2010년 8월

석사학위 논문

A Robust MAC Protocol for Ad Hoc Networks using Directional Antennas

조선대학교 대학원

컴퓨터공학과

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2010년 8월 25일

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지도교수　모상만

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Abbreviations and Notations

ACK	Acknowledgement
AST	Angle Signal Table
BTr	receive Busy Tone
BTt	transmit Busy Tone
CR	Communication Register
CMAC	Cooperative MAC
CRM	Circular RTS MAC
CRCM	Circular RTS and CTS MAC
CTS	Clear To Send
DBSMA	Directional Busy Signal Multiple Access
DBTMA/DA	Dual Busy Tone-based Multiple Access with Directional Antennas
DCF	Distributed Coordination Function
DCTS	Directional CTS
DD	Directional Directional
DLPS	Distributed Laxity-based Priority Scheduling
DMAC	Directional MAC
DMAC/DACA	Directional MAC with Deafness Avoidance and Collision Avoidance
DNAV	Directional NAV
DNT	Directional Neighbor Table
DO	Directional Omni
DoD	Diametrically opposite Directional
D-PRMA	Distributed Packet Reservation Multiple Access
DPS	Distributed Priority Scheduling
DRTS	Directional RTS
DT	Deafness Table
EC	Extended area Communication

EDNAV	Enhanced DNAV
EMAC	Efficient MAC
ESPRIT	Estimation of Signal Parameters via Rotational Invariant Techniques
FIFO	First In First Out
GPS	Global Positioning System
HD	High Distance
HMAC	Hybrid MAC
HoL	Head of Line
IEEE	Institute of Electrical and Electronics Engineers
IS	Invitation Signal
LCAP	Load-based Concurrent Access Protocol
LD	Low Distance
MAC	Medium Access Control
MACA	Multiple Access Collision Avoidance
MACA/PR	MACA with Piggy-backed Reservation
MACAW	Multiple Access with Collision Avoidance for Wireless
MANET	Mobile Ad hoc NETwork
MCMDA	Multi Channel MAC using Directional Antenna
MD	Medium Distance
MDA	MAC protocol for Directional Antennas
MMAC	Multihop Medium Access Control
NHDI	Next Hop Directional Information
NS	Network Simulator
OC	Omnidirectional area Communication
ONAV	Omni-NAV

ORTS	Omni-directional RTS
Q-SDMAC	Queue-Selectively Directional MAC
Ra-MAC	Range-adaptive MAC
RI-DMAC	Receiver Initiated-DMAC
RTR	Ready To Receive
RTS	Request To send
SCH	Schedule Update with Intelligent Feedback
SDMAC	Selectively DMAC
SINR	Signal to Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SOD	Start Of Dialog
SWAMP	Smart antenna based Wider-range Access MAC Protocol
SYN-DMAC	SYNchronized-DMAC
VCTS	Vertically opposite CTS
WMN	Wireless Mesh Network
WSN	Wireless Sensor Network
WTS	Wait To send

초록

방향성 안테나를 사용하는 애드혹 네트워크를 위한 견고한 MAC 프로토콜

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모바일 애드혹 네트워크는 통신 인프라를 갖추지 않은 분산 네트워크로서, 각 노드는 상황에 따라 라우터나 호스트 역할을 수행한다. MAC 계층은 공유 무선 매체에 대한 접근을 제어함으로써 인접 노드 상호간 통신을 관리하는 기능을 수행한다. 최근 애드혹 네트워크에서의 방향성 안테나의 채용이 크게 증가하고 있다. 방향성 안테나를 사용하는 애드혹 네트워크에서의 MAC 프로토콜은 공간 재사용, 전송 범위, 네트워크 용량을 증대시키는 잠재력을 지니고 있으며, 무방향성 안테나 시스템에서의 부정적 현상들을 크게 경감시켜 준다. 그러나 은폐 터미널 문제, 수신 불가(deafness), 이웃 노드 발견, 방향성 전파 감지의 취약점 등과 같은 제반 문제들을 안고 있다.

본 논문에서는 일차적으로 방향성 안테나를 사용하는 애드혹 네트워크를

위한 기존의 MAC 프로토콜들을 폭 넓게 조사 분석한다. 방향성 안테나를 사용하는 애드혹 네트워크를 위한 다양한 MAC 프로토콜들을 조사하고, 주요 특성과 네트워크 성능 측면에서 비교 분석한다. 그리고 다중 방향성 안테나를 사용하는 다중 채널 MAC (MCMDA) 프로토콜을 새롭게 제안한다. 제안한 MCMDA는 은페 터미널 문제와 수신 불가 현상을 감소시킴으로써 방향성 전송의 이용률 및 네트워크 용량을 크게 증대시켜 준다. 각 노드는 다중 채널과 다중 안테나의 결합에 의해, 하나의 노드에서 송신과 수신이 동시에 일어날 수 있도록 다중 인터페이스를 장착하고 있다. 다중 인터페이스, 다중 채널, 다중 안테나의 상호 결합은 네트워크 용량을 더욱 증대시키고 방향성 안테나 사용에 따른 부담을 경감시켜 준다. 제안한 MCMDA는 무방향성 전송과 방향성 전송 모두를 사용하며 채널을 예약하기 위해서 뿐만 아니라 은폐 터미널 및 수신 불가 문제를 감소시키기 위하여 제어 패킷인 DRTS, DCTS, VCTS를 사용한다.

제안 프로토콜은 NS-2.33 네트워크 시뮬레이터를 사용하여 그 성능이 광범위하게 평가되었다. 제안 프로토콜은 네트워크 전송률 및 종단간 지연시간의 측면에서 일반적인 IEEE 802.11 DCF 뿐만 아니라 방향성 안테나를 사용하는 DMAC과 비교해서도 대폭적인 성능 향상을 나타내었다.

ABSTRACT

A Robust MAC Protocol for Ad Hoc Networks Using Directional Antennas

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A mobile wireless ad hoc network is an infrastructureless distributed network, where each node can be a router or a host depending upon the situation. The Medium Access Control (MAC) layer is responsible for managing the communication between adjacent nodes by controlling access to the shared wireless medium. In recent years, the employment of directional antennas in ad hoc networks has increased significantly. MAC protocols in ad hoc networks with directional antennas have the potentiality of higher spatial reuse, larger coverage range and larger network capacity, which mitigates the negative effects associated with omni-directional antenna systems. However, they also suffer from some issues like hidden terminal problems, deafness, neighbor discovery, flaws with directional carrier sensing, etc.

In this thesis, an extensive study of MAC protocols for ad hoc networks using directional antennas is presented first. Various existing MAC protocols for ad hoc networks with directional antennas are investigated and compared in terms of major characteristics and network performance. Then, we propose a robust MAC protocol, multi-channel MAC using multiple directional antennas (MCMDA), which makes the better utilization of directional transmission and aims in increasing the network capacity, reducing the negative effects of hidden terminal problems and deafness. In the proposed protocol, each node is equipped with multiple interfaces such that concurrent transmissions and receptions take place in a node at the same time. The combination of multiple channels with directional antennas is also used at each node. The combined use of multiple interfaces with multiple channels and directional antennas can further improve the network capacity and, to a larger extent, mitigate the burdens related with the use of directional antennas. The proposed MCMDA uses both omni-directional and directional modes of communication and uses DRTS, DCTS and VCTS control packets not only to reserve a channel but also to reduce the hidden terminal and deafness issues.

The proposed protocol is evaluated through computer simulation using NS-2.33. It achieves significant performance improvement in comparison to the popular Directional MAC (DMAC) as well as IEEE 802.11 DCF in terms of network throughput and end-to-end delay.

1. Introduction

A typical wireless ad hoc network comprises of mobile nodes that are capable of self-organization. The links in ad hoc networks are usually temporary and wireless, and the link quality changes dynamically and unpredictably. Ease of configuration and deployment has made ad hoc networks much sought in the modern communication environments. The practical uses and benefits of wireless ad hoc networks are being realized in the fields like: emergency services such as natural disasters, telemedicine, vehicular communications, traffic monitoring, military applications, etc [6].

In comparison to the wired networks, wireless networks have constraints of bandwidth. The capacity of wireless ad hoc networks is significantly lower than the wired networks. Also, effects of multiple access, fading, noise, interference would add up in lowering the throughput of wireless ad hoc networks [24]. Lower link capacities in wireless ad hoc networks lead to congestion [24]. The nodes in ad hoc networks are operated on batteries, so energy conservation turns out to be the prime focus. Poor link capacity and congestion may lead to fast exhaustion of wireless nodes. The functions and procedures required for communication between two nodes in a network are dealt by MAC layer. MAC protocol ensures reliable, efficient and fair sharing of wireless resources. Various MAC protocols for wireless ad hoc networks have been proposed in order to better utilize the limited bandwidth.

In most ad hoc networks, omni-directional antennas have been popularly used for wireless communication using single channel. In recent years, the necessity of directional antennas is raised in order to cope with the issues of limited channel bandwidth, lower throughput, and limited energy supply. The constraint of limited channel bandwidth can be exploited by using multiple, non-overlapping channels. In single channel networks, the network performance decreases with the increase in the number of nodes. The use of multiple channels maintains network performance even with the increase in the number of nodes.

In ad hoc networks using directional antennas, MAC protocols should be designed (i) to increase the spatial reuse and transmission range by having nodes concentrate the transmitted energy only towards their destination's direction, resulting in higher signal to noise ratio (SNR), (ii) to achieve higher gain, (iii) to lower power consumption, and (iv) to reduce interference [4, 10, 23, 25]. Though, the use of directional antennas over omni-directional antennas in MAC protocols for ad hoc networks is gaining popularity, we cannot overlook some issues like hidden terminal problems, deafness and neighbor discovery that are introduced by the use of directional antennas.

In this thesis, after a thoughtful study of various existing MAC protocols with directional antennas in ad hoc networks, we introduce a novel high-performance MAC protocol for ad hoc networks with directional antennas, which operates using multiple interfaces, multiple-channels and multiple directional antennas on a node. The use of multiple interfaces enhances the network capacity by allowing simultaneous transmissions and receptions at the same time. Thus, a full duplex communication mode can be realized [33]. We use multiple non-overlapping channels. Since there is no interference due to simultaneous transmissions in one or more non-overlapping channels, multiple channels can be utilized at the same time, increasing the network capacity. The directional antennas in our protocol are implemented in static approach [34]. Each interface is attached to one channel and one directional antenna. The proposed MCMDA makes the use of vertically opposite CTS (VCTS) in addition to the directional RTS (DRTS) and directional CTS (DCTS). The use of VCTS control packets helps in minimizing the effects of hidden terminals and deafness and, thus, leads to the enhancement of the network performance.

The performance results show that the use of multiple directional antennas works better when the network topology is non-linear. MCMDA has achieved fairly higher throughput in comparison to the existing IEEE 802.11 DCF [37] and DMAC [1] protocols. We also found that the delay in MCMDA is very low compared to the other two protocols. Through simulation study we found that the control overhead incurred in MCMDA is larger than IEEE 802.11 DCF and DMAC. The use of multiple channels and an additional control packet, VCTS, has increased the control overhead in MCMDA. This overhead is justifiable because a multi-channel node acts as multiple nodes and the significant performance improvement is guaranteed.

