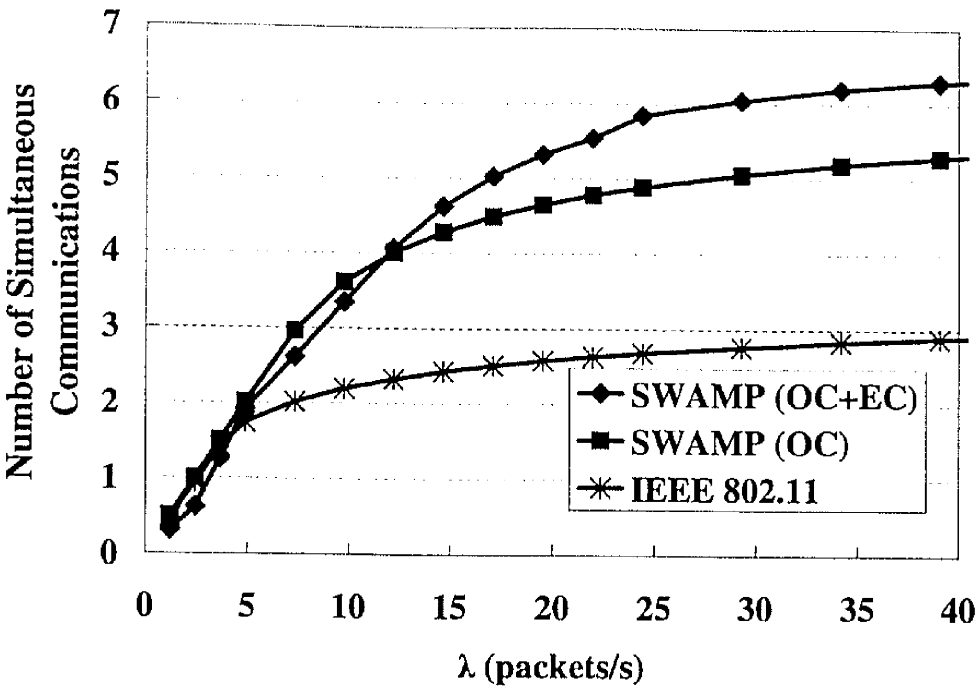


Figure 4.17: Number of simultaneous communications.

with the IEEE 802.11, the number of simultaneous communications of SWAMP has improved twice and more by the use of omni-NAV and/or DNAV. It implies that the channel utilization of SWAMP is increased due to spatial reuse of the wireless channel.

Overhead

Fig. 4.18 shows the overhead of SWAMP and IEEE 802.11. The overhead is defined as the average number of bits transmitted to deliver 1 bit of payload to the receiver at the MAC layer. Overhead becomes large when a large number of control bits are transmitted and/or frames are retransmitted. As SWAMP modifies the IEEE 802.11 control frame formats to deliver location information, it has more overhead than IEEE 802.11 when the offered load is low. IEEE 802.11 becomes large, whereas SWAMP (OC) has relatively stable overhead when the offered load is more than 50 kbps per node. This is because SWAMP (OC) allows terminals that are located in a hidden position or an exposed position of omni-antennas employed

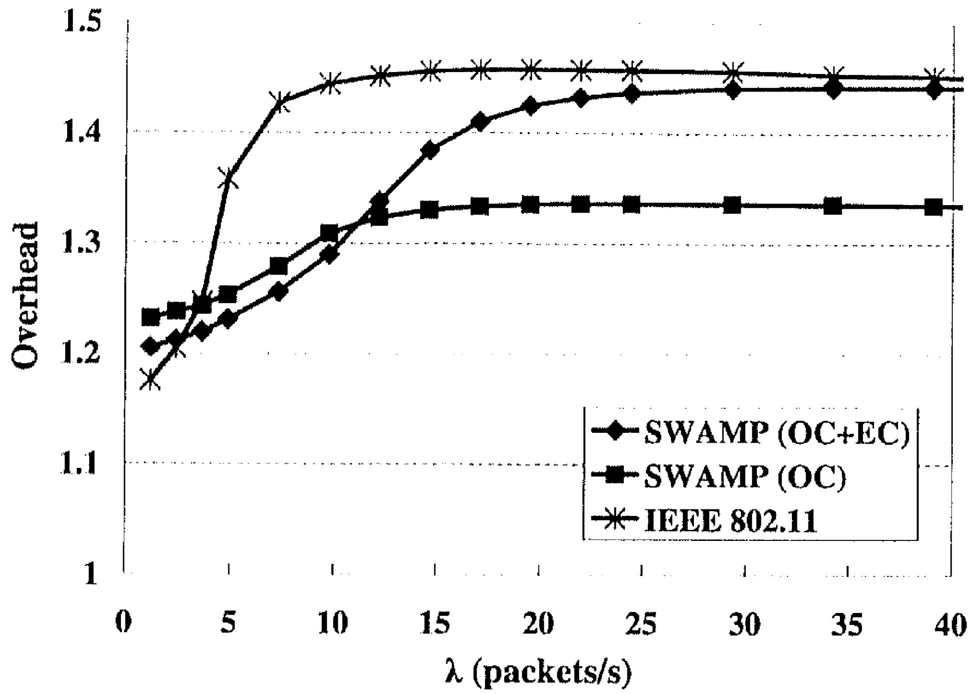


Figure 4.18: Overhead.

to initiate their communication after the expiration of omni-NAV. This suppresses the retransmissions of RTS from neighbor nodes. SWAMP (OC+EC), however, introduces large overhead when the offered load is high. This is because deafness and directional hidden-terminal problem appear in EC-mode. These problems are discussed in depth in the later chapters.

End-to-End Delay

Fig. 4.19 shows the average end-to-end delay. The end-to-end delay is the time interval that calculates the instant a data packet is generated at the source node to the instant the data packet is received at the destination node. It can be observed that SWAMP has remarkably less delay than IEEE 802.11. SWAMP (OC) has better delay performance than IEEE 802.11. This is due to the omni-NAV, and thus it is not necessary that the node waits until the completion of ACK. SWAMP (OC+EC) has the best performance because the packet is delivered to the destination in fewer hops, and the store-and-forward overhead is reduced. Therefore, the performance of

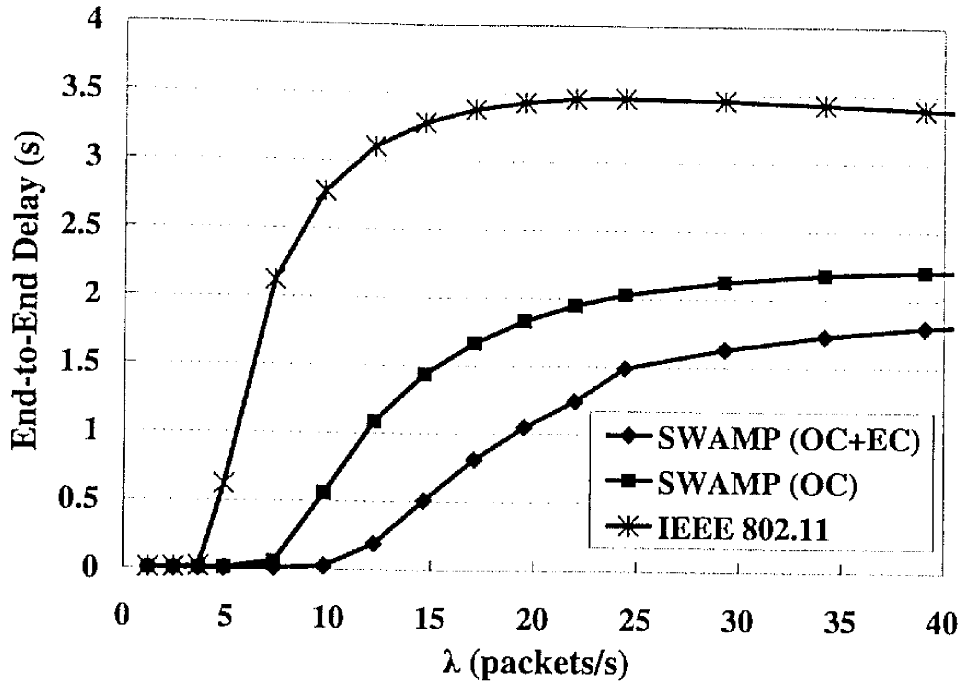


Figure 4.19: End-to-end delay.

a wider transmission range communication is more effective in a multi-hop ad hoc network.

Effects of Mobility

Fig. 4.20 shows the aggregate throughput when the maximum speed is changed and λ is set to 25 to investigate the effects of the mobility on the throughput performance. SWAMP (OC) improves the throughput twice and SWAMP (OC+EC) improves three times compared with the IEEE 802.11 irrespective of the mobility of nodes. The reason of the throughput degradation when the maximum speed is high is mainly because that the intended receiver node moves out of range of the transmitter during waiting in the queue though it is located within the range when the packet is generated.

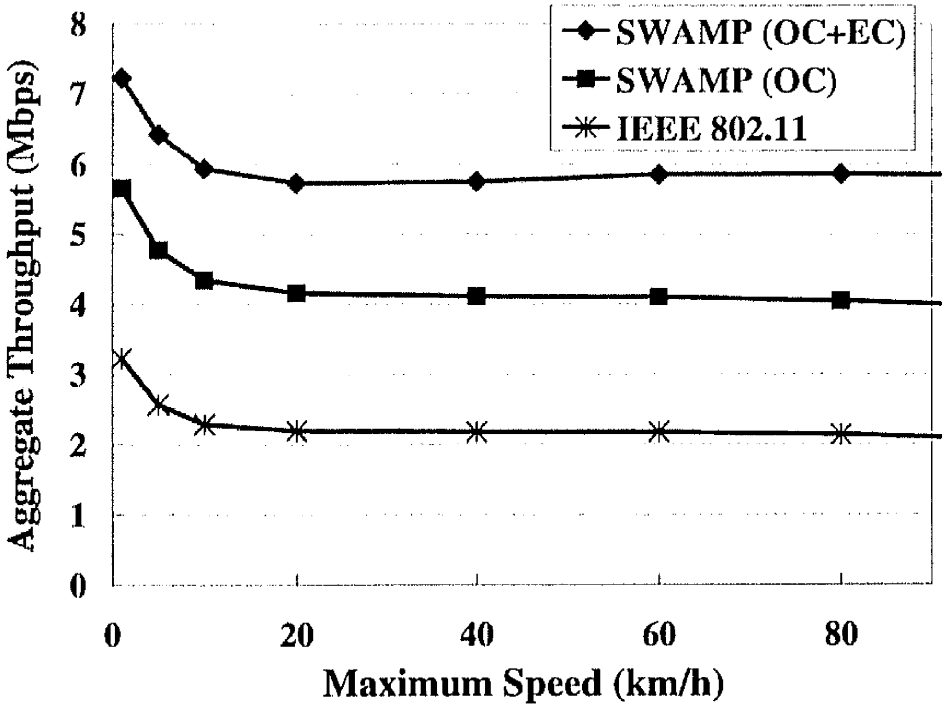


Figure 4.20: Effects of the mobility of nodes.

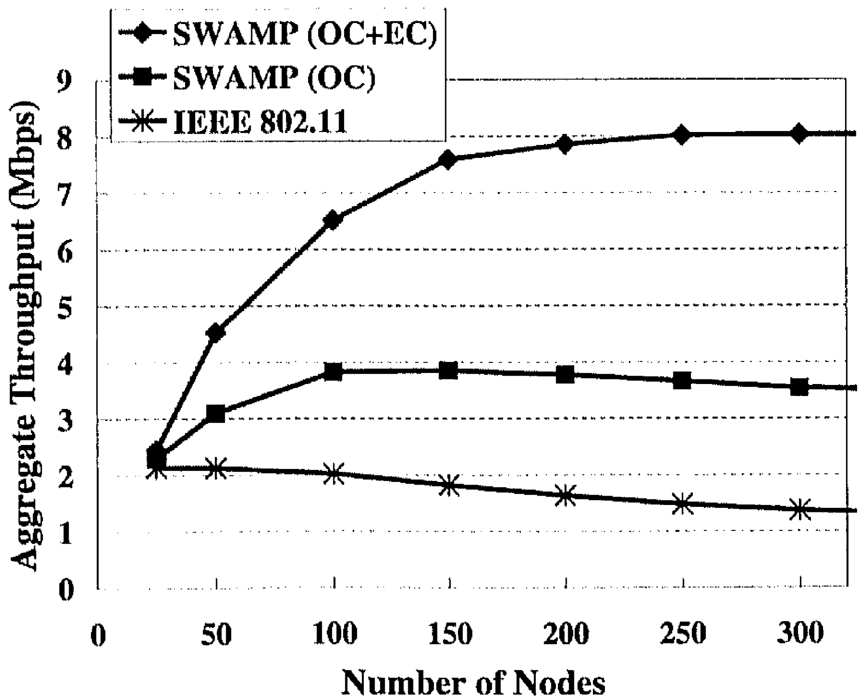


Figure 4.21: Effects of the density of nodes.

Effects of Density

To evaluate the effects of the density, we change the number of nodes in Fig. 4.21 (λ is 25). When the density is low, there is no difference between three protocols because of the low contention. The throughput of IEEE 802.11 decreases as the density increases due to the high contention. On the other hand, SWAMP achieves the higher throughput as the density increases. This is because directional transmissions reduce the contention and increase spatial reuse of the wireless channel, therefore the number of simultaneous communications is increased. In addition, it can be concluded that SWAMP is not degraded with the increase of node density because the overheads for obtaining the directional information are not increased due to using only usual control frames differently from the results of the periodical Hello packet transmission schemes [64, 45, 69]. These results prove that our neighbor discovery scheme is effective under the various node mobility and density in mobile ad hoc networks.

Effects of Retry Limits

Fig. 4.22 shows the throughput and end-to-end delay with the different values of the maximum EC-retry limits (from 1 to 20) when the area size is 1000m $\times$ 1000m, number of nodes is 100, and λ is 20. The retry limit is defined to be 7 in the IEEE 802.11 standard. As shown in Fig. 4.22, although an increase in the allowable number of retransmissions can increase the probability of a successful transmission and improve the throughput, excess retransmissions lead to degradation of the throughput and delay performance. This is because that excess retransmissions influence the neighbor nodes and waste the wireless channel, and the backoff time (the contention window size) is also increased.

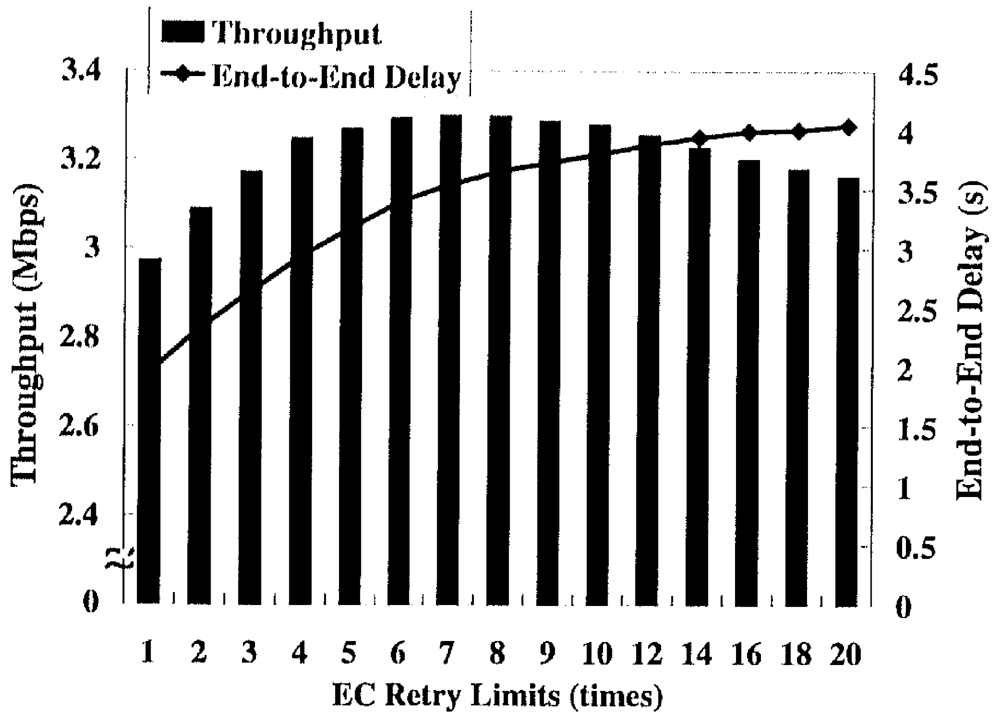


Figure 4.22: Effects of the retry limits.

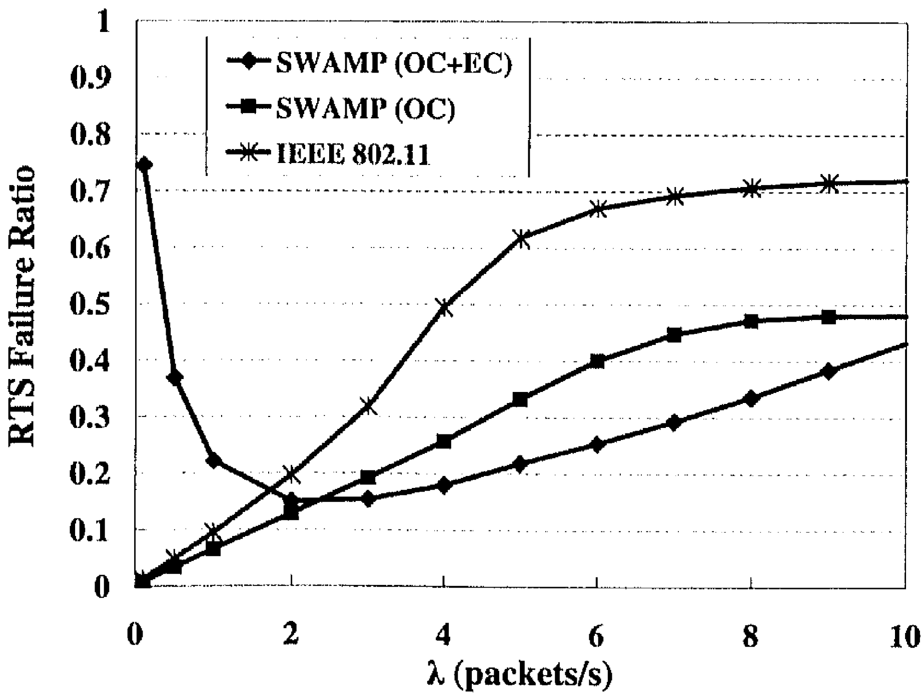


Figure 4.23: RTS failure ratio.

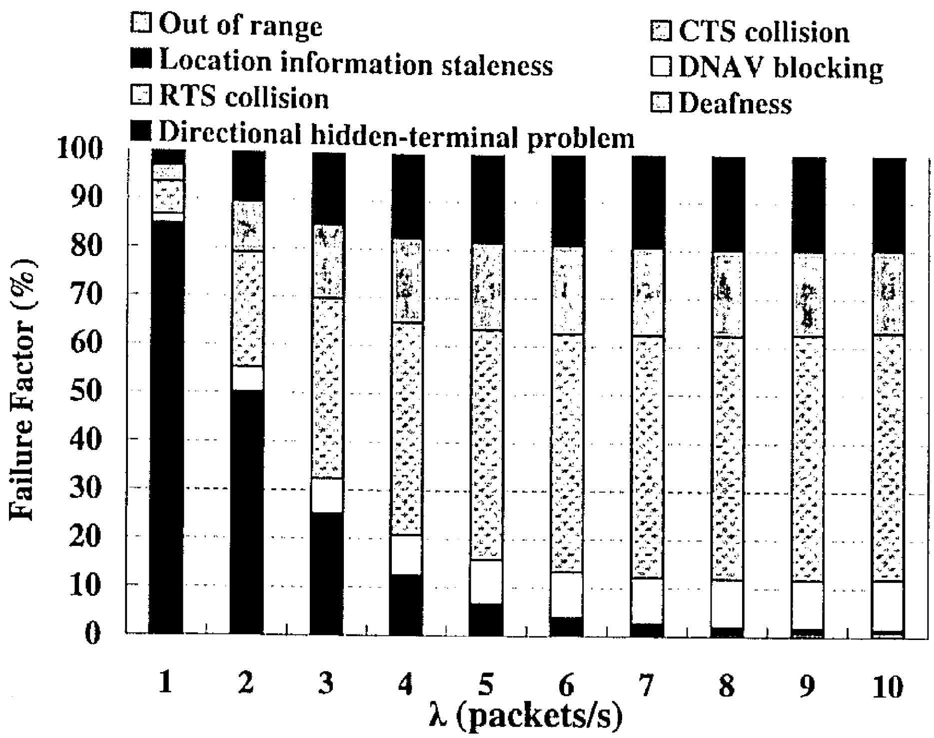


Figure 4.24: Communication failure factors of SWAMP (OC+EC).

