WIRELESS LANS WITH SMART ANTENNAS

by
ERDEM ULUKAN

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the requirements for the degree of
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ABSTRACT

Smart antenna systems not only enable users to have high quality links but also increase network throughput by allowing spatial reuse of wireless channels by the use of directional transmission. However performance of smart antenna systems is limited because of the increased hidden terminal problem and deafness of nodes. In this work, we have proposed the Angular MAC (ANMAC) protocol that avoids both problems through medium access tables in the nodes that keep track of the locations of the destination nodes as well as all communicating neighbors. We present detailed performance analysis of ANMAC considering different topologies and traffic scenarios, and we show that SDMA cannot be fully exploited without a smart scheduler. We have also proposed ANMAC with Location based Scheduling (ANMAC-LS) and compared its performance with other smart antenna approaches and omni 802.11 MAC. We prove the efficacy of location based scheduling in wireless networks with smart antennas, and we also show the effects of antenna orientation on throughput, using realistic antenna patterns and the ANMAC protocol. We have also analyzed the effect of contention window size on the performance of the network. By adjusting the contention window according to channel conditions, we can always get the maximum network throughput. We propose an updating algorithm for contention window, and we have analyzed the results both analytically and through simulations.

ÖZET

Akıllı Anten (AA) sistemleri yüksek kalitede bağlara olanak tanımasının yanı sıra kablosuz kanalların uzaysal tekrar kullanımını sağlayarak ağda üretilen iş miktarını artırmaktadır. Ancak akıllı anten sistemlerinin başarımı saklı ve sağır istasyon problemleri yüzünden sınırlıdır. Bu çalışmada istasyonlarda tutulan tablolar yardımı ile bu problemleri ortadan kaldırmayı amaçlayan açısal tabanlı bir ortam erişim protokolü (ANMAC) önerilmektedir. ANMAC için değişik topolojilerde ve trafik senaryolarında ayrıntılı başarım analizi yapılmış, uzay bölmeli çoğullamaya (SDMA) tam olarak erişilebilmek için akıllı bir paket çizelgecisine ihtiyaç olduğu gösterilmiştir. Bununla beraber konum tabanlı çizelgelemeli ANMAC (ANMAC-LS) önerilmiş ve başarımı diğer akıllı anten yaklaşımlarıyla ve IEEE 802.11 MAC protokolü ile karşılaştırılmıştır. Akıllı anten kullanan kablosuz sistemlerde konum tabanlı çizelgelemenin etkisi ispatlanmış ve gerçek anten paternleri kullanılarak anten huzmesi yönlendirmesinin ağda iş çıkarmaya etkisi gösterilmiştir. Bununla birlikte istasyonların çarpışmayı önlemek amacıyla kullandığı çekişme penceresi değerinin ağın başarımına etkisi incelenmiştir. Bu değerin doğru ayarlanması ile ağda her zaman en yüksek başarımı elde etmek mümkündür. Çalışmamızda bu doğru değeri elde etmeye yarayan dinamik bir algoritma da sunulmuştur.

To my lovely family

ACKNOWLEDGEMENTS

I would like to thank my supervisor Asst.Prof. Özgür Gürbüz who gave me one of the biggest chances in my life. I am grateful for her guidance and advice about every detail of this thesis. I hope that I would not lose her support and friendship throughout my life.

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ABBREVIATIONS

ACK: Acknowledgment frame

ANMAC: Angular MAC

ANMAC-LS: ANMAC with Location Scheduling

AN-CTS: Angular CTS

AN-RTS: Angular RTS

AP: Access Point

BER: Bit Error Rate

BSS: Basic Service Set

CCA: Clear Channel Assessment

CCK: Complementary Code Keying

CMA: Constant Modulus Algorithm

CSMA: Carrier Sense Multiple Access

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

CSMA/CD: Carrier Sense Multiple Access with Collision Detection

CTS: Clear To Send

CW: Contention Window

dB: Decibels

DoA: Direction of Arrival

DCF: Distributed Coordination Function

D-CSMA: Directional CSMA/CA

D-CSMA-LS: Directional CSMA/CA with Location Scheduling

DECT: Digital European Cordless Telephony

DIFS: Distributed Interframe Space

D-MAC: Directional MAC

D-NAV: Directional Network Allocation Vector

DRTS: Directional RTS

DS: Distribution System

DSSS: Direct Sequence Spread Spectrum

DWTS: Directional Wait To Send

EIFS: Extended Interframe Space

ESS: Extended Service Set

FCS: Frame Check Sequence

FH: Frequency Hopping Spread Spectrum

GPS: Global Positioning System

ID: Station Identifiers

IEEE: Institute of Electrical and Electronics Engineers

IFS: Inter Frame Space

IP: Internet Protocol

IR: Infrared

ISM: Industrial, Scientific and Medical

LAN: Local Area Network

MAC: Medium Access Control

MIMO: Multi Input Multi Output system

NAV: Network Allocation Vector

OCTS: Omni directional CTS

OFDM: Orthogonal Frequency Division Multiplexing

OPNET: Optimum Network Engineering Tool

OSI: Open Systems Interconnection

ORTS: Omni directional RTS

P_ACK: Polling Acknowledgement

PCF: Point Coordination Function

PHY: Physical Layer

PIFS: Priority Interframe Space

PLCP: Physical Layer Convergence Procedure

PMD: Physical Medium Dependent

RA: Receiver Address

RF: Radio Frequency

RLS: Recursive Least Squares

RTR: Ready To Receive

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SDMA: Spatial Division Multiple Access

SIFS: Short Interframe Space

SINR: Signal to Interference plus Noise Ratio

SIR: Signal to Interference Ratio

SNR: Signal to Noise Ratio

STA: Station

TA: Transmitter Address

TDD: Time Division Duplex

UNII: Unlicensed National Information Infrastructure

WLAN: Wireless LAN

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1 INTRODUCTION

The need for high quality links and great demand on high throughput has motivated new enhancements and work in wireless communications such as smart antenna systems. Smart (adaptive) antennas enable spatial reuse and they increase the communication range because of the directivity of the antennas [1]. However these enhancements quantified for the physical layer may not be efficiently utilized, unless the Media Access Control (MAC) layer is designed accordingly. Using directional antennas in place of omni directional antennas introduce some problems such as hidden terminal problem and the deafness of nodes. Hidden terminal problem arises when two sender nodes, which are out of range of each other or unaware of each other's transmission, transmit packets at the same time to the same receiver, resulting in collisions at the receiver. Since sender nodes are out of range of each other, they do not detect carrier even though the other node is sending data, and if their data packets reach the destination at the same time, these packets are dropped due to collision at the receiver. In addition, another problem is the deafness, where communicating nodes are unaware of the communication of other nodes with directional transmission.

The goal of the using directional antennas is to maximize the performance of the WLANs by increasing throughput, range and Signal-to-Interference-Plus-Noise Ratio (SINR). Directional antennas provide an increase in radiated power because of focusing the transmitter power on one direction. This improves the range of the transmitter. The antennas work reciprocal, and for this reason, the received power at the receiver is also increased. On the other hand, the directivity of the antenna allows the node to cancel interfering signals arriving at the receiver from other directions.