II. Background Concepts

In this section, we present a literature review of the fundamental concepts in the field of research. We believe that a comprehensive knowledge of the literature of the field of research has a profound impact in building the understandability.

A. Wireless Ad Hoc Networks

Ad hoc literally means "for a specific purpose". A wireless ad hoc network is a decentralized wireless network which is often created temporarily to perform a specified function [2]. The wireless nodes in ad hoc networks organize themselves without the help of any infrastructured network. Ad hoc networks are gaining much popularity because they are easy to configure and deploy in remote geographical areas where constructing a wired network is difficult and costly. An Ad hoc network can be easily integrated with other wireless infrastructure network, resulting in a large application area. Thus, wireless ad hoc networks are more practical in the fields of emergency services, vehicular communications, traffic monitoring, military applications, etc [6]. Wireless ad hoc networks can be classified as:

1. Mobile Ad hoc Networks (MANETs)

MANET is an easily deployed and self configurable network which does not require any pre-existing infrastructure. The nodes in MANETs are mobile which causes the topology to change from time to time [2]. Since the nodes are mobile, they may fall out of the communication range of other nodes. In this case, wireless nodes act as routers by forwarding the traffic which is not related to them. Vehicular ad hoc network is a special type of MANETs.

2. Wireless Mesh Networks (WMNs)

The nodes in WMNs establish an ad hoc network and maintain mesh connectivity. A WMN consists of mesh routers, mesh clients and gateways. The WMNs can be classified as Infrastructure/Backbone WMNs, Client WMNs, and Hybrid WMNs. In Infrastructure/Backbone WMNs, the mesh-routers form a mesh of self-configuring, self-healing links among themselves which act as an infrastructure for the clients [26]. In Client WMNs, the configuration and the routing are performed by the network formed by the client nodes. Hybrid WMNs is the combination of Infrastructure/Backbone WMNs and Client WMNs. The mesh clients can mesh with other mesh clients or use mesh routers to access the network [26].

3. Wireless Sensor Networks (WSNs)

The concept of Wireless Sensor Networks came into existence by the necessity of battlefield surveillance in military applications. Since then, WSNs are being used in various areas like industrial process monitoring and control, machine health monitoring, environment and habitat monitoring, healthcare applications, home automation, and traffic control [28]. A typical node in WSN comprises of a radio transceiver, a small micro-controller and a battery. The sensed data are sent via radio transmitter either directly or through a data concentration center to the base station (BS).

B. MAC Protocols in Wireless Ad hoc Networks

The communication between the nodes are controlled and managed by MAC layer by providing access to the shared channel. MAC layer is dedicated to resolve the anomalies occurring in the physical layer by performing error corrections [29, 30]. MAC protocols are the functions and procedures used by the MAC layer to ensure reliable, efficient and fair sharing of wireless resources. MAC protocols must be designed with the view to address the issues like: distributed operation of the protocol, efficient bandwidth utilization, synchronization of the nodes, minimization of access delay, minimization of control overhead, minimization of power consumption, minimization of hidden and exposed terminal problems etc. Various MAC protocols for wireless ad hoc networks have been proposed in order to better utilize the limited bandwidth and address the above mentioned issues [29]. Figure 2.1 presents the classification of MAC protocols for ad hoc networks.

In the contention based protocols without reservation or scheduling (ex. MACA, MACAW etc), the reservation of bandwidth is not made. Where as in contention based protocols with reservation mechanism (ex. MACA/PR, D-PRMA etc), the bandwidth is reserved beforehand.

Distributed scheduling between the nodes is done in case of contention based protocols with scheduling mechanism (ex. DPS, DLPS etc). Use of directional antennas in MAC protocols (ex. DMAC) helps in reducing signal interference, increase system throughput and enhance the channel reuse.

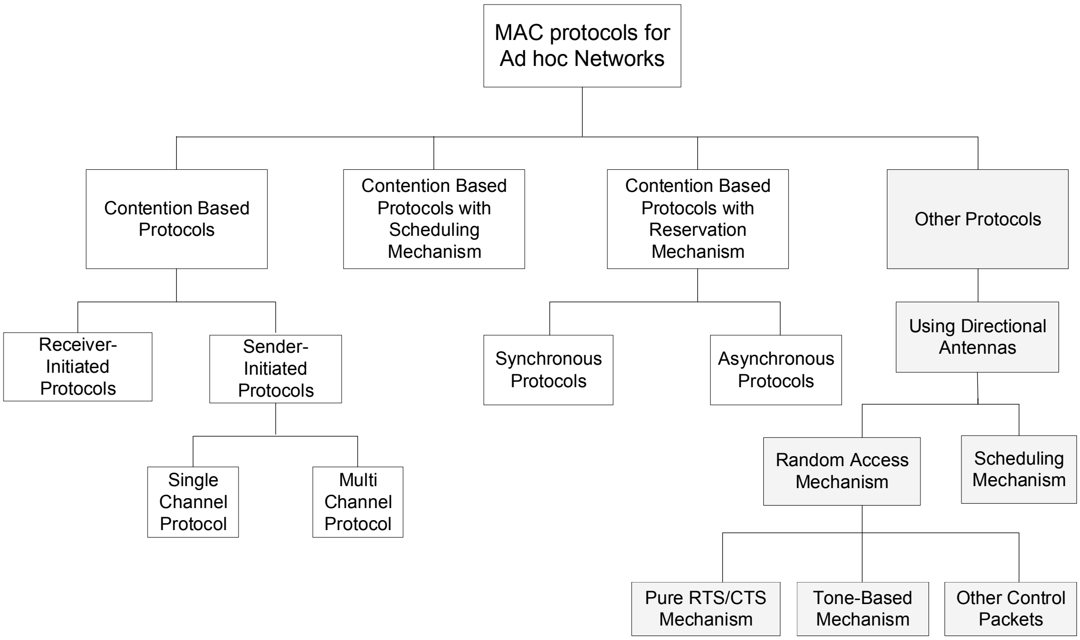

Figure 2.1: Classification of MAC protocols in ad hoc networks.

C. Antennas

The mobile nodes in ad hoc networks are generally equipped with omni-directional antennas. However, the usage of directional antennas helps in improving the network capacity. In this section, we present brief descriptions about the antenna types in regard to different types of antennas used in MAC protocols for ad hoc networks in recent years.

1. Omni-directional Antennas

The omni-directional antenna system is a single element system, where the radiation and the reception powers are equal in all directions. The radiation pattern in omni-directional antenna system resembles the ripples dispersing outward when a pool of water is hit by a stone. There is enough scattering of signals in comparison to the amount of signal received by the intended receiver [31]. This contradicts the minimum energy utilization of the mobile nodes. This inefficiency limits the use of omni-directional antennas to a larger extent.

2. Directional Antennas

The directional antenna system radiates or receives in defined directions which help to increase the performance by increasing the power in particular direction and minimizing the interference from other sources [20, 31]. Increase in power at a particular direction helps in achieving larger ranges. With the passage of time, and with the requirement of various communication advancements, directional antenna has evolved to become more intelligent. In fact, more appropriately, directional antenna system has evolved as an intelligent antenna system over a decade’s time. Following are the various types of antenna system.

(a) Sectorized Systems

The sectorized antenna system makes use of the combination of directional antennas. It follows the similar notion of cellular area. It just makes slight modification by dividing the area into sectors which are then covered using directional antennas in the same base station. In doing so each sector acts as an independent cell, whose coverage range becomes larger in comparison to using omni-directional antennas [31].

(b) Diversity Systems

The diversity antenna system incorporates two or more antenna element at the base station. This system uses two methods namely, switched diversity and diversity combining, to improve the effective strength of the received signal [31].

In the switched diversity, only one antenna is used at a time. But the system continuously switches between the antennas so that it can use the element with largest output.

In the diversity combining, the phase error in two multipath signals is corrected and both the signal powers are combined to produce gain.

(c) Smart Antenna Systems

We have been hearing about smart antennas in recent years. However, antennas aren't quite smart, it is rather the antenna systems that are smart [31]. A smart antenna system is actually an antenna array with a digital signal-processing capability to transmit and receive in an adaptive, spatially sensitive manner. Smart antenna system provides increased range, better spatial reuse, multipath rejection, low interference along with enhanced capacity [25, 31]. Smart antennas are categorized as switched beam systems and adaptive array systems.

Switched beam system consists of predefined fixed beams which are highly sensitive to a particular direction or sector. This system is smart in the sense that it is able to detect signal strength, and select from one of several predetermined, fixed beams, and switch from one beam to another as the node moves throughout the sector. Though this system provides higher spatial reuse, but the performance is limited because of the fixed beam pattern [25, 31].

Adaptive array system is considered as the most advanced smart antenna system. The use of efficient signal processing algorithms enables adaptive array systems to differentiate between desired signals, multipath and interferences. It uses Direction of Arrival (DoA) algorithm for signal transmission/reception and continuous tracking. In comparison to switched beam system, adaptive array system provides interference suppression and low hardware redundancy [25, 31]. Thus, it can achieve greater performance improvements than switched beam systems.

D. MAC Issues with Directional Antennas

There is no doubt that the network throughput can be improved by the use of directional antennas in ad hoc networks. Use of directional antennas also provides wider coverage range and reduced power consumption. However, there is nothing as ideal. There are some access problems that come into existence with the use of directional antennas. In this section, we present some of the MAC issues that are associated with the use of directional antennas.

1. Hidden Terminal Problem

The directional transmission of RTS/CTS in ad hoc networks with directional antennas may lead to hidden terminal problems of the following kinds.

(a) Hidden Terminal due to Asymmetry in Gain

If any one or both of the two nodes are in omni-directional mode and out of range then, when they both beam-form towards each other they may fall within range which might cause collision [20]. A more clear explanation to this problem can be presented with the help of figure 2.2. In figure 2.2 two nodes X and Y are communicating directionally with gain G^d towards each other. Z listening omni-directionally with gain G^o is unaware of this communication. Upon receiving a packet to deliver to X (nearer to Z) it changes to directional mode and does carrier sensing towards X with gain G^d and finds the channel to be idle. Now, as both Z and Y are beam-formed towards X with gain G^d, there are high chances for the data sent by Z to interfere the ongoing communication between X and Y [3, 20].

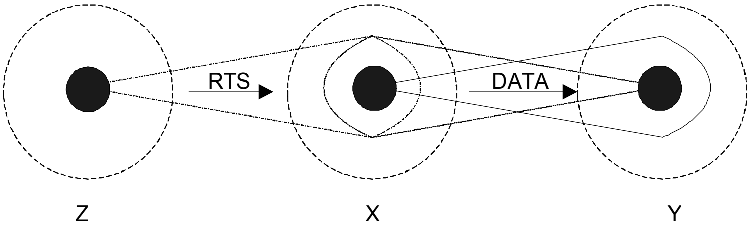

Figure 2.2: Hidden terminal due to asymmetry in gain.

