

# A Directional-Antenna Based MAC Protocol for ad hoc Wireless Networks

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# Abstract

Directional antennas have been extensively used in designing MAC protocols for wireless ad hoc networks in recent years. Directional antennas provide many advantages over the classical antennas which are omnidirectional. These advantages include spatial reuse and increase in coverage range. One of the main considerations in designing MAC protocols for static wireless networks is to reduce power consumption at the sensor nodes. This is usually done by imposing transmission and receiving schedules on the sensor nodes. Since it is desirable for a sensor network to be self managed, these schedules need to be worked out by individual nodes in a distributed fashion. In this paper, we show that directional antennas can be used effectively to design an energy efficient MAC protocol for wireless sensor networks. Our MAC protocol conserves energy at the nodes by calculating a scheduling strategy at individual nodes and by avoiding packet collisions almost completely.

**Keywords:** wireless networks, multiple access control, directional antennas

**CR Categories:** C.2.2 [Computer-Communication Networks]: Network Protocols

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## CHAPTER 1

# Introduction

This chapter gives a background and an introduction to the subject. It also includes motivations to this honours thesis. This chapter presents the main objective with this study and the thesis outline.

## 1.1 Background

Ad hoc wireless networks work in the absence of any fixed infrastructure. The routing and resource management in such an network is done in a distributed manner. In comparison with infrastructure-based networks, a node in an ad hoc wireless network needs more intelligence so that it can function not only as a network host for transmitting and receiving data but also as a network router for routing packets from other nodes. The applications of ad hoc wireless networks include military applications, collaborative and distributed computing, emergency operations, wireless mesh networks, wireless sensor networks, and hybrid wireless network architectures [9].

Ad hoc networks have special features which are not applicable to wired networks. The nodes may be mobile. There are no centralized coordinators. An important feature of ad hoc networks is medium access control (MAC) in the MAC layer of OSI/ISO network architecture. The protocols on this layer perform the challenging task of resolving contention among nodes, while the nodes are sharing a common medium for transmitting data. The major issues to be considered in designing a MAC protocol for ad hoc wireless networks include distributed operation, synchronization, hidden terminals, exposed terminals, throughput, access delay, fairness, real-time traffic support, resource reservation, ability to measure resource availability, capability for power control and adaptive rate control. As radio spectrum is limited, the bandwidth available for communication in such networks is highly restricted. Access to this shared medium should be fair, with all nodes receiving a fair slice of the available bandwidth, and also the bandwidth should be utilized efficiently. The MAC protocol must try to maximize

this bandwidth efficiency.

## 1.2 Problem Overview

The *hidden terminal problem* is significant in reducing the performance of ad hoc wireless networks. It refers to the collision of packets at a receiving node due to the simultaneous transmission from those nodes that are not within the direct transmission range of each other, but are within the transmission range of the receiver. Traditional carrier sense multiple access protocol (CSMA) does not perform well in ad hoc networks because of the high rate of collisions. A node senses the medium and when the channel is free, it transmits packets. This means that when two nodes out of the transmission range of each other transmit packets to the same receiver at the same time, collision occurs. Thus, the throughput of an ad hoc wireless network under traditional CSMA protocol is usually low. In order to reduce collisions and increase the throughput of ad hoc wireless networks, carrier sense multiple access / collision avoidance (CSMA/CA) protocol has been proposed [14]. This is the most popular protocol in most ad hoc wireless networks. Its main idea is that a node that has packets to transmit first sends a Request To Send (RTS) message to its destination and asks if it can transmit packets to its destination. If such a handshake between the node and its destination is successful, the destination sends a Clear to Send (CTS) packet back by attaching the requesting node's address to it. The requesting node starts transmitting data once it receives the CTS packet. All other nodes receiving the CTS packet backs off from sending. If not, the node will choose another time to communicate with the destination. CSMA/CA guarantees that the collision rate is much lower than traditional CSMA. However, it does not solve the *hidden terminal problem* completely. Furthermore, the handshake between a source and its destination consumes communicating time, which means CSMA/CA increases latency. Another disadvantage is that when a node is transmitting, all its neighbours except the destination are blocked.

MAC protocols that use directional antennas for transmission have advantages over protocols that use omnidirectional transmission. Directional transmission improves channel reuse, increases the throughput of networks, saves power, and increases transmission coverage. An ad hoc wireless network using a directional antenna-based MAC protocol permits nodes to transmit and receive packets in a selective sector so that they do not need to interfere with their neighbours omnidirectionally. Therefore, it is possible that more nodes are able to transmit packets to their destinations at the same time. Compared to omnidirectional MAC protocol, directional MAC protocols save power because nodes only trans-

mit packets using a sector and can reach other nodes at a longer distance using less power [4, 15].

However, directional transmission causes some serious problems. The major problem is the increase of the instance of the *hidden terminal problem*. In order to solve the problem, a node in an ad hoc wireless network needs to synchronize its receiving and transmission times with its neighbours correctly so that the number of collisions can be reduced and also no node starves during communication.

### 1.3 Objective

In this thesis, We plan to design a new MAC layer protocol for static wireless networks. Each node will divide its  $360^\circ$  transmission range into six angular sectors (each sector is  $60^\circ$ ) for transmitting and receiving packets. At any time, a node listens only to a particular sector and can receive transmissions from other nodes only within this sector. At the beginning, each node will advertise itself to and collect information from its neighbours using the traditional CSMA protocol. After that, each node synchronizes its transmitting and receiving transmissions with its neighbours so that it will not receive two packets at the same time within a single sector, and not transmit packets to its neighbours within the same sector to prevent collisions. When each node finishes this synchronization step, it will start transmitting data packets to other nodes using directional antennas. Therefore, the collisions in the network are reduced and each node also does not suffer from starvation.

### 1.4 Thesis Outline

The rest of this thesis is organized as follows. We discuss some previous work on MAC protocols based on directional antenna in Chapter 2. We discuss several problems related to the use of directional transmission in wireless networks in Chapter 3. We discuss our protocol in Chapter 4. Our simulation results are presented in Chapter 5. Finally we make some concluding remarks in Chapter 6.

## CHAPTER 2

# Previous Work

## 2.1 Smart Antenna Technology

Nodes in a wireless network transmit packets to their neighbours by propagating electromagnetic waves through space (channel). When a node is receiving a packet, the level of power in the node is higher than a threshold. When it is idle, its power level is lower than a certain threshold [12].

When a node propagates a signal in all directions, it is called omnidirectional transmission. Nodes using this type of transmission are equipped with an omnidirectional antenna which keeps the power level equal in all directions. Also all its neighbours will receive such an omnidirectional transmission. This wastes useful space as many transmissions can be blocked by a single omnidirectional transmission.

Smart antennas have potential advantages over omnidirectional antennas. A smart antenna is equipped with an array of antenna elements. Each antenna element is used to control the transceiver to transmit signals in a particular transmission range. In many situations, nodes in a wireless network need to communicate with preferred neighbours. Hence, omnidirectional transmission may not be the most efficient method of communication in these situations. In directional transmission, a node can communicate with its neighbours in a selective way, by transmitting in a sector by using a directional antenna.

The smart antenna techniques have three advantages. Firstly, a node transmitting packets to its neighbours need not use the whole circular range of transmission [11]. This can increase the reuse of space for message transmission in an ad hoc wireless network. Secondly, some directional antennas are able to suppress interference when a node is transmitting or receiving in a predetermined sector [13]. This reduces collision of messages in the network. Those two advantages can improve the performance of an ad hoc network considerably. The third advantage is the concentration of power in directional transmission. This can be used in two different ways. One possibility is the increase of transmission

range and nodes can reach neighbours that are further away by concentrating directional transmission in narrow sectors [1]. The other possibility is to reduce the power level in directional transmission so that a node can still reach its neighbours that it can reach in omnidirectional transmission, however it now spends much less power [7].

## 2.2 MAC Protocols Using Directional Antenna

### 2.2.1 Carrier Sense Multiple Access with Collision Avoidance

The traditional CSMA MAC protocol does not guarantee the delivery of any transmission. IEEE 802.11 uses a protocol called carrier sense multiple access with collision avoidance (CSMA/CA) for transmission. This protocol is a four-way handshake. In this protocol, all the neighbours of the sender that receive request to send (RTS)/clear to send (CTS) handshake and the receiver defer transmission during the period when the sender is transmitting the packet by using a network allocation vector (NAV). This protocols is described below:

- A node, when it is ready to transmit a packet, first senses the channel. If the channel is free, the node does not transmit a data packet immediately. Instead, it transmit a RTS packet omnidirectionally, which contains much fewer bits compared with a data packet.
- The RTS packet asks the receiver for transmission permission. Also, it informs the nodes that are located within the transmission range of the sender of the potential transmission that the sender is planning to transmit packets in the near future. The nodes that receive the RTS will keep silent until the sender finishes the whole four-way handshake with its receiver.
- If the receiver successfully receives the RTS packet from the sender, it considers if it will grant the the sender permission to send the data. If the receiver gives permission, it will transmit a CTS packet immediately back to the sender in omnidirectional mode.
- The CTS packet informs the neighbours of the receiver of the potential transmission so that other nodes keep silent for a certain period of time when the sender is sending the data.
- After the sender receives this CTS, it starts transmitting data and starts a timer which is used to tell itself the maximum time of the ACK return.

However, CSMA/CA protocol does not solve the *hidden terminal problem* completely because if a node within the transmission range does not receive RTS or CTS before the real data is transmitted, it still can transmit packets to other nodes. This may interfere with the transmission of the sender and its receiver. Also this protocol increases the propagation delay because of the use of the four-way handshake scheme.

## 2.2.2 Directional MAC Protocols

Omnidirectional transmission used in CSMA protocols defers some nodes' transmissions to reduce collisions, as a result the throughput of the network is reduced. In order to increase throughput, several MAC protocols that use directional antennas have been proposed. Based on the CSMA/CA, a node divides the 360° transmission range into a number of fixed sectors. A node uses only one sector to communicate with another node at any time. Therefore, its neighbours that are not located in its transmission sector may be able to transmit packets to other nodes at the same time.

Some protocols mix both omnidirectional and directional transmissions to transmit packets in order to solve the disadvantages of CSMA/CA. Nasipuri et al. [10] propose a basic directional MAC (DMAC) protocol. In this protocol, the transmission of RTS and CTS are omnidirectional, DATA and ACK are directional. The main purpose of this protocol is to inform neighbours of the sender and the receiver of a potential transmission within a specific sector of the sender and receiver nodes. The neighbours that successfully receive the RTS/CTS can determine which node they cannot transmit to during that period of time and then find a free-from-interference transmission sector if they have one. Compared with DMAC protocol, Directional RTS MAC protocol uses directional RTS and omnidirectional CTS transmissions before starting transmitting data. More details about this protocol can be gained in Ko et al. [5]. Korakis et al. [6] propose circular directional RTS MAC protocol. In this protocol, a node sends directional RTS in consecutively circular directions until it scans all the area around the node. Each node that receives the RTS defers transmission for a certain period of time. After that, the destination sends a CTS directionally. And then the node transmits data and receives its ACK through a directional transmission. These protocols based on CSMA/CA protocol aim to improve the throughput of ad hoc wireless networks through directional transmission. They have better performance than CSMA/CA [5, 6, 10]. However, none of them can guarantee the delivery of data. They cannot solve the *hidden terminal problem* completely. Furthermore, the four-way handshake communication still introduces latency in data transmission.