One key advantage of using directional antennas is the ability to achieve Spatial Division Multiple Access (SDMA) [2], [3]. In SDMA, stations are separated by their locations, and by the use of proper MAC, simultaneous transmissions can occur at the same time and same frequency. The existing algorithms proposed for SDMA, e.g., [4], [5], assume contention free, reservation based medium access. In both schemes, synchronization and initialization are important issues to be addressed in realistic scenarios. On the other hand, SDMA with random access is challenging in realistic scenarios, especially when packet destinations are not known. Since the medium is shared, the stations have to determine which stations and which sectors are idle in order to avoid collisions and retries. Queuing delays can grow unboundedly if a packet at the head of the sender's queue is destined to a busy node or towards a busy sector, also resulting in low throughput.

Previously, in the literature, applications of directional antennas in wireless networks have been investigated. In [6], Vaidya et al proposed a MAC protocol for the use of directional antennas together with Global Positioning System (GPS) to determine the direction to communicate with a given destination. It has been shown that, directional transmission causes the deafness problem, where a node attempts to transmit to another node that is already busy. When the transmission of a busy station cannot be detected by an attempting station, successive collisions and retries are caused, and consequently, the throughput gained from directional transmission is reduced. In [7], a solution to deafness is proposed by using simple tones to inform other stations. In [8] and [9] Directional CSMA/CA is proposed for 2, 4 and 8 sectored antennas, but both algorithms suffer from the deafness problem.

In this thesis, we are proposing a new MAC protocol, the Angular MAC (ANMAC) that includes location finding. The stations exchange modified RTS/CTS messages, namely angular RTS/CTS, for training with each other to determine their respective locations in a much faster and more efficient way. With the help of the angular RTS/CTS messages, a medium access table is constructed to track the locations of not only the destination nodes but also all communicating neighbors. With this feature, our protocol enables angular CSMA and Space Division Multiple Access. In ANMAC, the deafness problem is also addressed and solved. ANMAC avoids hidden terminal problem by using angular RTS/CTS messages and prevents deafness by informing surrounding nodes via sending dummy bits on other sectors for the remaining part of the data packet.

Later, we extend the ANMAC framework with a location-based scheduler to support SDMA with random access. The new protocol is named as ANMAC with Location Scheduling (ANMAC-LS). The location-based scheduler utilizes the location information, which is already available through the medium access table of the ANMAC protocol. ANMAC-LS fully exploits the advantage of directional transmission in spatially divided channels, while still avoiding the hidden terminal problem and deafness, and guaranteeing range extension by using only directional antennas.

For evaluating our protocol, we modeled the proposed ANMAC protocol and physical layer with the actual IEEE 802.11b physical layer characteristics along with realistic antenna and wireless channel models in OPNET. We analyzed the throughput and media access delay performance of our protocol and compared it with the previously designed directional MAC protocols.

We have also analyzed the affect of contention window size on the performance of the network. The 802.11 standard uses a fixed value for minimum contention window, which can cause long delays in lightly loaded networks and many collisions in crowded networks. By adjusting the contention window size according to channel conditions, we can always get the maximum network throughput. In this thesis, we proposed an updating algorithm for contention window. We have analyzed the results both analytically and through simulations.

The rest of the thesis is arranged as follows. Chapter 2 provides an overview of the IEEE 802.11 Standard and smart antenna systems including the research done to integrate smart antennas to wireless networks. Chapter 3 provides the summary of our protocol, Angular MAC (ANMAC), including station properties, basic protocol operation, SDMA support, deafness problem, the location based scheduler and selection of contention window size according to channel conditions. The operation of the protocol is discussed over a sample scenario. Chapter 4 discusses the system model including antenna and network models, how they are built and used, and the simulation environment. Chapter 5 presents our performance evaluation and simulation results. We have compared our protocol with similar protocols and analyzed the performance under different scenarios and with different packet sizes. Finally, section 6 includes our conclusions and directions for future work.

2 BACKGROUND

2.1 IEEE 802.11 Wireless LAN Standard

This chapter contains overview of the 802.11 Standard [10]. It is given to understand the basic concepts, the principle of operations, and the reasons behind some of the features and/or components of the Standard [11], [12].

2.1.1 IEEE 802.11 Architecture

802.11 WLAN is based on cellular architecture where the system is divided into cells. Each cell is called Basic Service Set (BSS). In infrastructure mode, base station (called Access Point, AP) can orchestrate the stations and coordinate the access of stations (STA) to the wireless medium and form the cells. On the other hand, the cells can be formed by stations without an infrastructure (more specifically without an Access Point), which is called the Ad Hoc Mode.

The Access Points are connected through some kind of backbone (called Distribution System or DS), typically Ethernet, and in some cases wireless itself.

The combination of all elements in the Wireless LAN including the different cells, their respective Access Points and the Distribution System, is seen to the upper layers of the OSI model, as a single 802 network, and is called as Extended Service Set (ESS). The ESS is shown in Fig.2.1.

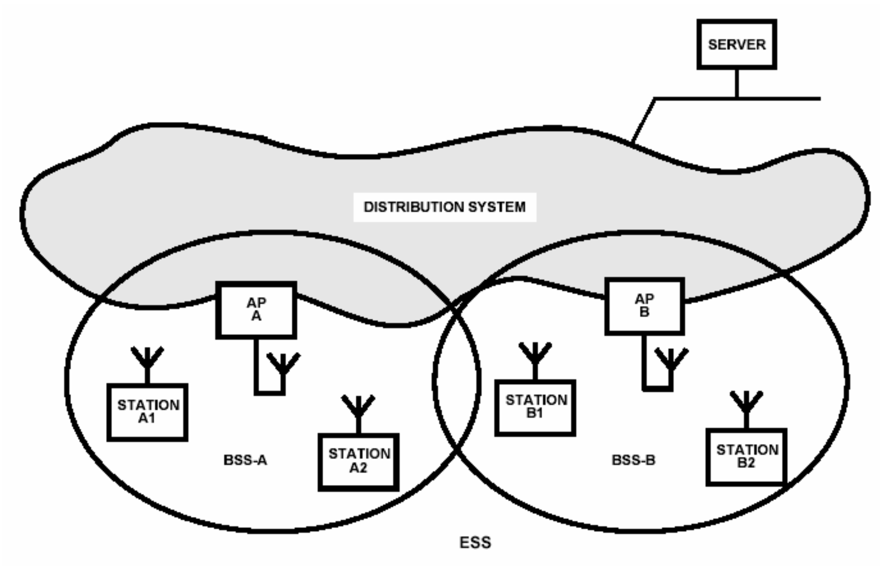


Fig.2.1 802.11 WLAN with all components [11]

The 802.11 protocol covers MAC and Physical Layers (Fig.2.2). Beyond the functionality usually performed by the MAC layer, there are other functions performed by the 802.11 MAC that are typically related to upper layer protocols, such as Fragmentation, Packet Retransmissions, and Acknowledgements. The MAC layer defines two different access methods, the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF).