Communication Failure Factors

Fig. 4.23 shows the RTS failure ratio of three protocols. RTS failure ratio (RFR) is calculated as follows.

$$RFR = 1 - \frac{N_{CTS}}{N_{RTS}}, \tag{4.1}$$

where N_{RTS} is the number of transmitted RTS frames towards the intended receiver and N_{CTS} is the number of successful CTS frames.

Fig. 4.24 shows the communication failure factors of SWAMP (OC+EC). Communication failure factors in directional MAC protocols are classified as follows [60].

- Out of range: The addressed receiver node moves out of range of the transmitter's communication range.

- CTS collision: The receiver node sends CTS, however the transmitter cannot receive it because of collision.

- Location information staleness: The gap between the cached location information and actual location of the addressed node becomes larger than the beamwidth.
- DNAV blocking: The receiver node receives RTS correctly, but cannot send CTS because DNAVs are set in the direction of the transmitter.
- RTS collision: RTS is not received correctly by the receiver since other nodes are transmitting (i.e., the receiver node is an exposed-terminal, or more than two nodes transmit control frames concurrently).
- Deafness: The receiver node cannot receive RTS because the receiver is beamformed towards the direction away from the transmitter.
- Directional hidden-terminal problem: Hidden terminal due to asymmetry in gain or hidden terminal due to unheard RTS/CTS [58].

As shown in Fig. 4.23 and Fig. 4.24, SWAMP increases the communication failure due to location information staleness especially when the offered load is low (out of range and CTS collisions are almost 0 % in Fig. 4.24). This is because the gap between the NHDI and actual location of the neighbor node is large when the frequency of update of the NHDI is low, and nodes try to communicate frequently and attempt multiple retransmissions under such situations. Therefore, handling issue of location information staleness is significant in directional MAC protocols in low load.

Another main factor of communication failure is RTS collision. Since RTS collisions mainly occur due to congestion, it may not be possible to completely eliminate it.

Deafness and directional hidden-terminal problems are also reduce the probability of successful transmissions, which may not arise in the case of omni-directional transmissions. Therefore, there is a tradeoff between spatial reuse of the wireless channel using directional transmissions and collision avoidance using omni-directional transmissions.

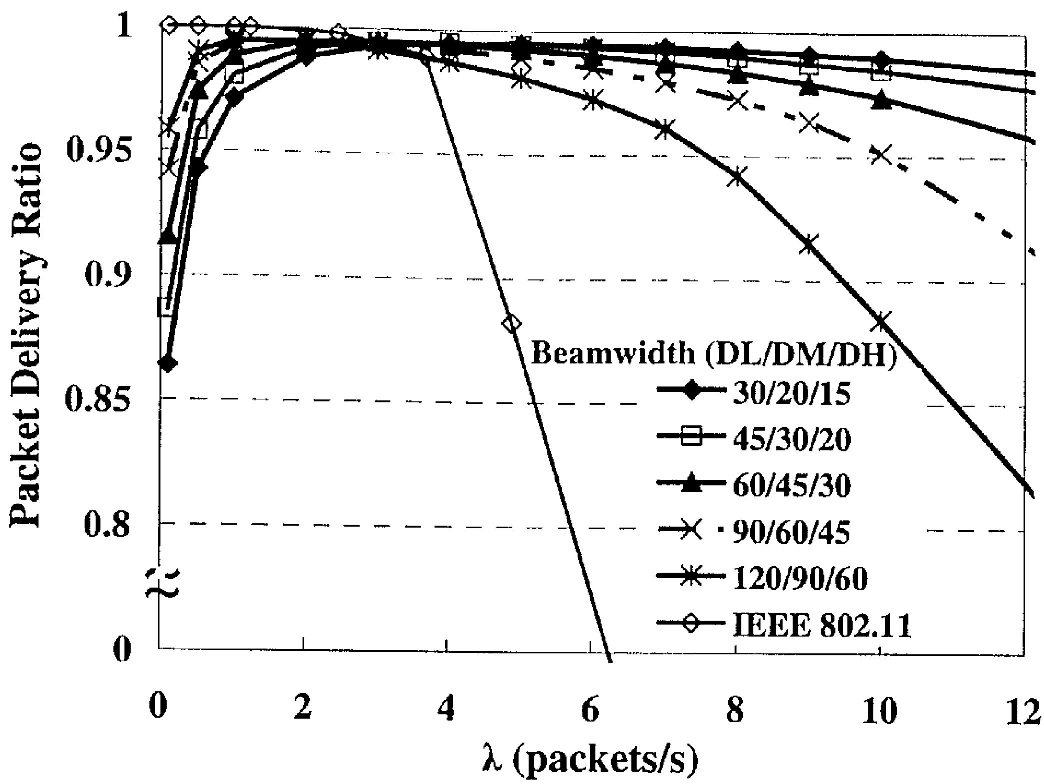


Figure 4.25: Effects of the beamwidth (degrees).

There are communication failure factors of SWAMP, but that may arise with other directional MAC protocols as well.

Effects of Beamwidth

To handle the issue of location information staleness and to improve the reliability of the table based directional transmission, dynamic adaptation of parameters related to the reliability of the transmission such as the beamwidth and lifetime of the table information can be available.

In this section, we confirm the effects of the different values of these parameters on the performance of our proposed MAC protocol.

Fig. 4.25 shows the effects of the beamwidth. SWAMP uses three kinds of directional beam (i.e., DL, DM and DH). We set up five different sets of beamwidths while the transmission range of each beam is kept according to Fig. 4.2. When λ is low, the cases using wider beamwidths have better performance. This is because that the frequency of update of the NHDI table entry is low and the gap between the NHDI and actual location of the neighbor nodes is large. Under these situations, the wider beamwidth is suitable for struggling with location information staleness. When λ is high, to the contrary, narrower beamwidths have better performance. If the network traffic is high, each node can acquire the NHDI frequently by overhearing the communication between neighboring nodes and the NHDI is maintained fresh and accurate. Therefore, the narrower beam can reduce the interference and contention among nodes and improve the spatial reuse when the NHDI is sufficiently accurate and reliable. It implies that the optimization of the beamwidth based on the network traffic or the freshness of the table information mitigates location information staleness and improves the efficiency of spatial reuse.

Fig. 4.26 shows the effects of the different values of the beamwidth on RTS failure ratio. It can be seen that wide beamwidth reduces the RTS failure compared with narrow beamwidth in low offered load. This is because the RTS transmission using wide beamwidth can cover the addressed node and fill the angle gap.

We have confirmed that the adaptation of the beamwidth requires not only the surrounding traffic information but also the mobility of nodes. Fig. 4.27 shows the relation among the elapsed time from NHDI receipt, average angle gap, and the mobility of nodes. It can be seen that the gap between the NHDI and actual location of the neighbor nodes becomes larger as the time elapses and the nodes move faster.

Effects of TTL of NHDI Table

Fig. 4.28 shows the effects of the lifetime of NHDI table information. Each node maintains an NHDI table with one record for every node that receives NHDI in SWAMP. In the NHDI table, the TTL (Time to Live) represents the lifetime of the entry and it is related to the reliability of the transmission. TTL is decreased during the progress of time. If the TTL expires, the corresponding record is deleted.

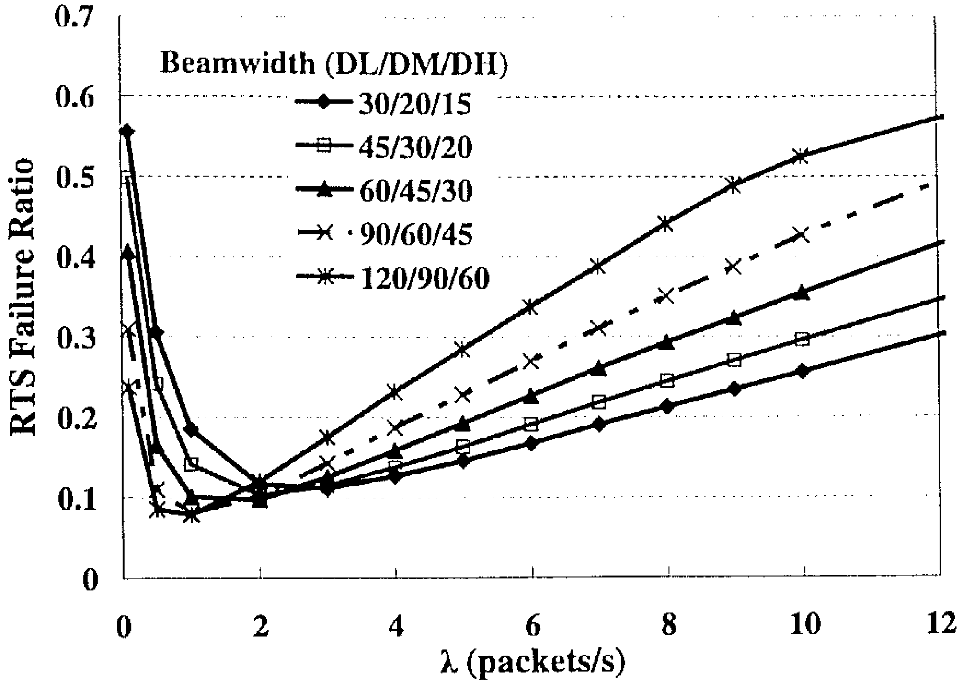


Figure 4.26: Effects of the beamwidth on RTS failure ratio.

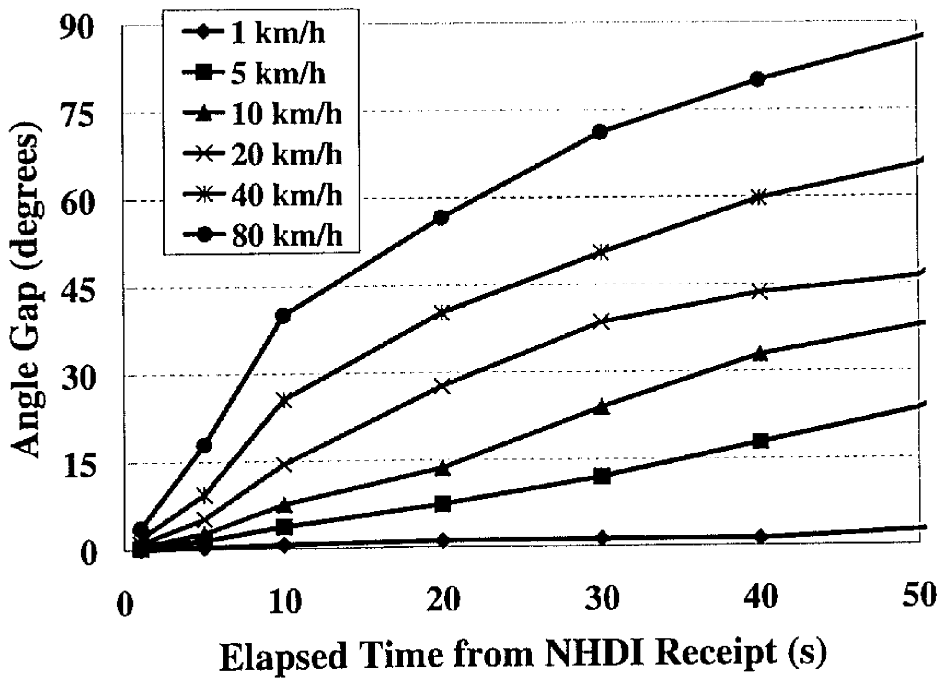


Figure 4.27: Elapsed time from NHDI receipt and angle gap.

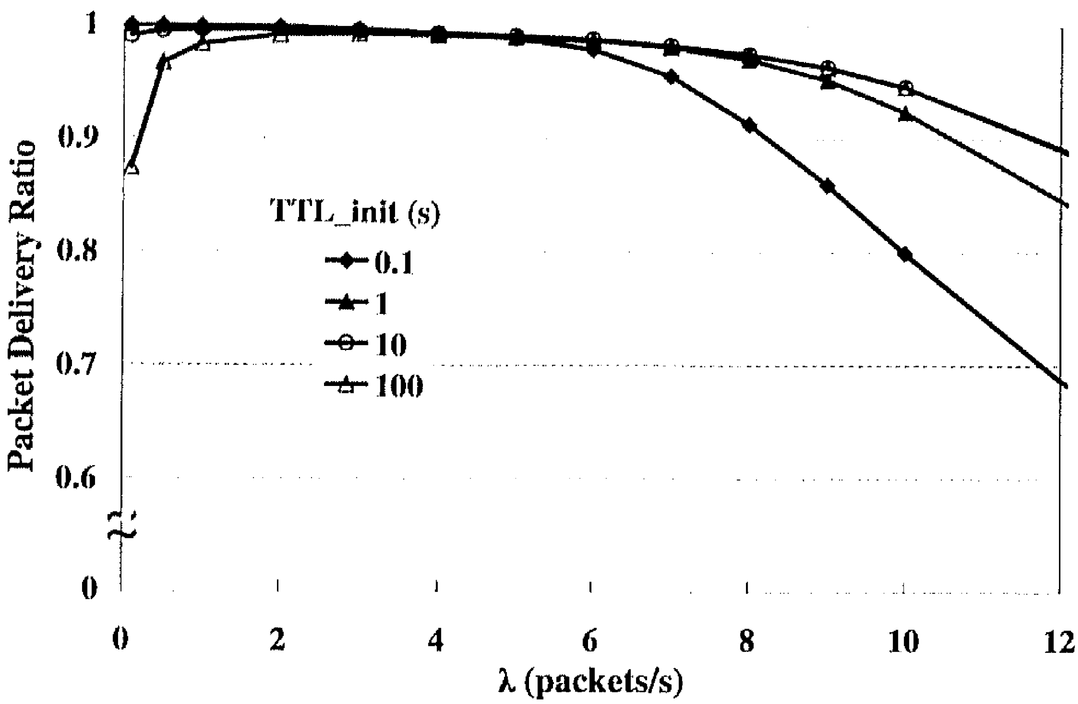


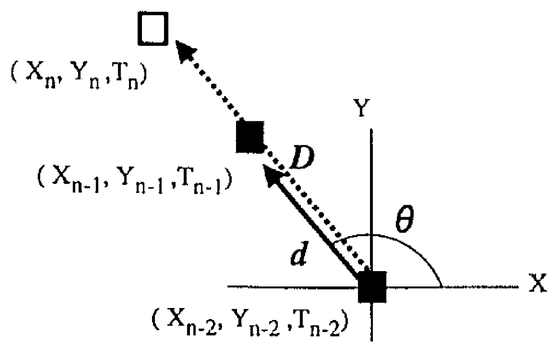
Figure 4.28: Effects of the TTL.

When the NHDI is obtained that is already registered, it is updated and the TTL is initialized (TTL_init).

As shown in Fig. 4.28, the cases using the large TTL_init are unsuitable compared with the cases using small one when λ is small because the transmission based on the obsolete table information deteriorates the reliability. As λ becomes larger, however, the cases using the small TTL_init grow rapidly worse. This is because that the NHDI entry is deleted frequently although it is sufficiently accurate and reliable. In this case, each node cannot gain the benefits of directional communications. Therefore, the reliability of the transmission and the overall network performance has the relation of a trade-off. To adapt the TTL_init dynamically, we must consider the network load, mobility of node, and QoS (Quality of Service) requirement.

Effects of Mobility Prediction

SWAMP and most of the previous works on directional antennas based MAC protocols use the table to maintain the direction of neighbor nodes. Therefore, each



$$d = \sqrt{(X_{n-1} - X_{n-2}) + (Y_{n-1} - Y_{n-2})}$$

$$D = d \times \frac{T_n - T_{n-2}}{T_{n-1} - T_{n-2}}$$

$$X_n = D \times \cos\theta + X_{n-2}$$

$$Y_n = D \times \sin\theta + Y_{n-2}$$

Figure 4.29: Linear prediction algorithm.

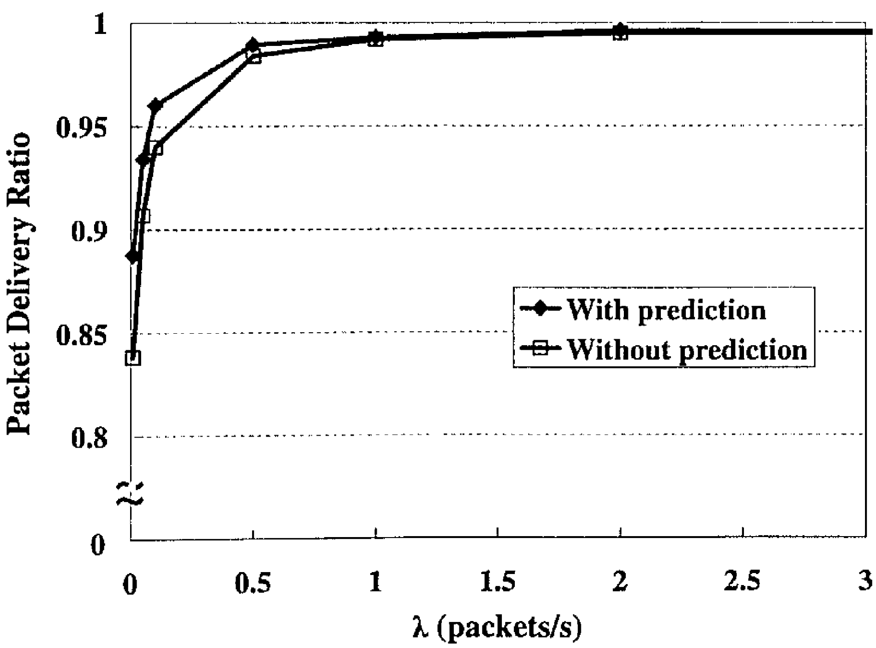


Figure 4.30: Effects of the mobility prediction with arrival rate.

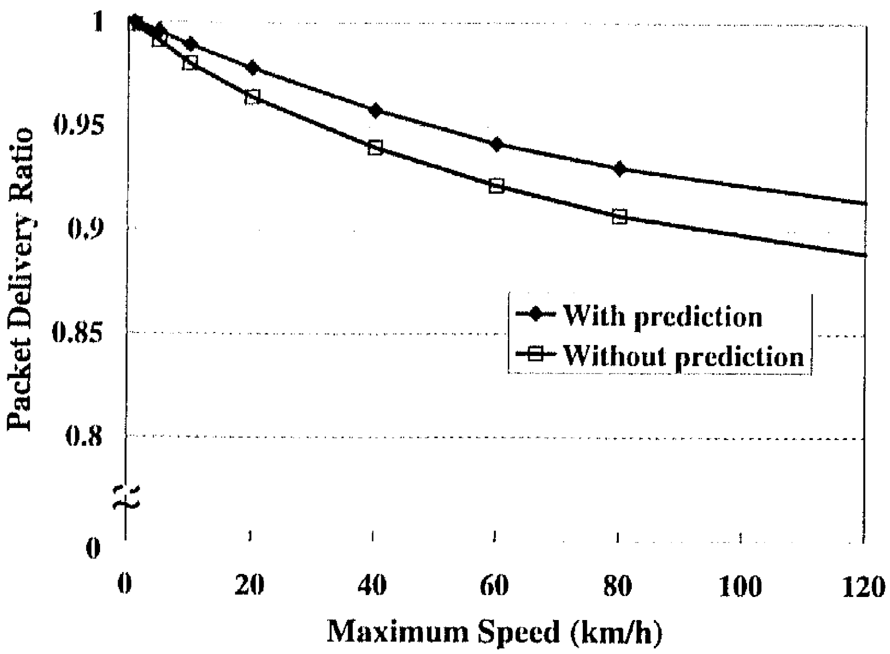


Figure 4.31: Effects of the mobility prediction with mobility.

node can predict the mobility of neighbor nodes based on the history of the location information and its receipt time. Because the mobility prediction algorithm is out of the scope of this thesis, we use the simplest linear prediction algorithm to predict the direction of the neighbor nodes. Assume that (X_{n-2}, Y_{n-2}) and (X_{n-1}, Y_{n-1}) are location information of a neighbor node at time T_{n-2} and T_{n-1}, respectively. Current location of the node (X_n, Y_n) at time T is estimated by Fig. 4.29. Other mobility prediction algorithms are proposed in [79, 80], these are used to predict the link expiration time.