## 2.3 MAC Protocols for Wireless Sensor Networks

Since the nodes in a sensor network are static and they usually have periodic exchange of packets with their neighbors, it is possible to design MAC protocols that essentially find efficient scheduling strategies. Most of the MAC protocols designed for sensor networks take this approach. Ye et al. [18] developed the S-MAC protocol for scheduling communication in sensor networks. S-MAC organizes the sensor nodes into slots. Each slot in S-MAC is a fixed duty cycle consisting of a short listen period of 300ms and a sleep period. All nodes in the network are free to choose their slots. S-MAC puts a node into sleep mode for a period of time and then wakes it to allow the node to listen to its neighbors. This scheme requires synchronization among neighboring nodes to minimize clock drift. Thus at the beginning of each cycle a node broadcasts a SYNC packet and the neighboring nodes update each other's schedules. To avoid collisions, S-MAC uses RTS/CTS mechanism. However, the fixed listening period of S-MAC may not be sufficient in high traffic loads. Also, it allows a node that has more data to send to monopolize the wireless channel.

Dam and Langendoen [16] proposed the Timeout MAC (T-MAC) protocol to alleviate S-MAC's fixed duty cycle problem. T-MAC implements an adaptive duty cycle that consists of a variable length active period and a sleep period. Lu *et al.* developed a data gathering MAC (D-MAC) protocol for sensor networks. Each slot in this protocol is divided into a receiving, a sending and a sleeping period. D-MAC is limited to data gathering applications and not suitable for general data exchange applications.

There are also several proposed MAC protocols using Time Division Multiple Access (TDMA) scheme. TDMA-based MAC protocols separate nodes in time, i.e., nodes do not interfere with each other's transmissions and hence collision is avoided. The Lightweight Medium Access (LMAC) protocol is developed by van Hoesel and Havinga [17]. In this protocol, a node can own a time slot for transmitting and receiving messages without contending for medium access. When an active node controls a time slot, it can broadcast a control message section of its frame and transmit the data afterwards. Neighboring nodes listen and check the control message. If they are the intended receiver of the packet, they receive the data packet afterwards. Otherwise, they go to the sleep mode and wake up at the next time slot. In contrast to the other MAC protocols for sensor networks discussed above, LMAC does not use RTS/CTS/ACK scheme and puts the issue of transmission reliability at the physical layer. Nodes maintain a scheduling table and select a slot number that is not in use within a two-hop neighborhood. A time slot is only reused at least three hops apart. Kulkarni and Arumugam [8] proposed the Self-Stabilizing TDMA (SS-TDMA) protocol

that uses a fixed schedule for the lifetime of a network. SS-TDMA is designed to operate on a regular grid topology such as rectangular, hexagonal and triangular. In all the MAC protocols designed for sensor networks, the central theme is to save energy and avoid collisions. Hence, all these protocols work out a scheduling policy in the network by which each node knows when to send or receive messages. Since each node negotiates a schedule with its neighbors, it is ensured that collisions do not occur while neighbors are communicating. However, collisions still may occur due to transmissions by nodes that are one-hop away. In our protocol, we try to avoid collisions by working out a global schedule by which nodes send and receive messages. This global schedule is worked out in a completely distributed manner.

## CHAPTER 3

# Problem with Directional Antennas

Our protocol aims to improve the performance of static ad hoc networks through reducing collisions during transmissions. Each node in the network is equipped with directional antennas and is able to communicate with other nodes in specific sectors.

### 3.1 The Problems of Wireless Transmission

Packet collisions in wireless networks are higher than those in wired networks. As nodes in a wireless network transmit and receive packets through wireless channels, the range of transmission is limited. In comparison, in a wired network each node can communicate with fewer nodes. Also, a node transmitting packets in CSMA mode cannot guarantee that all of its neighbours definitely sense that transmission.

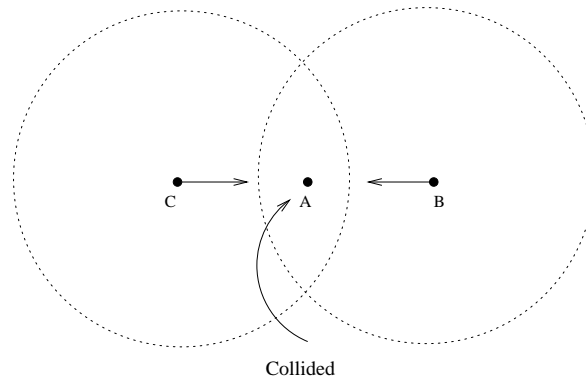


Figure 3.1: Collisions occur at node A because it is in omnidirectional communication mode.

Some neighbours may receive more than one packet at the same time, thus losing all the packets. Figure 3.1 shows that both node B and C transmit packets to

node A at the same time. The collision occurs at A. This is because B and C, when they want to transmit packets to A, cannot sense the transmission from each other. It is called the *hidden terminal problem*.

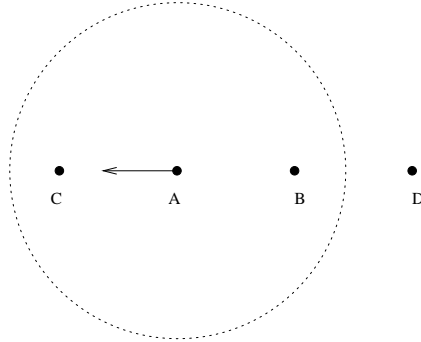


Figure 3.2: Node B cannot transmit packets to node D as it senses the transmission from node A at that time.

Furthermore, the *exposed terminal problem* has negative effects on the performance of the network. Node A in figure 3.2 is transmitting to C. As node B senses the transmission, it will not transmit packets to D. Although B transmitting to D does not interfere A's transmission, it still is prevented at that time. We call that the *exposed terminal problem*.

## 3.2 The Problem of Transmission Using Directional Antennas

### 3.2.1 Increase of Hidden Terminal Problem

A node in an ad hoc network that uses directional antennas to transmit packets has less coverage on its neighbours. For example, when node C transmits packets to A in CSMA mode ( figure 3.3(a)), B senses the transmission and does not prepare to transmit. However, if node C uses directional antenna to transmit packets in figure 3.3(b), B does not sense the transmission. If B transmits packets to A, collision occurs at A. Directional antennas increase the number of simultaneous transmissions, thus it increase the chances of collisions occurring in an ad hoc network.

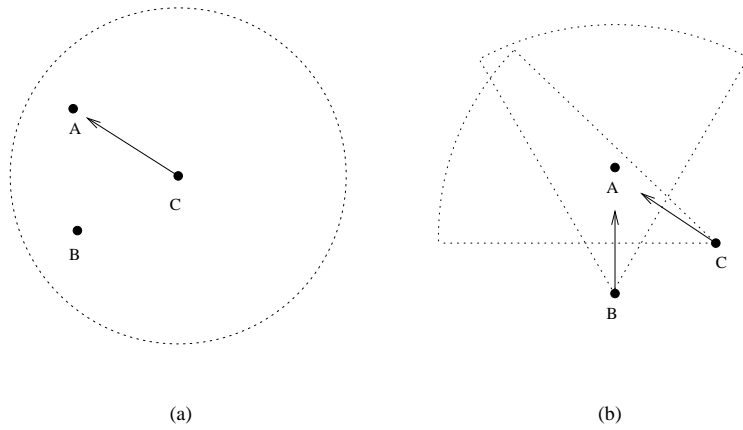


Figure 3.3: Node B and C try to transmit packets to node A. (a) Node C transmits packets to node A in omnidirectional transmission mode, and node B does not transmit. (b) Node C transmits packets in directional transmission mode, and node B transmits packets to node A as well at same time. Therefore, collisions occur at node A.

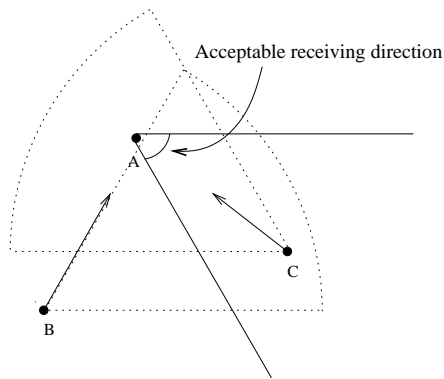


Figure 3.4: Node B transmits a packet to node A when node A is receiving a packet from node C. As the packet from node B is not in A's receiving sector, it is ignored by node A.

### 3.2.2 Interference Suppression Causes Packet Loss

Interference suppression of directional antennas causes packet loss during the transmissions in networks. Node B at figure 3.4 transmits packets to A, when A is receiving from C. A at that time only accepts the transmissions from the sector that is facing C, and other sectors are not attended by A. Thus, the packet from B to A is lost.

### 3.3 Basic Ideas to Reduce Collisions and Packet Loss Using Directional Antennas in ad hoc Networks

In order to reduce collisions in the network when directional antennas are used, firstly the antennas at each node should be able to suppress interference. In figure 3.4, node A receives a packet from C in an angular direction. If B transmits a packet to A at the same time, A is not interfered by that transmission from B because of the ability of interference suppression of directional antennas. Therefore, at that time collision does not occur at A.

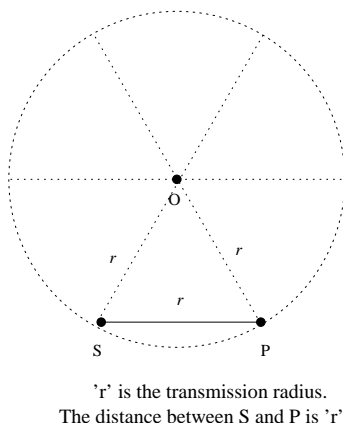


Figure 3.5: Node O is equipped with 6 equal angular sectors and each sector is  $60^\circ$ . The distance between node S and P equals to  $r$  and is also the longest length in one sector of node O. Therefore, node S and P do not transmit simultaneously.

Secondly, each node transmitting using directional antennas follows a pre-computed schedule of tasks to avoid collisions at receiver nodes. We divide each node's transmission range into six equal angular sectors. In principle, it is possible to use an arbitrary number of sectors, however, we have used six sectors in most of

our simulations. The angle of each sector is  $60^\circ$  (figure 3.5). As the longest distance between two nodes in a  $60^\circ$  sector is the radius of transmission range, when node S arranges time for communication to O and broadcasts this information in CSMA mode (figure 3.5), P, located in the same sector of O, can receive the arrangement packet. Therefore, when P arranges a time slot for communication with O, it can avoid arranging the same time slot for communicating with S.