(b) Hidden Terminal due to Unheard RTS/CTS

This problem arises when P is communicating with Q directionally as shown in figure 2.3. R and S are other two nodes in the vicinity of P.

While P is beam-formed towards Q, R gets a packet destined to S. Now the RTS/CTS handshake between R and S is unheard by P. Later, on finishing the communication with Q, P that is unaware of the ongoing communication between R and S, gets data packet destined to R. Thus node P's transmission may cause collision in the ongoing communication between R and S [3].

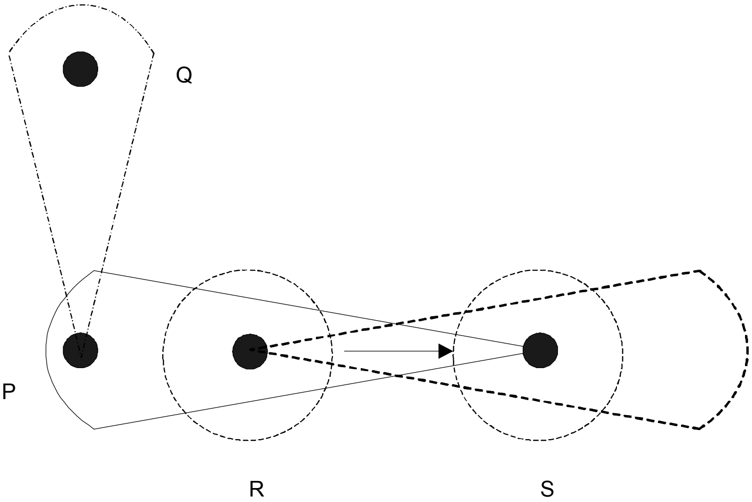

Figure 2.3: Hidden terminal due to unheard RTS/CTS.

2. Deafness

This problem arises when the intended receiver node is unable to receive packet due to the antenna gain pattern [1, 3, 7, 13]. Let us consider P, Q, R and S nodes in figure 2.4. A packet arrives at P destined for S. P communicates with S through R. R then beam-forms in the direction of S. As the communication between R and S is going on, Q or P may have packets for R. But, as R is in directional communication with S, Q or P cannot establish the communication. They assume congestion to be the cause of failure and back-off longer before attempting again. Now, after multiple failure and back-off, the back-off duration increases. This causes the nodes P or Q to wait until the back-off expires before next attempt to retransmit even after S finishes its communication.

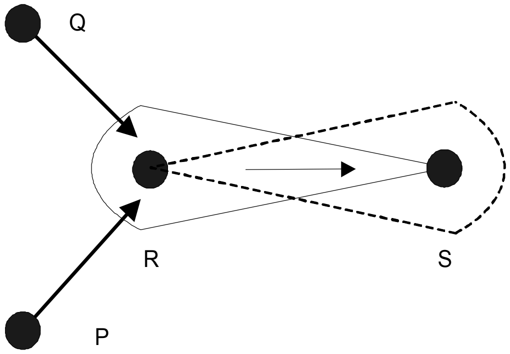

Figure 2.4: A scenario of deafness.

3. HoL Blocking Problem

MAC layer makes use of FIFO queues in order to manage the packets to be sent through the shared medium. This scheme introduces Head of Line (HoL) blocking problem for the protocols using directional antennas. If a packet in top of the queue is blocked because the medium is not free in that direction, then other packets which are in the queue with some other direction are also blocked [22, 32]. For example, we can see in figure 2.5 that node P has packets for Q, R and S. S and T are in communication with each other. So, when a packet for S is at the top of the queue, P has to wait until the medium is free. This causes unnecessary waiting for Q and R [32].

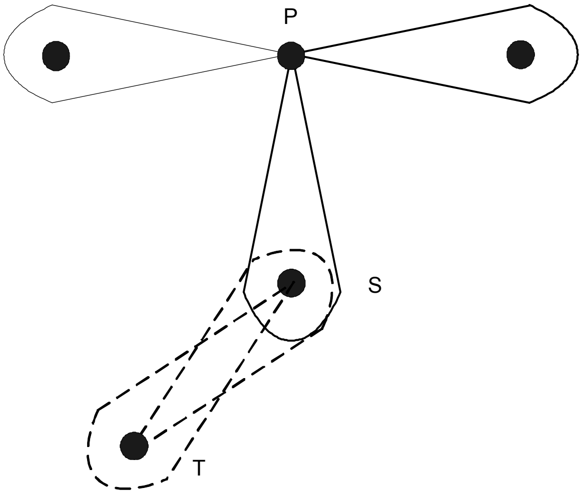

Figure 2.5: A Scenario of HoL blocking problem.

4. Neighbor Location and Neighbor Discovery

The information about the location of neighbor is vital in case of directional antenna to enhance the link quality. This information helps the transmitting nodes to beam-form in the direction of the receiver so that the gain is maximized [25, 27]. Exact location information reduces the effect of interference from other nodes to a large extent.

Devices, such as GPS, are used in nodes to determine the location of the neighbors. GPS is costly and doesn't work in indoor environment. These limitation refrain GPS from easy usability.

Various schemes have been proposed to solve the issue of neighbor discovery. Actually neighbor discovery must be supported with the direction of arrival information also. So, for simplicity, many existing protocols assume that the positions of neighbors are known ahead.

III. Related Works

A. Conventional Protocols

In [1], Ko et al., presented Directional MAC protocol (D-MAC) which introduces the mechanism of directional and omni-dal transmission of control, DATA and ACK packets depending upon the situation. Two schemes have been proposed in DMAC. According to scheme 1, RTS, DATA and ACK packets are sent directionally, whereas CTS packets are sent omni-directionally. Thus, the node overhearing CTS only blocks the antenna over which CTS was heard. Scheme 2 applies both Directional RTS (DRTS) and Omni directional RTS (ORTS). ORTS are sent if none of the directional antenna of the node are blocked, else the node will send DRTS. Combined use of DRTS and ORTS reduces the chances of collision.

The exact location of the neighboring node is not known priori the start of data transfer as the nodes are viable to be in the state of motion in ad hoc networks. Nasipuri et al. [2] proposed a MAC protocol that is able to find the neighbor location. The exchange of RTS/CTS packets is done omni-directionally. The receiver of RTS notes the antenna that received the maximum power of RTS packet. The transmitter of RTS also estimates the direction of CTS transmitter and thus the RTS-CTS handshake is performed and the directional link is established. Now, the DATA and ACK are transmitted directionally. The other nodes overhearing the RTS/CTS will defer their transmission to the communicating nodes. Thus this successfully reduces the interference.

Choudhury et al. in [3] proposed two MAC protocols namely Basic DMAC protocol and Multi-hop RTS MAC protocol. The Basic DMAC protocol attempts to exploit the spatial reuse property of directionality. However, the problems like hidden terminal, anomaly in shape of silenced region and deafness persists in basic DMAC protocol.

Multi-hop RTS MAC protocol (MMAC) [3] attempts to exploit the benefit of higher transmission range of directional antennas. The MAC layer is able to decide upon the DO-neighbor route to DD-neighbor by the information from upper layer. The intended transmitter reserves the channel to its intended receiver by making use of the DO-neighbor route to its DD-neighbor. Thus, reserving the channel helps other nodes to defer their transmission. This protocol also makes use of high priority forwarding RTS packet, on receiving this packet the DNAV tables are not updated. The transmission of multi-hop RTS packets is probable to suffer from failure of transmission; this may lead to delay in packets delivery because of retransmissions.

Huang et al. in [4] proposed DBTMA/DA protocol as a modification to DBTMA protocol. This protocol enhances the channel capacity by the directional transmission of RTS/CTS frame, data frame and dual busy tones. This protocol uses busy tones BTr/BTt (receive busy tone/transmit busy tone). A node transmitting or receiving data sends BTr/BTt directionally, which can be heard by all the nodes within the transmission range.

Choudhury et al. in [5] proposed ToneDMAC to address the problem of deafness caused by the use of directional communication. In this protocol, the two nodes performs directional communication starting with the exchange of DRTS and DCTS. Other neighboring nodes, attempting to communicate with these nodes, face failure. Assuming congestion to be the cause of failure, the neighboring nodes increases the backoff timer after each failure. The two nodes upon completing the communication send omni-directional out-of-band tone which informs the neighbors that the cause of failure was deafness of the communicating nodes and not congestion. The neighboring nodes cancel its remaining back-off and opt for smaller, random value and attempt retransmission. A node can deduce the transmitter of the tone by its unique identifier and hash function. ToneDMAC helps in better channel utilization, with decreased dropping of packets and transmission failure.

Korakis et al in [6] proposed CRM which is capable of full exploitation of directional antenna. In this protocol RTS is transmitted directionally, consecutively over all antenna beams. This mechanism benefits because no prior knowledge of receiver location is required. This protocol makes the use of the location table which maintains information about node itself, its neighbor, the beam index on which the node heard the packet and the beam index on which the neighbor sent the packet. This record helps in keeping track of the neighbor.

This protocol however, doesn't have CTS communication directionally, which lowers the spatial reuse, thus cannot fully exploit directional antenna.

Ueda et al. in [7] proposed EMAC which is receiver-oriented and rotational sector based directional MAC. It maintains the neighborhood directional information in AST (Angle Signal Table). In this protocol control packets are transmitted with a preceding tone. This enables the receiver to track the best possible direction of receiving the signal and thus, reception of control packets are done in that direction. The transmission and reception of DATA and ACK are done directionally.

In [8], Takata et al. proposed SWAMP for the higher spatial reuse and greater transmission range. There are two access modes namely, OC-mode (omni-directional area communication access mode) and EC-mode (Extended area communication access mode). When the transmitter has no knowledge about the receiver node OC-mode is used. In this mode neighbor of the receiver/transmitter gets the directional information of the nodes that lies within an area that is double the communication range. This information is termed as NHDI (Next Hop Directional Information). EC-mode is used when the transmitter has the knowledge of the receiver through NHDI table.

Jakllari et al in [9] presented a modified CRM protocol called CRCM which attempts to fully exploit the use of directional antenna. The objective of this protocol is to solve the issues of hidden terminal, deafness and neighbor's discovery. The basic operation of this protocol is similar to CRM; however this protocol introduces the use of directional transmission of CTS packets. The receiver of DRTS sends DCTS to the transmitter, in addition to this the receiver also sends DCTS to other neighbors that are in the coverage range of receiver and not the transmitter. These neighboring nodes were unable to hear the DRTS and, thus, could interfere with the ongoing transmission.

However, the transmission of multiple packets for single data packet has chances of degrading the MAC performance.

In [10] Gossain et al. presented a novel scheme to solve the issues of deafness and hidden terminals. MDA maintains a Directional Neighbor Table (DNT) which is established during route discovery phase. Though CRM and CRCM considerably lower the region of deafness they cannot overcome this issue completely. MDA performs (Diametrically opposite Directional) DoD transmission of RTS and CTS on those sector where neighbors are found. MDA uses Enhanced DNAV (EDNAV) scheme. EDNAV comprises of DNAV and DT (Deafness Table). Both DNAV and DT are involved for information while sending a packet, where as one of them is updated upon receiving a packet. The use of EDNAV helps in clearly identifying the scenario of deafness and collision.