<table>
<tr><td colspan="5">802.2</td><td rowspan="2">Data Link Layer</td></tr>
<tr><td colspan="5">802.11 MAC</td></tr>
<tr><td>FHSS</td><td>DSSS</td><td>IR</td><td>OFDM</td><td>CCK</td><td>PHY Layer</td></tr>
</table>

Fig.2.2 IEEE 802.11 layers description

2.1.2 Basic Access Method (DCF) and CSMA/CA

The basic access mechanism, called Distributed Coordination Function (DCF), is basically a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. In Ethernet, another type of CSMA protocol is used, which is Carrier Sense Multiple Access with Collision Detection (CSMA/CD) [13].

In CSMA, a station desiring to transmit senses the medium, if the medium is busy (i.e. some other station is transmitting) then the station will defer its transmission to a later time [14]. If the medium is sensed free then the station is allowed to transmit. These kinds of protocols are very effective when the medium is not heavily loaded, since it allows stations to transmit with minimum delay, but there is always a chance of stations transmitting at the same time (collision), caused by the fact that multiple stations may sense the medium free and decide to transmit at once. The MAC layer can coordinate the retransmission of the packet in case of a collision, which will cause significant delay. In Ethernet, the retransmission phase is based on the Exponential Random Backoff algorithm [15].

Collision Detection mechanism is a good idea on a wired LAN but it cannot be used on a Wireless LAN environment, because of two main reasons;

i. Implementing a Collision Detection Mechanism would require the implementation of a Full Duplex radio, capable of transmitting and receiving at once, an approach that would increase the price significantly. It is also hard to implement simultaneous transmission and reception in nearby frequency bands.

ii. In a wireless environment we cannot assume that all stations hear each other (which is the basic assumption of the Collision Detection scheme), and the fact that a station willing to transmit and senses the medium free, does not necessarily mean that the medium is free around the receiver area.

In order to overcome these problems, in DCF mode, 802.11 uses a Collision Avoidance mechanism together with a positive Acknowledgement scheme, as follows; A station willing to transmit senses the medium, if the medium is busy then it defers. If the medium is free for a specified time (Distributed Inter Frame Space, DIFS) then the station is allowed to transmit. The receiving station will check the CRC of the received packet and will send back an acknowledgement packet (ACK). Receipt of the acknowledgement will indicate the transmitter that no collision has occurred. If the sender does not receive the acknowledgement in the required duration then it will retransmit the packet until it gets acknowledged or thrown away after a given number of retransmissions. Fig.2.3 shows a schematic of the access mechanism.

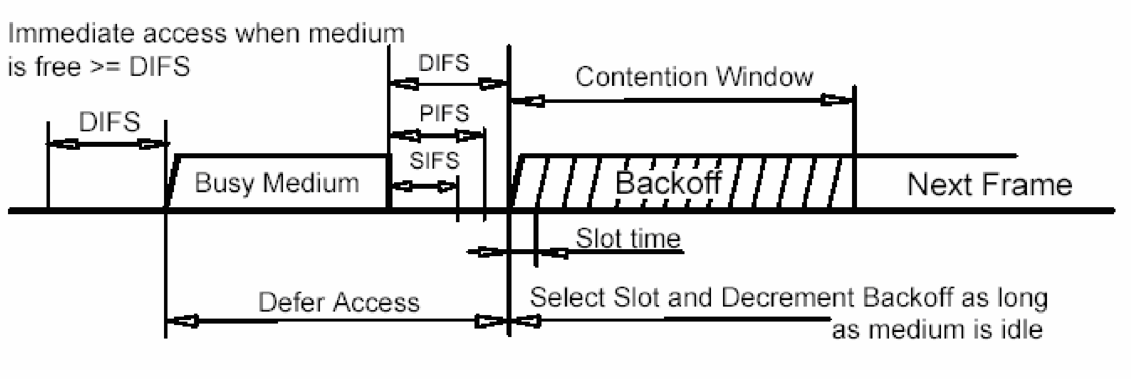


Fig.2.3 Basic access method and Timing [11]

Carrier sensing alone does not prevent collisions, since in some cases, stations may not hear each other. The 802.11 standard defines a *Virtual Carrier Sense* mechanism in order to reduce the probability of collision of two stations. A station willing to transmit a packet first transmits a short packet called RTS (Request To Send), which includes the source, destination addresses, and the duration of the following transaction (i.e. time required to transmit the packet and the respective ACK), the destination station responds if the medium is free with a response control Packet called CTS (Clear To Send), which includes the same duration information. All stations receiving either the RTS or the CTS set their Virtual Carrier Sense indicator (Network Allocation Vector, NAV), to the given duration, and they use this information together with the Physical Carrier Sensing signal while listening to the medium. Figure 2.4 shows a transaction between two stations, and the NAV setting of their neighbors. This mechanism reduces the probability of a collision on receiver area by a station that is *"hidden"* from the transmitter, since that station will hear the CTS and "reserve" the medium as busy until the end of the transaction. The duration information on the RTS also protects the transmitter area from collisions on the ACK packet. It should also be noted that RTS and CTS exchange also reduces the overhead of collisions. Since RTS and CTS are short frames, collisions are recognized and recorded faster (This is true for data packets significantly bigger than the RTS/CTS. The standard allows for short packets to be transmitted without the RTS/CTS transaction, and this is controlled per station by a parameter called RTS Threshold).

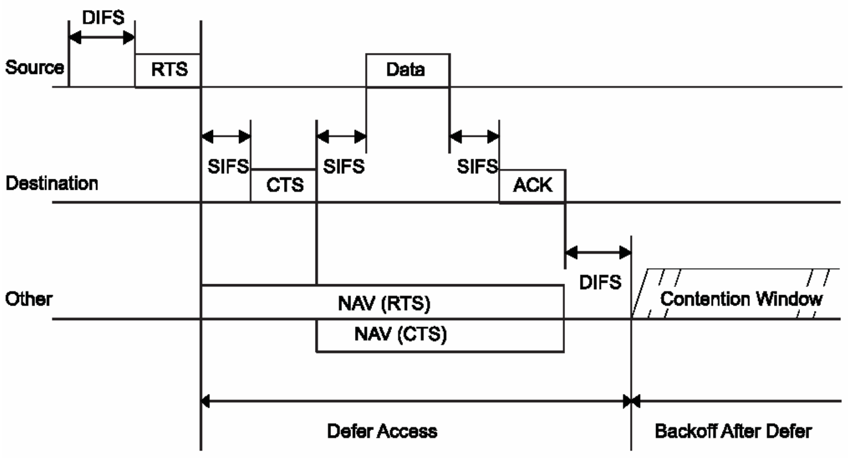


Fig.2.4 RTS/CTS/data/ACK and NAV setting [10]

Due to high Bit Error Rate (BER) of radio links, the probability of a packet to get corrupted increases with the packet size. Corrupted packets need to be retransmitted until they are delivered successfully, which increases the overhead. 802.11 MAC protocol allows a simple packet fragmentation and reassembly mechanism.

2.1.3 Inter Frame Spaces

The 802.11 standard defines 4 types of Inter Frame Spaces, which are used to provide different priorities for accessing the channel.

Slot Time, is defined in such a way that a station will always be capable of determining if another station has accessed the medium at the beginning of the previous slot.