In order to avoid packet loss and collisions, a protocol needs to arrange all nodes' transmissions in a selective way.

## CHAPTER 4

# Our Protocol

The protocol includes two phases. In the first phase, a node transmits packets in CSMA mode. In the second phase, each node transmits packets using directional antennas with interference suppression. Each node starts transmitting packets to advertise itself through the network in CSMA mode in the first phase. After a period of time, when each node has the locations of all its neighbours, it arranges the neighbours into its six sectors. According to the locations of the neighbours and concentration of nodes in each sector, the nodes arrange transmitting and receiving time slots for directional transmission to avoid collisions and subsequent packet loss. After that, the nodes enter the second phase and communicate with the neighbours following the pre-arranged slot list.

### 4.1 Physical Layer Facilities

Each node is assumed to have only one radio transceiver, which can transmit and receive only one packet at any given time. The transceiver is assumed to be equipped with six directional antennas, each antenna having a conical radiation pattern, spanning an angle of  $60^\circ$  (figure 3.5). It is assumed that the transmissions by adjacent antennas never overlap, that is, the complete attenuation of the transmitted signal occurs outside the conical range of the directional antenna. The MAC protocol is assumed to be able to switch every antenna individually or all the antennas together in the active or passive mode. The radio transceiver uses only the antennas that are in active mode. The receiver node uses receiver diversity while receiving on all antennas. This means that the receiver node uses the signal from the antenna which receives the incoming signal at maximum power, and it discards the others. In the normal case, this selected antenna would be the one whose conical range is directed towards the source node whose signal it is receiving. It is assumed that the radio range is the same for all directional antennas of the nodes. In order to detect the presence of a signal, a threshold signal power value is used. A node concludes that the channel is active only if

the received signal strength is higher than this threshold value. It is assumed that the orientation of sectors of each antenna element remains fixed, and the distances covered by directional and omnidirectional transmission are the same.

## 4.2 Collision Details

Collisions occur at receivers in an ad hoc wireless network. More than one packet received by a receiver at the same time cause collisions. Collisions in an ad hoc wireless network under a MAC protocol using directional antennas include two cases. First, a receiver is in omnidirectional mode. If it receives more than one packet from other nodes simultaneously, the packets are collided at the receiver (see figure 3.1). Second, a receiver is able to suppress interference in directional mode. In this case, as long as the node does not receive more than one packet from its current receiving sector, no collisions occur. Figure 4.1(a) shows node A receiving packets from C. Both B and C are transmitting to A at the same time. Since A's receiving sector only gets packets from node C, collisions do not occur. The packets transmitted by B are ignored when they reach A due to interference suppression. However, in figure 4.1(b) A receives two packets from B and C at same time and also in the same receiving sector. In this case collision occurs.

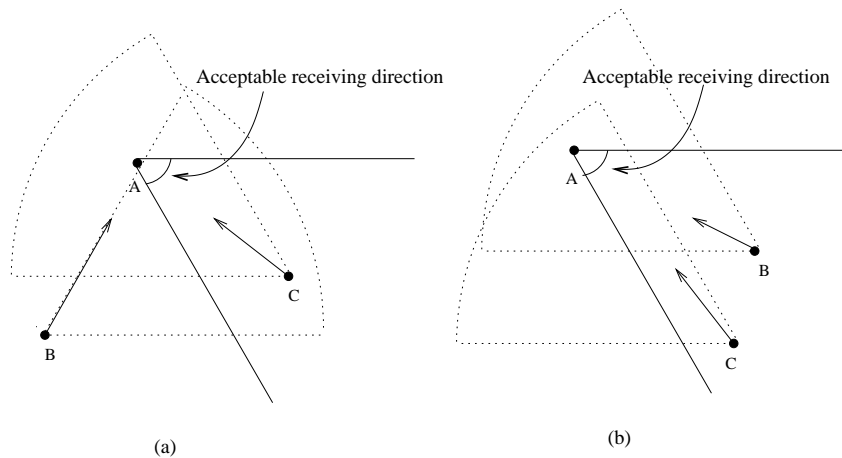


Figure 4.1: (a) Collisions do not occur at node A because node A's antennas suppress interference. (b) Node A suffers from collision because two packets come from the same receiving sector.

### 4.3 Neighbour Location

A node has to know its neighbours' locations and density for arranging communication time for them. It is assumed that a global position system (GPS) is used in each node of the network. Each node knows only its own location. When a node transmits a packet at the start of the first phase, the packet includes the location of the node. When a node receives such a packet from one of its neighbours, it calculates the receiving sector and the sender's sending sector by using the locations of the sender and itself.

Node P transmits a packet to Q at location  $(x_Q, y_Q)$ . Q receives the packet and knows P's location,  $(x_P, y_P)$ . The distance between P and Q,  $Dis_{QP}$ , is calculated by using the formula

$$Dis_{QP} = \sqrt{(x_Q - x_P)^2 + (y_Q - y_P)^2} \quad (4.1)$$

The angle of P,  $Ang_{P \rightarrow Q}$  located within the transmission range of Q is calculated by

$$Ang_{P \rightarrow Q} = \left| \arcsin \left( \frac{y_P - y_Q}{Dis_{QP}} \right) \times \left( \frac{180}{\pi} \right) \right| \quad (4.2)$$

Then P checks its position relative to Q. If P is towards right and above Q,

$$Ang_{P \rightarrow Q} = Ang_{P \rightarrow Q} \quad (4.3)$$

If P is towards left and top of Q,

$$Ang_{P \rightarrow Q} = 180 - Ang_{P \rightarrow Q} \quad (4.4)$$

If P is towards the left and bottom of Q,

$$Ang_{P \rightarrow Q} = 180 + Ang_{P \rightarrow Q} \quad (4.5)$$

If P is towards the right and bottom of Q,

$$Ang_{P \rightarrow Q} = 360 - Ang_{P \rightarrow Q} \quad (4.6)$$

After we calculate  $Ang_{P \rightarrow Q}$ , we know in which sector  $R$  of Q P is located by using  $Ang_{P \rightarrow Q} \div 60$ . For example,  $Ang_{P \rightarrow Q}$  is  $90^\circ$ . As  $90 \div 60$  is 1, sector  $R$  is 1.

As the sector direction and range is fixed, we know the sender's sending sector  $S$  from the receiver's receiving sector  $R$  by using  $S = (R + 3) \bmod 6$ .

Thus, when Q receives a packet from P, Q is able to know in which sector of Q P is located and from which sector P sends the packet.

## 4.4 Sequence of Arranging the Sending and Receiving Schedules

In order to reduce the time to arrange slots between nodes in the network in the first phase, a node in its local area is assessed by different priorities for arranging its slots. It starts arranging transmission time only after its neighbours who are in higher priorities finish their arrangement. The basis of assigning priorities for nodes depends on the number of neighbours that a node has. For example, figure 4.2 shows node C and its neighbours, A, B, and D. C has 3 neighbours. No other node in the local neighbourhood has the same number of neighbours as C. C has top priority for the time arrangement in its local area. B and A are assessed in second level priority, and D has the least. C arranges the time slots to communicate with its neighbours first, and other nodes keep silent in the network, because they know C has higher priority than them in their own local area. When node C finishes the arrangement, nodes B and A start arranging.

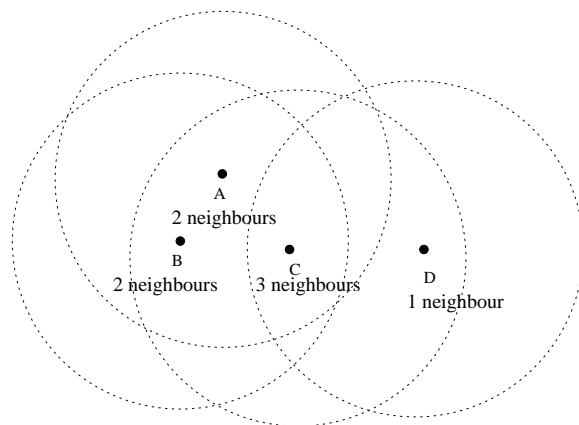


Figure 4.2: Node C has maximum number of neighbours in its local area.

Each node advertises its presence in the beginning of the first phase. Each node comes to know about its neighbours through these messages. Next, each node

counts its neighbours and broadcasts its number of neighbours to its neighbours. Each node knows its priority in its local neighbourhood after this.

## 4.5 Determination of Time Slots

We first discuss some difficulties in arranging the schedules in our protocol. Node A may have more than one neighbour in one of its sectors. In order to avoid collisions at A, the neighbours have to transmit packets to A in different time slots. The synchronization for transmissions to A must be considered in our protocol. For example, if A is receiving from one direction (figure 4.1)(b), there will be a collision if both B and C transmit packets to A at the same time.

A node is able to communicate in only one of its sectors at a time. If more than one node that are in different sectors of the node transmit packets to the same node simultaneously, packets are lost. Therefore, the protocol also needs to synchronize the sending and receiving slots of neighbours to avoid packet loss. In figure 4.1(a), A is receiving a packet from C. At the same time B is transmitting a packet to A as well. As directional antennas are able to suppress interference, the packet from node B is lost.

### 4.5.1 Location Table Creation

For synchronizing transmissions, each node creates and maintain a location table. The location table contains all the information about a node, its neighbours and its two-hops-away nodes. The location table is used to keep track of the communication relationships between a node and its neighbors, so that a node can arrange transmitting and receiving slots appropriately. The location table's information is obtained from received packets in the first phase.

	<b>A</b>	<b>B</b>	<b>C</b>
<b>A</b>			
<b>B</b>			
<b>C</b>			

Table 4.1: The location table of node A after adding a new entry for node C.

In the blank area, each row number is mapped to a sender identity, and a column number is mapped to a receiver's identity. For example, table 4.1 records the information of sender B to receiver C in the row of node B and the column of

node C. When a node receives a packet and it contains a new node identity, a new row and a new column are added to the table.

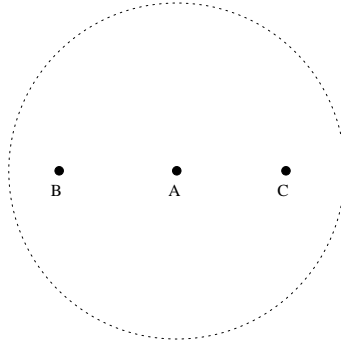


Figure 4.3: Node B and C are out of transmission range of each other. B and C cannot communicate directly.

It should be noted that not all of the entries in a location table are used. The maximum number of entries in a location table is always greater than the number of entries that are actually used. In table 4.1, node A has two neighbours, B and C, however, the number of entries of node A's location table is nine. However, the diagonal entries of the table are useless because they represent the same node. Moreover, if an entry's sender is out of transmission range of its receiver, it is useless. For example, B and C in figure 4.3 do not communicate with each other directly. The entry of sender B and receiver C in table 4.1 and vice versa is useless.

#### 4.5.2 Content of Entries

An entry includes a sender's and its receiver's identity, the communication sectors of the sender and the receiver, and the time of transmission (see table 4.2).