Fig. 4.30 and Fig. 4.31 show the packet delivery ratio with and without the mobility prediction versus the arrival rate (when maximum speed = 40 km/h) and the mobility speed (when $\lambda = 0.1$) respectively. As shown in Fig. 4.30 and Fig. 4.31, the mobility prediction improves packet delivery ratio due to the improvement of the reliability of the transmission, especially when the arrival ratio is low and the node mobility is high.

4.7 Summary

This chapter proposed a novel directional MAC protocol, called SWAMP. SWAMP utilizes the directional beam effectively to increase the spatial reuse of the wireless channel and to extend the transmission range. SWAMP contains the neighbor discovery mechanism by forwarding the NHDI, which can obtain the direction information of the nodes within an area two times farther than omni-directional beam. SWAMP is composed of two access modes. OC-mode mitigates the hidden-terminal problem and the exposed-terminal problem, and increases the spatial reuse of the wireless channel. EC-mode extends the transmission range. Simulation results show that the throughput of SWAMP is roughly 3.5 times against IEEE 802.11, that SWAMP has remarkably less delay, and that there is a performance improvement of SWAMP irrespective of node mobility and density. This chapter then investigated the effects of the issues of directional MAC protocols, such as location information staleness and deafness, on the network performance. Results show that location information staleness is one of the significant issues among the communication failure factors, especially when the traffic is low. Moreover, this chapter showed that the different values of the beamwidth and lifetime of the table information have an impact on the performance of protocol. These parameters can be optimized based on the network traffic, the freshness of the table information, the mobility of nodes and the QoS requirement to mitigate location information staleness and to improve the overall network performance. Another major problem of directional MAC protocols is deafness, which is not solved in SWAMP. The next chapter addresses the deafness problem.

Chapter 5

Solutions to the Deafness Problem

5.1 Introduction

Directional antennas are expected to provide significant improvements over omni-directional antennas in wireless ad hoc networks. Directional MAC protocols, however, introduce new kinds of problems arising from directivity. One major problem is deafness, caused by a lack of state information of neighbor nodes (i.e., idle or busy). This chapter addresses the issue of deafness in directional MAC protocols and proposes DMAC/DA (Directional MAC with Deafness Avoidance) [81] to overcome deafness. DMAC/DA modifies the previously proposed MAC protocol, MDA (MAC protocol for Directional Antennas), to reduce the number of control messages and also maintain the ability to handle deafness. In DMAC/DA, WTS (Wait To Send) frames are simultaneously transmitted by the transmitter and the receiver after the successful exchange of directional RTS and CTS to notify the on-going communication to potential transmitters that may experience deafness. WTS frames are transmitted only through those sectors where potential transmitters are located to reduce the control overhead. Furthermore, DMAC/DA is enhanced by the next packet notification, called DMAC/DA with NPN (Next Packet Notification), to distinguish transmitters from neighbor nodes. DMAC/DA with NPN reduces the overhead involved in unnecessary transmission of WTS frames caused in basic DMAC/DA. This chapter then proposes RI-DMAC (Receiver-Initiated Directional MAC) [82] to overcome the issue of deafness in directional MAC protocols for wireless ad hoc networks. RI-DMAC handles deafness reactively using a polling scheme. RI-DMAC is a combination of sender-initiated and receiver-initiated operations. The sender-initiated mode is used as the default mode and the receiver-initiated mode is triggered when the transmitter may suffer from deafness. In RI-DMAC, each node maintains a polling table and polls a potential deafness node (potential transmitter) using the RTR (Ready To Receive) frame after the completion of every dialog. The potential deafness node can recognize that the intended receiver becomes idle, and deliver a packet immediately after receiving RTR. Among potential deafness nodes in the polling table, the least recently transmitted node is selected as a polled node to improve fairness.

We evaluate our protocols and other conventional protocols, totally 10 protocols, through extensive simulation study in terms of throughput, control overhead and packet drop ratio, with different values of parameters such as the number of flows, data size and beamwidth. In addition, qualitative evaluation of 10 MAC protocols is presented to highlight the difference between our proposed directional MAC protocols and existing MAC protocols

Section 5.2 discusses the deafness problem in depth. Section 5.3 provides the antenna model assumed in our proposed protocols. Section 5.4 proposes DMAC/DA, an optimized control frame transmission mechanism to overcome the deafness problem and to solve the tradeoff between spatial reuse and deafness avoidance. Section 5.5 proposes RI-DMAC, a novel polling scheme to handle the deafness problem. Section 5.6 evaluates our proposed MAC protocols, DMAC/DA, DMAC/DA with NPN and RI-DMAC, compared to existing directional MAC protocols which handle the deafness problem. Section 5.7 concludes this chapter.

5.2 Deafness Problem

Fig. 5.1 shows communication failure factors of DMAC with DPCS [58] obtained by simulations with parameters described in Section 5.6.1. Results show that most of communication failures occur due to deafness and the deafness problem is

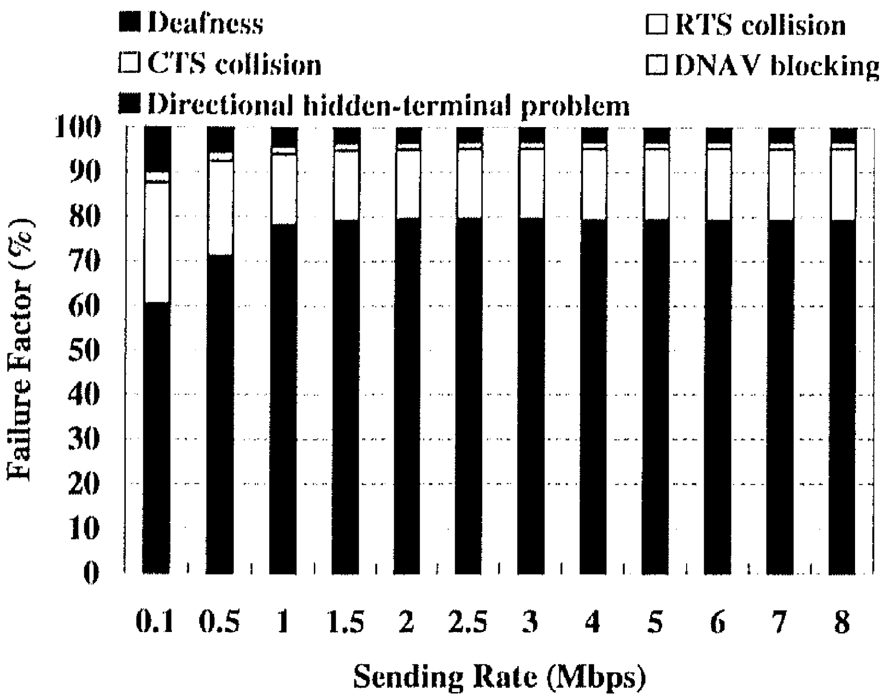


Figure 5.1: Communication failure factors of DMAC.

a significant problem in directional MAC protocols.

As discussed in [70], the deafness problem leads to unproductive retransmissions and the wastage of the wireless channel. Fig. 5.2 illustrates deafness situations where directional links are indicated by arrowed lines, and there are three flows (i.e., A to B, B to C, and C to D). We consider DMAC with DPCS [58] to explain deafness. Assume that nodes A and B have packets to be sent at the beginning of the sequence in Fig. 5.2. Each of these nodes points its beam towards the intended receiver and performs backoff in the Directional mode. In this case, node B sends RTS to C first. Node A is unaware of the communication between node B and node C because A does not overhear the directional signals between B and C. While B is communicating with C, A attempts to communicate with B, but it fails because B has its beam pointed towards C, and B is deaf with respect to A. In this thesis, the transmitter, which suffers from deafness, is referred to as deafness node. Then, deafness node A backs off and repeatedly attempts to communicate. Even though B

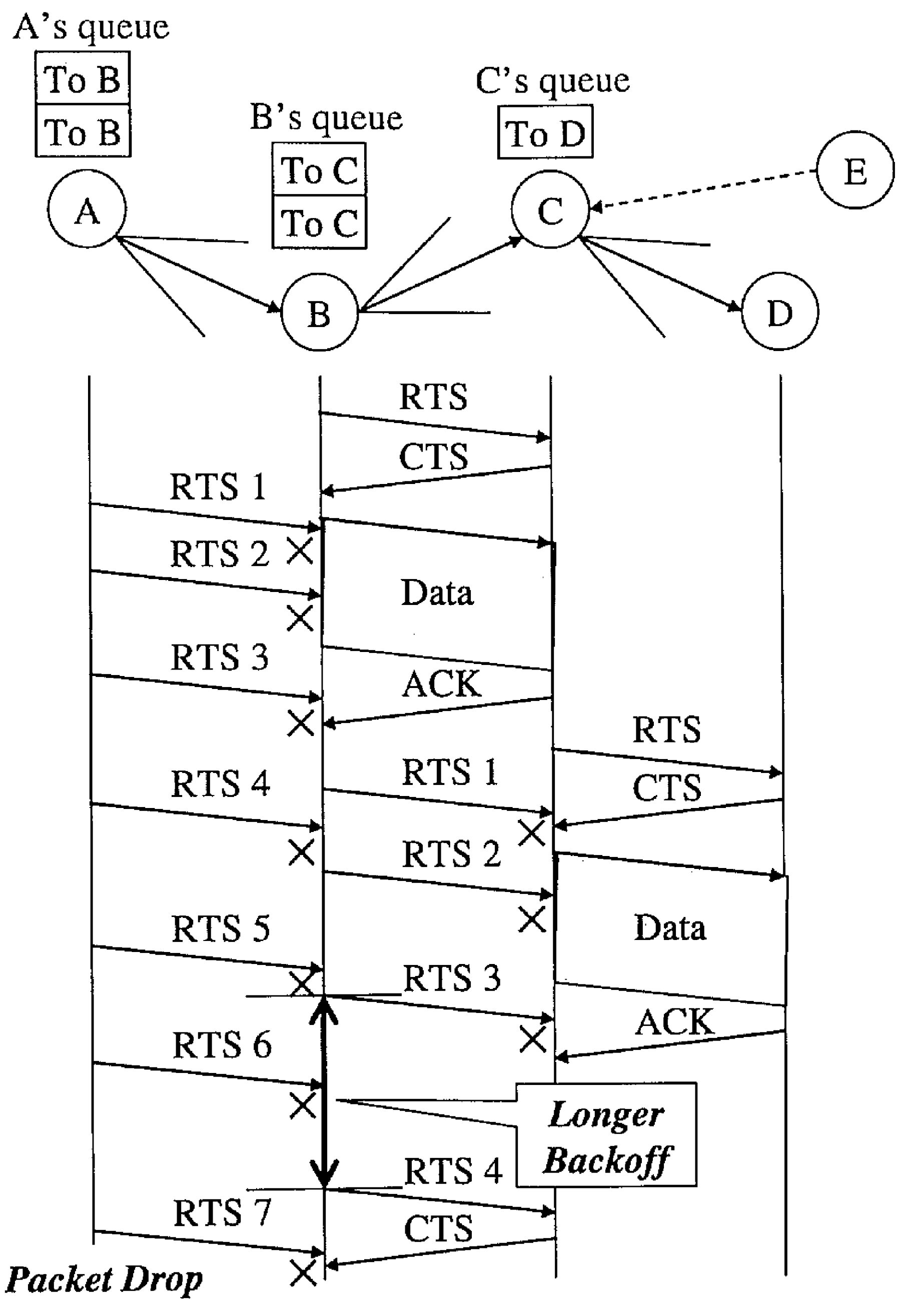


Figure 5.2: Deafness situations.

completes packet delivery to C, B keeps its beam towards C during backoff periods to deliver the next packet, and remains deaf to A. It may result in a packet drop at A after unproductive retransmissions. Deafness problem also appears in the neighborhood of the receiver. If node E attempts to communicate with C while C is receiving Data from B, it suffers from deafness.

Another problem of deafness is the wastage of the wireless channel. After the completion of the communication between B and C, a packet is generated at C. Node C switches to the Directional mode and sends the packet to D. After the communication between C and D, C becomes idle and switches back to the Omni mode because there is no packet in its queue. Node B, however, cannot detect the completion of the communication between C and D by both physical and virtual carrier sensing. Node B thus cannot initiate a transmission immediately because it has a longer backoff time due to the fact that the contention window is doubled for each retransmission, and the wireless channel remains unused during this period.

Because of these situations, the deafness problem leads to excessive packet drops, longer delay, wastage of the wireless channel, and unfairness. As a result, the throughput of DMAC with DPCS degrades significantly as shown in Fig. 5.3.

Deafness problem does not appear when each node is equipped with the omnidirectional antenna because A can overhear the signal from B when B is communicating with C, and A does not try to initiate any transmissions. On the other hand, in DMAC, the RTS and CTS frames are transmitted in the restricted area and each node cannot acquire the on-going transmission information of neighborhoods. Therefore, deafness is mainly caused by a lack of state information of neighbor nodes, whether idle or busy. While directional transmissions can increase spatial reuse of the wireless channel by reducing interference between nodes, each node cannot identify the state of neighbor nodes (i.e., idle or busy) because frame transmissions are restricted in the specific area.

To solve the deafness problem, several directional MAC protocols use additional control frames to inform neighboring nodes of imminent communication, such as

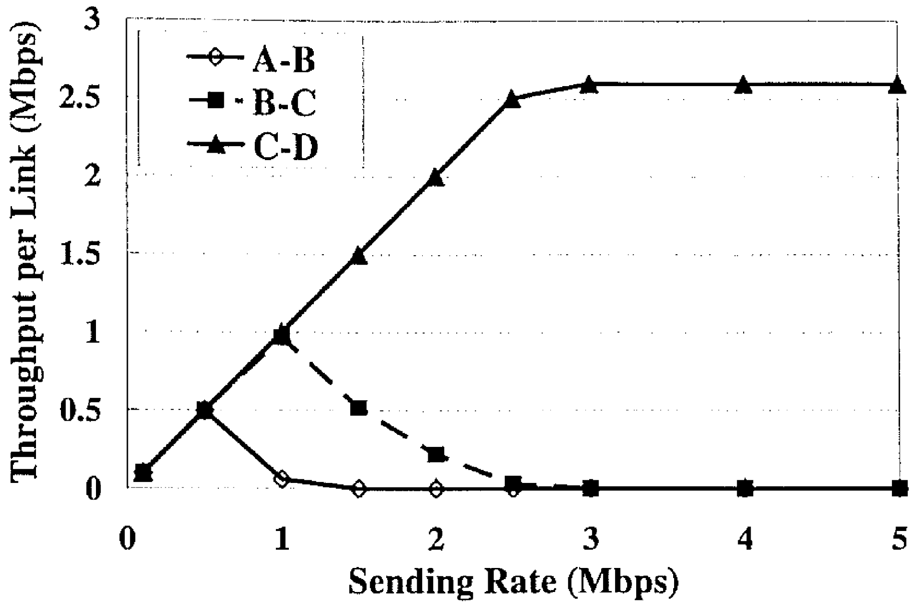


Figure 5.3: Effect of deafness in DMAC with DPCS.

CRM, CRCM and MDA. These protocols, however, may incur not only the delay and large control overhead as the number of beams increases but also collisions between control frames. Obviously, there is a fundamental tradeoff between deafness avoidance using control frames and the overhead reduction using the optimized control frame transmission mechanism. This chapter addresses this tradeoff.

5.3 Antenna Model

We assume that each node is equipped with a switched beam antenna system which is comprised of M fixed beam patterns (Fig. 5.4). Non-overlapping directional beams are numbered from 1 to M, starting at the three o'clock position and running clockwise. The antenna system possesses two separate modes: Omni and Directional. In Omni mode, a node receives signals from all directions with gain G^o. An idle node waits for signals in Omni mode. After a signal is sensed in Omni mode, the antenna detects the beam (direction) on which the signal power is strongest and goes into the Directional mode. In Directional mode, a node can point its beam towards a specific direction with gain $G^d(> G^o)$. Most existing research assumes

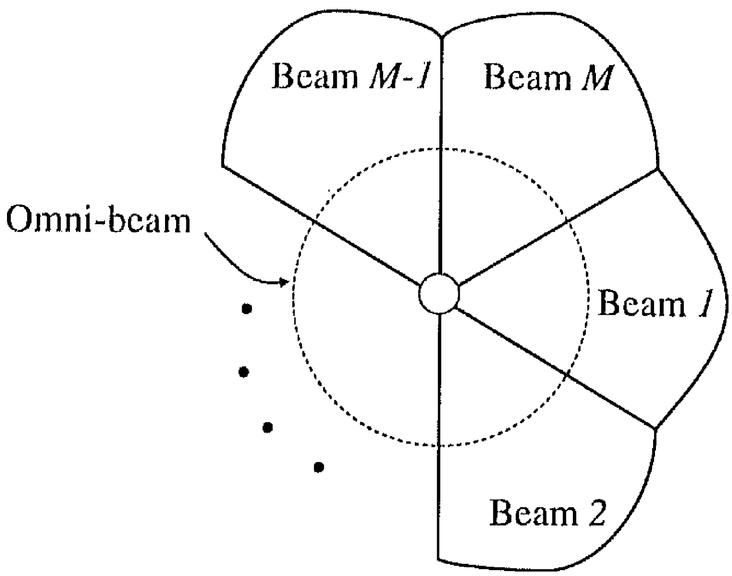


Figure 5.4: Antenna model with M beams.

the same antenna model. We assume that the directional antenna pattern is a perfect circular sector with a constant gain within the sector, and there is no antenna gain outside the sector. In DMAC/DA, the Omni mode is used for receiving signals, while the Directional mode is used for transmission as well as reception.

5.4 DMAC/DA

5.4.1 Neighbor Table

In DMAC/DA, each node maintains a neighbor table with one record for every node that it has heard. Initially, the neighbor table is empty and it is continuously updated upon overhearing any transmission. Table 5.1 shows the structure of neighbor table (example of A's neighbor table in Fig. 5.5). The record of Table Table 5.1 means that A can transmit or receive from D by beam 3. Beam number field maintains the beam from which the node heard the frame and it is updated whenever each node receives any frame, regardless of whether the frame is sent to the node. Deafness duration field represents the duration that D is deaf (busy). The detail description of this field is mentioned in the next section. Link activity field indicates the reception time of the previous transmission between D and A where D

Table 5.1: Neighbor table.

ID	Beam Number	Deafness Duration	Link Activity
B	1	–	B_{RxTime}
C	4	–	–
D	3	T_D	D_{RxTime}
E	2	–	–
F	6	T_F	F_{RxTime}
G	2	–	–

was the transmitter and A was the intended receiver. This field is updated by each reception of the Data frame addressed to itself. If D delivered packets to A in the near past, it is reasonable to consider that D is intending to deliver the next packet to A. Therefore, this field presents potential transmitters and it is used to select the beam in which the control frame should be transmitted. If the elapsed time from the previous transmission exceeds a certain threshold value, T_{DA}, it is removed from the table.

5.4.2 Procedures of DMAC/DA

DMAC/DA optimizes the control frame transmissions by sending WTS frames only through those beams where potential transmitters are found in order to reduce the number of control frames and also mitigate deafness properly.

Procedure of Communicating Nodes

We use Fig. 5.5 to explain the procedure of DMAC/DA. In DMAC/DA, each idle node stays in the Omni mode. When node A has a packet to be sent towards node B, firstly, it performs physical carrier sensing in the Omni mode during backoff periods as similar to DMAC with OPCS [70]. When the node senses a signal in backoff periods, it performs the beam scan to determine the direction of the arriving signal. If the estimated direction is in a different direction from that of the intended

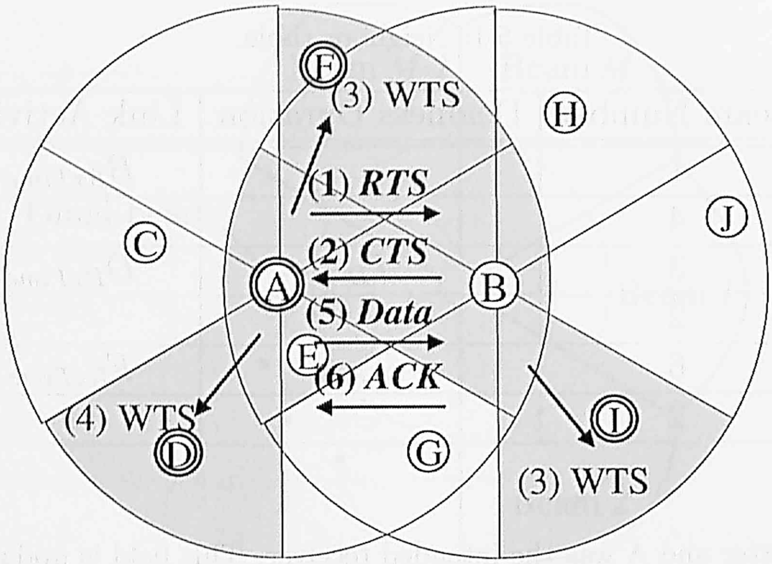


Figure 5.5: DMAC/DA.

receiver, then the transmitter continues backing off; otherwise the transmitter considers that channel is busy. If the transmitter receives RTS addressed to it during backoff periods, the transmitter freezes the backoff timer and replies with CTS. It can mitigate unproductive retransmissions due to "persistent deafness" arising from directional physical carrier sensing. However, the channel wastage due to deafness is not solved.