Pan et al in [11] proposed a two-channel MAC protocol which uses directional antenna that can operate in omni and directional modes depending upon the situation. When a node is transmitting data frames then it is done in directional mode. Omni mode is used for receiving signals and frames other than data frames.

This protocol also makes use of two channels namely, control channel for transmission of RTS/CTS, ACK frames and data channel for transmission of DATA frames.

In [12], Kulkarni et al. proposed DBSMA protocol which is able to meet most of the requirements of MAC protocol using directional antennas. The transmission and reception of all control frames, data and idle listening are done directionally. In idle state, a node rotates so that the hearing direction of its antenna can listen in all direction. There is no use of any other control packet except RTS and CTS, thus reducing overhead. A busy tone is transmitted after successful reception of RTS, till the DATA and ACK transmission is completed.

IS (Invitation Signal), a narrow-band signal similar to busy tone, is used to determine the direction for the reception of RTS message.

Li et al in [13] proposed Directional MAC with Deafness Avoidance and Collision Avoidance. This protocol uses switched beam antenna system and is able to beam-form in any antenna beam for transmission and reception. This protocol performs omni-directional back-off, and senses the channel busy if there is signal in its intended direction of transmission. This protocol also performs the sweeping of RTS/CTS in all direction so that all DO neighbors are informed of the transmission/reception that is to take place. It makes use of Deaf Neighbor Table (DNT) and the time after which the deaf neighbor will be available. The nodes receiving sweeping RTS/CTS, update its DNAV on direction and distance of node to transmitter and receiver, thus avoiding collision.

Wang et al. [14] proposed a synchronized MAC protocol to address the issues of using MAC protocols with directional in ad hoc networks. The timing structure of SYN-MAC consists of three phases: random access phase (Phase I), DATA phase (Phase II) and ACK phase (PHASE III). Channel contention and route discovery are performed in Phase I, parallel collision-free data transmission takes place in Phase II, parallel contention free ACK transmission takes place in Phase III. Nodes in Phase I can be in any of the three modes: sending, receiving or pending.

Receiver Initiated DMAC [15] proposed by Takata et al., mainly focuses on solving the deafness issue with directional antenna. This protocol has both sender-initiated and receiver-initiated operations. Sender initiated operation is default whereas receiver initiated operation is triggered only when a transmitter encounters deafness [15, 32]. This protocol makes the use of polling table to poll the potential deafness node using RTR (Ready To Receive) frame after each complete dialog. After receiving RTR, the potential deaf node infers that the intended receiver is idle. The least recently transmitted node is selected from the polling table of deaf node to improve fairness.

Directional MAC/Deafness Avoidance protocol is proposed by Takata et al. [16] to solve the issue of deafness. It introduces the WTS (Wait to Send) frames. This protocol maintains a neighbor table with the potential transmitters. When two nodes are to communicate, the sender verifies, by physical carrier sensing, the number of beams in which potential transmitters exist. It also checks its DNAV table and neighbor table to find out the potential transmitters and their DNAV setting. The number of potential transmitters is included in RTS and sent to the intended receiver directionally [9, 32]. The receiver also finds out number of intended transmitters and includes this value in CTS. After RTS/CTS handshaking, both the sender and receiver transfer WTS frames to the intended transmitters. Upon receiving the WTS frames, the intended transmitters defer their own transmission and recognize the nodes as busy.

Liu et al. in [17] proposed an ESPRIT protocol which uses two channels and operates on two modes, omni and directional. All packets are transmitted in omni mode in channel one, and in directional mode in channel two. The protocol makes use of two NAV tables, ONAV and DNAV. ONAV gives the information about the blocking of channel one and DNAV informs the period during which channel two cannot be used. The whole process of communication is simplified into four steps as: RTS transmission, RTS reception and CTS transmission, CTS reception and DATA transmission and DATA reception and ACK transmission.

Munari et al, [18] proposed cooperative MAC protocol which attempts to exploit the benefits of using directional antenna and improves the overall network performance. Each node maintains a Communication Register (CR) which contains the record of all the communications that are taking place. RTS/CTS frame in CMAC are sent in circular fashion as in CRM. The combined use of circular handshaking and multiple receptions helps in reducing the impact of deafness. Cooperation among nodes is achieved by informing the nodes that intend to switch to idle mode, about the communication that has started concurrently.

In [19], Jain et al. presented a Hybrid MAC (HMAC) protocol which makes use of information obtained from physical layer and network layer for its operation. It uses of SCH frame which is transmitted to the node that falls away from the communication range of sender while transmitting RTS/CTS. HMAC uses same packet format for control messages and IFS so it is said to be compatible with IEEE 802.11. HMAC is efficient in mitigating the deafness problem to larger extent.

LCAP [20], proposed by Arora et al. exploits the use of directional antenna further by power control mechanism. LCAP introduces a novel idea of concurrent transmission in the same neighborhood. If the SINR at receiver is higher than some threshold value $SINR_{th}$, then the transmission can take place even if the direction is already reserved.

It uses two different channels for data and control packets. However, these channels are not used simultaneously. This protocol also minimizes the interferences that may occur due to the use of directional antenna.

Ra-MAC [21] is a range-adaptive MAC protocol for ad hoc networks proposed by Chen et al. It makes use of smart antennas and adjusts the transmission ranges according to the distance between the communicating node pairs. This protocol has proposed the concept of LD (Low-Distance), MD (Medium-Distance) and HD (High-Distance) patterns of adaptive transmission ranges. The dual access mode as described in Ra-MAC performs LD-communication when receiver is 1-hop neighbor of the transmitter. HD pattern is used to perform MD-communication by sending HD-RTS. This protocol makes use of additional control packet Start of Dialog (SOD), which attempts to minimize hidden terminal problem and deafness. R-DNAV used in this protocol is an extension of DNAV with distance information.

Li et al. in [22] proposed the SDMAC protocol which addresses the issues of deafness, new hidden terminal by making use of two types of DRTS and DCTS. Type I DRTS/DCTS initiates the communication between the sender and receiver. These control packets contain additional fields as “Outgoing Beam” which gives the beam number used in current communication and “Beam Status” which gives the traffic status in all beam directions. Type II DRTS/DCTS is used to inform the neighbors of sender and the receiver about the data transmission that will take place. Each node maintains a deafness table and records its deaf neighbors and their duration of deafness. SDMAC also addresses the problem of deafness due to mobility.

Two improvements over SDMAC that are also proposed are Queue-SDMAC (Q-SDMAC) and Q-SDMAC with cache. Q-SDMAC schedules the packet in a queue thus helps to overcome Head-of-Line (HoL) blocking problem. Q-SDMAC with cache just caches the neighbor node ID and the incoming direction of packets from the node.

B. Comparison

In table 3.1(a, b and c), we have analyzed the protocols in terms of the mode of physical carrier sensing and the mode of communication during the transfer and receive of control packets, DATA and ACK. This table also gives information about the use of additional packets.

In table 3.2, we have compared the MAC protocols in parameters like antenna model, gain, spatial reuse, range extension, use of DNAV and SINR/SNR. Higher spatial reuse can be obtained when there is higher directional communication, which in turn increases the range of extension.

Higher directional communication also helps in avoiding interference, thus increasing SINR.

In table 3.3, we have summarized the impact of the different issues on the surveyed MAC protocols with directional antenna.

Table 3.1 (a): Comparison based on the transmission and reception modes of various packets (O: omni-directional, D: directional).

		DMAC Scheme 1	**DMAC Scheme 2**	**Nasipuri et. al**	**MMAC**	**DBTMA/DA**	**Tone DMAC**	**CRM**	**EMAC**
Physical Carrier Sensing		D	D	O	D	-	D/O	O	O
RTS	**TX**	D	O/D	O	D	D	D	Rot.D	O
	RX	O	O	O	O	O	O	O	Cir.D
CTS	**TX**	O	O	O	D	D	D	D	O
	RX	O	O	O	D	O	O	O	Cir.D
DATA	**TX**	D	D	D	D	D	D	D	D
	RX	O	O	D	D	D	O	D	D
ACK	**TX**	D	D	-	D	-	D	D	D
	RX	O	O	-	D	-	O	D	D
Others		-	-	-	-	Dual busy tone	(OoB) Tone	-	-

Table 3.1 (b): Comparison based on the transmission and reception modes of various packets (O: omni-directional, D: directional).

		SWAMP OC/EC	**CRCM**	**MDA**	**Two Channel MAC**	**DBSMA**	**DMAC-DACA**	**SYN-MAC**	**RI-DMAC**
Physical Carrier Sensing		-/-	-	-	-	D	-	-	O
RTS	**TX**	O/D	Rot.D	D	O	D	Sweep D	D	D
	RX	O/O	O	O	O	D	O	O	D
CTS	**TX**	O/D	D	D	O	D	Sweep D	D	D
	RX	O/O	O	O	O	D	O	O	D
DATA	**TX**	D/D	D	D	D	D	D	D	D
	RX	-/D	D	D	O	D	-	D	D
ACK	**TX**	D/D	D	D	-	D	D	D	D
	RX	-/D	D	D	-	D	-	D	D
Others		SOF	DCTS for unaware nodes	DOD-RTS/CTS	RFA	Busy Tone	-	CRTS	RTR

Table 3.1 (c): Comparison based on the transmission and reception modes of various packets (O: omni-directional, D: directional).

		DMAC/DA	ESPRIT Channel 1/2	CMAC	HMAC	LCAP	Ra-MAC	SD-MAC
Physical Carrier Sensing		O	-/-	-	D	-	-	-
RTS	**TX**	D	O/-	Rot.D	D	O	O	O
	RX	O	O/-	O	O	O	O/LD/HD	D
CTS	**TX**	D	O/D	Rot.D	D	D	D	D
	RX	D	O/-	O	O	D	D	D
DATA	**TX**	D	-/D	D	D	D	D	D
	RX	D	-/D	D	D	D	D	D
ACK	**TX**	D	-/D	D	D	D	D	D
	RX	D	-/D	D	D	D	D	D
Others		WTS	-	-	SCH	-	SOD	TypeI/II-DRTS/DDCTS

Table 3.2: Comparison with respect to various system parameters.