<b>Content</b>	<b>Description</b>
occupy	Used to check if the communication between the source node and the destination node is possible. If it is, occupy is set to 1 (true). Otherwise, it is set to 0 (false)
srcid	Source node identity
destid	Destination node identity
ssector	The sector that the source node uses for sending to the destination
rsector	The sector that the destination node uses for receiving from the source node
sslot	The time slot that the source node uses to send frame to the destination.
spos	The current position that the source node is in its communication cycle.
srcycle	The communication cycle of the source node
numneig	The number of neighbours of the source node
localslot	The time slot that is converted from 'sslot' into the local node.
entrance_time	The time remaining that the source node will enter phase two
finish_arranging_slot	If the source node finishes arranging slots for its neighbours, this is set to 1 (true). Otherwise this is set to 0 (false).
slot_arranger	The node identity that arranged this slot for the source node. (it can be the source node itself or its neighbour who has higher priority than it.)

Table 4.2: The elements of an entry in location table.

### 4.5.3 The Use of Location Table

A node arranges a suitable communication slot based on its location table. The node is able to decide at what time it transmits/receives and in which sector so that the future transmissions do not cause collision or packet loss.

In the location table of a node, the entries in first row represent the information of the node transmitting to its neighbours. The entries in the first column represent the information of the node receiving from its neighbours. The main aim of

	<b>A</b>	<b>B</b>	<b>C</b>
<b>A</b>		$A \rightarrow B$	$A \rightarrow C$
<b>B</b>	$B \rightarrow A$		$B \rightarrow C$
<b>C</b>	$C \rightarrow A$	$C \rightarrow B$	

Table 4.3: The location table of node A which is holding the transmission. For example, entry  $B \rightarrow A$  means that the transmission from node B to A

the protocol is to arrange time slots for the entries so that when the node is transmitting or receiving directionally in the second phase, it can avoid collisions and packet loss. For example, table 4.3 shows the location table of A. The first row indicates the information of A transmitting to its neighbours, B and C. The first column indicates the information of A receiving from B and C. The protocol need to arrange time for those entries for avoidance of collision and packet loss.

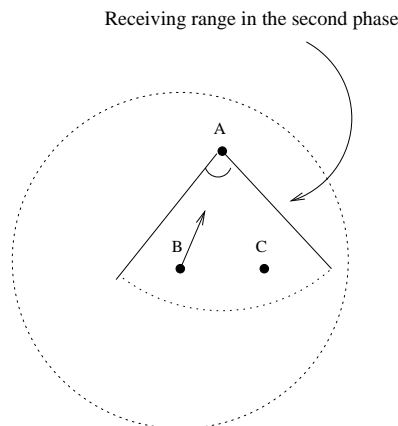


Figure 4.4: Node B informs node A about the transmission time in the second phase. Because at that time node B is still in omnidirectional transmission, node C can receive the information about the transmission.

Figure 4.4 shows B has chosen a slot to transmit a packet to A. As the location table information is exchanged through omnidirectional transmission in the first phase, when C receives this information, it tries to avoid transmitting to A at the same time as B does.

Moreover, if C and B are not located in the same receiving sector of A in figure 4.1(a), when B arranges a time to transmit packets to A, it finds A will receive a packet from node C the at same time. That will cause potential packet loss. Thus, B need to arrange another time for the transmission.

#### 4.5.4 Checking and Handling of the Potential Collision and Packet Loss

A node maintains a location table for communicating with its neighbours. When the node is arranging the time for the transmissions in the second phase, it is necessary to find a suitable time to avoid the potential collisions and packet loss so as to improve the performance of the network. We now explain how to find potential collisions and packet loss and how to arrange the time for the node.

In order to arrange suitable slots for a node, the protocol should be considered from two points of view. One is how a node detects potential collisions in the network. The other is how a node synchronizes with other nodes so that the potential collisions or packet loss can be avoided in future. A node handles those two problems by mainly depending on the location table. Every time a node receives a packet, it is updated in the table. The location table of the node contains sufficient information about the node and its neighbors, and other nodes located two hops away.

##### Two Representations of Packet Loss or Collision in Location Tables

	<b>A</b>	<b>B</b>	<b>C</b>
<b>A</b>		<i>Slot 1</i>	Slot 2
<b>B</b>	Slot 3		
<b>C</b>	<i>Slot 1</i>		

Table 4.4: Transmission time slots gained in node A's location table. Two entries  $A \rightarrow B$  and  $C \rightarrow A$  uses time slot 1 to transmit packets. Node A cannot do two actions at one time slot. Therefore, node A must rearrange the conflict.

	<b>A</b>	<b>B</b>	<b>C</b>
<b>A</b>		<i>Slot 1</i>	Slot 2
<b>B</b>	Slot 3		
<b>C</b>	Slot 0	<i>Slot 1</i>	

Table 4.5: Entries  $A \rightarrow B$  and  $C \rightarrow B$  are using the same time slot. This causes collision at node B as they are in the same receiving sector of node B.

As we have explained above, the transmitting and receiving slots of a node are kept in the first row and the first column of its location table. Every time the

node receives a new packet it updates the table. It checks whether there are more than one entry having a same slot in the table. If there is, it means that the node will do more than one job in the same slot. As this is impossible, it is necessary for the node to resolve the contention so that only one entry uses that slot. For example, both entry  $A \rightarrow B$  and entry  $C \rightarrow A$  of node A contains *slot 1* in table 4.4. Only one of them can be used. Thus, the node needs to resolve the contention to avoid the potential collisions and packets loss in phase two.

Moreover, the communication slots of a node may interfere with other nodes' transmission when the direction of the antenna of the destination does not point towards it. An example is given in table 4.5. Both node A and C transmit packets to node B. This causes packet loss as the two transmissions collide at node B. Therefore, either node A or C should change its time slot for packet transmissions to B.

### Detection of Potential Collisions or Packet Loss

	A	B	C	D
A		Slot 1	<i>Slot 3</i>	
B				<i>Slot 3</i>
C	Slot 2			
D				

Table 4.6: A corresponding representation of node A in figure 4.5. Although both entries  $A \rightarrow C$  and  $B \rightarrow D$  occupy the same transmission slot, it does not cause collisions or packet loss.

Every time when a node receives a packet, it examines its location table for checking if the information of the packet causes potential collisions. Firstly, the node examines its transmitting and receiving slots. If more than one entry occupy the same slot, collisions and packet loss will occur in the second phase. Next, it requires to examine the entries of its own communication and other nodes' transmission entries. If more than one entry occupy the same slot, collisions will occur. However, this is always not the case. A counter example is shown in figure 4.5. In this case, the location table of node A represented in table 4.6 shows that entries  $B \rightarrow D$  and  $A \rightarrow C$  occupy the same 'slot 3'. However, they are not interfering with each other during the transmission. Thus node A and B are able to do their jobs simultaneously.

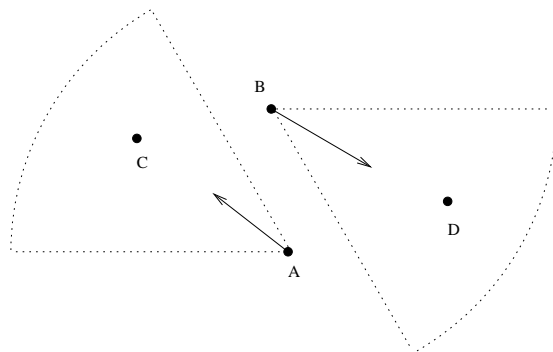


Figure 4.5: Node A transmits packets to node C, at the same time node B transmits packets to node D. The two transmissions do not suffer from collisions or packet loss.

### Elimination of Potential Collisions and Packet Loss

The sequence of arranging times depends on the priorities of nodes in their local area. The local area refers to the node and its neighbours. This sequence can significantly reduce the completion time of the first phase. However, this does not mean that only one node decides on its slots in its local area at one time. It is possible to have more than one node to arrange their time simultaneously. If two or more nodes choose the same time for transmissions, this causes collisions or packet loss. An example is in figure 4.6. Both nodes B and C have top priorities in their local areas. They both can arrange slots for A independently. When nodes B and C arrange the same time for transmission to A, A can receive from only one direction. Therefore, it causes packet loss from the other direction. The protocol needs to decide when potential collision or packet loss occurs at A, which node is responsible for changing the slot, node A, B, or C.

First, we clarify that it is not the case that a node always chooses its slots itself. This is because a higher priority node arranges both transmission and receiving slots for the lower ones. A time arranger of the node could be the neighbour of the node or the node itself. In a location table, each entry has its time arranger associated with it. If the transmissions of two nodes are conflicting in a location table, the time arranger that has a lower number of neighbours will change the time. For example in figure 4.6, B is the time arranger for communication between B and A, and C is the time arranger for communication between C and A. When B detects the conflict, as it knows C has a higher number of neighbours than itself, B will change the slot in the location table. However, if both B and C have the same number of neighbours (e.g., figure 4.7), any one of the nodes can change

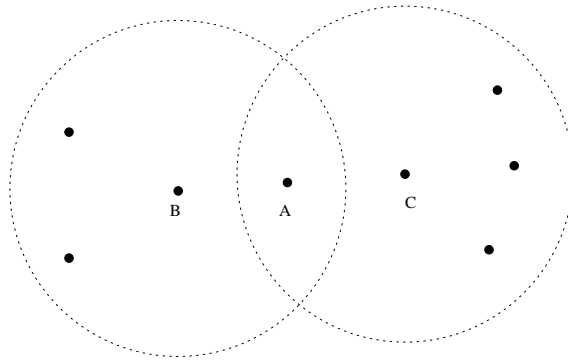


Figure 4.6: Node B and C have highest number of neighbours in their own local area. They can start arranging time slots before their neighbours.

the time.

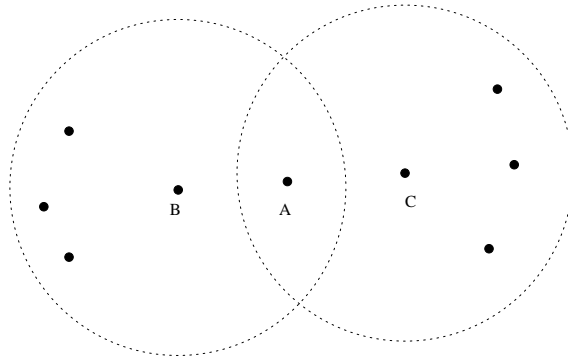


Figure 4.7: Node A receives the arranged time slot from nodes B and C, and it finds both nodes will transmit packets at the same time. Node A informs this conflict to them. One of the nodes will change the time slot.

Although 6 sector division let the nodes in one sector know each other's transmission to avoid collision, it is still possible to have collisions. An example is given in figure 4.8. If both B and C transmit packets to node A simultaneously, it causes collisions. It is assumed that node B and C have the same number of neighbours. Node C arranges time for communication with A and broadcasts this information, but node B does not receive it due to collisions. Recall that the communication in the first phase is through CSMA and collisions may occur. When B arranges time for communication between B and A, it does not know the communication between node C and A. Thus, it is possible for node B to arrange time for conflicting communications. Therefore, by using location table when C

receives the information from B, it will change its slots for communication with A. Though there is chance of collision while the nodes exchange their location tables in the first phase, we give sufficient time for the nodes to settle down with consistent location tables.