If the channel remains idle during backoff periods, node A determines the number of WTS frames K_A (out of $M-1$) should be transmitted after the successful exchange of RTS and CTS. It checks its own neighbor table and also DNAV table for each beam whether potential transmitters are located and DNAV is not set in its beam. Unlike MDA, all beams except the beam towards B are checked in order to inform all potential transmitters of imminent communication. Note that if DNAV is set in the corresponding beam, this beam is removed from K_A even though there are potential transmitters. K_A is included in its RTS and then node A switches to the Directional mode and sends RTS in the direction of B and waits for the CTS. If node B receives RTS, it also determines the number of WTS frames K_B. Then, node B switches to the Directional mode and sends CTS including K_B. Only after the RTS/CTS handshake is successfully completed, A and B send WTS frames simultaneously using the selected beams. Node A transmits WTS frames from the beam that is located just right of the one o'clock position, and node B starts from the beam of the five o'clock position in Fig. 5.5 where the potential transmitters of A are F and D, the potential transmitter of B is I, and the number of beams M is six. WTS frames are sequentially transmitted counter-clockwise to avoid collisions between WTS frames. The frame format of WTS is the same as that of RTS. Duration field of each frame can be decremented accurately because node A can obtain K_B from the CTS and node B vice versa. After both of the nodes complete WTS transmissions, node A sends the directional Data frame and node B sends the directional ACK frame if the Data frame is correctly received. Both A and B switch back to the Omni mode after the Data/ACK frame exchange.

Procedure of Neighboring Nodes

When the neighbor nodes receive the WTS, these nodes set the sender of the WTS as a deaf node in the deafness duration field of its own neighbor table and defer their own transmissions addressed to the deaf node until the entire data transmission completes. This can prevent packet drops due to unproductive retransmissions caused by the deafness problem.

In addition, if the neighbor node fails to communicate with the sender of WTS and the backoff procedure is invoked before receiving WTS, it discards the frozen backoff counter and reselects a new backoff counter from [0, CW_{min}] for the next attempt. Fig. 5.6 shows this scenario. This reduces the channel wastage due to unnecessary backoff caused by the deafness problem. Note that DNAV table is not updated by reception of WTS. In Fig. 5.5, while node D receives WTS transmitted by A and refrains from initiating transmission addressed to A, it can communicate with node E without interference between the on-going communication between A and B. DNAV table is updated only when the node receives RTS or CTS. In addition, the transmission of WTS frames is also useful to update the location of neighboring

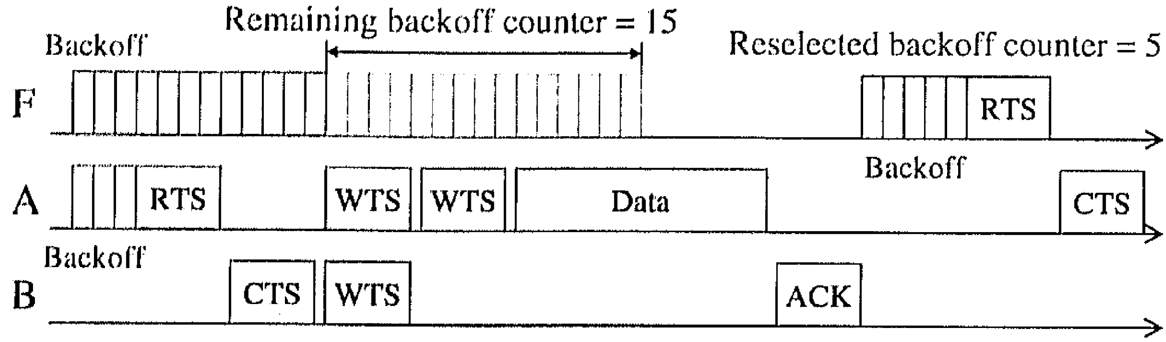


Figure 5.6: Handling the wastage of the wireless channel.

nodes.

5.4.3 DMAC/DA with NPN

In this section, we propose enhanced DMAC/DA, called DMAC/DA with NPN (Next Packet Notification). Basic DMAC/DA uses the history of the previous communications to select potential transmitters. Therefore, if the potential transmitter does not have more packets addressed to the same receiver, WTS frame transmitted to the node is unnecessary. If each node can acquire the next packet information of neighbor nodes, it can transmit WTS frames more properly to mitigate deafness and also reduce the control overhead. Therefore, in DMAC/DA with NPN, if there is a packet addressed to the same receiver in the head of its queue (i.e., a next packet), the transmitter sets More Data bit in the frame control header of the Data frame; otherwise the bit is set to zero. When the node receives the Data frame, it checks More Data bit whether the transmitter has more packets to send for it or not. Link activity field of the neighbor table is updated only when More Data bit is set. Procedures of DMAC/DA with NPN are the same as that of basic DMAC/DA except for the update policy of the link activity field.

5.5 RI-DMAC

5.5.1 Polling Table

Each node maintains a polling table to poll a potential deafness node in RI-DMAC. Table 5.2 shows the structure of the polling table. The polling table presents the nodes which have a packet addressed to the node and may experience deafness. To construct the polling table, if there is a packet addressed to the same receiver in the head of its queue (i.e., a next packet), the transmitter appends a size of the next packet to the Data frame header (a 16-bit additional field) for each transmitted packet; otherwise the field is set to zero. When the node receives the Data frame, it checks the frame header and updates its own polling table with its reception time.

In Fig. 5.7, when node B transmits the first packet in the queue, it notifies node C that the next packet is also addressed to node C because the receiver of the second packet in B's queue is node C. When node C receives the Data frame, the next packet information of node B is stored in C's polling table. On the other hand, when node B transmits the second packet, the next packet field of the Data frame header is set to zero because the third packet of node B is not addressed to node C. In this case, the entry for node B is removed from C's polling table after receiving the second packet from node B. Even though the fifth packet in B's queue is intended for node C, this information is not included when transmitting the second packet. This is because we assume a FIFO queue at each node and if node C acquires the information about the fifth packet of node B, node C cannot determine when to poll node B. RI-DMAC is not a pure receiver-initiated MAC protocol but the combination of the sender-initiated and the receiver-initiated operations. The receiver-initiated mode is triggered only when the receiver knows the next packet in the transmitter's queue is destined for itself. Otherwise, the sender-initiated mode is used as the default mode (e.g., for first generated packet or intermittent packets). Therefore, it is not necessary for each node to know all neighbors' packet information. If the elapsed time of the entry exceeds a certain threshold value T_{RI}, it is removed from the table for handling mobility. Conventional receiver-initiated

Table 5.2: Polling table.

ID	Next Packet Size	Reception Time
X	L_X	T_X
Y	L_Y	T_Y
Z	L_Z	T_Z

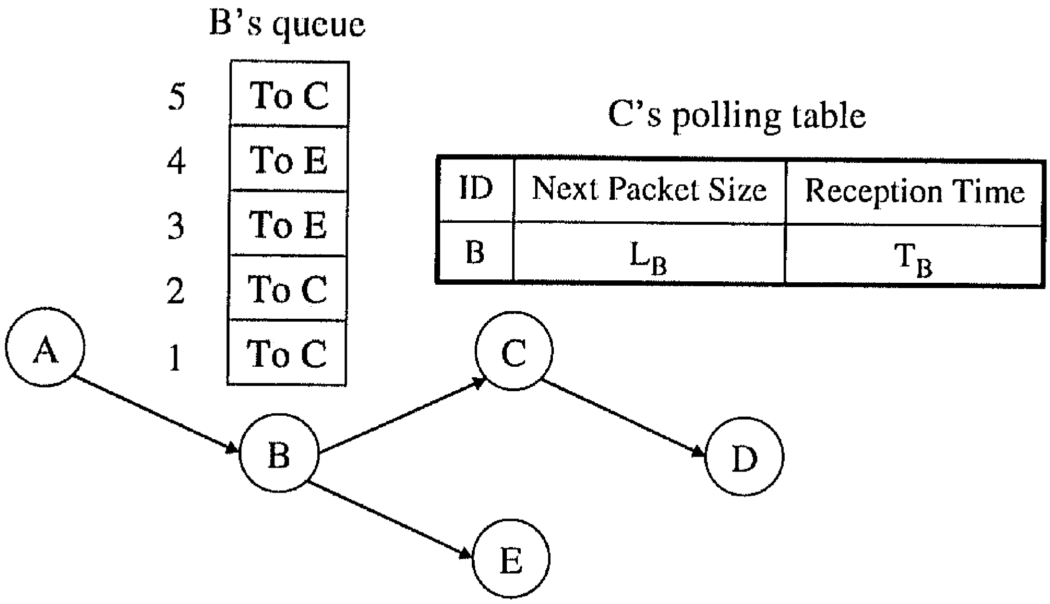


Figure 5.7: Construction of the polling table.

MAC protocols, such as [39] and [76], require the traffic estimator that predicts the packet arrivals of neighbor nodes based on the previous history to poll the neighbors. Unlike these protocols, RI-DMAC does not require the traffic estimator by using a combination of sender-initiated and receiver-initiated operations.

5.5.2 Polling Scheme

The existing research exploits either circular transmission of RTS/CTS, additional control channels, or clock synchronization to handle deafness by notifying the state of the node to neighbors, which may incur control overhead and complexity. RI-DMAC uses neither one of these approaches. Instead, RI-DMAC uses the RTR

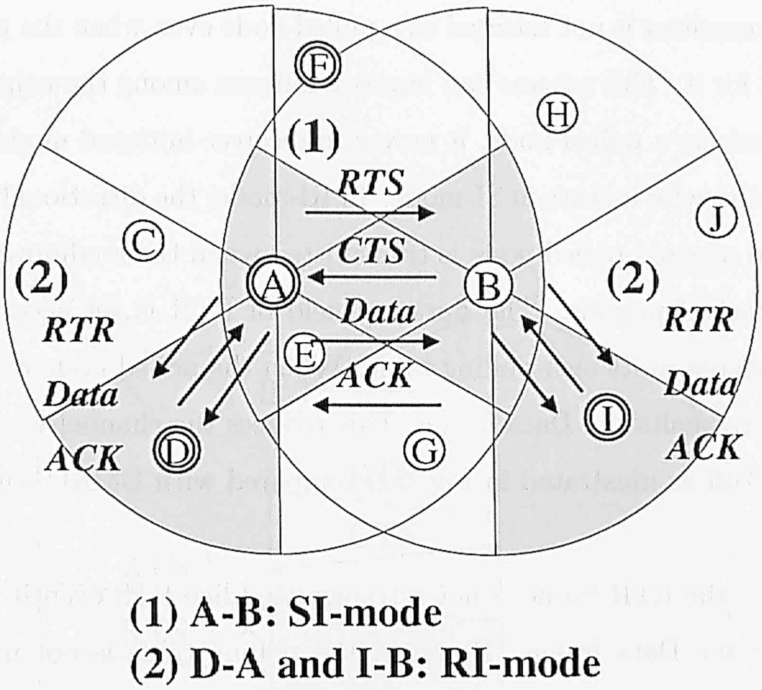


Figure 5.8: RI-DMAC.

frame to poll a potential deafness node after the completion of every dialog. While the idea behind RI-DMAC is not bounded to any directional MAC protocols, for simplicity of discussion, this paper assumes DMAC with OPCS [58] as the baseline MAC protocol.

In RI-DMAC, all frames are transmitted and received directionally to exploit range extension. The channel reservation and data communication phases are similar to DMAC. Initially, all nodes operate in sender-initiated mode (SI-mode) using a four-way handshake (Fig. 5.8 (1)). After exchanging the Data/ACK frames, the transmitter and the receiver check its own polling table whether potential deafness nodes exist or not. If more than two nodes are registered in the polling table, it also checks its reception time and the longest delayed node (i.e., the least recently transmitted node) is selected as a candidate for a polled node among potential deafness nodes. Furthermore, the receiver compares the wait time of its own pending packet with that of the polled node. If the wait time of its own pending packet is longer than that of the polled node, the receiver node cancels its polling. Note that the previous transmitter is not selected as a polled node even when the polling table is empty except for it. This scheme can improve fairness among the neighbor nodes.

If the node selects a polled node, it moves to receiver-initiated mode (RI-mode) (Fig. 5.8 (2)); otherwise it stays in SI-mode. In RI-mode, the directional RTR frame addressed to the selected polled node is transmitted when the medium remains idle for DIFS and backoff periods. The duration field of RTR is set according to the packet size registered in its own polling table. When the polled node receives RTR, it immediately transmits the Data frame. This reduces the channel wastage due to unnecessary backoff as illustrated in Fig. 5.9 compared with DMAC with DPCS in Fig. 5.2.

In RI-DMAC, the RTR frame is not retransmitted like RTS even if the receiver does not receive the Data frame. However, the polling table is not updated and the polled node may be selected again as the polled node at the next opportunity. Neighboring nodes that overheard RTR update its DNAV with the duration field contained in RTR, in similar with RTS.

Unlike other receiver-initiated MAC protocols, in RI-DMAC, the sender transmits RTS even when the receiver is in the RI-mode and it may receive RTR as illustrated in Fig. 5.9. This is because when RTR is not received successfully due to collision or deafness, the transmitter should wait for the next RTR from the receiver, and it may result in the wastage of the wireless channel and increase the delay as in other receiver-initiated MAC protocols.

Fig. 5.10, Fig. 5.11 and Fig. 5.12 show the flowchart of RI-DMAC at the sender side, receiver side and RI-mode respectively, as the summary of our proposed scheme.

5.6 Performance Evaluation

5.6.1 Simulation Model

We make the following assumptions. Transmission range of the omni-directional antenna is 250 m and that of the directional antenna is 500 m. The data rate

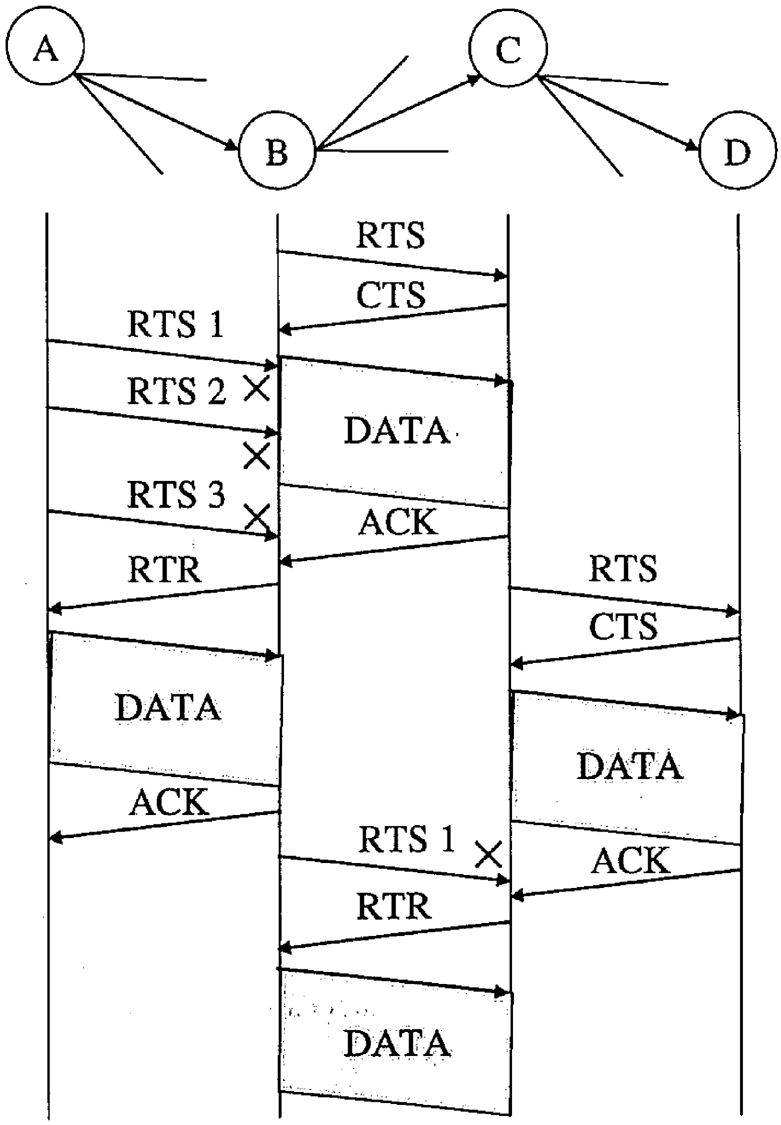


Figure 5.9: Sequence of RI-DMAC.

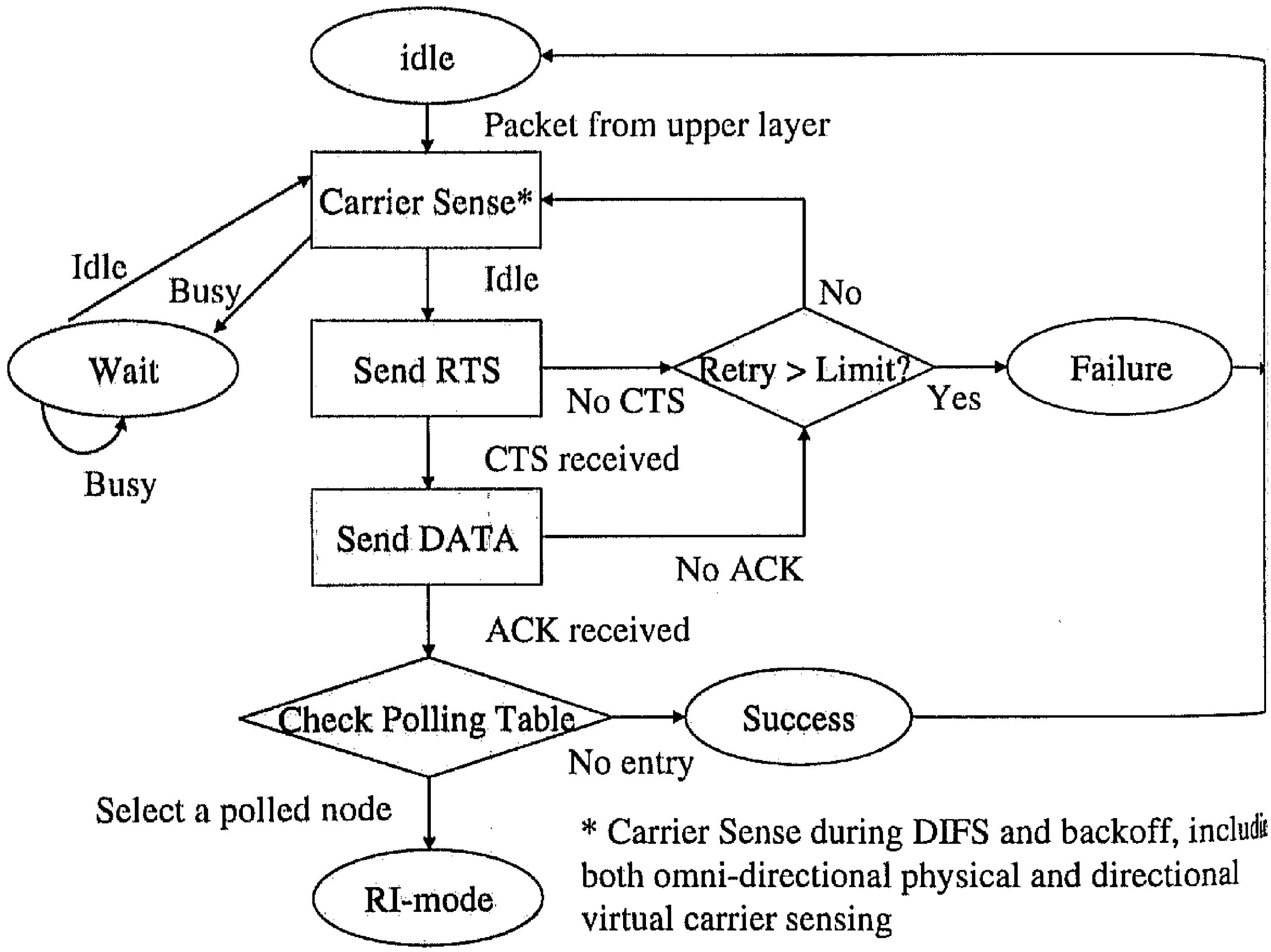


Figure 5.10: Flowchart of RI-DMAC (Sender side).