	Antenna Model	Gain	Spatial reuse	Range Extension	DNAV	SINR/ SNR	Overhead
DMAC	Switched beam	$G^o=G^d$	Low	Low	No	Low	Low
Nasipuri et.al	Switched beam	$G^o=G^d$	Very Low	Very Low	No	Low	Low
MMAC	Steered beam	$G^o<G^d$	High	High	Yes	High	Medium
DBTMA/DA	Switched beam	$G^o<G^d$	Medium	Medium	No	Medium	Low
Tone DMAC	Switched beam	$G^o<G^d$	Medium	Medium	No	Medium	Medium
CRM	Switched beam	$G^o<G^d$	Medium	Medium	Yes	High	High
EMAC	Switched beam	$G^o<G^d$	Medium	Medium	Yes	Medium	Medium
SWAMP	Switched beam	$G^o<G^d$	High	High	No	Medium	Medium
CRCM	Switched beam	$G^o<G^d$	Medium	Medium	Yes	High	Very High
MDA	Switched beam	$G^o<G^d$	Medium	Medium	EDNAV	Very High	Medium
Two Channel MAC	Switched beam	$G^o<G^d$	Very Low	Very Low	No	-	Low
DBSMA	Switched beam	$G^o<G^d$	High	High	Yes	High	Very Low
DMAC-DACA	Switched beam	$G^o<G^d$	Medium	Medium	Yes	Low	Low
SYN-MAC	Switched beam	$G^o<G^d$	Medium	Medium	No	High	Low
RI-DMAC	Switched beam	$G^o<G^d$	High	High	Yes	Very High	Low
DMAC/DA	Switched beam	$G^o<G^d$	High	High	Yes	Very High	Low

ESPRIT	Switched beam	$G^o<G^d$	Medium	Medium	Yes	Medium	Medium
CMAC	Switched beam	$G^o<G^d$	Medium	Medium	No	High	Medium
HMAC	Switched beam	$G^o<G^d$	Medium	Medium	HNAV	High	Medium
LCAP	Switched beam	$G^o<G^d$	Very High	High	Yes	High	Low
Ra-MAC	Switched beam	$G^o<G^d$	High	Very high	RDNAV	High	Very Low
SDMAC	Switched beam	$G^o<G^d$	High	High	Yes	High	Medium

Table 3.3: Impact of different issues on MAC protocol design.

	Impact of Issues		**Neighbor Disc./Info**
	Hidden Terminal	**Deafness**	
DMAC	High	High	Low
Nasipuri et.al	High	High	Low
MMAC	Medium	Medium	Medium
DBTMA/DA	Low	Medium	Low
Tone DMAC	Medium	Low	Low
CRM	Low	Medium	Medium
EMAC	Low	Medium	High
SWAMP	Low	Medium	High
CRCM	Low	Low	High
MDA	Low	Low	High
Two Channel MAC	Low	Medium	Medium
DBSMA	Very Low	Low	High
DMAC-DACA	Medium	Low	Medium
SYN-MAC	Low	Low	Medium
RI-DMAC	Medium	Very Low	High
DMAC/DA	Medium	Very Low	High
ESPRIT	Medium	Medium	High
CMAC	Low	Very Low	Low
HMAC	Medium	Medium	Medium
LCAP	Low	Low	High
Ra-MAC	Low	Low	High
SDMAC	Very Low	Low	Very High

IV. System Model

A. Network Model

We have assumed the ad hoc network setup which implies a wireless, infrastructureless network. When a new node enters the network, the network can self configure to connect the nodes spontaneously. The nodes in ad hoc networks are battery powered and, once deployed the recharging of these nodes becomes impossible. So, the prime objective of ad hoc networks is that the nodes remain active for longer period of time by consuming lower power for the network to be functioning properly [1,2]. Factors such as interference and short transmission range lead to packet loss and retransmissions, which increase power consumption. Many protocols have been proposed, which make the use of directional antenna to mitigate the problem of power consumption by increasing the transmission range [1-22]. We have reviewed some of these protocols in section III. But the issues of hidden terminals, deafness and neighbor discovery still persist as mentioned in section II.

We assume multi-interface, multi-channel network model where each node is equipped with multiple directional antennas. Each interface in a node is associated with a channel and a directional antenna. The simultaneous communication of a node with more than one node can be possible by the use of multiple channels with directional antennas. The use of multiple interfaces at each node provides concurrent transmissions and receptions It enables full-duplex communication mode. Therefore, the use of directional antennas and multiple channels increases the capacity of wireless networks.

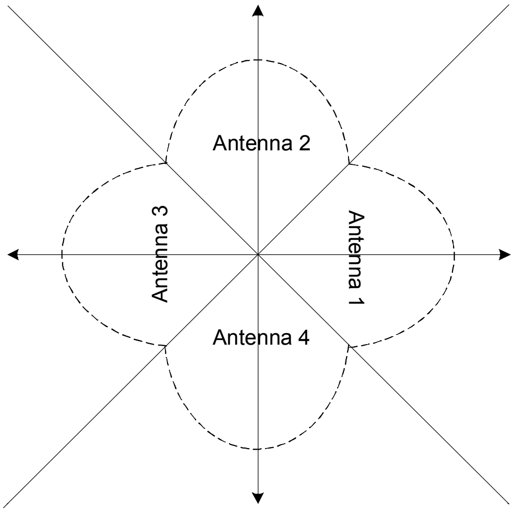

Figure 4.1: Antenna model taken into account.

B. Antenna Model

We use multiple antennas at each node. Each node has multiple interfaces and each interface is attached to a directional antenna. Each directional antenna is used by a specific channel. The directional antennas attached to the node radiate conically and the combination of these antennas covers the entire plane of 2л radians. We assume that the gain of the side lobes is negligent in comparison to the gain in the main lobe. The proposed MAC protocol can switch the antennas as either active or passive. Each antenna can operate on omni-directional and directional mode.

Figure 4.1 depicts the antennas arrangement. The start of first directional antenna is at 0 degrees of horizontal-axis of the Cartesian coordinates systems. It is assumed that these antennas are fixed and radiates in the defined angle and direction even when the nodes are in motion. In figure 4.1 we assume the node is equipped with four antennas where each directional antenna can transmit over an angle of 90 degrees. The behavior of multiple directional antennas benefits in providing sharply focused beams to the sender or the receiver. This, in turn, reduces the signal-to-interference-plus-noise ratio (SINR) and creates an environment for multi-user communication. G^d is the gain in directional mode which is greater than G^0, the gain in omni-directional mode. The gain of antenna at a particular direction is given by

$$G(\vec{d}) = \eta \frac{U(\vec{d})}{U_{avg}} \qquad (1)$$

where, U_{avg} is the power density in all directions, $U(\vec{d})$ is the power density in direction $\vec{d}$ and η is the efficiency of antenna. Efficiency is always less than 1, because of the energy losses. The gain $G(\vec{d})$ provides directional gain compared to the omni-directional gain.

We have used the directional antenna model based on [35], in which multiple channel and multiple directional antennas are used in order to enhance bandwidth utilization. The use of directional antenna in multi-channel environment helps to reduce the issues of hidden terminal and deafness, aims to acquire higher spatial reuse and range extension and, thus, achieve increased network throughput and lower the latency.

In addition to DRTS and DCTS, Vertically opposite CTS (VCTS) is defined as a new control frame. VCTS is sent on the antenna that is vertically opposite to the antenna over which DCTS is sent. from [10], the estimation of antenna over which VCTS is transmitted is given by

$$A_{VCTS} = \begin{cases} A_{DCTS} + \dfrac{N}{2} & if \quad A_{DCTS} \le \dfrac{N}{2} \\ A_{DCTS} - \dfrac{N}{2} & if \quad A_{DCTS} \ge \dfrac{N}{2} \end{cases} \qquad (2)$$

where, N is the number of antennas used. A_{VCTS} is antenna number over which VCTS is sent [8]. A_{DCTS} is the antenna number over which DCTS is sent. For example, if four antennas are equipped in each node ($N=4$), and DCTS is transmitted over antenna 3 ($A_{DCTS}=3$), VCTS is transmitted over antenna 1 ($A_{VCTS}=1$) according to equation 2.

It is assumed that four directional antennas are used as presented in figure 4.1. In case of the number of directional antennas is increased, in addition to sending VCTS on vertically opposite antenna, it is also sent on the antennas adjacent to vertically opposite antenna. So far, we have not experimented with the case of using more than four antennas per node. Note that the use of multiple antennas in itself is very costly. In addition, as the number of antennas is further increased, the number of channels should also be increased, which will make the problems of co-channel interference more severe.

V. The Proposed Protocol

A. Overall Operation

As mentioned earlier, the proposed MCMDA protocol is based on directional transmissions and receptions. Only the mode of reception of the RTS is omni-directional. MCMDA works on the principle of using multiple directional antennas at each node. The multiple directional antennas help in increasing the coverage range and achieving higher directional gain. We have also used multiple interfaces and multiple channels at each node which helps in concurrent receptions and transmissions. Each channel has an antenna at its disposal. Each received signal is analyzed in terms of the power of reception. The channel and the antenna associated with the maximum receiving power are then reserved for the complete communication process. The use of multiple directional antennas provides the ability to estimate the location of the neighboring node while the use of multiple-channels helps in simultaneous communications between various nodes.

The proposed protocol not only minimizes interference and increases network capacity by using multiple-channels with directional antennas in a node but also decreases the issues of hidden terminals and deafness by proper use and orientation of the directional antennas. The neighboring nodes get the information of the ongoing communication on a particular channel and directional antenna of the node by overhearing vertically opposite CTS (VCTS). In order to avoid the wastage of energy that is probable to occur due to the duplicate information about the ongoing transmission obtained from DRTS, the VCTS transmission over the antenna must be estimated beforehand. This estimation varies with the number of antennas being used. In figure 4.1, we have assumed the use of four antennas. In case of more antennas, VCTS may be transmitted over more than one antenna. The VCTS must be transmitted such that it doesn’t overlap the region of directional RTS (DRTS) and VCTS.

The working scheme of the proposed protocol is as follows:

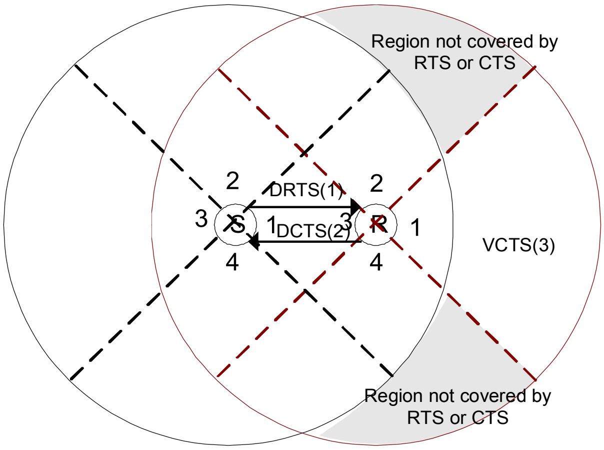

Figure 5.1: Coverage range in new protocol.

1. RTS-CTS Handshaking

The sender initiates the communication by sending DRTS on free channels. The reception mode of the DRTS is omni-directional. The receiver, upon receiving the DRTS over all antennas, estimates the maximum power of the DRTS reception. This informs the receiver about the directional position of the transmitting node. The receiver then sends the DCTS on this antenna receiving with the highest power. Thus, the channel is reserved and then directional communication is then established between the sender and the receiver. Upon receiving DRTS, the neighbors, other than intended receiver, update their DNAV table and defer their transmission in the direction of the sender. Deferring the transmission in this particular direction means that the communication over this channel is prohibited. Thus, this channel is used without interference.