SlotTime = CCATime + RxTxTurnaroundTime + AirPropagationTime + MACProcessingDelay

CCATime is the minimum time (in µs) the CCA mechanism has available to assess the medium within every time slot to determine whether the medium is busy or idle. RxTxTurnaroundTime is the maximum time (in µs) that the PHY requires to change from receiving to transmitting the start of the first symbol. AirPropagationTime is the anticipated time (in µs) it takes a transmitted signal to travel from the transmitting station to the receiving station. MACProcessingDelay is the nominal time (in µs) that the MAC uses to process a frame and prepare a response to the frame [10].

SIFS - Short Inter Frame Space, is used to separate transmissions belonging to a single dialog (e.g. Packet-Ack). SIFS is the minimum Inter Frame Space, and there is always at most one single station to transmit at this given time hence having highest priority over all other stations. This value is a fixed value per PHY and it includes the delay for the transmitting station to switch back to the receive mode and get ready for decoding the incoming packet.

SIFSTime = RxRFDelay + RxPLCPDelay + MACProcessingDelay + RxTxTurnaroundTime

RxRFDelay is the nominal time (in µs) between the end of a symbol at the air interface to the issuance of a PMD-DATA indicate to the PLCP. RxPLCPDelay is the nominal time (in µs) that the PLCP uses to deliver a bit from the PMD receive path to the MAC [10]. Definitions for MACProcessingDelay and RxTxTurnaroundTime are given in the Slot Time formula.

PIFS - Point Coordination IFS, is used in Point Coordination Function (PCF) mode by the Access Point (or Point Coordinator, as called in this case), to gain access to the medium before any other station. This value is SIFS+Slot Time.

DIFS -Distributed IFS, is the Inter Frame Space used for a station willing to start a new transmission, which is calculated as SIFS+2*Slot Time. Stations defer for DIFS duration, to make sure the link is idle.

EIFS - Extended IFS, is a longer IFS used by a station that has received a corrupted packet. This is needed to prevent a station (which could not decode the duration information from the packet for the Virtual Carrier Sense mechanism) from colliding with a future packet belonging to the current dialog.

2.1.4 Exponential Backoff Algorithm

After a collision, the colliding stations will attempt transmission again. Backoff is a well known method to resolve contention between different stations willing to access the medium. This method requires each station to choose a Random Number between 0 and a given number, and wait for this number of Slots before accessing the medium, while checking the medium (i.e. checking whether a different station has attempted to transmit), which reduces the collision probability. In exponential backoff, each time a station chooses a slot and it happens to collide, it increases the maximum number for the random selection exponentially [15].

The 802.11 standard defines an Exponential Backoff Algorithm, which must be executed in the following cases; **(1)** If the station senses the medium as busy before the first transmission of a packet. **(2)** After each retransmission **(3)** After a successful transmission. The only case when this mechanism is not used is when the station decides to transmit a new packet and the medium has been free for more than DIFS.

Exponential backoff algorithm of 802.11 works as follows: If the medium is determined to be busy at first attempt, the station (STA) defers until the end of the current transmission. Prior to attempting to transmit again, immediately after a successful transmission, the station selects a random backoff interval; equal to *Backoff Time*.

$$BackoffTime = Random\ ([0,\ CW])\ *\ SlotTime \qquad (2.1)$$

where CWmin ≤ CW ≤ CWmax.

Collision Window (CW) is the time during which the network can detect a collision between packets. After collisions at each attempt, CW is increased by a factor of two, as shown in Fig.2.5. The backoff interval counter is decremented while the medium is idle and it is frozen when a transmission is detected in the channel. When a successful transmission is obtained CW is set to CWmin.

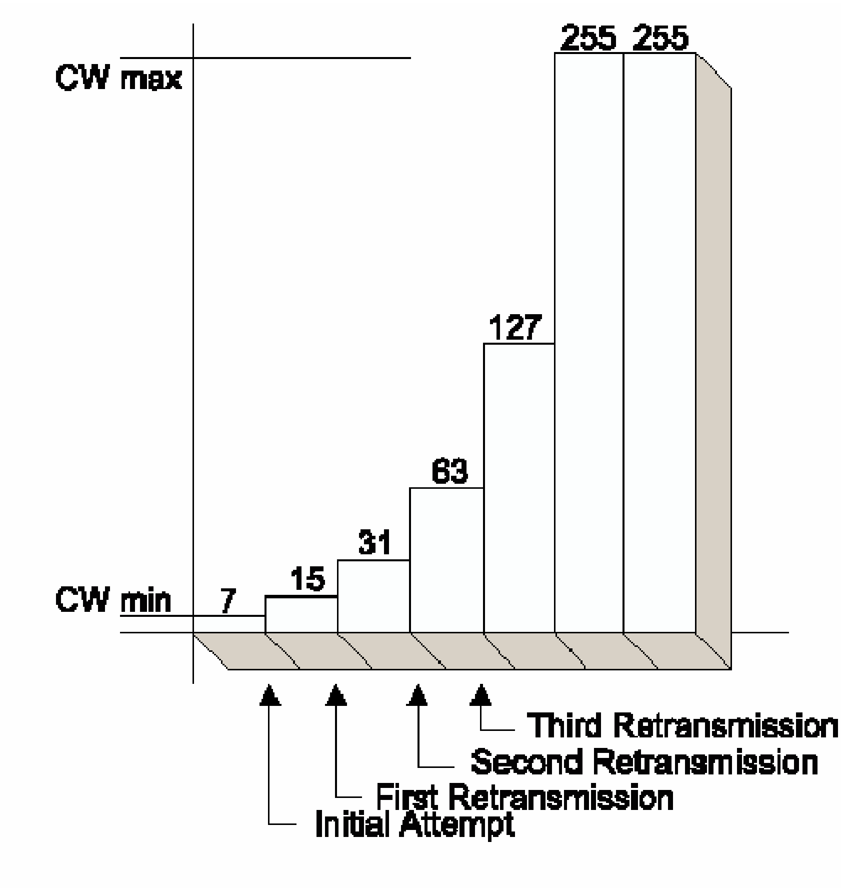


Fig.2.5 An example of exponential increase of CW [10]

2.1.5 Frame Types

In 802.11, there are three main types of frames:

i. Data Frames: Frames that are used for data transmission

ii. Control Frames: Frames that are used to control the access to the medium (i.e. RTS, CTS, and ACK)

iii. Management Frames: Frames that are transmitted the same way as data frames to exchange management information, but they are not forwarded to upper layers.

Each of these types is as well subdivided into different subtypes, according to their specific function.

Each packet is preceded by a packet *Preamble & PLCP* Header, which are defined by the physical layer.

Preamble: This field includes symbols for synchronization, channel estimation and start frame for frame timing.

PLCP Header: It contains information that will be used by the PLCP layer to decode the frame (data rates, etc.).