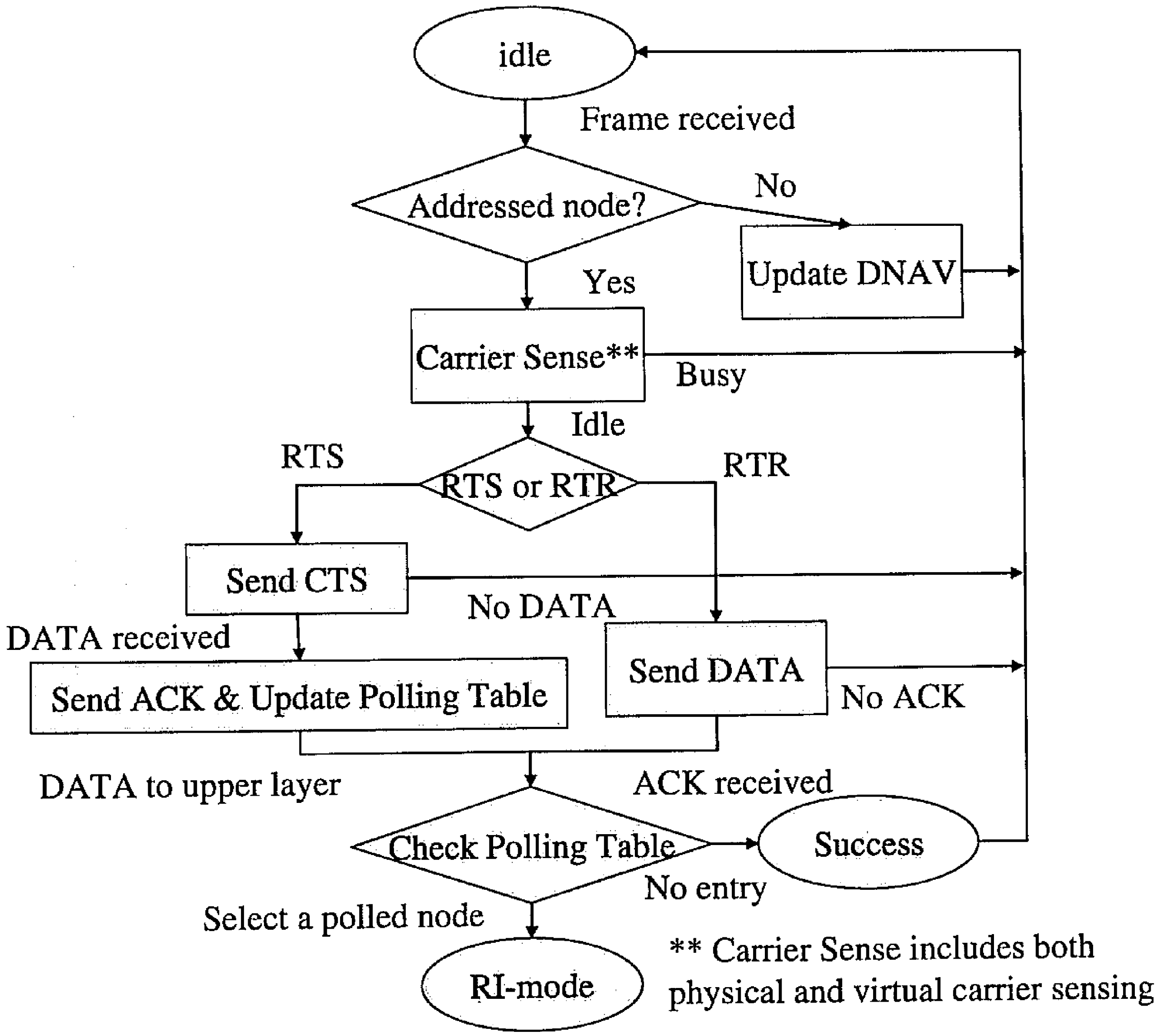


Figure 5.11: Flowchart of RI-DMAC (Receiver side).

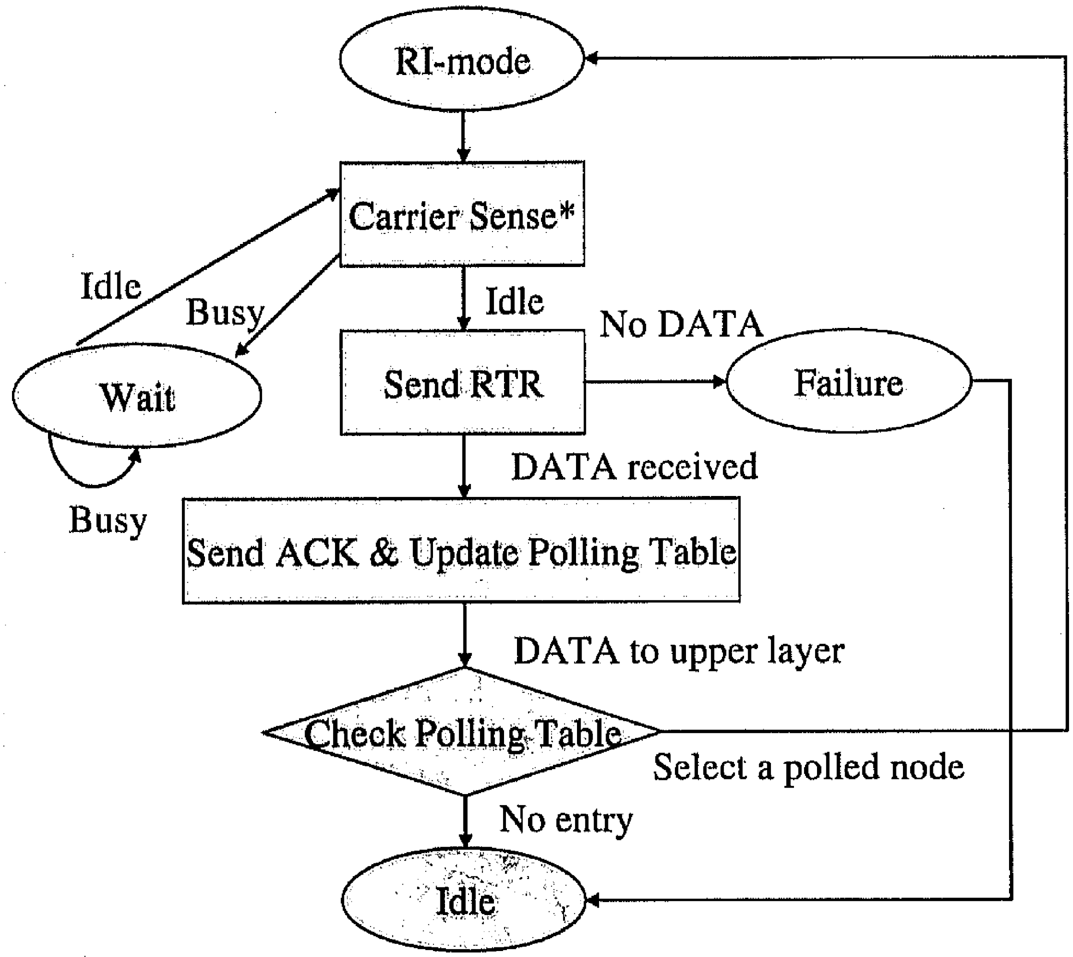


Figure 5.12: Flowchart of RI-DMAC (RI-mode).

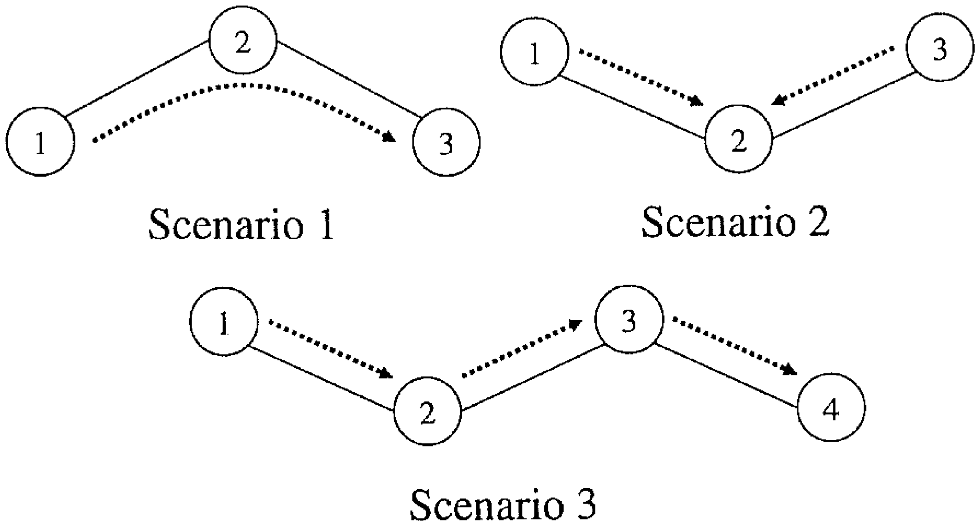


Figure 5.13: Scenarios used for evaluating deafness.

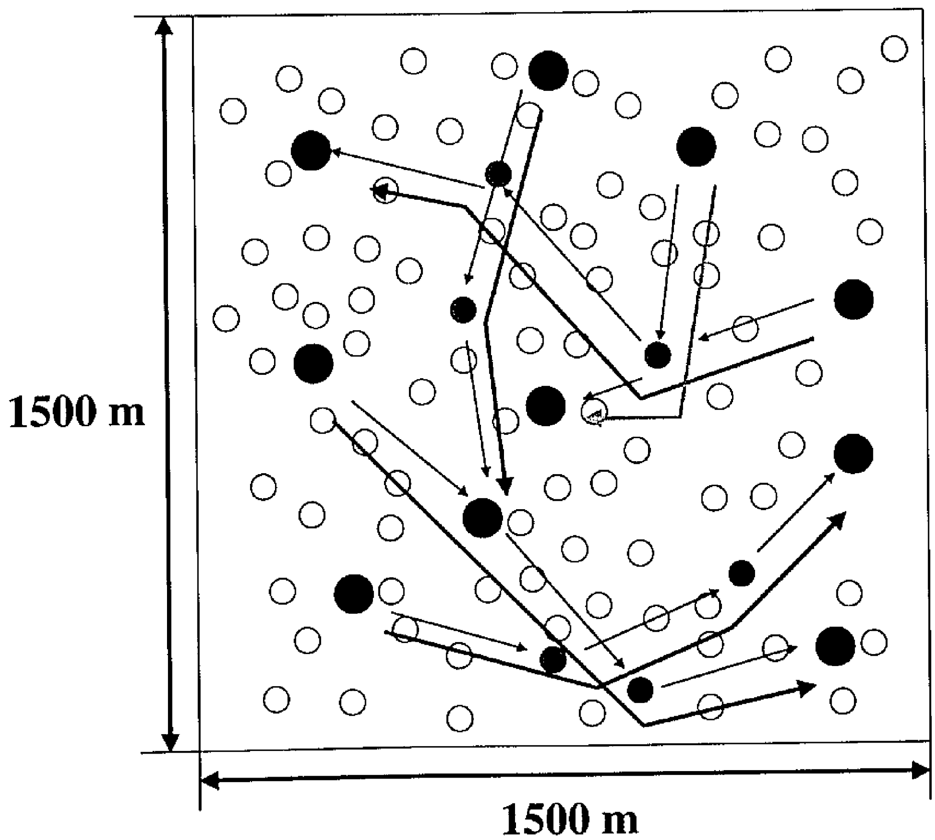


Figure 5.14: Example of multihop random topology.

is 11 Mbps. Because this chapter focuses on handling deafness, for simplicity of discussion, we assume that each node knows the location of neighboring nodes a priori to point the beam in the appropriate direction. Mechanisms to determine the neighbors' location are proposed in [69, 77]. We do not consider mobility in our simulations. We change the parameters such as the sending rate of each flow, number of flows, data size and number of beams. Other parameters not described in this section, such as the interframe space and the contention window size, follow the IEEE 802.11 (DSSS) specifications [16]. Simulation results are the average of 10 runs, and one million application packets are generated for each simulation. In most cases, the 95 percent confidence interval for the measured data is less than 5 percent of the sample mean.

We first consider three deafness scenarios (Fig. 5.13) same as in [70]. In these scenarios, we assume that the data size is 512 bytes and the number of beams M in directional MAC protocols is six.

We also consider the multihop random topology (Fig. 5.14). We assume that a hundred nodes are arranged at random in a square area with dimensions of 1500 m. Random source-destination pairs of CBR traffic are chosen at random and the routes are statically assigned using shortest path.

The following 10 MAC protocols are evaluated in terms of throughput, overhead, packet drop ratio and so on.

- RI-DMAC
- DMAC/DA
- DMAC/DA with NPN
- MDA [74]
- CRM [72]
- CRCM [73]

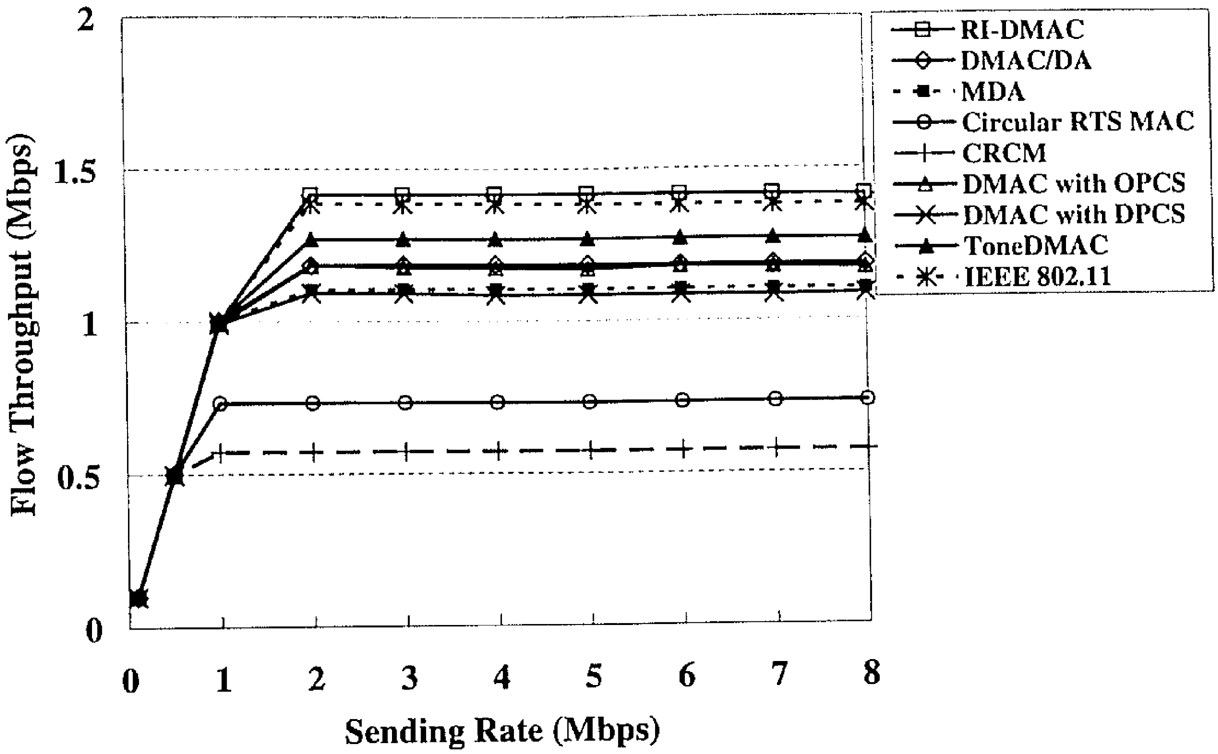


Figure 5.15: Throughput for scenario 1.

- DMAC with OPCS [70]
- DMAC with DPCS [58]
- ToneDMAC [70]
- IEEE 802.11 [16]

5.6.2 Simulation Results

Scenario 1

In scenario 1, node 1 intends to communicate to node 3, using the route through node 2. As described in Section 5.2, node 1 is a deafness node when node 2 is communicating with node 3. This scenario measures only the effect of deafness in directional MAC protocols because spatial reuse is not possible. Because there is no difference between basic DMAC/DA and DMAC/DA with NPN in these scenarios, results of DMAC/DA with NPN are omitted. The throughput versus the offered

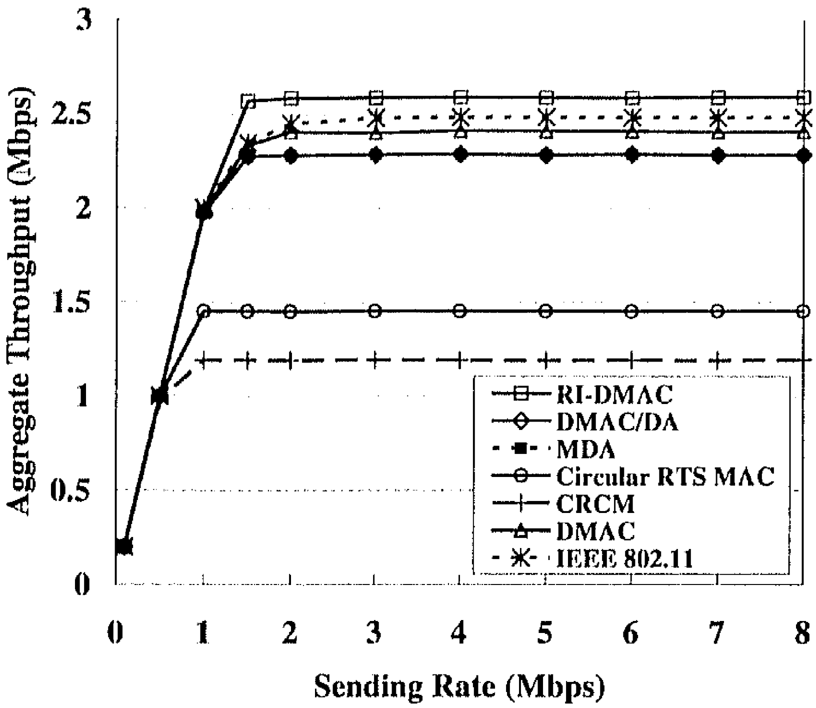


Figure 5.16: Throughput for scenario 2.

load in scenario 1 is shown in Fig. 5.15. IEEE 802.11 performs better than existing directional MAC protocols because the deafness problem does not appear when omni-directional antennas are used. RI-DMAC outperforms IEEE 802.11 because it solves deafness properly and reduces control frames compared with a four-way handshake. Although ToneDMAC also solves deafness using omni-directional out-of-band tones, throughput of ToneDMAC is lower than IEEE 802.11 because the available data rate for data communication is 10.5 Mbps due to allocating the bandwidth to the control channel. Circular RTS MAC and CRCM are inferior to DMAC because of the overhead of circular transmissions.

Scenario 2

Fig. 5.16 shows the throughput of seven protocols in scenario 2. In scenario 2, two nodes intend to communicate to the same node and spatial reuse is also impossible. RI-DMAC outperforms others because it reduces the channel wastage

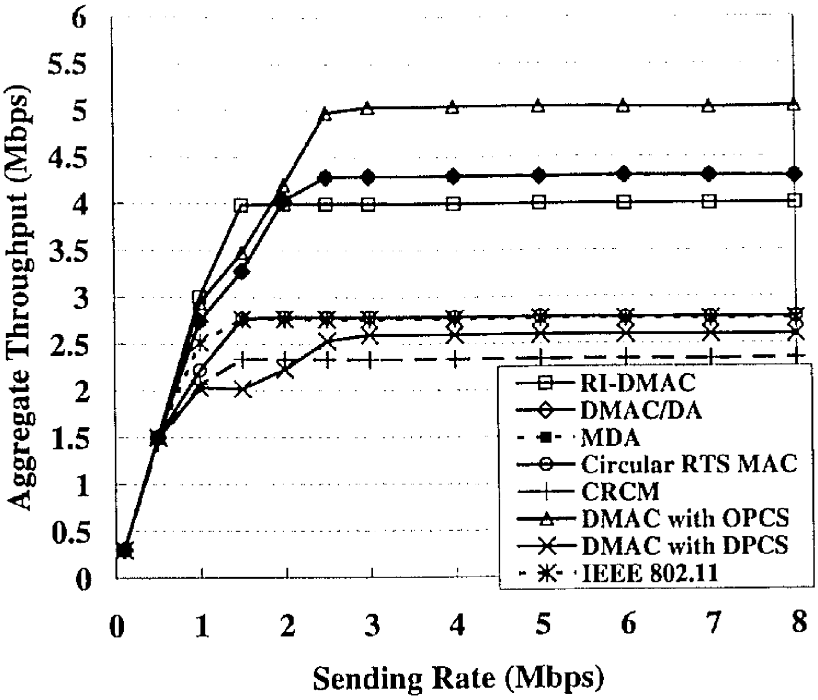


Figure 5.17: Throughput for scenario 3.

due to unnecessary backoff. Omni-directional carrier sensing does not solve deafness in scenario 2 because node 1 cannot hear the signal from node 3, and vice versa. It is only useful when the transmitter is also the receiver of other links. Therefore, the benefit of polling scheme is evident from the performance improvement of RI-DMAC over DMAC. As in scenario 1, directional MAC protocols with multiple control frame transmissions achieve lower throughput than DMAC.