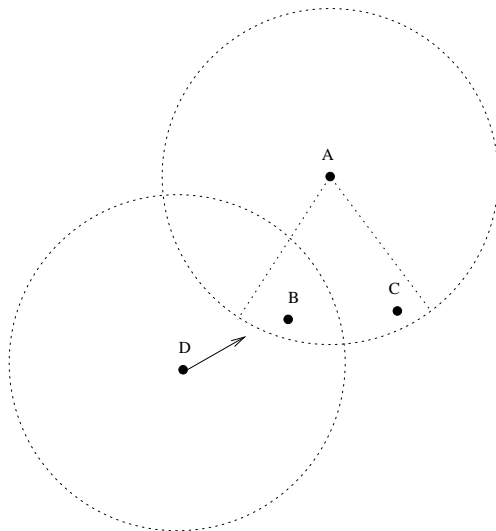


Figure 4.8: Node B does not receive the notice about when node C transmits packets to node A due to collision. When node B arranges time slot for node A, node C receives it and tries to avoid transmitting to node A at the same time as node B.

## 4.6 Time Conversion

In order to reduce collisions in the networks, time arrangement for each node is very important. The time arrangement is used to control when a node should use which sector for transmission or receiving. Furthermore, each node's location table contains not only its own time arrangement for communication but also its neighbours', and the nodes located at a distance of two-hops.

We view the communication of each node in the second phase in a cyclic fashion. Each node always repeats the same cycle of tasks in terms of either sending messages to or receiving messages from its neighbours. For example, it is assumed that a node need to do four communication tasks and each task is done within one time slot. In the first slot of the cycle, the node receives a packet from sector one. It transmits a packet in sector two in slot 2 etc. Each node in the

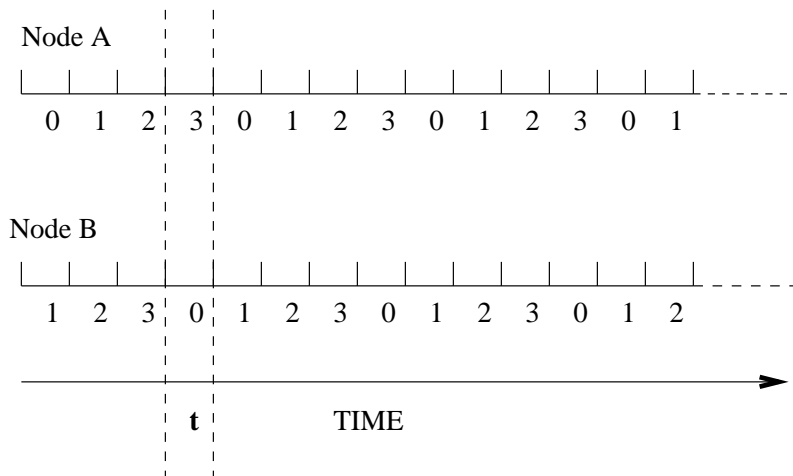


Figure 4.9: Nodes A and B have same communication cycle with period 4. However, when node A is in time slot 3, node B is in time slot 0.

network organizes all its tasks in a similar cyclical fashion. A node in the phase of directional transmission only follows the cycle of tasks that it has determined in the first phase. The problem is that each node has different period of the cycle. For example, node A's cycle may include four time slots, but B's may include eight. When A receives a packet (in the first phase) which indicates that B will transmit packets to it at B's time slot 2, A does not know which of its slots corresponds to B's slot 2. Furthermore, even if all the nodes in the network have the same length cycle, at any particular time they can be in different positions of their own cycle. An example is given in figure 4.9. A and B have same length cycle. Each of the cycles contains four time slots. When both of the nodes are in time  $t$ , A is at time slot 3, but B is in time slot 0. As B knows that A transmits packets for A in time slot 3 of A's cycle, it is necessary for B to convert A's time slot 3 into its own time slot in the cycle.

In our protocol, each node synchronizes its cycle with all its neighbours' cycles, and also determines its slots with respect to its neighbors. Nodes in a network have same cycle length  $C$ . At time  $t$ , node A is in slot  $t_A$  and B is in slot  $t_B$ . A converts  $t_B$  into its own,  $t_{A \leftarrow B}$ , by using

$$t_{A \leftarrow B} = |t_A - t_B| \bmod C \quad (4.7)$$

When A receives the information about B transmitting packets to A in B's slot,  $CommB_{B \rightarrow A}$ , A converts  $CommB_{B \rightarrow A}$  to its own,  $CommA_{A \leftarrow B}$ , by using

$$CommA_{A \leftarrow B} = (CommB_{B \rightarrow A} + t_{A \leftarrow B}) \bmod C \quad (4.8)$$

For example in figure 4.9, node A knows B in slot 0 and itself is in slot 3 at time  $t$ . A converts B's slot into its own by using " $|3 - 0| \bmod 4$ ". Thus, A knows that B is in A's slot 3, when B is in its own slot 0. When A receives the information about B will transmit packets to A in B's slot 2, A uses " $(2 + 3) \bmod 4$ " to convert to its own slot. Therefore, A knows B will transmit packets to A in A's slot 1.

## 4.7 Entering the Second Phase

As this protocol is proposed for ad hoc wireless networks, there is no centralized arbiter to control all the nodes. Each node may enter the second phase at a different time. The nodes use both omnidirectional (in the first phase) and directional transmission (the second phase). The problem is that each node in the network should be able to collect the necessary information about its neighbours and work out a synchronized location table with its neighbours before it enters the second phase.

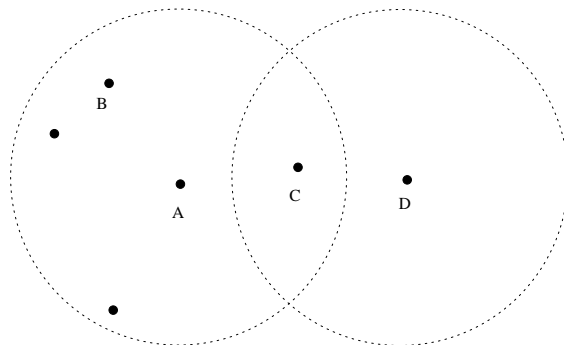


Figure 4.10: Node C never receives the location table from node A. Therefore, it cannot enter the second phase.

If the protocol allows a node to enter second phase immediately when it finishes synchronizing its location table and time slots, the high priority nodes will enter earlier than the low priority ones. However, when a higher priority node finishes arranging, it is not necessarily true that all the neighbors that have lower priorities than it receive its location table correctly. In addition, the network is in wireless transmission. This may happen due to the use of the standard CSMA protocol in the first phase. An example is given in figure 4.10. Node A has the maximum

number of neighbours in its neighbourhood. It is the node with the highest priority in its local area. When A starts arranging its time slots, the neighbours wait to receive the location table of A. After A enters the second phase, C does not receive time slots for communicating with A because the two transmissions from A and D are collide at node C. In addition, other neighbours of A are not within the transmission range of C. Thus, node C will never receive the location table from A any more. As a result, C will never finish arranging its communications with all of its neighbours and will never enter phase 2.

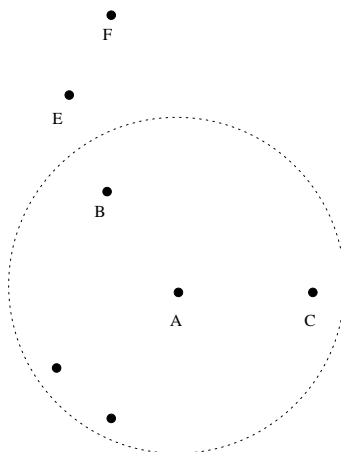


Figure 4.11: Node A finishes arranging. Then node B and C start arranging transmission slots. When node C finishes arranging but node B does not, node A must wait until node B finishes as well.

The protocol disallows the high priority nodes from entering the next phase once they finish time arrangement. Instead, when the high priority nodes finish arranging, they still continuously broadcast their location tables omnidirectionally in CSMA mode. This gives more chances to the nodes that did not receive the arranged slots before because of collisions. The sequence of starting arrangement is from top priority nodes to bottom priority nodes. When the bottom priority nodes finish arranging (actually all the time slots of the bottom nodes in the network are usually arranged by their neighbours), they broadcast a prepare-to-enter message including a waiting time to their neighbours, and then enter the second phase when the waiting time is over. The other nodes receive the message with the time and prepare to enter the second phase.

Moreover, although the waiting time of a node elapses, it is still disallowed to enter phase 2 if there is a neighbour that has lower priority which is still not prepared to enter the second phase. This is because when a higher priority node's waiting time ceases, it still does not guarantee all of its neighbours successfully

receive the arranged slots from them. For example, figure 4.11 shows that node A has the local highest number of neighbours and finishes arranging first, then its neighbours B, C, and others start arranging their time slots. After a period of time, C finishes arranging and informs A of a waiting time. A receives that message and waits. When A's waiting time ceases, B has still not finished arranging its slots because it still has not received the arranged time from A due to interference from node F. Therefore, A must wait for node B and the other neighbours finishing.

## CHAPTER 5

# Simulation

### 5.1 Objective

This evaluation aims to compare the performance of our new directional MAC protocol with normal CSMA. We evaluate our protocol in a number of static wireless networks.

### 5.2 Simulation Environment

To evaluate the performance of our directional MAC protocol compared with normal CSMA, we developed a network simulator which simulates network communication. In this simulator, time is divided into a number of slots. The transmission channel is implemented as a buffer. A packet in the channel is held in one buffer element. A node can perform only one action in a time slot. Furthermore, propagation delay of packet transmission is considered to be zero. The receiver receives a packet as soon as the sender sends it.

For the directional-antenna model, the simulator assumes that each antenna is of same range of coverage and angle of sector. The coverage sectors of consecutive antennas do not overlap each other. It is assumed that omnidirectional antennas have the same range as directional antennas. Directional antennas are able to face to only one direction in each time slot. However, the directional antennas are able to point to any direction in any slot. In other words, we assume zero movement time for antennas. For example, an antenna may face to sector 0 in time slot 0, and then face to sector 5 in time slot 1. Furthermore, when a directional antenna of a node is in one direction, any packets from other directions will be ignored by the node and they do not cause collisions.

Furthermore, in regard to transmission error, the simulator assumes error-free physical layer transmission as we want to concentrate on a MAC layer protocol.