MAC Frame Format:

The MAC frame is used for data and management frames and its general format is shown in Figure 2.6;

Octets 2	2	6	6	6	2	6	0-2312	4
Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Frame Body	FCS

← MAC Header →

Fig.2.6 General MAC frame format [10]

a. Frame control: Includes Protocol version, type, retry, etc.

b. Duration/ID: Duration value used for the NAV calculation

c. Address-1: Recipient address

d. Address-2: Transmitter address

e. Address-3: If FromDS then it is original Source Address, If ToDS then it is the destination address

f. Address-4: Used when Wireless DS is used.The frame is transmitted from one AP to another

g. Sequence Control: Used to represent the order of different fragments belonging to the same frame and to recognize packet duplications

h. CRC: It is a 32 bit field containing a 32-bit Cyclic Redundancy Check (CRC)

RTS Frame Format:

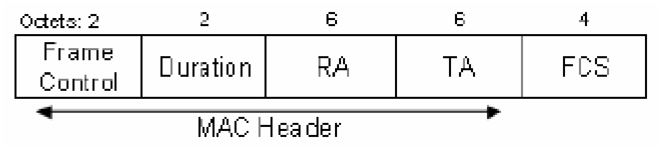


Fig.2.7 RTS frame [10]

a. Duration: Time required for transmitting the next Data or Management frame, plus one CTS frame, plus one ACK frame, plus three SIFS intervals.

b. RA: Address of the STA that is the intended immediate recipient of the next Data or Management frame.

c. TA: Address of the STA transmitting the RTS frame.

CTS Frame Format:

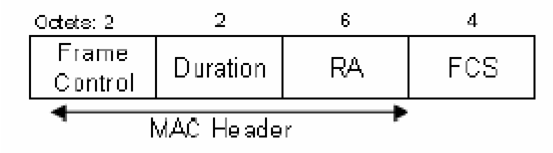


Fig.2.8 CTS frame [10]

a. Duration: It is obtained from the Duration field of the immediately previous RTS frame, minus the time, in microseconds, required to transmit the CTS frame and its SIFS interval.

b. RA: It is copied from the TA field of the immediately previous RTS frame to which the CTS is a response. It is actually the destination of this packet.

ACK Frame Format:

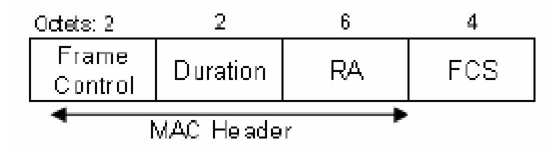


Fig.2.9 ACK frame [10]

a. Duration: It is obtained from the Duration field of the previous frame, minus the time, in microseconds, required to transmit the ACK frame and its SIFS interval.

b. RA: It is copied from the Address-2 field of the immediately previous frame. It is actually the destination of this packet.

2.1.6 Point Coordination Function (PCF)

Beyond the basic Distributed Coordination Function, there is an optional Point Coordination Function, which may be used to implement time-bounded services, like voice or video transmission. The Point Coordination Function makes use of the higher priority that the Access Point may gain by the use of a smaller Inter Frame Space (PIFS). In PCF mode, using the higher priority access, the Access Point issues polling requests to the stations for data transmission, hence controlling the medium access. In order to allow regular stations the capability to still access the medium, there is a provision that the Access Point must leave enough time for Distributed access in between the PCF.

2.1.7 Ad Hoc Mode

In certain circumstances the users desire to build up Wireless LAN networks without an infrastructure (more specifically without an Access Point). This may include file transfer between two notebooks' users, a coworkers' meeting outside the office, etc. The 802.11 Standard addresses this need by the definition of an "ad hoc" mode of operation. In this case there is no Access Point and part of its functionality is performed by the end-user stations (like Beacon Generation, synchronization, etc.), and other functions are not supported (like frame-relaying between two stations not in range, or Power Saving).

2.1.8 Physical Layer

The 802.11 standard also defines the specifications for the physical layer that will be used by the air interface. The specification is mainly composed of characteristics such as type of modulation, carrier frequency of operation, channel bandwidth and transmission power.

The first draft of the standard supported the use of frequency hopping spread spectrum (FHSS), direct sequence spread spectrum (DSSS) and Infrared (IR) [10]. By the development of the standards, the specifications have been expanded to allow for higher data rates and the use of a different frequency band which resulted in 802.11b, the operation of the network is at data rates of 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps. The standard offers organizations an affordable, fast and easy to integrate wireless LAN solution. The standard can support 11 channels in the available 2.400-2.4835 GHz band. The coverage area supplied by 802.11b is 150 meters. By the increase of distance between wireless nodes, the effective data rate decreases. The 802.11b standard was the first to be used by industry and it allows the use of frequencies in the range 2.400-2.4835 GHz, which coincides with the frequency of operation of home appliances such as microwave ovens and DECT systems. The frequency band of the operation is referred to as the ISM (Industrial, Scientific and Medical) radio band. The IEEE 802.11a standard was introduced to provide increased data rates. IEEE 802.11a can support data rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps and operates at the 5 GHz band referred to as the UNII (Unlicensed National Information Infrastructure) radio band. The gain in bandwidth is obtained by using orthogonal frequency division multiplexing (OFDM) modulation. The two standards, 802.11a and 802.11b are not compatible with each other. In order to use both standards together 802.11g is introduced, which uses (OFDM) to enable high data rates in 2.4 GHz frequency band.

2.2 Overview of Smart Antenna Technology

A smart antenna system is defined by the IEEE, an antenna system that has circuit elements associated with its radiating elements such that one or more of the antenna properties are controlled by the received signal [16]. In these systems, each transmitter located at a certain place has its unique pattern, which is also called spatial signature [17].

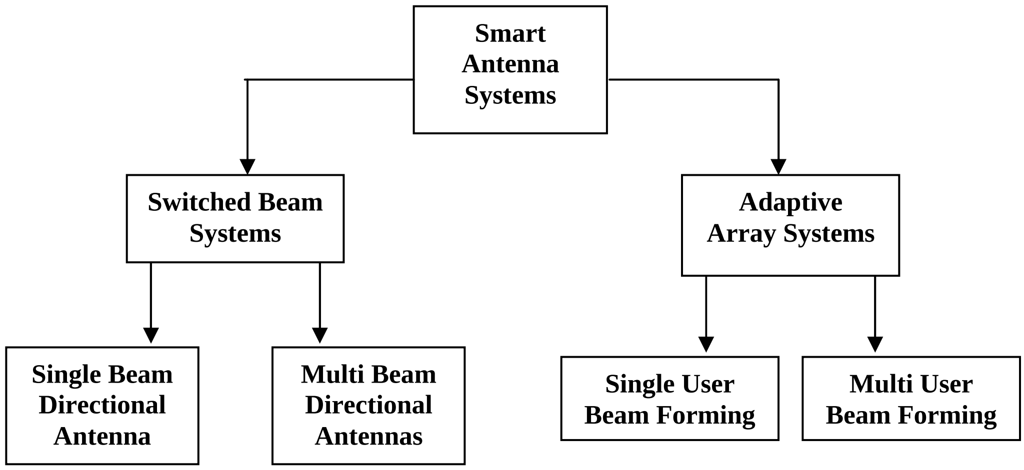
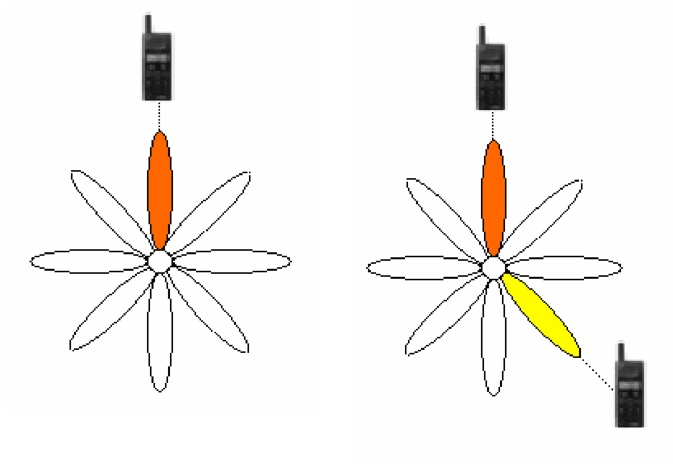