2. Use of Vertically Opposite CTS (VCTS)

It can be possible that the neighbor of the receiver may be waiting to transmit packets during this communication for the channel being used. In order to avoid such scenario, receiver transmits VCTS on the angle that is vertically opposite to the angle of DCTS transmission. The estimation of the antenna (over which VCTS is to be sent) depends upon number of antennas being used, as given in equation 2. This VCTS informs the other possible senders to defer their transmission over this channel till the communication is over.

3. The Working Scheme

In the figure 5.1 we can see that the sender S sends DRTS on free channels. The receiver R, upon receiving the DRTS, replies with the DCTS on the direction that received the DRTS with highest power.

Immediately after sending the DCTS, the receiver sends VCTS. This lets its neighbor be informed of the ongoing communication over the particular channel. Thus, the proposed protocol significantly reduces the problem that may arise due to hidden terminals.

For more clear view of the transmission of DRTS, DCTS, VCTS,, DATA and ACK in the proposed protocol, timing diagram is depicted in figure 5.2. The other nodes in figure 5.2 represent nodes in the transmission range of receiver.

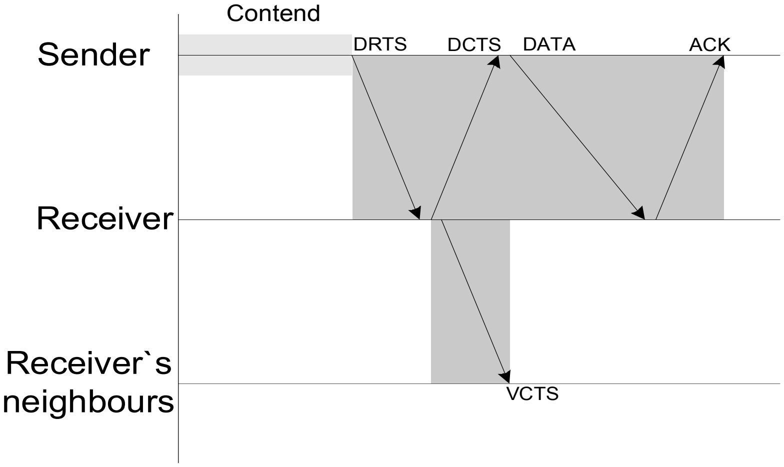

Figure 5.2: Timing sequence diagram.

B. State Transition

Figure 5.3 shows the state transition diagram at both the sender and the receiver.

The sender has four states: *Idle*, *Check for intended receiver*, *Wait for DCTS, Wait for ACK*. While the sender is in *idle* state, if it gets a packet to send, it checks if the intended receiver is free to receive or not by checking its DNAV. If the intended receiver is busy, the sender keeps on checking its DNAV; otherwise, it goes to *wait for DCTS* state after sending DRTS to the receiver. At *wait for DCTS* state, if timeout occurs before receiving DCTS, the sender retransmits DRTS and stays in *wait for DCTS* state; however, if the sender gets DCTS from the receiver, it goes to *wait for ACK* state after sending DATA to the receiver. At *wait for ACK* state, if the sender receives negative acknowledge (NAK) or timeout occurs, it goes back to *wait for DCTS* state after sending DRTS again; however, if the sender receive ACK, it goes to the initial *idle* state.

The receiver and neighbours have two states: *Idle* and *wait for DATA*. While the receiver and neighbours are in *idle* state, if they receive DRTS, they check which node is the intended receiver. If a node is the intended receiver, it goes to *wait for DATA* state after sending DCTS and VCTS; otherwise, it updates its DNAV and stays in *idle* state. Note here that the DRTS sent by the sender is also received by other neighbouring nodes that are not the intended receiver and, thus, these nodes should update their DNAV table and defer their transmission in the direction of the intended communication. At *wait for DATA* state, if the receiver receives DATA, it sends back ACK and goes to *idle* state. However, if timeout or data failure occurs, it sends NAK and also goes to *idle* state. There is also the process of updating DNAV at the receiver.

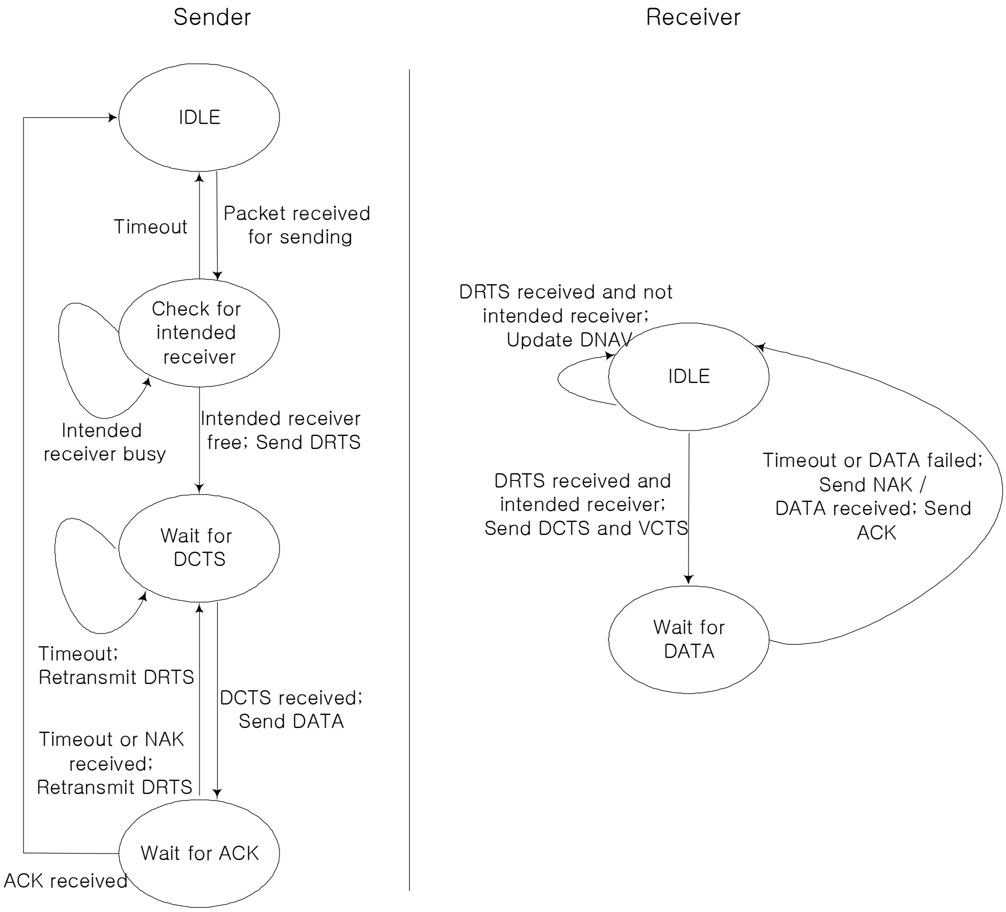

Figure 5.3: State transition diagram.

C. Channel Allocation

We have allocated multiple channels to multiple directional antennas and the associated interfaces. This scheme has some pros and cons. The static allocation of channels to antennas increases the network capacity.

There is no need of switching between available channels, this helps to overcome the delay that occurs due to channel switching. However, using multiple channels has some interference issues associated with it. Choosing a set of non-overlapping channels and allocating interfaces beforehand may limit the performance because the dedicated channel may not be free at certain time. A more dynamic approach of allocating channel to interfaces as and when needed can improve the network capacity even further.

VI. Performance Evaluation

A. Simulation Environment

We have used NS-2.33 [36] and have incorporated an extension as proposed in [35] for performance evaluation of the proposed MCMDA protocol. This incorporated extension in NS-2.33 allows configuring the wireless nodes with multiple interfaces and also provides a directional antenna model. The simulation parameters for our simulation are summarized in Table 6.1. For the simulation we used a nodes deployed in an area of 1000 m × 1000 m. Each node has four directional attached at angles 0, 90, 180 and 270 degrees associated with radio interfaces.

Table 6.1: Simulation parameters.

Parameter	**Value**
Queue length	50
Number of interfaces	4
Number of channels	4
Number of antennas in each node	4
Data rate (Mbps)	5, 6, 7, 8, 9, 10 and 11
Transmission power (Watt)	0.28183815 (~250m)
Reception power (Watt)	3.652E-10 (~250m)
Packet size (Bytes)	1500

The three different topologies for the simulation of the proposed protocol: 10-node linear topology and 10-node non-linear topology and 4x4 mesh topology are as shown in figures 6.1, 6.2 and 6.3 respectively. The simulation time was set to 50 seconds. The wireless transmission power was set to 0.28183815 Watt, which is equivalent to the transmission range of 250 meters.

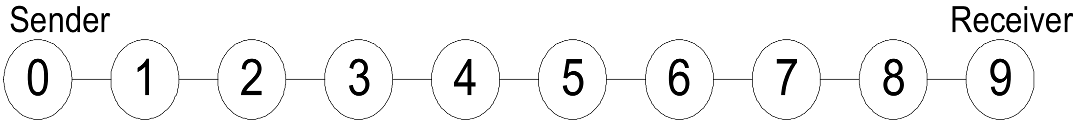

Figure 6.1: 10-node non-linear topology for simulation.

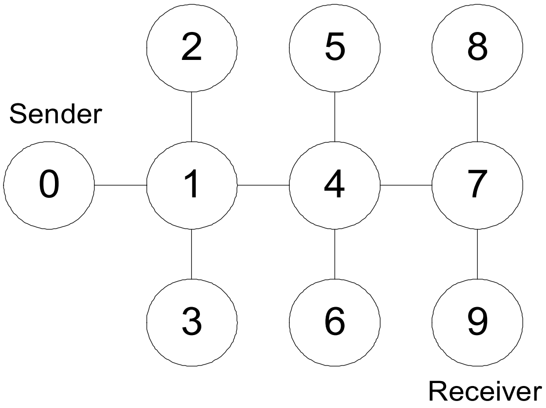

Figure 6.2: 10-node non-linear topology for simulation.

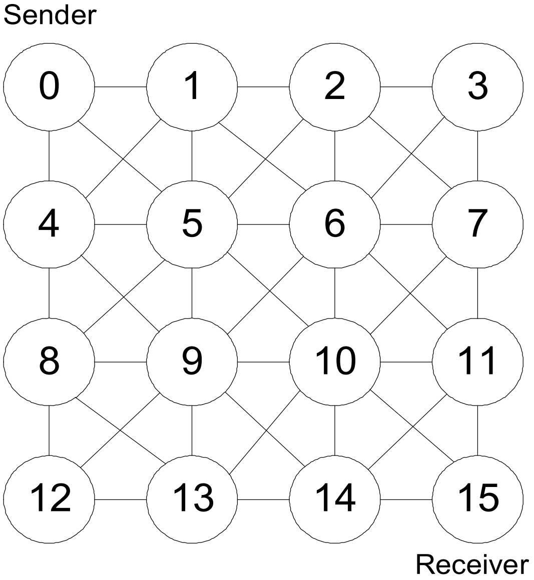

Figure 6.3: 4x4 mesh topology for simulation.