### 5.3 Performance Metrics

In order to evaluate the performance of our MAC protocol, we define collision ratio and packet delivery ratio as the two main metrics. Sometimes, we need collision number and packet delivery number to compare whether the new protocol really outperforms CSMA. We consider the packets which contain real data, i.e., the packets of the nodes exchange for transferring data to each other. This is because nodes transmitting data are at all the time in our protocol except when they do not have the locations of their neighbours. In other words, as long as a node knows its neighbours' locations, it will transmit data no matter directionally or omnidirectionally. When a packet from a node is in the first phase of our protocol and is about compromising the node's communication slots with another node in omnidirectional transmission, the head part of it is about compromising information, and the rest is data.

It is necessary to explain what the two main metrics calculate during the simulation. Collision ratio is the number of collided data packets divided by the total number of transmitted data packets. Packet delivery ratio is the number of delivered data packets divided by the total number of transmitted data packets. I define that if a data packet collides at a receiver, it is a collision. If it is received by the receiver successfully, it is a delivered data packet.

### 5.4 Simulation Scenarios

We generated four topologies which are randomly distributed nodes in a fixed  $400 \times 400m^2$ . Each topology guarantees that the whole network is connected, and there is no more than one node at the same location. Two of the topologies have 100 nodes each. The other two have 200 nodes each. The topologies which have the same number of nodes has different number of neighbours restriction for each node. One topology allows a maximum of three neighbours per node, and the other allows a maximum of eight neighbours per node.

We analyze the performance of our protocol in five scenarios. Each node in the network sends packets to its neighbours in time slots. This constitutes the traffic in the network. We specify the simulation time for all the five scenarios as 20000 time slots as this gives the nodes enough time to complete the first phase as well as work in the second phase for an extended period. We measure the performance of our protocol mainly on packet delivery ratio.

In the first scenario, we evaluate the performance of the new protocol compared with 0.9-persistent CSMA. In the 0.9-persistent CSMA protocol, each node trans-

Scenario	Persistence	Number of Sectors	Number of Nodes	Number of Maximum Neighbours
<b>1</b>	0.9	6	100	3
<b>2</b>	0.9	6	100, 200	3
<b>3</b>	0.1, 0.5, 0.9	6	100	3
<b>4</b>	0.9	6	100	3, 8
<b>5</b>	0.9	6, 8, 12	100	3

Table 5.1: A summary of the evaluation parameters used in the simulation.

mits with a probability of 0.9 when it finds the channel free. Secondly, we increase the number of nodes in the network. We use both 100-node and 200-node networks to evaluate our protocol. Next, we change the CSMA persistence. We choose 0.1, 0.5, and 0.9 persistent CSMA for a 100-node network and use the three persistence values to compare our protocol with the corresponding CSMA protocol. Recall that the nodes use the CSMA protocol in the first phase of our protocol. In scenario four, we use another 100-node network in which each node can have maximum of 8 neighbours. In other words, we increase the density of network topology to compare our protocol with CSMA. The final scenario aims to increase communicating sectors of each node. We compare our protocol with CSMAs by using 6, 8, and 12 antenna elements. The values used in the five scenarios are summarized in table 5.1.

## 5.5 Simulation Results and Analysis

### 5.5.1 Scenario One

The packet delivery ratio under our protocol is about double compared to 0.9-persistent CSMA after approximately 6000 time slots of the simulation (figure 5.1). At about time slot 4000, there is a short period when our protocol's performance is worse than that of CSMA, i.e., the delivery ratio is less than that in CSMA. However, after that period, the ratio increases sharply until it reaches about 80 percent. Before 4000 time slots, the ratio is same. This is because our protocol is based on the CSMA protocol. In the initial phase, its performance is same as that of the CSMA protocol. After a period of time, when each node collects neighbours' information, some nodes enter phase 2 (i.e., use directional transmission) earlier than other nodes which still work in omnidirectional trans-

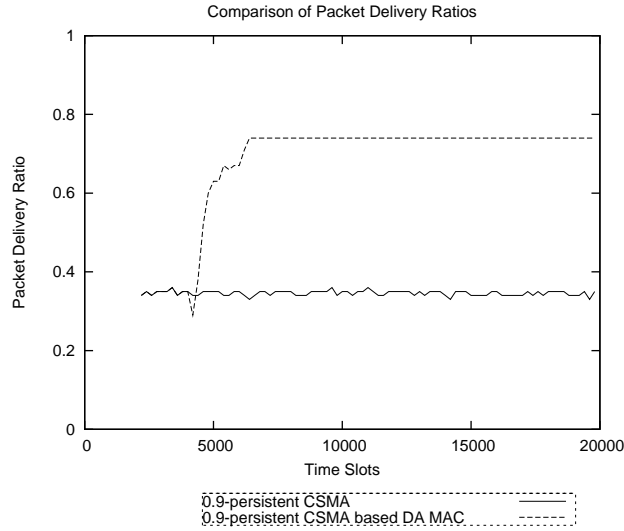


Figure 5.1: The comparison of packet delivery ratios between our protocol and CSMA based on 0.9-persistent, 6 sectors for each node, and maximum of 3 neighbours for each node in a 100-node network.

mission phase (i.e., phase 1). At that period, both directional and omnidirectional transmissions exist in the network. This reduces the performance of the network. However, after a short period, as more and more nodes enter phase 2, the packet delivery ratio increases. When all the nodes enter phase 2, they transmit packets according to a fixed schedule. The ratio of packet delivery under our protocol is consistently high in the second phase. In contrast, the CSMA protocol's ratio is unsteady and always fluctuates.

Note that the ratio of packet delivery never reaches the maximum level of 1 in our protocol. This is due to two reasons. Our protocol uses the CSMA protocol in the first phase, resulting in significant packet loss. Moreover, each node does not usually arrive at a perfect schedule for its operation in the second phase. As a result there is always some chance of collisions and subsequent packet loss during the operation of the network in the second stage.

Figure 5.2 shows that the ratio of collisions using our protocol is much less than that using the CSMA protocol. Furthermore, the ratio nearly reaches zero, but never zero. Once again, this is because there are some nodes that are unable to reach a perfect schedule in the first phase due to high rate collisions in omnidirectional transmission.

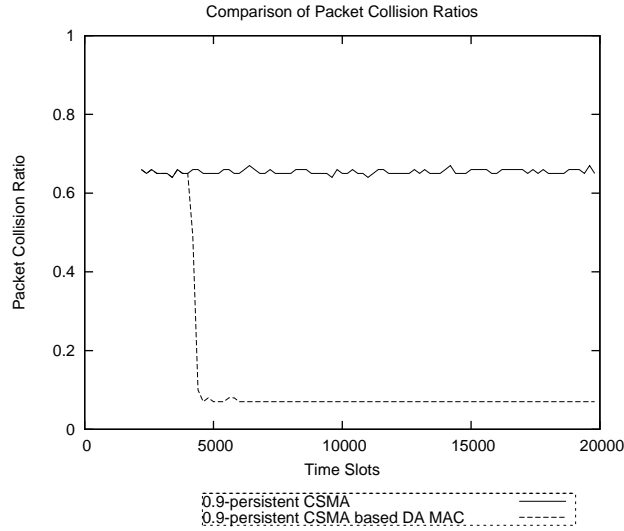


Figure 5.2: The comparison of packet delivery ratios between our protocol and CSMA based on 0.9-persistent, 6 sectors of each node, and maximum 3 neighbours for each node in 100-node network.

### 5.5.2 Scenario Two

We compare the performance of our protocol with CSMA in 100-node and 200-node networks. Each network restricts the maximum number of neighbours for each node to three. From figure 5.3, the ratios of packet delivery for our protocol in both the networks are much higher than the CSMA protocols. The delivery ratio of the 200-node network is about 10 percent higher than the ratio from 100-node network. Both networks' performances are significantly higher than the CSMA protocol. Moreover, the time for all the 200 nodes entering directional transmission phase (the second phase of the protocol) is a little faster than the time for 100 nodes.

The delivery ratio of the 200-node network is higher than that of the 100-node network in our protocol. As the 200-node network has more packets and hence more traffic, nodes become more correct to compromise with each other. Another possible reason is that the topology of the 200-node network is better for synchronizing the schedules in the first phase.

Figure 5.3 shows that CSMA in the 100-node network performs a bit better than that in the 200-node network. However, our protocol in the 200-node network performs better than that in the 100-node one. It is possible that our protocol can increase the performance of a wireless network better in larger networks.

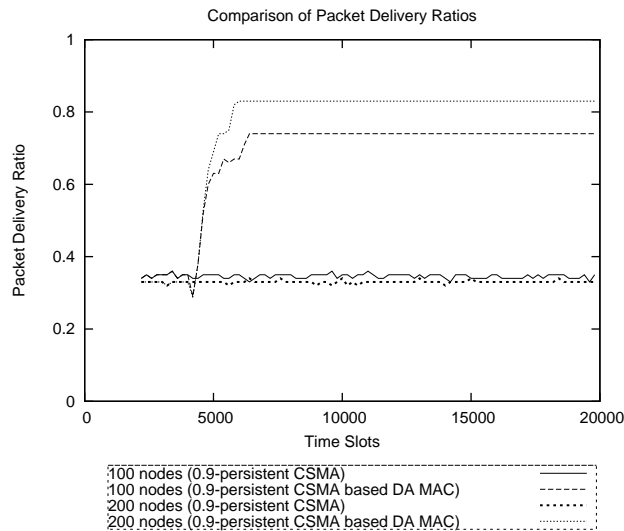


Figure 5.3: The comparison of packet delivery ratios between our protocol and CSMA based on 0.9-persistent, 6 sectors of each node, and maximum 3 neighbours for each node in 100-node and 200-node networks.

### 5.5.3 Scenario Three

A significantly different result from the previous two scenarios is that 0.1-persistent CSMA achieved the highest ratio of packet delivery (figure 5.4). The three DA protocols that are based on 0.1-persistent, 0.5-persistent, and 0.9-persistent CSMA perform better than 0.5 persistent and 0.9 persistent CSMAs.

The reason 0.1-persistent CSMA performs best is because the probability of transmitting a packet is the least among all the protocols. However, this does not mean that 0.1-persistent protocol outperforms any of the other protocols. This is because evaluating a protocol does not depend only on the ratio of delivery of packets but also on the actual number of packets delivered. Figure 5.5 shows that the number of packets delivered under 0.1-persistent CSMA is least (each point in the graph represents the total number of packets transmitted in 200 time slots). 0.1-persistent CSMA guarantees a packet delivery most of the time, but on the other hand it has fewer opportunities for the nodes to transmit packets as the low transmission probability.