Scenario 3

In scenario 3, "deadlock" [70] problem occurs; all nodes on a chain may fail to communicate except for the last communicating pair on the chain. Fig. 5.17 shows the throughput of eight MAC protocols in scenario 3. Although RI-DMAC performs better than DMAC with OPCS under 1.5 Mbps sending rate, DMAC with OPCS outperforms RI-DMAC when the sending rate is high. To analyze and explain this situation, throughput per link of DMAC with DPCS, DMAC with OPCS, RI-

DMAC and IEEE 802.11 are shown in Fig. 5.18, Fig. 5.19, Fig. 5.20 and Fig. 5.21, respectively. DMAC with DPCS suffers from "deadlock" as shown in Fig. 5.18. Although DMAC with OPCS mitigates "deadlock", link throughput of 2-3 is dramatically low. This is because it is hard for node 2 to acquire the channel to initiate a transmission. Node 2 can acquire the channel only if node 1 and node 3 are idle. Unlike node 2, nodes 1 and 3 can acquire the channel when an addressed node is idle. This is a serious fairness problem. Similarly, DMAC/DA, MDA, Circular RTS MAC and CRCM also suffer from this fairness problem. As shown in Fig. 5.20, throughput of each link is comparatively same in RI-DMAC. This is because our proposed polling scheme can select "the least recently transmitted node" as a polled node and solve the fairness problem. In IEEE 802.11, it also appears the fairness problem as discussed in [19]. This is because node 1 cannot overhear the signal between 3 and 4. When node 3 initiates a transmission, it transmits RTS omni-directionally and node 2 sets NAV. Under these situations, if node 1 transmits RTS to 2, node 2 cannot reply because of NAV. It reduces the possibility for node 1 to acquire the channel. Fig. 5.22 shows the fairness index of eight MAC protocols in scenario 3. We use the max-min fairness defined in [84]. Assuming the throughput of flow i is x_i, fairness index is calculated as

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

Results show that RI-DMAC outperforms others in terms of fairness because it solves the long-term fairness issue [19] using a combination of sender-initiated and receiver-initiated operations and the sophisticated polling scheme.

Multi-hop Random Topology

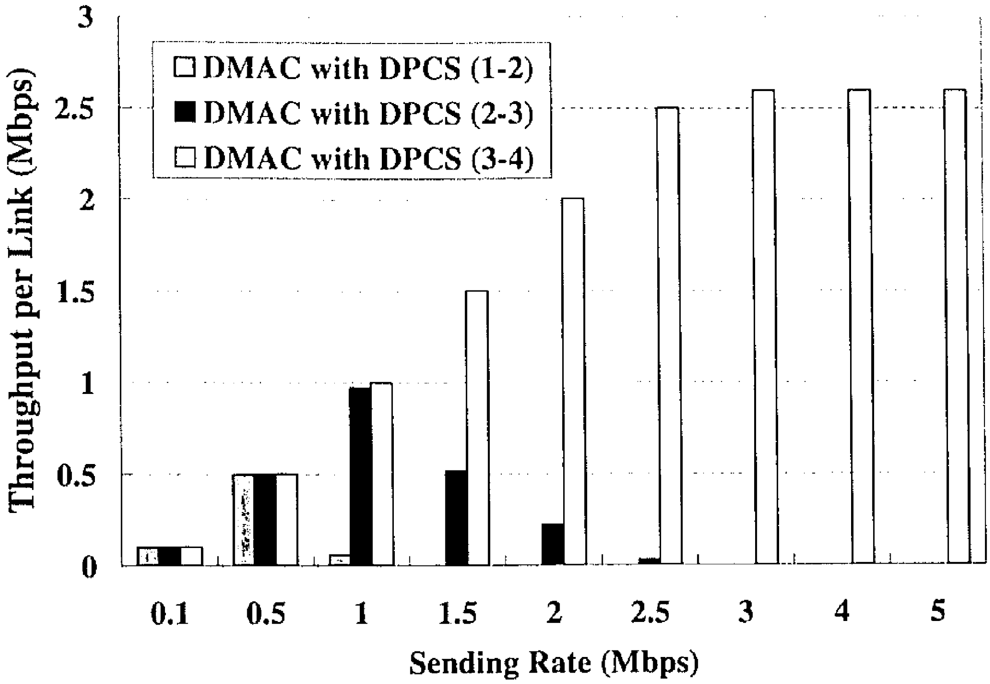


Figure 5.18: Link throughput of DMAC with DPCS.

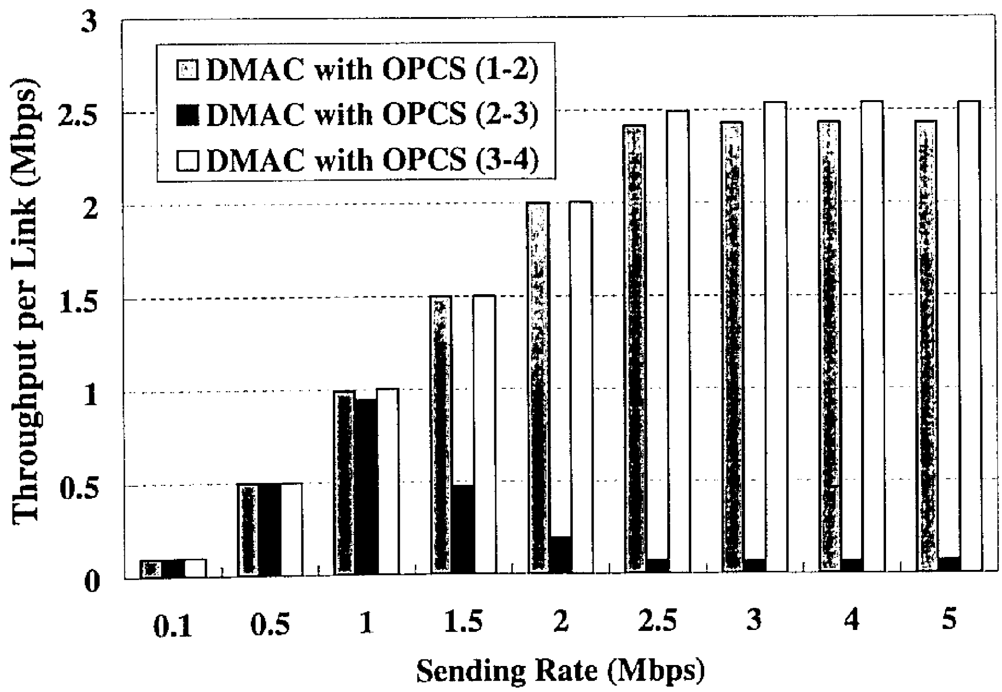


Figure 5.19: Link throughput of DMAC with OPCS.

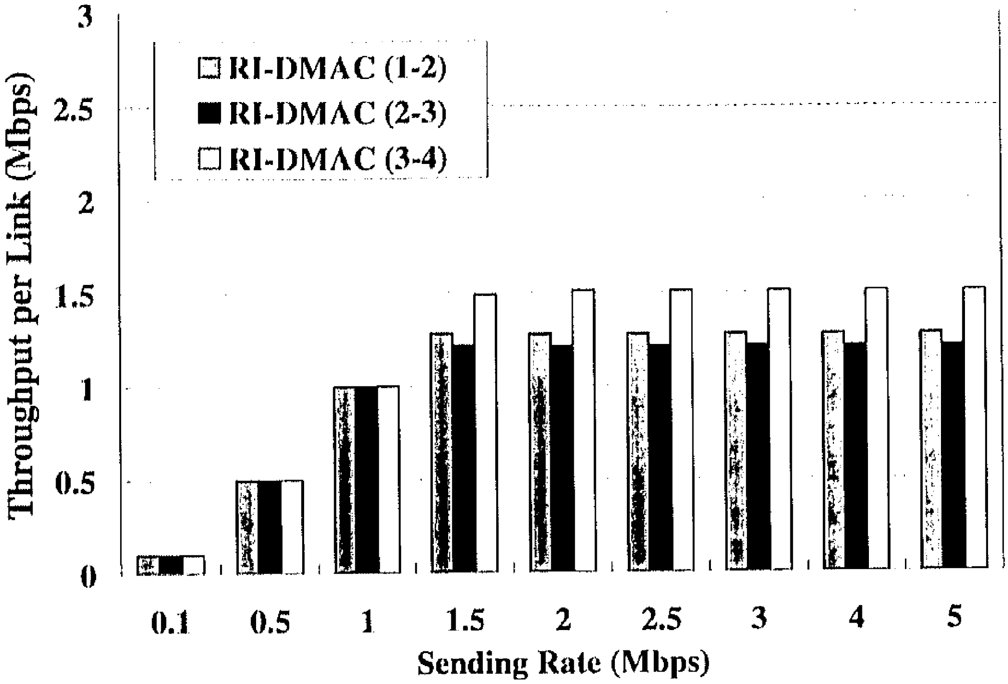


Figure 5.20: Link throughput of RI-DMAC.

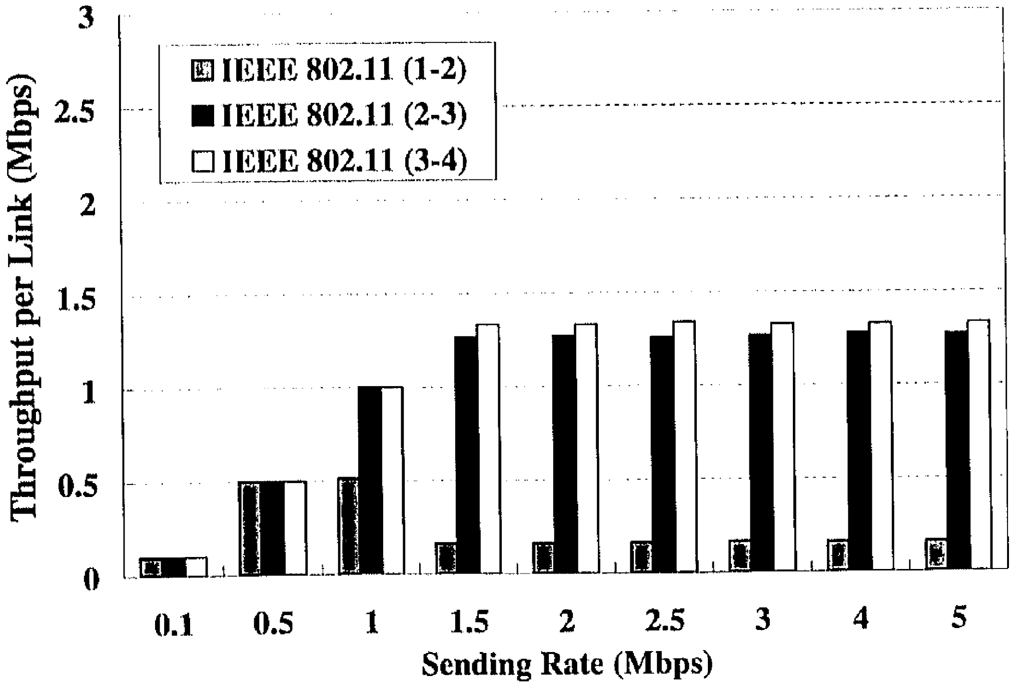


Figure 5.21: Link throughput of IEEE 802.11.

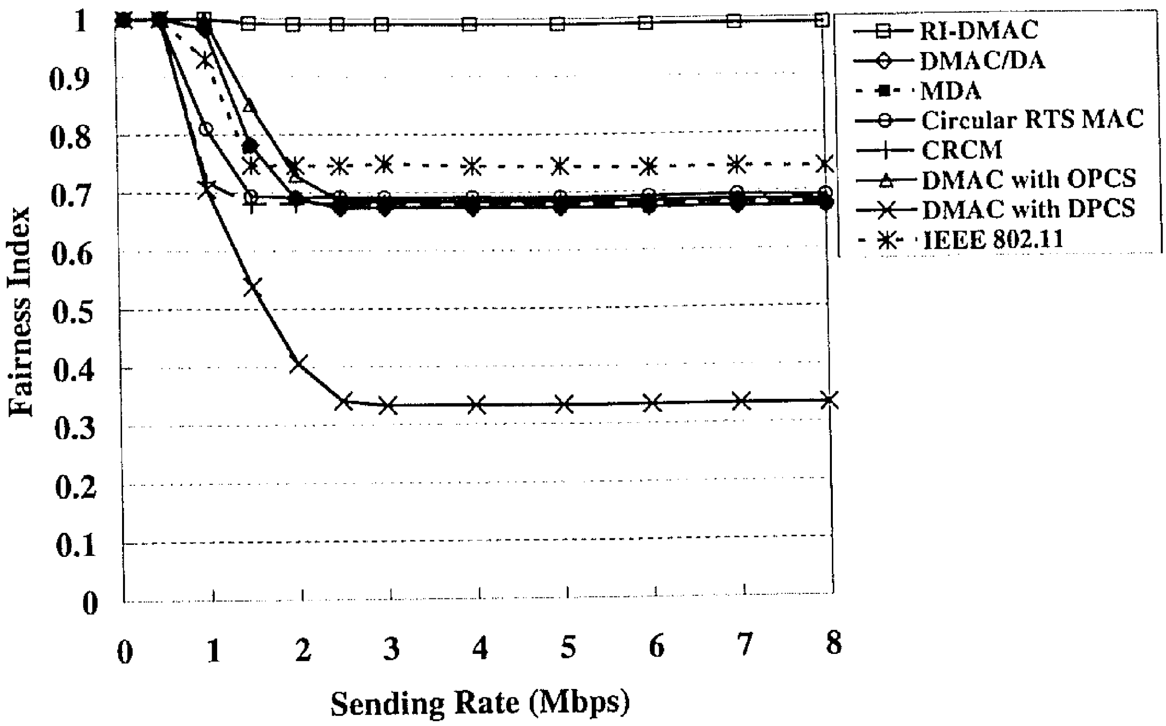


Figure 5.22: Fairness index for scenario 3.

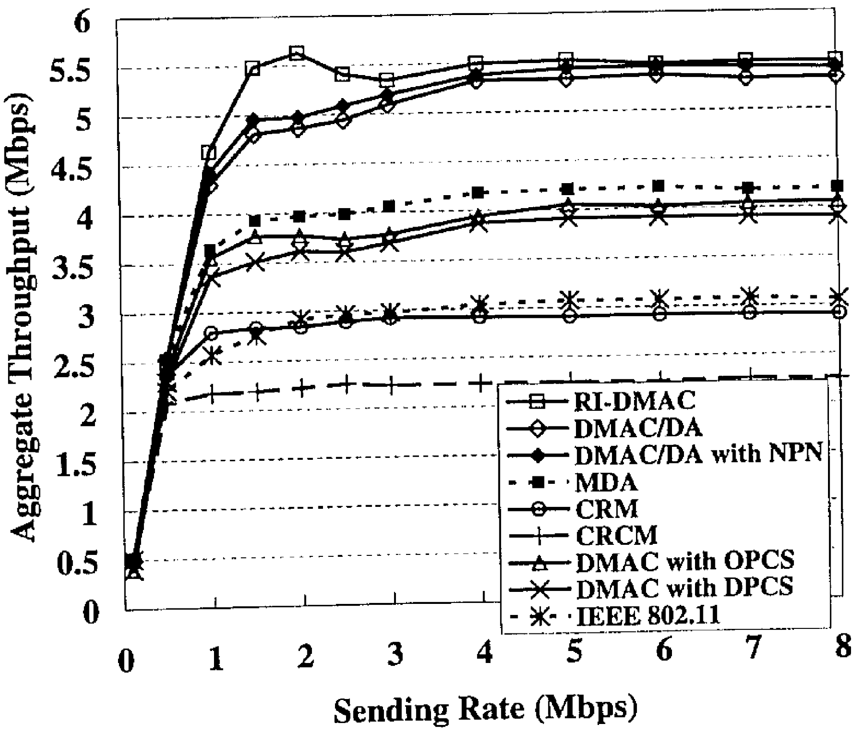


Figure 5.23: Aggregate throughput.

Throughput

In the multi-hop random topology scenario, we first evaluate the performance of different MAC protocols when the sending rate of each flow is changed, the number of flows is five, data size is 1024 bytes, and the number of beams is six. Fig. 5.23 shows the throughput performance of 9 MAC protocols. As shown in the figure, CRM and CRCM are inferior to IEEE 802.11 because these directional MAC protocols introduce the large control overhead and increase collisions. Throughput of MDA is higher than DMAC. This is because that MDA mitigates deafness proactively using selective circular RTS/CTS transmitted through beams with neighbors. DMAC/DA outperforms existing MAC protocols because it reduces the number of control messages compared with MDA, and also maintains the ability to handle deafness. Furthermore, DMAC/DA with NPN achieves higher throughput than basic DMAC/DA because it reduces the unnecessary WTS transmission compared with basic DMAC/DA based on the next packet information of neighbor nodes. RI-DMAC outperforms other directional MAC protocols because the proposed polling scheme alleviates deafness using the RTR frame transmitted by the receiver node for inviting the deafness node to transmit its packet and reduces control frames compared with a four-way handshake. Obviously, there is a fundamental tradeoff between deafness handling using control frame and the overhead reduction using the optimized control frame transmission mechanism. RI-DMAC balances this tradeoff and achieves the highest throughput.

RTS Failure Ratio and Deafness Ratio

We next investigate the RTS failure ratio and deafness ratio to confirm the ability for handling deafness of each directional MAC protocol. Deafness ratio is defined as the ratio of the communication failure due to deafness over the whole communication failure factors. Fig. 5.24 and Fig. 5.25 show the RTS failure ratio and deafness ratio, respectively. Because there is no significant difference between basic DMAC/DA and DMAC/DA with NPN in these performance indices, results

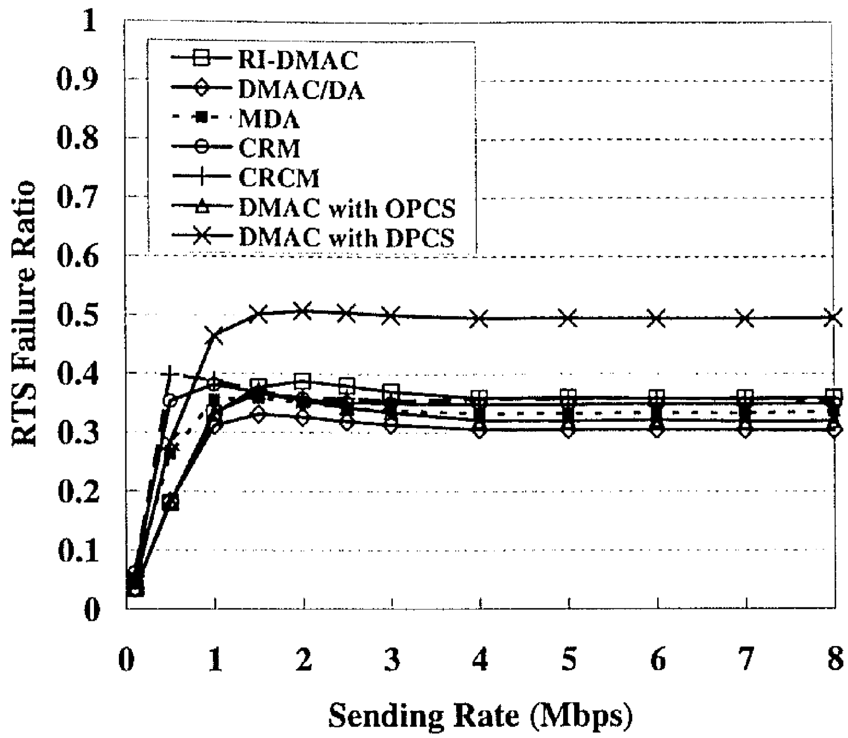


Figure 5.24: RTS failure ratio.

of DMAC/DA with NPN are omitted here. Results show that DMAC with DPCS suffers from deafness and that the most of communication failures occur due to deafness. DMAC with OPCS mitigates unproductive retransmissions of RTS and solves the deafness problem partially. Deafness ratio of CRM is higher than CRCM because deafness appears due to the transmission of single directional CTS. As shown in Fig. 5.25, it may not be possible to completely eliminate the deafness problem. It is interesting to note that deafness accounts for half of the failure factors even in conservative deafness avoidance schemes, such as CRCM and MDA. It implies that the tradeoff between deafness avoidance and spatial reuse is an important problem in directional MAC protocols. RTS failure ratio of DMAC/DA is lower than other directional MAC protocols and deafness ratio is almost the same as MDA. Although RI-DMAC reactively handles deafness at the specific node, deafness ratio of RI-DMAC is almost same as that of DMAC/DA or other conservative schemes.