We used three performance metrics for the performance evaluation of the proposed protocol: total throughput, delay and control overhead. The total throughput is the total amount of data transmitted per second. Therefore, the total throughput gives an idea of successful data transmission over a channel per unit of time. Greater throughput therefore means greater data transmission efficiency. The second performance metric average end-to-end delay is the average time taken for a data packet to be delivered from the source node to the destination node. Lower delay implies greater efficiency of data transmission. The control overhead gives the idea of the total number of control packets transmitted.

B. Simulation Results and Discussion

We have compared the proposed MCMDA with IEEE 802.11 DCF [37], D-MAC [1]. IEEE 802.11 DCF is a conventional MAC protocol which uses omni-direction antennas for the exchange of control and data packets. The exchange of RTS and CTS takes place prior to the DATA and ACK. Number of MAC schemes have been proposed that uses directional antennas. D-MAC scheme as proposed by Ko et al., is among the pioneer protocols that use directional antennas. Many other protocols have also been proposed either based on D-MAC scheme or to improve it. For fair comparison, we also evaluate the proposed MCMDA with a single channel as a special case because IEEE 802.11 DCF and DMAC operate on a single channel. We denote the single-channel MCMDA as MCMDA-S and the multi-channel MCMDA as MCMDA-M.

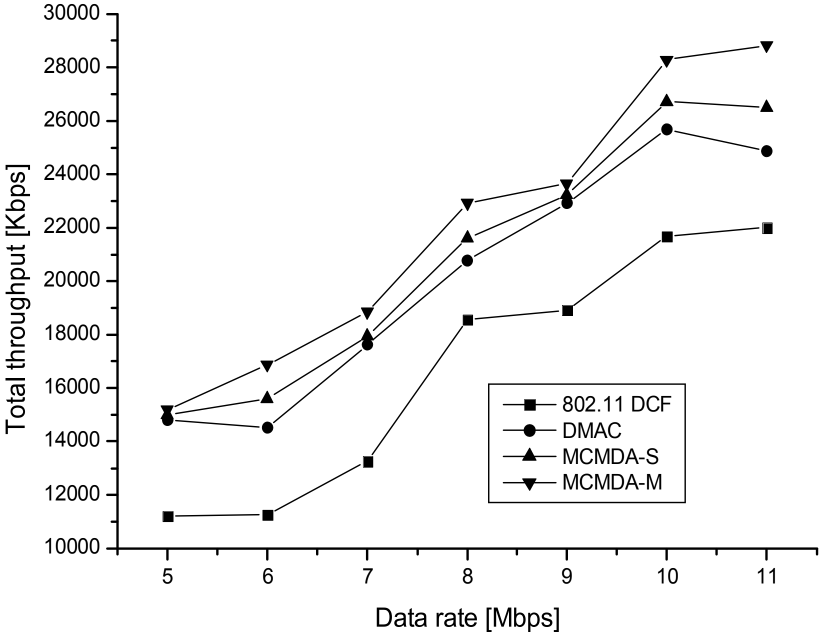

Figure 6.4: Total throughput in the 10-node linear topology.

Figures 6.4 and 6.5 show the total throughput and the average end-to-end delay of IEEE 802.11 DCF, DMAC and the proposed MCMDA along with the increased data rate, respectively, for 10-node linear topology. We have evaluated the throughput for node 4 in the 10-node linear topology because there are a large number of transmissions and receptions at node 4 as can be seen. The throughput and end-to-end delay of MCMDA are slightly improved in comparison to DMAC as expected. This is mainly because, in the linear topology, there is higher directional interference which results in a large number of control packet transmissions and data packet retransmissions. Note that IEEE 802.11 DCF with omni-directional antennas shows lower performance than DMAC and MCMDA. It is also observed in figure 6.5 that the end-to-end delay is minimal at the data rate of 8 Mbps in the given simulation environment.

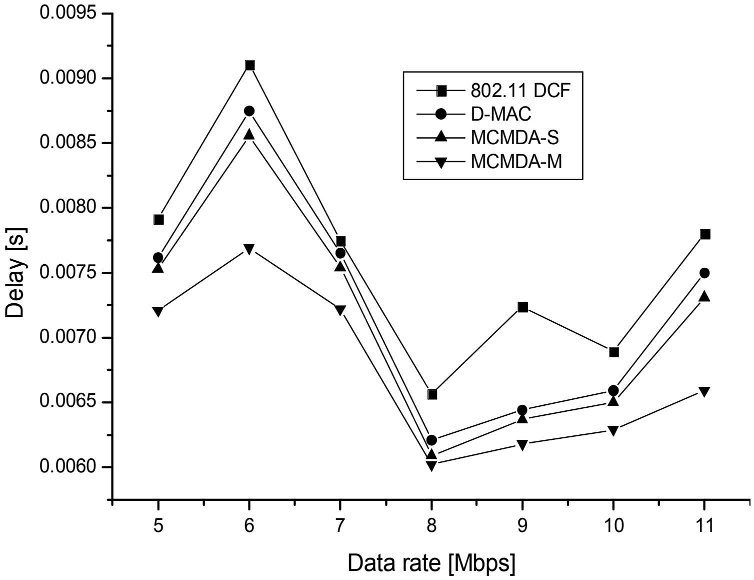

Figure 6.5: Average end-to-end delay in the 10-node linear topology.

In figures 6.6 and 6.7, the protocols under evaluation are compared in terms of the total throughput and the average end-to-end delay, respectively, for the 10-node non-linear topology. The throughput for node 4 is measured because node 4 is approximately at the middle position with respect to traffic. We can see that the proposed MCMDA outperforms IEEE 802.11 DCF and DMAC. In particular, MCMDA-M dramatically improves the end-to-end delay compared to the other protocols as shown in Figure 6.7. Note here that, in the non-linear topology, all the antennas can communicate with other antennas through available idle channels and, thus, the interference is reduced resulting in the less number of retransmissions.

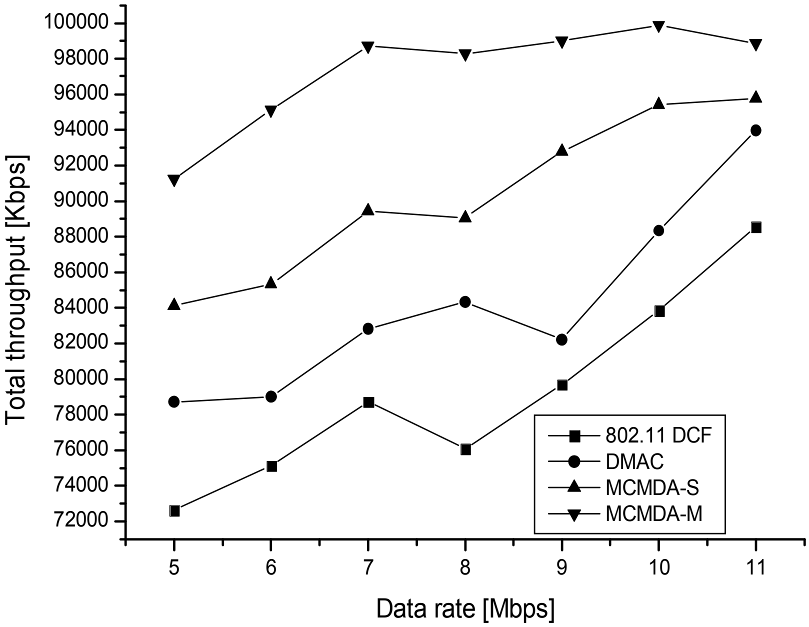

Figure 6.6: Total throughput in the 10-node non-linear topology.

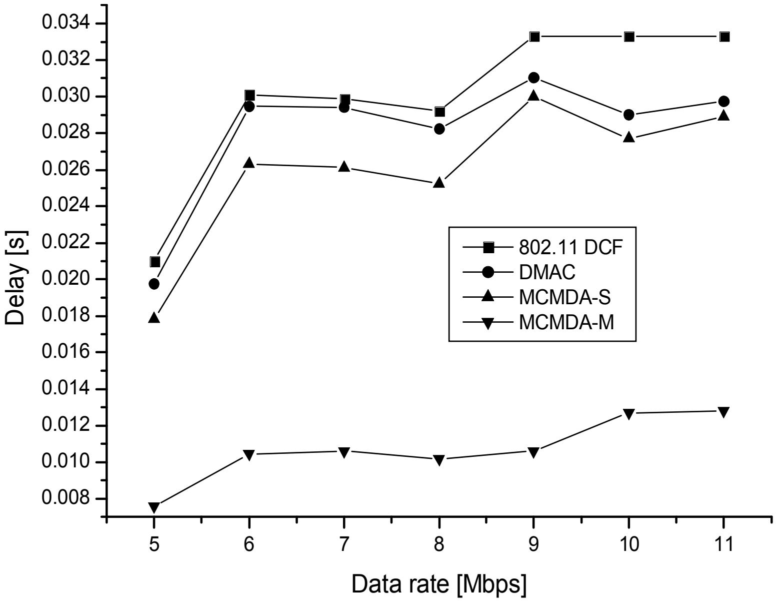

Figure 6.7: Average end-to-end delay in the 10-node non-linear topology.

Figures 6.8 and 6.9 show the performance of the protocols under evaluation for the 4 x 4 mesh topology. Note that the throughput for node 6 is measured because node 6 is one of the two nodes (nodes 6 and 9) located at the middle position with respect to traffic. As can be expected, the proposed MCMDA outperforms IEEE 802.11 DCF and DMAC for both throughput and end-to-end delay. Now, we can observe that as the topology is complicated and the number of nodes is increased, the proposed MCMDA improves the network performance much more and the multi-channel effect is significantly increased.

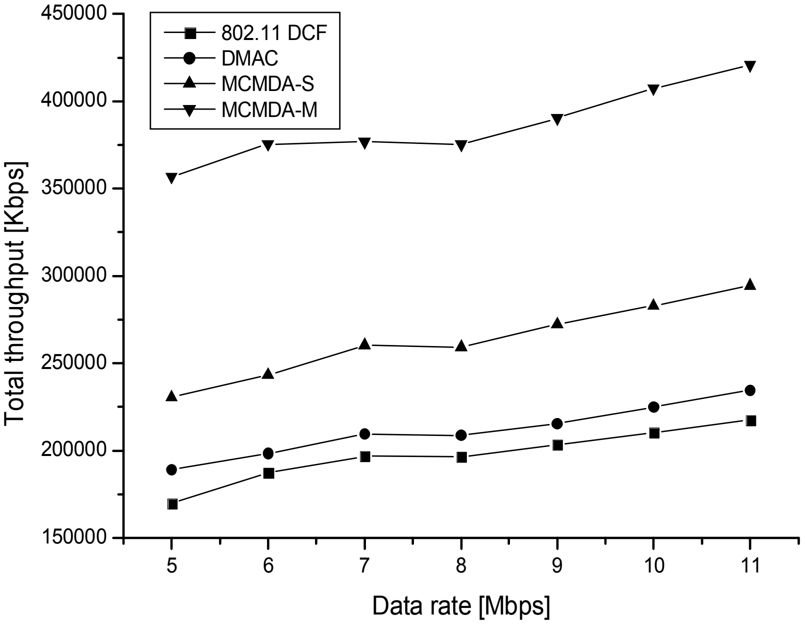

Figure 6.8: Total throughput in the 4x4 mesh topology.