In comparison, our protocol that is based on 0.1-persistent CSMA has the second highest ratio of packet delivery. This means lower persistent CSMA can give our protocol better performance and help nodes arrange transmission slots more correctly. The reason is that during omnidirectional transmission, low persistent

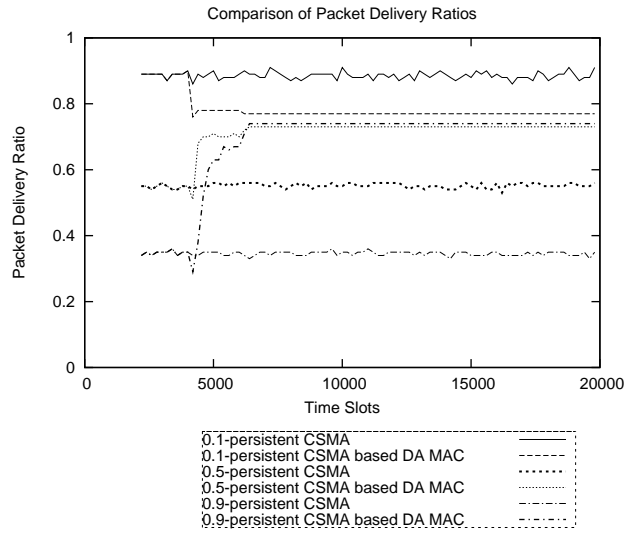


Figure 5.4: The comparison of packet delivery ratios between our protocol and CSMA based on 0.1, 0.5, and 0.9-persistent, 6 sectors of each node, and maximum 3 neighbours for each node in a 100-node network.

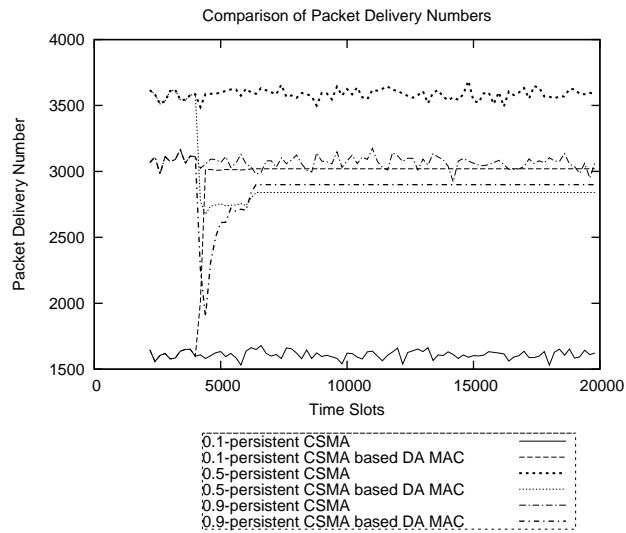


Figure 5.5: The comparison of packet delivery numbers between our protocol and CSMA based on 0.1, 0.5, and 0.9-persistent, 6 sectors of each node, and maximum 3 neighbours for each node in 100-node network

CSMA causes collisions fewer than high persistent CSMA. The nodes under low persistent CSMA synchronize transmission slots with others nodes more correctly because packet loss from the *hidden terminal problem* are less.

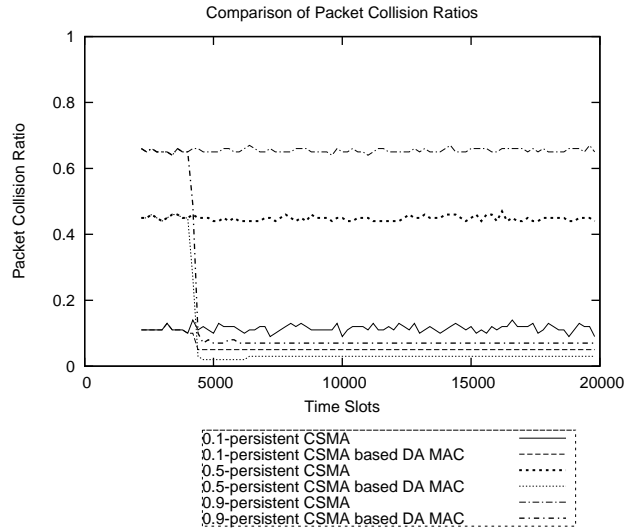


Figure 5.6: The comparison of packet collision ratios between our protocol and CSMA based on 0.1, 0.5, and 0.9-persistent, 6 sectors of each node, and maximum 3 neighbours for each node in 100-node network

Our protocol based on 0.1-persistent decreases the ratio of packet delivery when nodes start using directional transmission. A reason is that our protocol increases the rate of packet transmission when some nodes enter directional transmission phase. However, it also increase the chance of collisions or packet loss due to failure in synchronizing time slots. In figure 5.5, the number of packet delivery under our protocol based on 0.1-persistent is higher than that under 0.1-persistent CSMA. Furthermore, although the collision number under both the protocols are at the same level, the rate of packet loss are higher. Thus, packet loss increases during the transmission reducing the rate of successful delivery.

Both our protocol based on 0.9-persistent and 0.5-persistent perform in a similar way in the directional transmission stage. Although the transmission probability of each network is different, successful rate of synchronization in the first phase is almost the same. An additional evidence is that the packet delivery number for both protocols are almost the same in directional transmission phase (figure 5.5).

Furthermore, figure 5.6 indicates that our protocol based on any persistent CSMA causes less collisions than the CSMA. This shows that as our protocol is able to coordinate communication between the nodes in a network, collisions caused

by omnidirectional transmission are reduced during the directional transmission phase.

### 5.5.4 Scenario Four

This scenario aims to compare our protocol with CSMA in networks where the maximum number of neighbors for each node is varied. Two 100-node networks with maximum neighbour numbers are compared. One is restricted for each node to have a maximum of 3 neighbours, and the other is restricted for each node to have a maximum of 8 neighbours. As shown in figure 5.7, both packet delivery ratios under our protocols are much better than CSMA. Both of the networks under our protocol achieves same ratio of delivery when all the nodes enter the phase of directional transmission. However, the network with maximum of 3 neighbours per node is faster to enter the directional transmission phase than the other one. This is because it is easier for the nodes to synchronize their slots in the lower density network. Since the sequence of arranging slots is from the nodes who have more neighbours to those who have less, a node that has the least number of neighbours can synchronize its slots earlier.

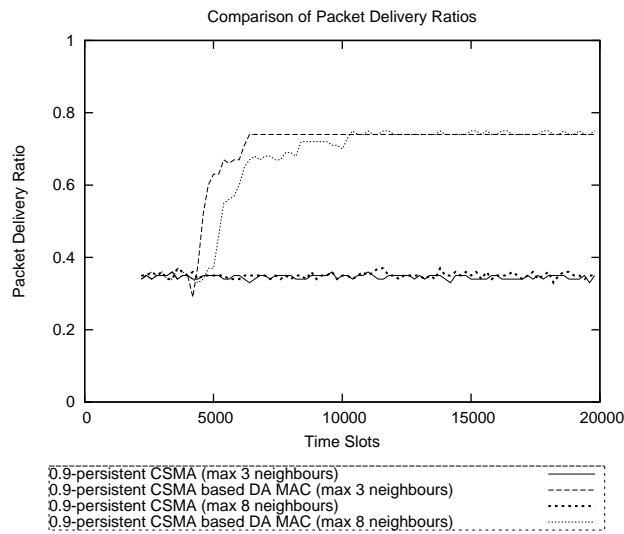


Figure 5.7: The comparison of packet delivery ratios between our protocol and CSMA based on 0.9-persistent, 6 sectors of each node, and maximum 3 and 8 neighbours for each node in 100-node networks.

Why the two differently density networks achieve approximately same ratios of packet delivery in directional transmission is because the packet delivery number

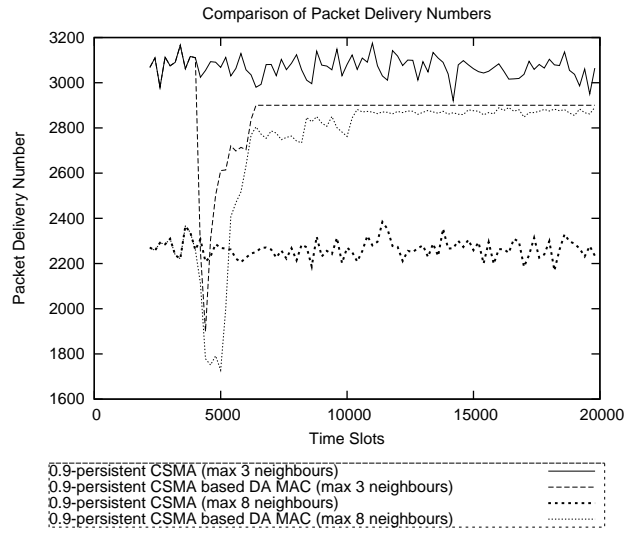


Figure 5.8: The comparison of packet delivery numbers between our protocol and CSMA based on 0.9-persistent, 6 sectors of each node, and maximum 3 and 8 neighbours for each node in 100-node networks.

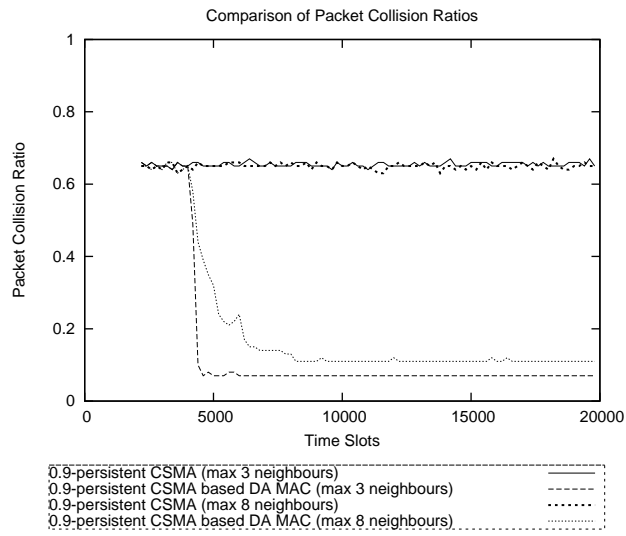


Figure 5.9: The comparison of packet collision ratios between our protocol and CSMA based on 0.9-persistent, 6 sectors of each node, and maximum 3 and 8 neighbours for each node in 100-node networks.

of both density networks are similar in figure 5.8 after they enter the second phase (each point in the graph represents the total number of packets transmitted in 200 time slots). However the collision number of both are different (figure 5.9). That means there exists packet loss that is caused by mismatch of sending and receiving sectors.

### 5.5.5 Scenario Five

In figure 5.10, our protocols with 6, 8, and 12 antenna elements achieve higher packet delivery ratio than CSMA. All the nodes enter the directional transmission phase approximately at the same time. However, using 12 antenna elements achieves higher ratio of packet delivery than the other two. There are two reasons for this. One is that each directional antenna element has less angle of coverage with higher density of elements. Each of the twelve antenna elements only use  $30^\circ$  sectors to transmit packets. Thus, a transmission in the network affects only a smaller area compared to using  $60^\circ$  antenna elements. This increases the chance of arriving at correct schedules in the first phase. Thus, smaller angular antenna elements reduce collisions. An evidence can be seen in figure 5.11. The number of collisions using 12 antenna elements is the lowest.