Fig.2.10 Classifications of Smart Antenna Systems

Figure 2.10 shows a generalized classification of smart antenna systems. There are basically two types of smart antennas: Switched beam systems and adaptive array systems. The switched beam system comprises only basic switching between separate directional antennas or predefined beams of an array, while enabling high directivity and gain [17]. Switched beam systems can be further divided into two groups: single beam and multi beam directional antennas. In single beam directional antenna systems (Fig.2.11.a), only one beam is active at a given time. No simultaneous transmissions are allowed, since in this system there is only one transceiver. On the other hand, multiple beam directional antenna system is an example of Spatial Division Multiple Access (SDMA) system. Here, each directional antenna beam can be used and thus multiple transmissions are allowed at the same time and frequency. The number of beams is equal to the number of transceivers as shown in Fig.2.11 (b).

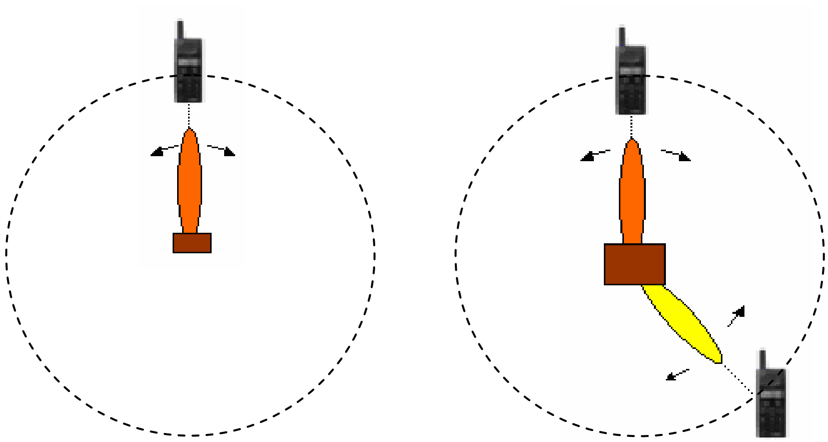


(a) single beam directional antenna

(b) multi beam directional antenna

Fig.2.11 Switched Beam Smart Antennas

Adaptive array systems apply adaptive beam forming where a Direction of Arrival (DoA) [18] algorithm is used to determine the direction of the signal received from the user. By this way, users can be continuously tracked. Also, interferer detection of the interferers can be added to beam forming systems, so that interference is cancelled by adjusting the radiation pattern nulls and thus the Signal to Interference Ratio (SIR) is increased.



(a) single user tracking

(b) multi user tracking

Fig.2.12 Adaptive Array Smart Antennas

Clearly, adaptive beam forming is more complex than switched beam systems. There are also two kinds of adaptive beam forming: In single user beam forming, the antenna beam is adjusted to track one user and cancel the interferers. In this case, a single transceiver is sufficient since only one user is active at a given time as shown in Fig.2.12 (a). In multi user beam forming, there are different beam patterns, and each beam tracks one user. Therefore, simultaneous transmissions are allowed and SDMA is achieved, Fig.2.12 (b).

All types of smart antennas change the broadcast nature of the wireless channel. Random access MAC algorithms that depend on sensing the link, specifically 802.11's MAC cannot be directly applied. The MAC layer will determine the actual throughput that the users will experience. In the ideal case (for a perfect MAC protocol and in Multi Input Multi Output system, MIMO), the throughput will be increased N fold, where N represents the number of spatial channels in use [19].

2.3 Overview of MAC Protocols for Smart Antennas

IEEE 802.11 medium access control (MAC) protocol and physical layers (PHY) are not designed to work with directional/smart antennas. In this section, we will revise the MAC protocols that are proposed in literature for smart antennas.

2.3.1 MAC Protocols with Switched Beam Systems

In single beam systems, the nodes are equipped with a switched system and they choose one of the predefined beams. A directional antenna can transmit over a small angle and several directional antennas can be used together to cover all directions (e.g. 4 antennas with 90^o aperture). Based on the location information (it may be obtained using the Global Positioning System (GPS) [6] or a station may inform its location information to its neighbors periodically using beacons [17]), the sender may select an appropriate directional antenna to send packets to the receiver.

In [6], Directional MAC (D-MAC) protocol was suggested by Vaidya et al, where RTS/CTS packets can be exchanged directionally and the data packets are sent directionally. In this protocol, it is assumed that every user knows its neighbors' locations. In 802.11, if a node X is aware of an on-going transmission between some other two nodes (due to the receipt of RTS or CTS from those nodes), it will not participate in a transfer itself – that is, X will not send an RTS, or send reply to an RTS from another node, while the transfer between other two nodes is in progress. The directional MAC protocol applies a similar logic, but on a per-antenna basis, i.e., D-MAC performs carrier sensing on a per-antenna basis. If antenna T at node X has received an RTS or CTS related to an on-going transfer between two other nodes, then node X will not transmit anything using antenna T until that transfer is completed. Antenna T is put into "blocked" state for the duration of the transfer. The duration of transfer is included in each RTS and CTS packet, therefore, each node can determine when a blocked antenna should become unblocked. RTS packets are sent in omni mode if none of the directional antennas are blocked, and they are sent directionally if one of the antennas is blocked. Omni directional transmission can be performed if and only if none of the directional antennas are blocked. However, CTS packets should always be sent in omni mode. However, after the channel is reserved between 2 nodes, data is sent directionally.

Figure 2.13 summarizes the operation of the D-MAC [6] protocol. The black bars indicate that these nodes are not allowed to transmit in the duration covered by bars. Suppose that, node B wants to transmit a data packet to node C. Since none of node B's antennas are blocked, it sends an Omni directional RTS (ORTS) to node C. After receiving the ORTS packet, node C replies with an Omni directional CTS (OCTS). Following the reception of OCTS packet successfully, node B sends the data packet directionally to node C. Nodes A and D defer their transmissions in that direction, so as not to interfere the transmission between B and C. Assume that node D also wants to transmit a packet to node E. This time node D sends Directional RTS (DRTS) to node E, and node E responds with OCTS. After receiving the OCTS from node E, other nodes such as node F is not allowed to transmit packets from their directional antenna that is faced to node E. Now, consider the case if G wants to transmit a packet to F and sends an ORTS. F cannot reply with OCTS, since it is blocked by node E, and G keeps on transmitting ORTS packets to F. As a solution for this case, F sends a Directional Wait To Send (DWTS) packet to G, indicating for how long it is blocked in the duration field. By this way, G defers its transmission. At the end of defer period, G sends its RTS packet, F responds with OCTS and directional data transmission starts between F and G.