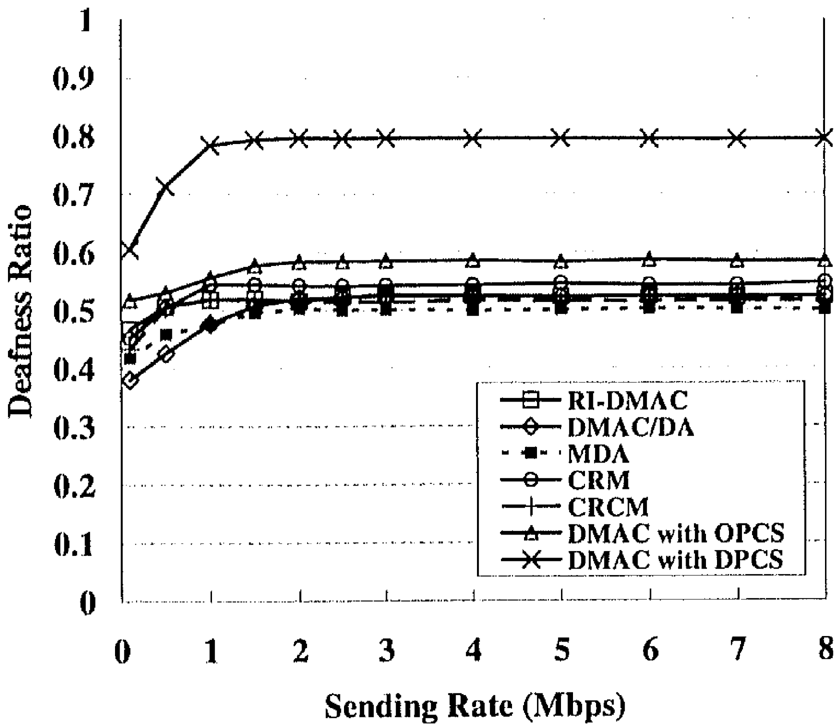


Figure 5.25: Deafness ratio.

Overhead

Fig. 5.26 shows the overhead performance, defined as the average number of bits transmitted to deliver one bit of payload to the receiver at the MAC layer. CRM and CRCM have large control overheads due to the circular transmission of RTS/CTS and the increasing of retransmissions. Overhead of DMAC/DA is lower than MDA because WTS frames are transmitted only through those sectors where potential transmitters are located to reduce the control overhead in DMAC/DA, whereas these frames are transmitted to all neighbors in MDA. RI-DMAC has lower overhead than proactive deafness handling schemes because it does not involve circular transmission of control frames.

End-to-End Delay

Fig. 5.27 shows the average end-to-end delay. CRM and CRCM have longer delay because these protocols not only incur large overhead but also spend a majority of

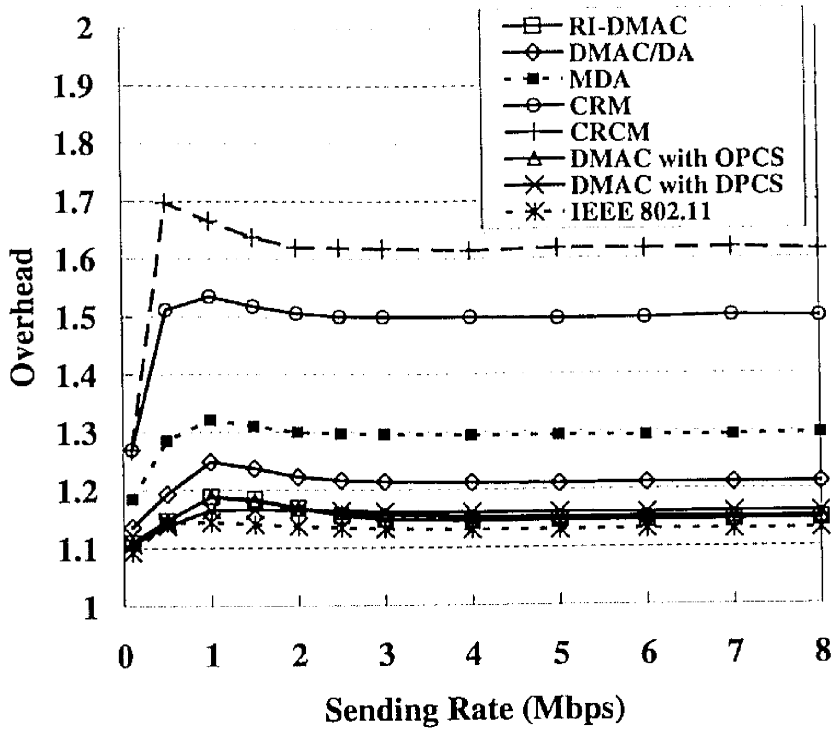


Figure 5.26: Overhead.

their time in transmitting control frames. It can be observed that DMAC/DA and RI-DMAC have less delay than MDA. This is because our proposed protocols have lower control overhead, and moreover, reduce idle time due to unnecessary backoff caused by deafness. In Fig. 5.27, results show that DMAC with DPCS outperforms others when the sending rate is high. Note that the results do not include the latency of packets that are dropped due to exceeding the maximum retry limit, which is set to 7 in our simulations, and also the routing overhead is not included. DMAC with DPCS suffers from excessive packet drops caused by deafness, and therefore route discovery procedures may be initiated throughout the network, which increase the end-to-end delay. Evaluating the impact of deafness on the network layer is projected for our future work.

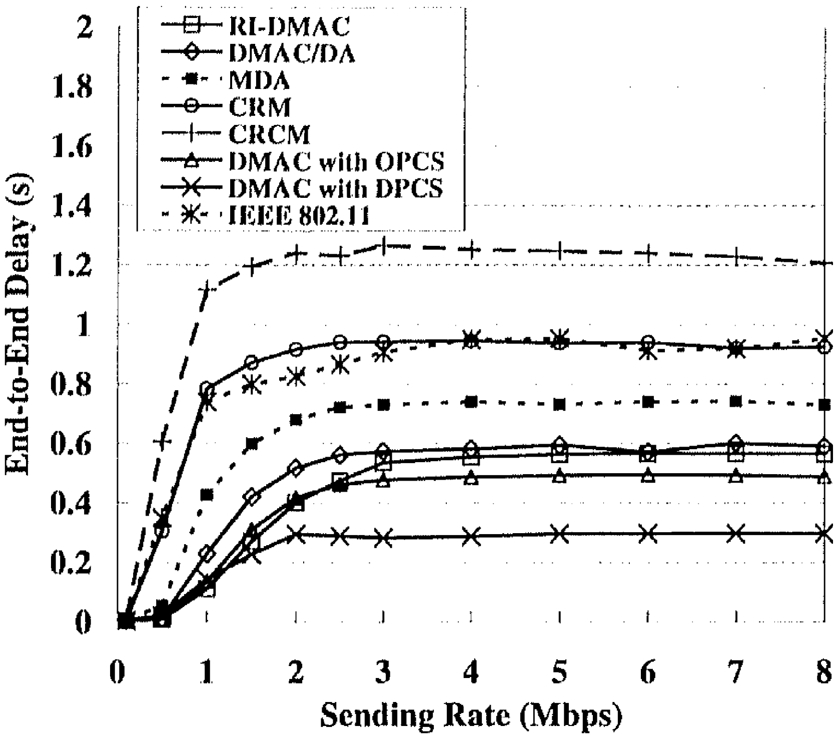


Figure 5.27: End-to-end delay.

Packet Drop Ratio

Fig. 5.28 shows the packet drop ratio due to exceeding the maximum retry limit. Results show that packet drop ratio of DMAC with DPCS is extremely high due to unproductive retransmissions of RTS caused by the deafness problem. Packet drop ratio of RI-DMAC is lower than others mainly due to overcoming the deafness problem reasonably, and it may prevent the expensive route rediscovery process.

Fairness

As discussed in [70], the deafness problem also leads to the unfair channel access problem. Results show that RI-DMAC outperforms others in terms of fairness. This is because our sophisticated polling scheme in RI-DMAC selects the least recently transmitted node as a polled node and it solves the long-term and short-term fairness issues [19].

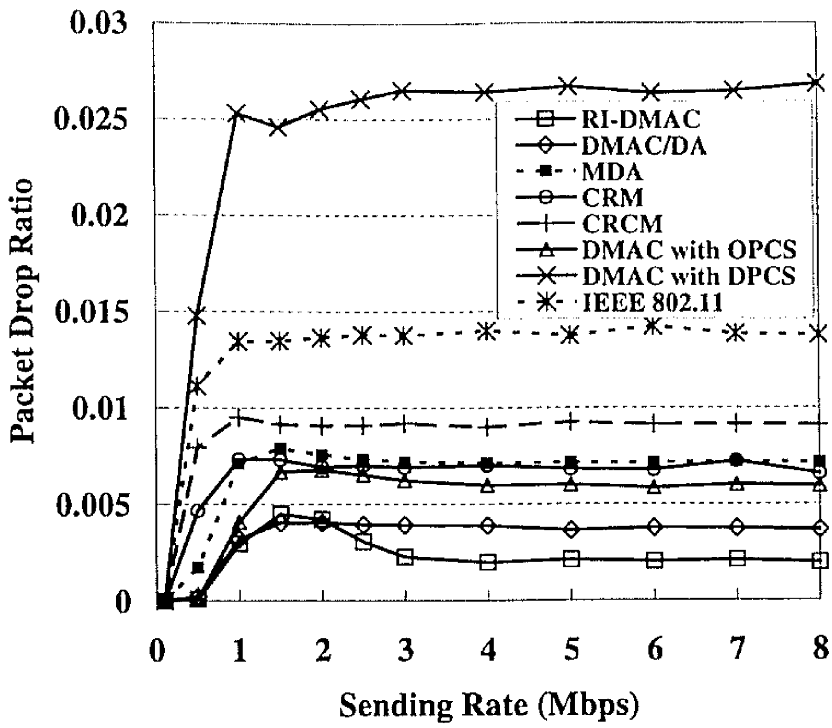


Figure 5.28: Packet drop ratio.

Effects of the Number of Flows

We next evaluate the MAC protocols with different number of flows, data size, and number of beams. Fig. 5.30 shows the aggregate throughput when the number of flows is changed from 1 to 30 (sending rate of each flow is 2 Mbps, data size is 1024 bytes and $M = 6$). Results show that MDA, CRM and CRCM cannot increase throughput performance as the number of flows increases because these protocols should transmit control frames through most of beams. On the other hand, DMAC/DA increases the throughput performance as the number of flows increases because it reduces the control overhead using the adaptive WTS scheme. In addition, the benefit of NPN is increased as the number of flows increases. This is because when the number of flows is large, each node participates in several flows and it has several packets addressed to different nodes in its queue. In this case, the notification of the next packet is more useful to transmit WTS frames properly and also reduce the control overhead.

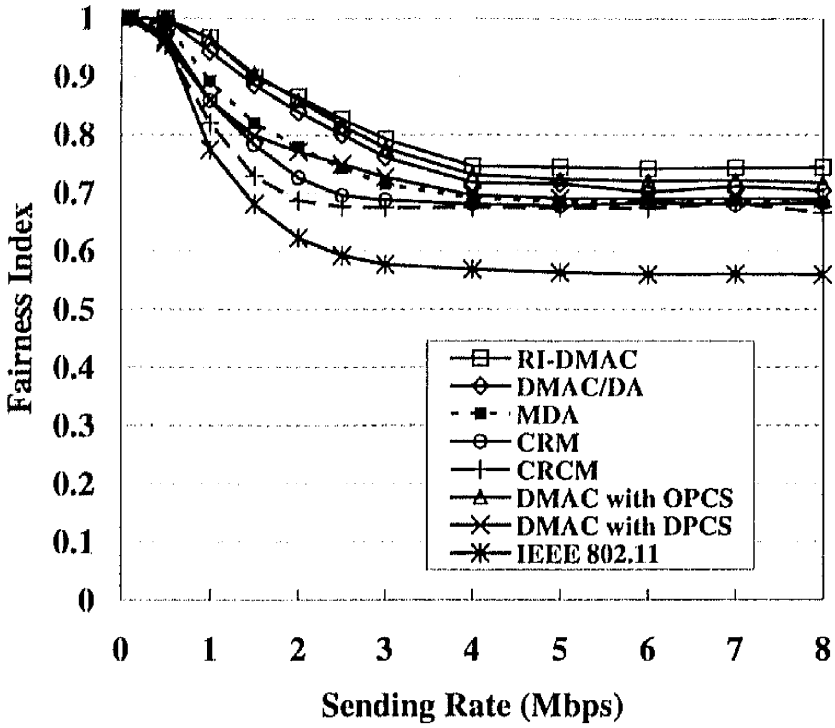


Figure 5.29: Fairness index.

Effects of the Data Size

Fig. 5.31 shows the effects of the data size. (sending rate is 2 Mbps, number of flows is 5 and $M = 6$). The control overhead relatively becomes small as the data size increases. On the other hand, when the data size is large, the duration that each node experiences deafness is increased and consequently the deafness problem becomes more serious. It can be seen that RI-DMAC outperforms other MAC protocols when the data size is not large. When the data size is large, to the contrary, DMAC/DA with NPN has better performance than RI-DMAC. This is because DMAC/DA with NPN uses multiple WTS frames to solve the deafness problem in all neighbors of communicating nodes which intend to communicate with the sender of the WTS. RI-DMAC solves deafness in one or two neighbor nodes using RTR, and other neighbors, which do not receive RTR, suffer from deafness again for a long time. Therefore, DMAC/DA with NPN has higher throughput then RI-DMAC when the data size and the number of deafness nodes are large.

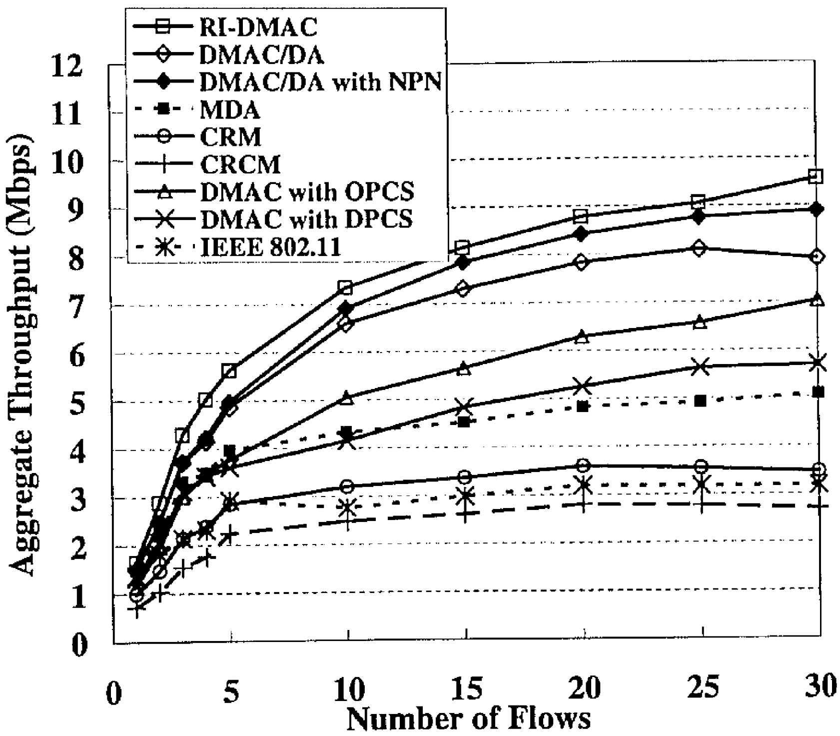


Figure 5.30: Effects of the number of flows.

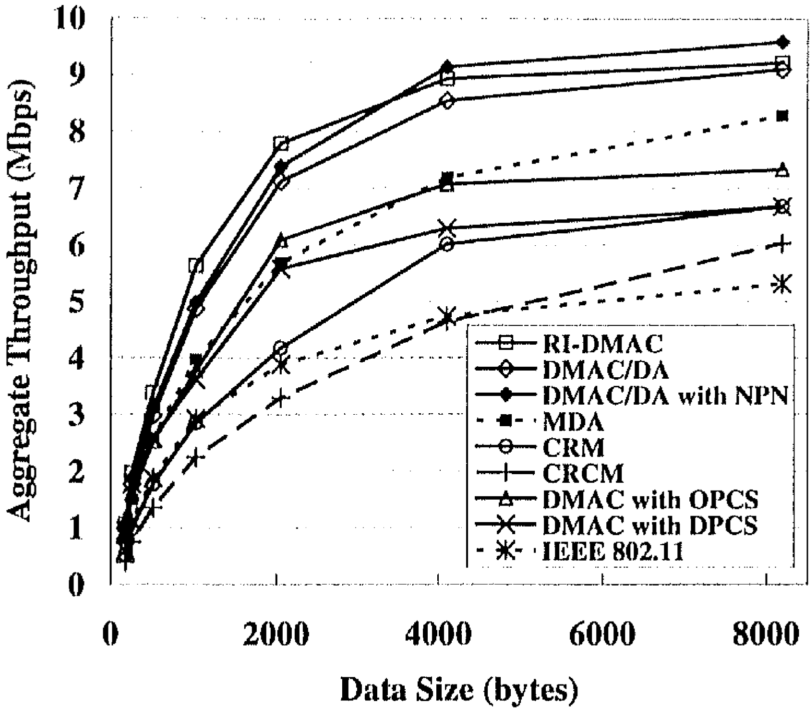


Figure 5.31: Effects of the data size.

Effects of the Number of Beams

Fig. 5.32 shows the throughput of directional MAC protocols when the number of beams M is changed from 4 to 24 (sending rate is 2 Mbps, number of flows is 5 and data size is 1024 bytes). The beamwidth becomes narrower as the number of beams increases, and spatial reuse capabilities are enhanced. CRM and CRCM cannot achieve high throughput because the number of control frames increases in proportion to the number of beams. On the other hand, DMAC/DA and RI-DMAC can achieve high throughput due to reducing the number of control messages and consequently allowing simultaneous communications.

Effects of the Table Entry Lifetime

Our proposed MAC protocols distinguish the potential transmitters from the neighboring nodes to solve the deafness problem and also reduce the control overhead. DMAC/DA and DMAC/DA with NPN use the neighbor table to do so, and

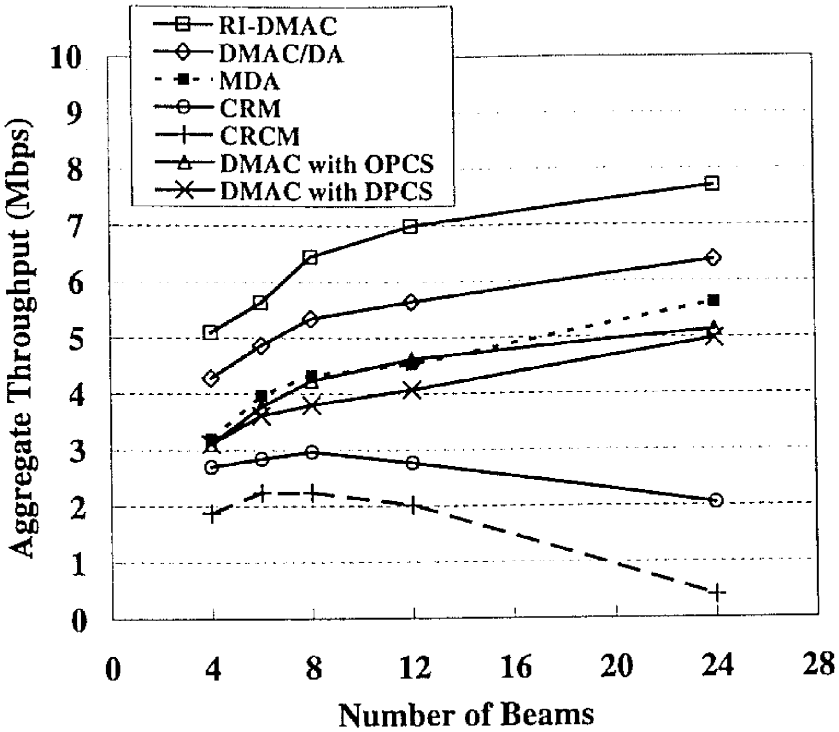


Figure 5.32: Effects of the number of Beams.