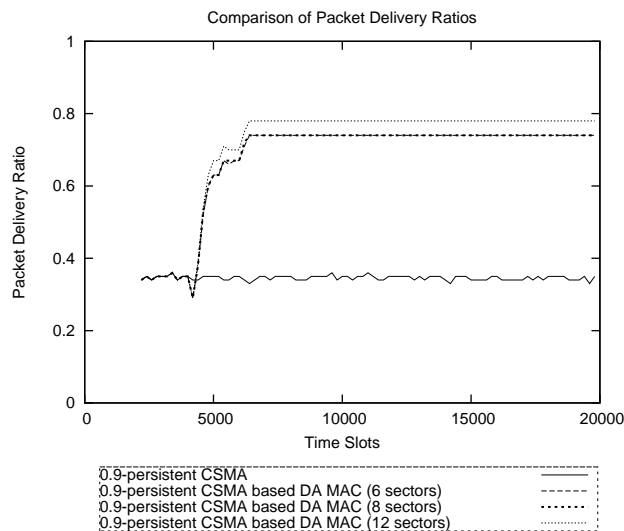


Figure 5.10: The comparison of packet delivery ratios between our protocol and CSMA based on 0.9-persistent, equipped with 6, 8, and 12 sectors for each node, and a maximum 3 neighbours for each node in 100-node network.

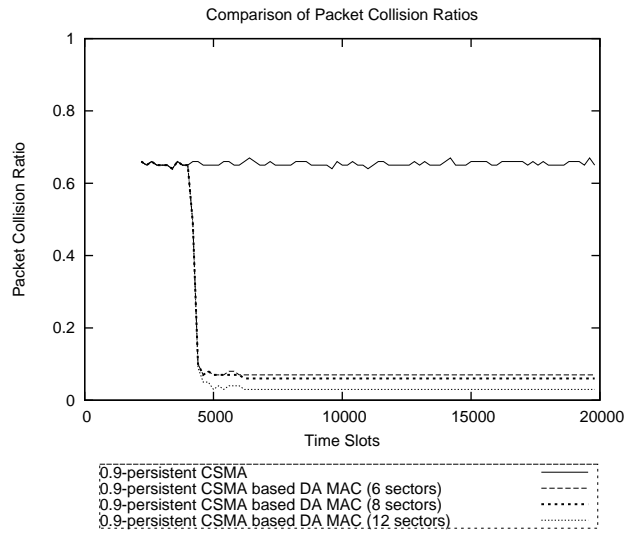


Figure 5.11: The comparison of packet collision ratios between our protocol and CSMA based on 0.9-persistent, equipped with 6, 8, and 12 sectors of each node, and a maximum of 3 neighbours for each node in a 100-node network.

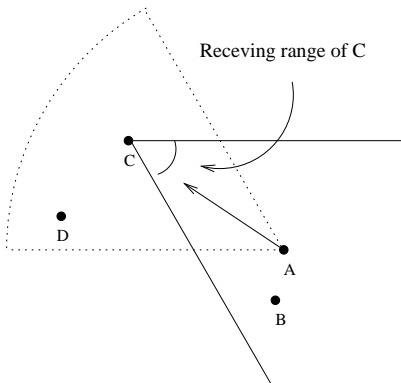


Figure 5.12: When node A transmits packets to node C, node B cannot transmit to node D because the potential transmission will interfere with node C receiving packets from node A.

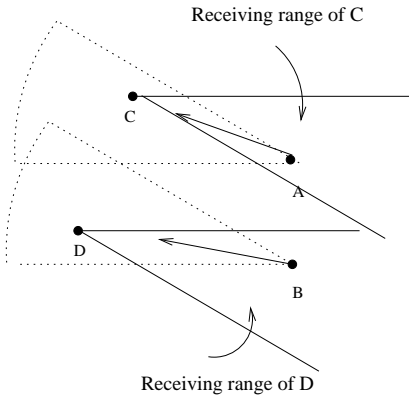


Figure 5.13: Due to reduction in the sector area, when node B transmits packets to node D, it does not interfere node C's receiving from node A.

The other important factor is that due to smaller angular antenna elements, a node has more choices to select its time slots and sectors. For example in figure 5.12, if node A arranges to transmit packets to node C in time slot 1, B cannot arrange to transmit packets to D at the same time to avoid collisions. Instead, B will choose another time slot to do the transmission. However, if the number of antenna elements increases to 12 and each angular sector is  $30^\circ$  (figure 5.13), B can arrange to transmits packet to D at the same time slot as when A transmits packets to C. Therefore, the ratio of packet delivery is a little higher than the other two. However, it is not always true that the network equipped with more directional antenna elements outperforms that with less elements because the performance of a network depends on many other aspects. If the density of a network is very high, transmission using more antenna elements may be good. If the density is low, high number of antenna elements does not help much to improve the performance of the network.

# Conclusions

We have presented our MAC protocol based on directional transmission and reception. Since smart antenna technology is improving at a rapid rate, it is desirable to take advantage of this technology to design better MAC protocols for ad hoc networks. There are several published papers on MAC protocols taking advantage of directional transmission in mobile ad hoc networks. However, the use of directional antennas for static ad hoc networks has not been explored much. On the other hand, there is a need to conserve battery power in each node in static wireless networks in general and in sensor networks in particular. Many of the sensor network MAC protocols are designed by synchronizing time slots among nodes.

In this report, we have designed a new MAC protocol using directional antennas specifically designed for sensor networks. We take advantage of directional transmission in two different ways. First, each node in the network synchronizes its slots with its neighbors for sending and receiving messages. Thus, a node can sleep when it is not communicating with its neighbors and hence save energy. Secondly, a node can reduce the power level for transmission in directional transmission and still can reach all its neighbors that are reachable through omnidirectional transmission. As a result, nodes can reduce their power level significantly in the second phase of our protocol when they are using directional transmission. Our simulations show that our protocol performs much better than the CSMA protocol in terms of reduced number of collisions and increased packet delivery ratio.

However, our protocol is designed for only static networks. The neighborhood of each node changes in mobile ad hoc networks and it is not possible to use our protocol in such a scenario directly. It will be interesting to see whether similar ideas can be used for designing a MAC protocol for mobile ad hoc networks.

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# Original Honours Proposal

## Background

Wireless networks use short-range radio transmission for communicating among nodes. The responsibility for communication in a wireless node or station is on the Medium Access Control (MAC) layer [14] which is a sub-layer of data-link layer of OSI network architecture. The function of this layer is to control the access to the wireless medium, so that multiple stations do not transmit their packets in the same region of space resulting in collisions and subsequent packet loss. It is known that the transmitting medium can be multiplexed in four dimensions, which are Space, Time, Frequency and Code. Time Division Multiplex (TDM) is most widely used for communication in ad hoc wireless networks. In the TDM scheme, only one station can use the medium for transmitting packets within the same region of space. Collision of transmissions is a serious issue in a shared medium as there is packet loss and a need for retransmission resulting in loss of bandwidth. In Carrier Sense Multiple Access (CSMA) Protocols, a station first senses the wireless carrier and transmits if the carrier is free. Otherwise, it backs off for a random interval of time. Compared to ALOHA, CSMA protocols increase bandwidth utilization of a wireless network.

The main problem with CSMA protocols for wireless communication is the possibility of collisions due to the hidden terminal problem [14], because a station could be out of the transmission range of another station. For example, when station A transmits to B, B could be busy receiving packets from another station C. But C and A are out of transmission range of each other and cannot sense each other's transmissions. As a result, the packets sent by A and C are lost due to collision at B. Request to send/Clear to send (RTS/CTS) is positive control over the use of shared medium in wireless network. RTS/CTS try to minimize collision among the hidden terminals through a hand-shaking scheme. However, RTS/CTS still cannot solve the collision problem completely.

## Aim

In this project, I plan to design a new MAC layer protocol for static wireless networks. Recently, there is significant progress in designing *directional antenna* for wireless nodes [1, 2, 3, 4, 6, 5, 10]. A directional antenna can receive or transmit wireless signals within a specified angular range and not necessarily within the  $360^\circ$  angle surrounding the node. The main advantage of a directional antenna is that it enables a node to receive and transmit messages in a selective way. If a node can coordinate its receiving or transmission activities in conjunction with the other nodes, this selective receiving and transmitting capability can be used for avoiding packet collisions.

Each node divides its  $360^\circ$  transmission range into several angular sectors. At any time, a node  $S$  only listens to a particular sector and can receive transmissions from stations only within this sector. Any transmission to  $S$  from outside this sector is lost. Similarly,  $S$  can transmit its own packets in one of its sectors. Another station  $R$  can receive packets sent by  $S$  if  $R$  is within the transmitting sector of  $S$  and  $S$  is within the receiving sector of  $R$ . A node listens to its receiving sectors in a round-robin fashion. A node can divide its  $360^\circ$  receiving zone into sectors depending on the concentration of its neighbours. If there is a higher concentration of neighbours in a particular direction, a node can associate several listening sectors in that direction. Moreover, a node can spend more time for a particular sector if the number of neighbours in that sector is high.

## Method

The main aim of this protocol is to adjust the receiving sectors of each node to satisfy the following condition. If there are multiple nodes within a receiving sector of a node  $S$ , all these nodes will be within the transmission range of each other. Each node knows when others in the transmission range will transmit packets to  $S$ . Hence, no two nodes will try to transmit packets to node  $S$  at the same time as they can virtually sense each other's transmission. As a result, the hidden terminal problem will be eliminated and there will be no need for retransmission of lost packets. The following is a brief discussion of the method that we will use. The description is with respect to a single node, however, it has to be remembered that this protocol will be executed by all the nodes in the network in an identical fashion.

There are two phases in the working of the MAC protocol. In the first phase, the MAC protocol will behave like an ordinary CSMA protocol. The purpose of this

phase is to collect information about the neighbours of a node. Once a node  $S$  knows all its neighbours, it decides on the sectors depending on the concentration of neighbours. It also informs all of its neighbours about its receiving sectors and how much time it will spend for each of its sectors. A node also informs all of its neighbours about when it will send packets to each of its neighbours. Furthermore, the node informs all of its neighbours about the current time according to its own clock. The neighbours can now determine their transmitting sectors depending on when they want to send packets to  $S$ . This protocol does not require any clock synchronization as long as each node is aware of the time according to each of its neighbours' clocks.

I aim to extensively simulate this MAC protocol for static wireless networks. Our simulation will involve a random distribution of nodes within a simulation area. I will compare the performance of our protocol compared to normal CSMA protocol.

## Timetable

The following is the timetable for the project:

<b>Semester 1</b>	
Week 1	Discuss project with my supervisor
Week 2	Write project proposal
Week 3	Finish and submit project proposal
Week 4	Design a MAC protocol
Week 5	Defend proposal to research group
Week 6–10	Continue to design the MAC protocol
Week 11	Revise and submit proposal
Week 12	Implement and test the protocol
<b>Semester 2</b>	
Week 1	Compare the new protocol with normal CSMA protocol
Week 2–8	Write dissertation
Week 9	Submit a draft dissertation
Week 10–11	Revise dissertation
Week 12	Finalize dissertation
Week 13	Give a seminar and produce a poster

Table A.1: Timetable of the project development

## Software and Hardware Requirements

I will use the Linux Redhat platform and C/C++ for our simulations.