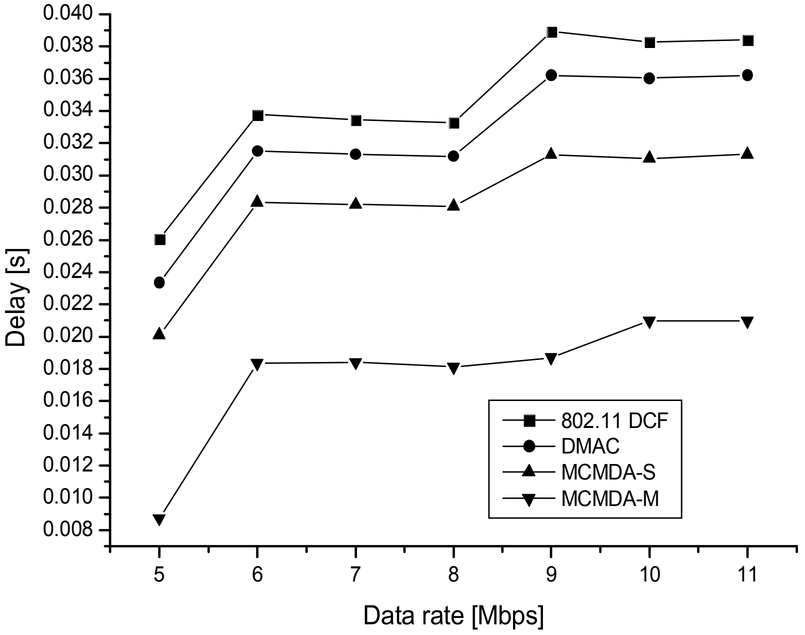

Figure 6.9: Average end-to-end delay in the 4x4 mesh topology.

Figures 6.10, 6.11 and 6.12 depict the control overhead incurred in linear, non-linear and 4x4 mesh topology. The control overhead in case of proposed MCMDA-M is fairly larger than the IEEE 802.11, D-MAC and MCMDA-S protocols. This is because multiple interfaces with multiple channels are used in our protocol for making concurrent transmissions and receptions possible. This overhead can be justified because a multi-channel node acts as multiple nodes and the significant performance improvement is guaranteed.

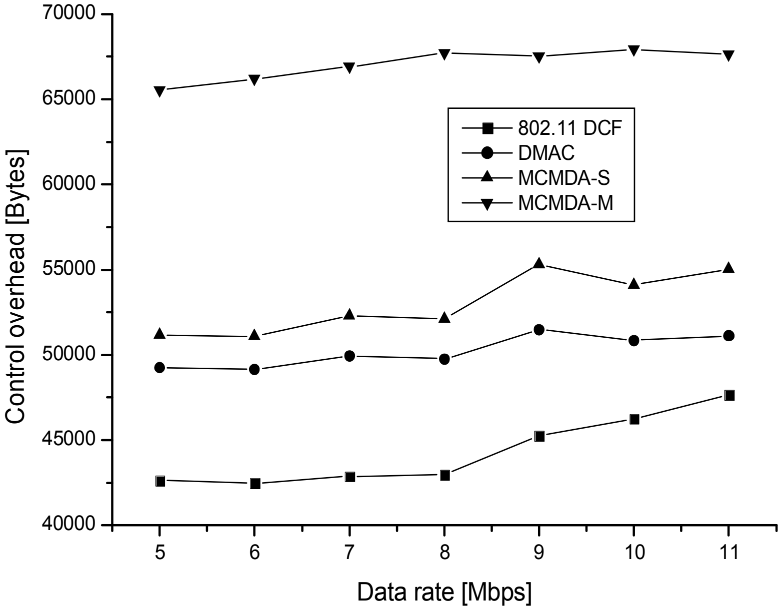

Figure 6.10: Control overhead in the 10-node linear topology.

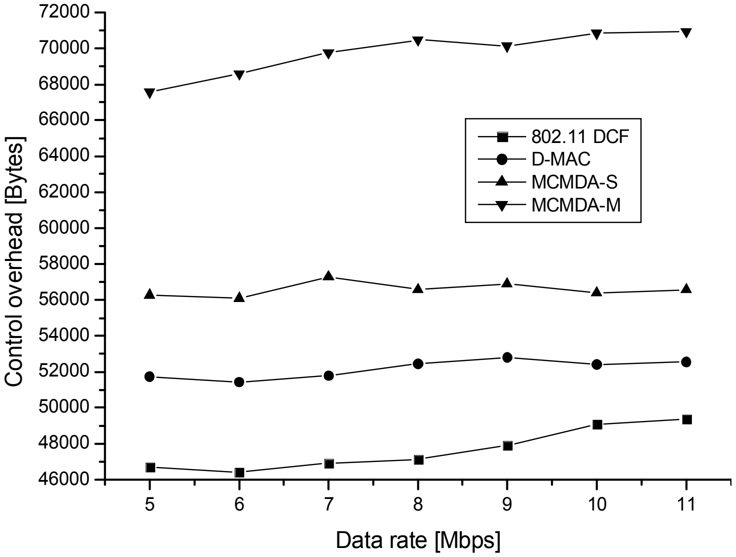

Figure 6.11: Control overhead in the 10-node non-linear topology.

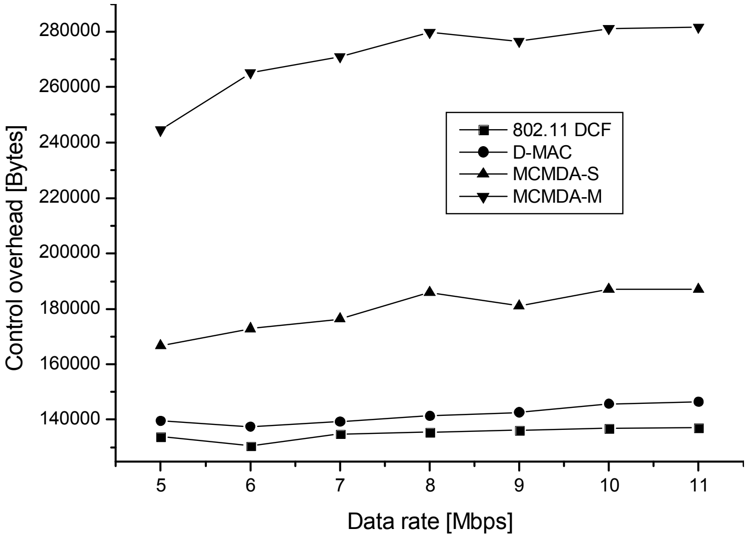

Figure 6.12: Control overhead in the 4x4 mesh topology

VII. Conclusion and Future Works

The importance of using directional antennas in MAC protocols for ad hoc networks has been focussed in this thesis. Some related issues that are of major concern for the MAC protocols to achieve higher performance have been reviewed. We have also discussed some meaningful existing works that lay the foundation of more research in the field of MAC protocols with directional antenna in ad hoc networks. In this thesis, we have proposed a novel MAC approach which works on the use of directional antenna over multiple channels. This approach aims at increasing the network capacity by increasing the bandwidth utilization. The effects of deafness and hidden terminals are also reduced in ad hoc networks by better utilizing the directional transmission. The proposed MAC approach makes maximum spatial reuse and thus achieves higher coverage range.

As a future work, we are going to introduce a more dynamic approach of this protocol. The association of directional antennas with multiple channels is defined ahead of communications. A better approach can be to assign channels to antennas dynamically. In this way, we can further increase the number of channels, keeping the number of antennas constant. One might infer that increasing the number of channels may cause interference if the channels are overlapping. The choice of channels can be done dynamically avoiding the selection of overlapping channels and, thus, increasing the network capacity even further.

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Acknowledgements

I offer the sincerest gratitude to my supervisor, Prof. Sangman Moh, who has supported me throughout my research and study at Chosun University. I am indebted to the encouragement, knowledge and freedom he has provided to work on my own way.

I would like to thank Prof. Ilyong Chung and Prof. Moonsoo Kang for their valuable guidelines in preparing this thesis work. I would specially like to thank Prof. Sangman Moh, Prof. Ilyong Chung, Prof. Seokjoo Shin, Prof. Moonsoo Kang, Prof. Sangwoong Lee and Prof. Inkyu Moon for their advices and lectures in my graduate school course works.

A great thanks to all my lab-mates and friends at Chosun University who have always been supportive and helpful. In particular, I would like to thank Navin Gautam for his friendship and help during my stay in Korea.

My deepest gratitude goes to my family for their unfailing love and support. I am indebted to my father, Prof. Pushpa Raj Sharma Khatiwada and my mother, Meena Sharma Khatiwada for the love and care they have always shown. I would also like to thank my brother

Madhup Khatiwada and sister-in-law Ganga Khatiwada for being my best counselors throughout my stay in Korea. Many thanks to my nephew, Pratyush Khatiwada, without whom my family acknowledgement would be incomplete.

Last, but not the least I am thankful to the Korean Government, Ministry of Knowledge Economy, National IT Industry Promotion Agency (NIPA), and Chosun University for granting me scholarships in various forms to pursue my master's degree.

(별 지)

저작물 이용 허락서

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논문제목	영문 : A Robust MAC Protocol for Ad Hoc Networks using Directional Antennas				

본인이 저작한 위의 저작물에 대하여 다음과 같은 조건 아래 조선대학교가 저작물을 이용할 수 있도록 허락하고 동의합니다.

- 다 음 -

1. 저작물의 DB구축 및 인터넷을 포함한 정보통신망에의 공개를 위한 저작물의 복제, 기억장치에의 저장, 전송 등을 허락함.
2. 위의 목적을 위하여 필요한 범위 내에서의 편집과 형식상의 변경을 허락함. 다만, 저작물의 내용변경은 금지함.
3. 배포・전송된 저작물의 영리적 목적을 위한 복제, 저장, 전송 등은 금지함.
4. 저작물에 대한 이용기간은 5년으로 하고, 기간종료 3개월 이내에 별도의 의사 표시가 없을 경우에는 저작물의 이용기간을 계속 연장함.
5. 해당 저작물의 저작권을 타인에게 양도하거나 출판을 허락을 하였을 경우에는 1개월 이내에 대학에 이를 통보함.
6. 조선대학교는 저작물 이용의 허락 이후 해당 저작물로 인하여 발생하는 타인에 의한 권리 침해에 대하여 일체의 법적 책임을 지지 않음.
7. 소속 대학의 협정기관에 저작물의 제공 및 인터넷 등 정보통신망을 이용한 저작물의 전송・출력을 허락함.

동의여부 : 동의(O)

2010년 8월

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