The protocol suggested above has better throughput performance than 802.11 where in some scenarios it doubles the throughput of 802.11. These results were obtained by simulations in [6]. In the D-MAC protocol, the location information can be included in RTS/CTS messages, where nodes get their own positions using GPS. However GPS is not suitable for indoor applications, so obtaining the location information is a problem.

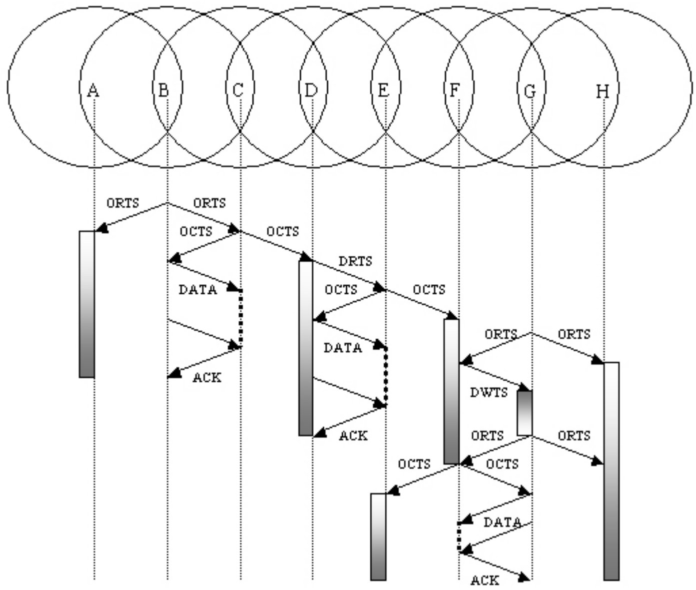


Fig.2.13 Operation of D-MAC protocol

In [20], another MAC protocol is proposed for single beam directional antennas, where the location information is obtained by Direction of Arrival Algorithm (DoA). This algorithm depends on selecting the antenna on which the maximum power has been received. All nodes are equipped with directional antennas. The nodes first exchange RTS and CTS packets in omni mode and the power and direction information is extracted from the RTS/CTS packets. When an RTS packet is sent, each directional antenna at a node receives the incoming RTS signal, but with different magnitudes. The antenna selector compares the received power at the antennas and chooses the maximum power received antenna. Then, the receiving node replies by a CTS packet in omni mode. This time the sender node selects its best antenna similarly, as shown in Fig.2.14. After the RTS/CTS exchange, the data packet is sent and captured with the selected directional antennas. Simulations in [20] show that, the peak throughput nearly doubles when 180^o directional antennas (2 beam sectors) are used in place of omni directional ones. On the other hand when the number of directional antennas per node is increased beyond 2, the incremental improvement of throughput is less pronounced. For example if 4 directional antennas are used, the improvement is 2.5 or 3 times over omni mode.

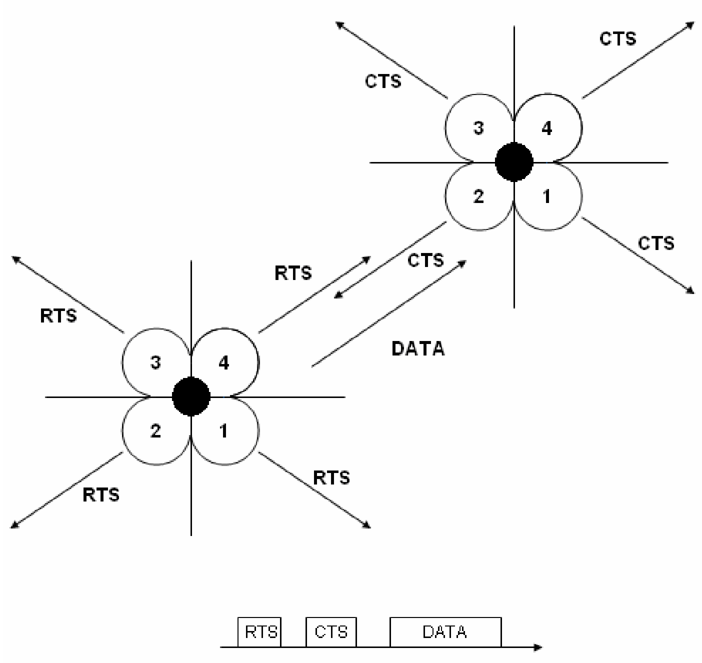
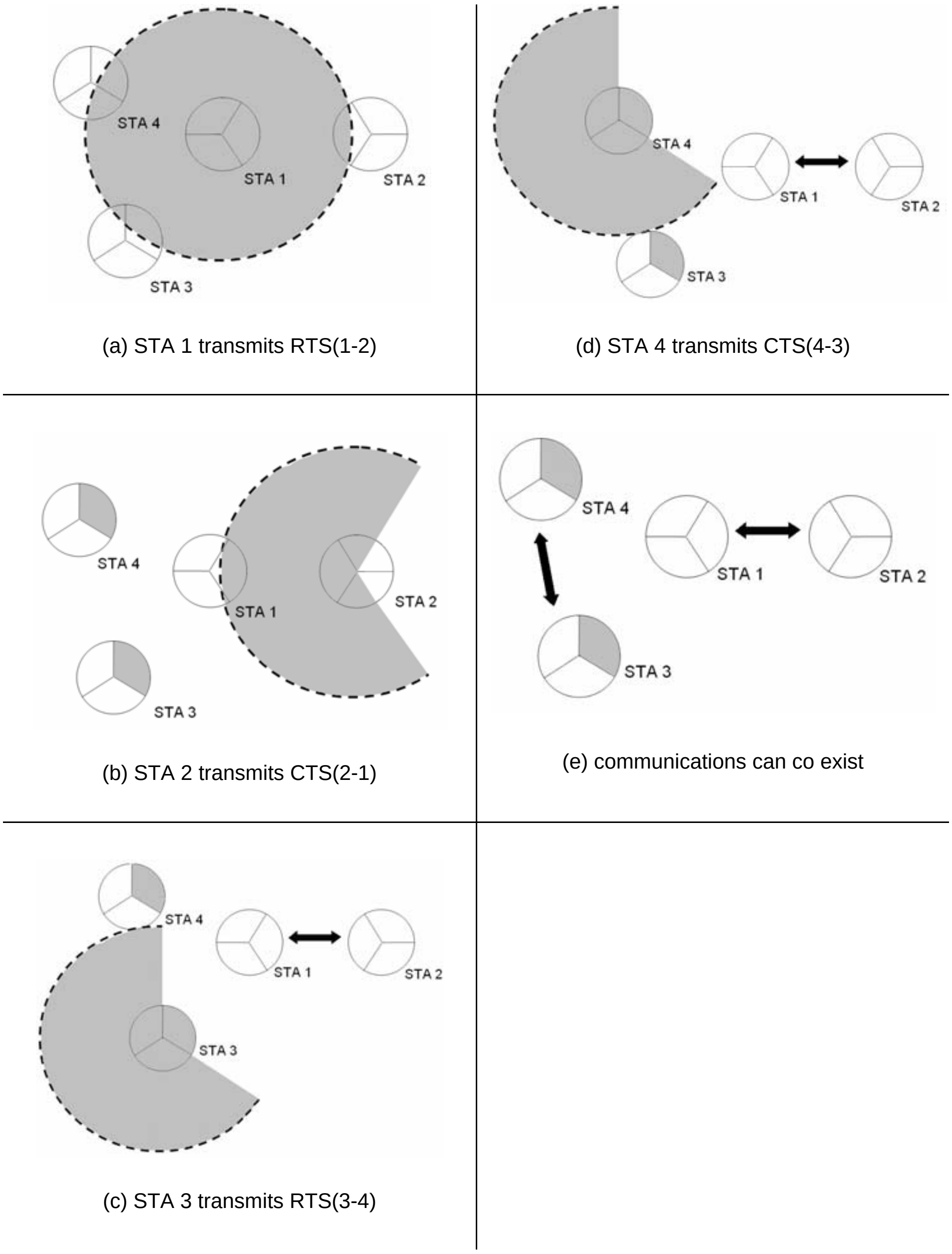