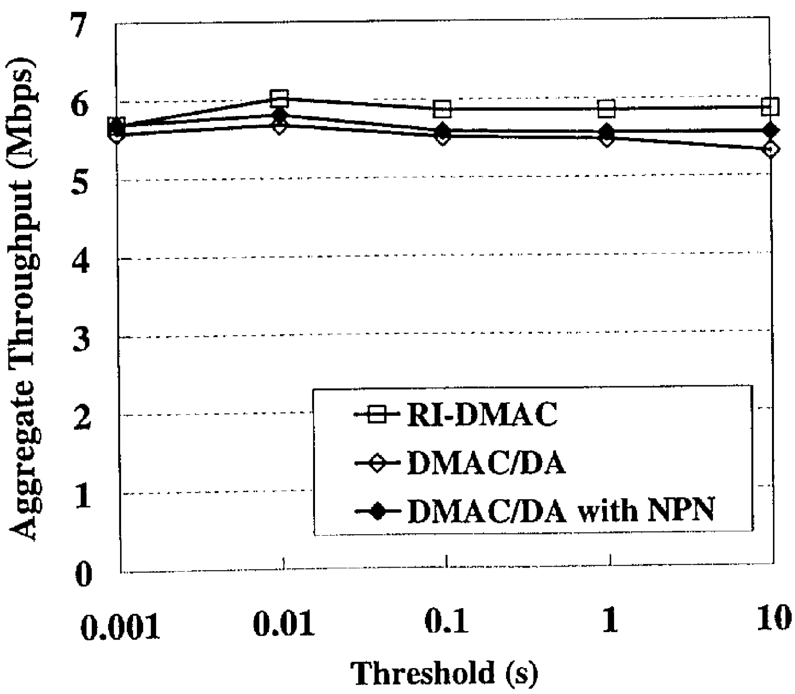


Figure 5.33: Effects of the threshold.

RI-DMAC uses the polling table. When the transmitters are changed frequently, our proposed protocols rely on the threshold value, T_{DA} or T_{RI}, which removes the stale entry of the table. To evaluate the effect of the threshold values, the following condition is used: Source-destination pairs of traffic are randomly switched in one simulation and the duration of one flow is randomly selected from (0, 10.0] (s). In this scenario, the potential transmitters of each node are changed dynamically according to the change of the flows. Fig. 5.33 shows the throughput of DMAC/DA, DMAC/DA with NPN and RI-DMAC when each threshold is from 0.001 to 10 (s) (sending rate is 2 Mbps, number of flows is 5, data size is 1024 bytes and M = 6). Results show that our proposed protocols achieve the highest throughput when the thresholds are set to 0.01. When the thresholds are small (e.g., in the case of 0.001), the entry is deleted frequently although the flow is still active. In this case, WTS frame or RTR frame is not transmitted to the deleted node and it suffers from deafness. On the other hand, when the thresholds are large, WTS frame or RTR frame is transmitted to the neighbor node even when the flow is no longer active. Although DMAC/DA with NPN and RI-DMAC notify the next packet information, the packet may be dropped due to exceeding the maximum retry limit. This deteriorates the throughput performance due to the overhead of unproductive transmissions. Therefore, there is an optimal value of the threshold, which solves the tradeoff between deafness handling and the overhead reduction. However, as shown in Fig. 5.33, the different values of the thresholds do not significantly affect the throughput performance. On the other hand, to optimize the threshold, we must consider the mobility of nodes as well as the traffic patter. This is included in our future work.

The throughput of 9 MAC protocols in this scenario is shown in Fig. 5.34, where the threshold value of 0.01 is used in our proposed protocols. Each protocol achieves higher performance compared with Fig. 5.23 because the traffic is distributed and spatial reuse is possible in this scenario. Results show that RI-DMAC has the highest throughput and DMAC/DA with NPN has the almost same performance as

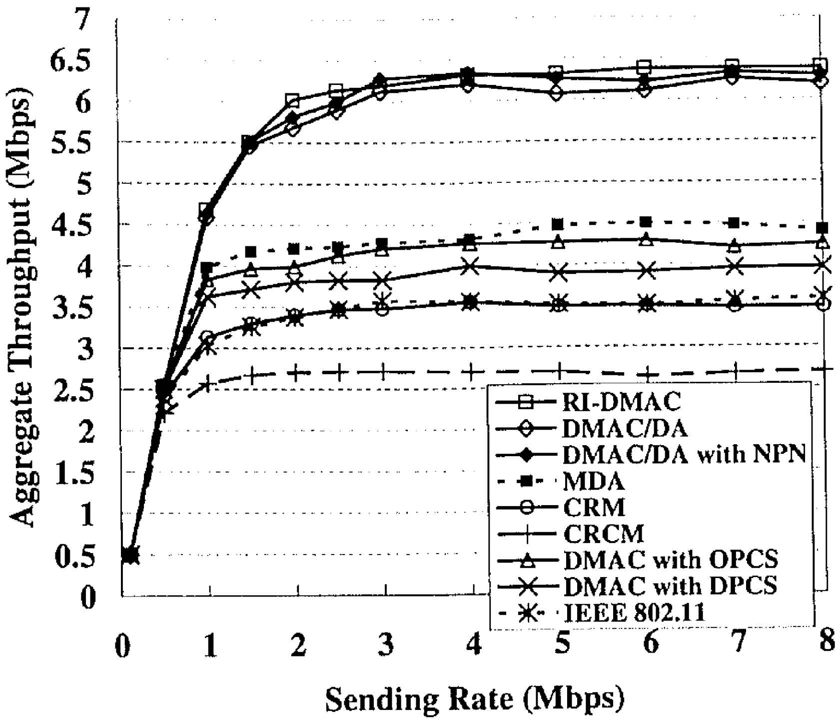


Figure 5.34: Throughput in scenario where flows are randomly changed.

RI-DMAC. It can be concluded that our proposed protocols solve the fundamental tradeoff between deafness handling and spatial reuse.

5.6.3 Qualitative Evaluation

Deaf Zone

The deaf zone is defined as the area that is not covered by the frame exchange between communicating nodes, originally defined by Choudhury and Vaidya. If a node is located within the deaf zone, it may experience deafness. We define the deaf zone ratio as the ratio of the deaf zone over the whole coverage area (i.e., normalized deaf zone). We calculate the deaf zone ratio of DMAC, Circular RTS MAC, and MDA. Because the deaf zone ratio of CRCM is almost zero, it is omitted here.

The whole coverage area of a communicating pair is obtained by [85]

$$W(r) = 2\pi R^2 - 2R^2 q(\frac{r}{2R}), \tag{5.2}$$

where R is the transmission range, r is the distance between the communicating nodes, and that $q(t) = \arccos(t) - t\sqrt{1-t^2}$.

The covered area of DMAC is given by

$$C_A(r) = \theta R^2 - \frac{r^2 \tan(\frac{\theta}{2})}{2}, \tag{5.3}$$

where θ is the beamwidth.

The probability density function of the distance r is

$$f(r) = \frac{2r}{R^2}, 0 \leq r \leq R. \tag{5.4}$$

Therefore, we can calculate the average deaf zone ratio of DMAC

$$D_A = \int_0^R \frac{2r}{R^2}(1 - \frac{C_A(r)}{W(r)})dr. \tag{5.5}$$

The covered area of Circular RTS MAC $C_B(r)$ is πR^2 and the average deaf zone ratio of Circular RTS MAC is given by

$$D_B = \int_0^R \frac{2r}{R^2}(1 - \frac{C_B(r)}{W(r)})dr. \tag{5.6}$$

Similarly, the covered area of MDA when the DOD procedure is carried out from the next beam through the opposite beam is

$$C_D(r) = \pi R^2 - \frac{\theta}{2}R^2 + \frac{\theta}{2}(R-r)^2. \tag{5.7}$$

Thus, the average deaf zone ratio of MDA is equal to

$$D_D = \int_0^R \frac{2r}{R^2}(1 - \frac{C_D(r)}{W(r)})dr. \tag{5.8}$$

Fig. 5.35 shows the average deaf zone ratio of three protocols when the transmission range R is 500 m. When the beamwidth θ is 60 degrees, the deaf zone ratio of DMAC, Circular RTS MAC, and MDA are 0.76, 0.22, and 0.14, respectively. Therefore, if the nodes are randomly placed according to a two-dimensional uniform distribution, 14 percent of neighbor nodes may still experience deafness in MDA. Note that deafness is caused when a node is located within the deaf zone and it intends to communicate with the transmitter or the receiver of the on-going communication. DMAC/DA notifies the on-going communication to all potential transmitters, and therefore the deaf zone ratio of DMAC/DA is ideally zero.

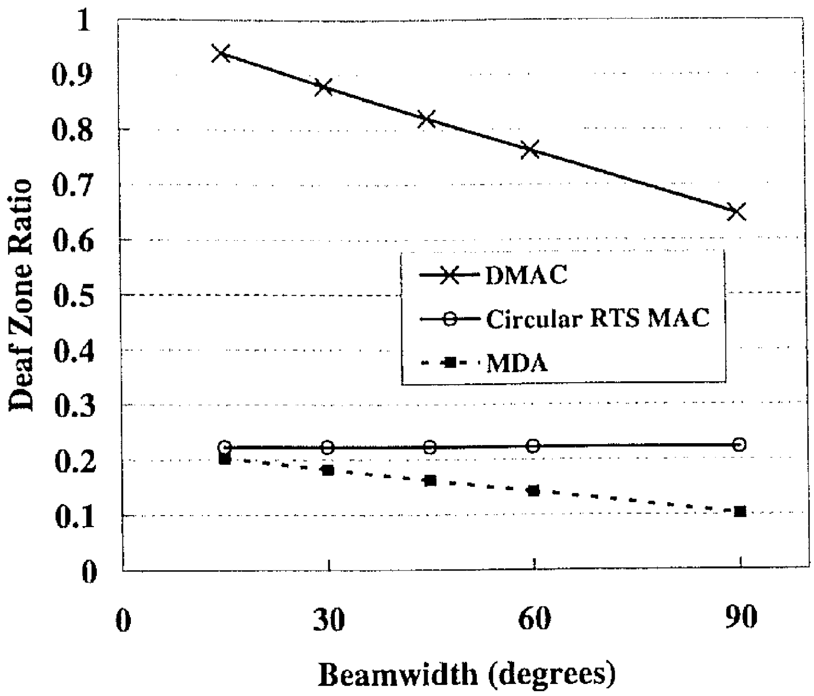


Figure 5.35: Deaf zone ratio.

Qualitative Evaluation of 10 MAC Protocols

Table 5.3 shows the qualitative evaluation of 10 MAC protocols to highlight the difference between the protocols. Deafness handling column in Table 5.3 represents that the protocol handles deafness proactively or reactively, and handling method column presents its handling method. ToneDMAC requires an additional tone channel and its related hardware, and SYN-DMAC assumes the system-wide synchronization is available, which requires GPS receivers or other synchronization schemes (see [71] and references therein), as indicated in the additional H/W column. Overhead, duration and deaf zone ratio of each protocol are calculated when there is no collision and retransmission, and the data size is 1024 bytes and the number of beams is six. These of DMAC/DA and MDA are adaptively changed according to the distribution of nodes and the traffic pattern. Duration is the time interval which calculates the instant the RTS is transmitted to the instant the ACK frame is received by the transmitter.

Table 5.3: Qualitative evaluation of 10 MAC protocols

Protocols	Antenna Model	Tx Range	RTS-type	CTS-type	Additional H/W	Deafness Handling	Handling Method	Overhead	Duration (ms)	Deaf Zone
RI-DMAC (SI-,ode)	Switched Beam	Directional	Single	Single	N/A	N/A	N/A	1.09	1.61	0.76
RI-DMAC (RI-mode)	Switched Beam	Directional	N/A	RTR	N/A	Reactive	RTR	1.08	1.40	0.76
DMAC/DA	Switched Beam	Directional	Single + Circular	Single + Circular	N/A	Proactive	Adaptive WTS	1.10-1.30	1.61-2.70	0-0.76
DMAC [58]	Switched Beam	Directional	Single	Single	N/A	N/A	N/A	1.09	1.61	0.76
Circular RTS MAC [72]	Switched Beam	Directional	Circular	Single	N/A	Proactive	Circular RTS	1.21	2.71	0.22
CRCM [73]	Switched Beam	Directional	Circular	Circular	N/A	Proactive	Circular RTS/CTS	1.28	3.37	0
MDA [74]	Switched Beam	Directional	Single + Circular	Single + Circular	N/A	Proactive	DOD RTS/CTS	1.10-1.22	1.61-2.27	0.14-0.76
ToneDMAC [70]	Switched Beam	Directional	Single	Single	Tone-Channel	Reactive	Out-of-band Tone	1.09	1.61 + tone	0
SYN-DMAC [71]	Switched Beam	Directional	Single	Single	Clock	Proactive	Timing-structure	1.10	one cycle	0.76
Nasipuri's MAC [61]	Switched Beam	Omni	Single	Single	N/A	Proactive	Omni-RTS/CTS	1.09	1.61	0
IEEE 802.11 [16]	Omni Beam	Omni	Single	Single	N/A	N/A	N/A	1.09	1.61	0

5.7 Summary

This chapter addressed the issue of deafness in directional MAC protocols for wireless ad hoc networks and proposed DMAC/DA to handle the deafness problem proactively. In DMAC/DA, the WTS frames are simultaneously transmitted by the transmitter and the receiver after the successful exchange of directional RTS and CTS to notify the on-going communication to potential transmitters that may experience deafness. In addition, we proposed DMAC/DA with NPN, enhanced DMAC/DA using the next packet notification.

This chapter then proposed RI-DMAC, a novel receiver-initiated mechanism to handle the deafness problem. RI-DMAC handles deafness problem reactively using a polling scheme and uses neither circular RTS/CTS nor additional control channel. In RI-DMAC, each node maintains a polling table and polls a potential deafness node using the RTR frame after the completion of every dialog. The potential deafness node can recognize that the intended receiver becomes idle, and deliver a packet immediately after receiving RTR. Among potential deafness nodes in the polling table, the least recently transmitted node is selected as a polled node to improve fairness.

This chapter evaluated the performance of our proposed MAC protocols, which solve the deafness problem. Simulation results show that RI-DMAC outperforms existing directional MAC protocols in terms of throughput, control overhead and packet drop ratio in the majority of scenarios investigated, especially when the numbers of flows and beams are large (e.g., up to 100% improvement compared with MDA). Results also show that DMAC/DA with NPN has higher throughput than basic DMAC/DA because it reduces the overhead involved in unnecessary transmission of WTS frames, and that DMAC/DA with NPN has higher throughput than RI-DMAC when the data size and the number of deafness nodes are large. Also, the qualitative evaluation of 10 MAC protocols was presented. The next chapter discusses the directional hidden- and exposed-terminal problems, other issues of directional MAC protocols.

Chapter 6

Conclusion

Although the use of directional antennas in ad hoc networks is expected to provide significant improvements, directional MAC protocols inherently introduce new kinds of problems arising from directivity, such as the determination of neighbors' location, deafness, directional hidden- and exposed-terminal problems. This thesis mainly proposed three directional MAC protocols. One is SWAMP for the determination of neighbors' location. The others are DMAC/DA and RI-DMAC for the deafness problem. In this chapter, we summarize the contributions of this thesis.

In Chapter 2, we first classified wireless networks and summarized the classification of wireless MAC protocols. Among the categories, contention-based MAC protocols are used in ad hoc networks. This chapter also explained the major problems in wireless MAC protocols. Finally, we reviewed the typical examples of contention-based wireless MAC protocols; ALOHA, CSMA, MACA, MACA-BI, and IEEE 802.11.

Chapter 3 discussed the existing directional MAC protocols. This chapter first mentioned the concept of directional antennas. Directional antennas have the ability to point the beam in a particular direction using the array of antennas, and these are broadly divided into two types based on the level of intelligence. Switched beam antennas have a fixed number of beams and select one beam for directional transmission or reception. Steered beam antennas, on the other hand, can point the main lobe in any direction. We then described the benefits of directional antennas in ad hoc networks, such as high spatial reuse and range extension. We discussed the common problems of directional MAC protocols, which should be considered when designing the MAC protocol. The problem of determination of neighbors' location is the fundamental problem to control the directional beam towards the communication partner. The deafness problem and directional hidden-terminal problem are caused by a lack of state information of neighbor nodes. Directional exposed-terminal problem reduces the number of possible concurrent communications due to overhearing unproductive data frame which is not addressed for the node. Finally this chapter presented the conventional directional MAC protocols. In these protocols, the issues of directional MAC protocols are not well addressed.

In Chapter 4, we proposed a novel directional MAC protocol, called SWAMP, for the determination of neighbors' location. SWAMP utilizes the directional beam effectively to increase the spatial reuse of the wireless channel and to extend the transmission range. SWAMP contains the neighbor discovery mechanism by forwarding the NHDI, which can obtain the direction information of the nodes within an area two times farther than omni-directional beam. SWAMP is composed of two access modes. OC-mode mitigates the hidden-terminal problem and the exposed-terminal problem, and increases the spatial reuse of the wireless channel. EC-mode extends the transmission range. We evaluated the performance of SWAMP compared with IEEE 802.11. Simulation results show that the throughput of SWAMP is roughly 3.5 times against IEEE 802.11, that SWAMP has remarkably less delay, and that there is a performance improvement of SWAMP irrespective of node mobility and density. This chapter investigated the effects of the issues of directional MAC protocols, such as location information staleness and deafness, on the network performance. Results show that location information staleness is one of the significant issues among the communication failure factors, especially when the traffic is low. Moreover, this chapter showed that the different values of the beamwidth and lifetime of the table information have an impact on the performance of protocol. These parameters can be optimized based on the network traffic, the freshness of the table information, the mobility of nodes and the QoS requirement to mitigate location information staleness and to improve the overall network performance. Another major problem of directional MAC protocols is deafness, which is not solved in SWAMP.

Chapter 5 addressed the issue of deafness in directional MAC protocols for wireless ad hoc networks and proposed DMAC/DA to handle the deafness problem proactively. In DMAC/DA, the WTS frames are simultaneously transmitted by the transmitter and the receiver after the successful exchange of directional RTS and CTS to notify the on-going communication to potential transmitters that may experience deafness. In addition, we proposed DMAC/DA with NPN, enhanced DMAC/DA using the next packet notification. We then proposed RI-DMAC, a novel receiver-initiated mechanism to handle the deafness problem. RI-DMAC handles deafness problem reactively using a polling scheme and uses neither circular RTS/CTS nor additional control channel. In RI-DMAC, each node maintains a polling table and polls a potential deafness node using the RTR frame after the completion of every dialog. The potential deafness node can recognize that the intended receiver becomes idle, and deliver a packet immediately after receiving RTR. Among potential deafness nodes in the polling table, the least recently transmitted node is selected as a polled node to improve fairness. We evaluated the performance of our proposed MAC protocols, which solve the deafness problem. Simulation results show that RI-DMAC outperforms existing directional MAC protocols in terms of throughput, control overhead and packet drop ratio in the majority of scenarios investigated, especially when the numbers of flows and beams are large (e.g., up to 100% improvement compared with MDA). Results also show that DMAC/DA with NPN has higher throughput than basic DMAC/DA because it reduces the overhead involved in unnecessary transmission of WTS frames, and that DMAC/DA with NPN has higher throughput than RI-DMAC when the data size and the number of deafness nodes are large. Also, the qualitative evaluation of 10 MAC protocols was presented.

The issues of directional MAC protocols affect not only at the MAC layer but also at the upper layers. Future work should investigate the effects of these issues on the upper layer performance. In addition, ad hoc routing protocols using directional antennas are included in our future work.

This thesis addressed the determination of neighbors' location and the deafness problem. Because the idea behind our proposed solutions are not bounded to any directional MAC protocols, these solutions can be combined into a single MAC protocol based on the situation.

The applications of this work include ITS, wireless mesh networks, and peer-to-peer networks as the part of future ubiquitous networks. We hope that our work contributes to the promotion of the ubiquitous society.

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