Fig.2.14 Operation of DoA based MAC [20]

In [8] dividing the channel by directivity of sector antennas is proposed, which is named as “Directional CSMA/CA (D-CSMA)”. This proposal makes channel usage efficient since many terminals can transmit their packets simultaneously. The terminals adjust the NAVs in each sectored antenna. When packets arrive at one station (STA), even in the case when there is only one available sector, a STA can transmit its own packets by the available sectors left after sensing and contending for the channel. In Fig.2.15, the meshed sector is the adjusted NAV. After the handshaking between STA1 and STA2, STA3 can transmit data to STA4 by using available antenna. To sum up, there is a case when STAl can share the same channel with STA3 at the same time.

In the proposed protocols of [20] and [8], there is major drawback: If a node attempts to transmit to another node that is already busy in a direction that cannot be detected by the attempting station, the deafness problem occurs. Since destination node cannot reply, successive collisions and retries are caused and the throughput gained from directional transmission is reduced.



(a) STA 1 transmits RTS(1-2)

(b) STA 2 transmits CTS(2-1)

(c) STA 3 transmits RTS(3-4)

(d) STA 4 transmits CTS(4-3)

(e) communications can co exist

Fig.2.15 System image of D-CSMA [8]

Deafness is the problem of nodes that are unaware of the communication of other nodes with directional transmission, which was introduced by Vaidya and Choudhury in [21]. Consider the example, in Figure 2.16: Node A would not attempt communication to node C, if A was aware of the ongoing dialog between C and D. However if node A is unaware of the communication between C and D, it will send RTS packet repeatedly unless it is equal to the RTSLongRetryLimit that is 7 in IEEE 802.11. Unfortunately, at the end of retries, node A will drop the packet.

Vaidya and Choudhury proposed to use ToneDMAC algorithm in [21] for this deafness problem. They suggested using some portion of the frequency spectrum as a control channel in the same band of wireless local area networks to warn the surrounding nodes. Surely, this forces a new regulation in the frequency band of WLAN systems to implement their proposed protocol.

Korakis et al have proposed to steer the RTS beam and send data in different directions sequentially [22]. This requires some time delay to finish steering and establishing the link. During the steering interval, all nodes in the network remain silent and the network capacity is wasted. In addition, the exchanged RTS and CTS messages in [22] do not allow the other nodes start communication immediately after start up.

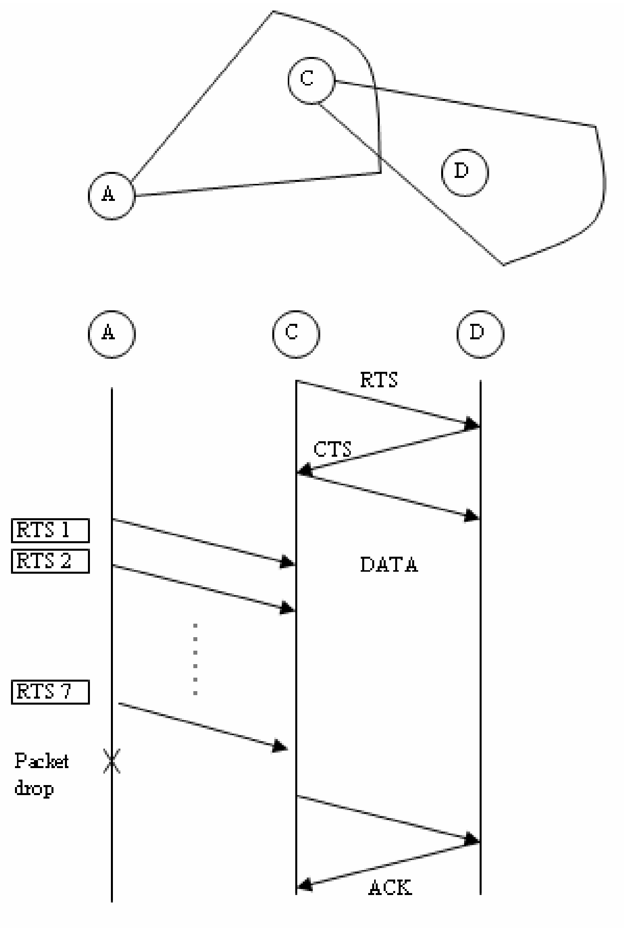


Fig.2.16 Problem of deafness [21]

In the next subsection we consider adaptive smart antennas and we present some MAC protocols proposed for adaptive beam forming systems.

2.3.2 MAC Protocols with Adaptive Beam Forming Systems

Adaptive beam forming systems rely on algorithms that steer the main lobe of the antenna beam in the direction of the desired user and simultaneously place nulls in the direction of the interfering users' signals. The tradeoff in the beam forming systems is the effect of the length of the training sequence [23]. Popular beam forming algorithms like Recursive Least Squares (RLS) algorithm use a training sequence to obtain the desired beam pattern, while blind beam forming methods such as the Constant Modulus Algorithm (CMA) do not impose such a requirement [24].

Single user beam forming allows nodes to change the direction of their single beam pattern to the signal of interest more accurately than single switched beam systems. Larger Short Interframe Space (SIFS) time (the shortest interval between frames) or longer RTS/CTS packet sizes have been proposed to allow more time for antenna adaptation [25]. A Time Division Duplex (TDD) system is preferred so that the estimated weighting coefficients will be valid in both the base-to-remote and remote-to-base directions.

Govindarajula proposed a MAC layer protocol for ad hoc networks with nodes that are equipped with smart antennas and use single user beam forming [26]. In the proposed protocol, training packets are exchanged after the successful reception of RTS and CTS packets. As shown in Figure 2.17, the transmitter and receiver training sequences, TXTRN and RXTRN, are used to adjust the antenna weights, at both the transmitter and the receiver. Then data packet is sent to the destination node directionally. After the transmission ends, the antennas are set back to omni mode. It is also important to note that, the Network Allocation Vector (NAV) covers until the end if TXTRN packet for neighbors in omni mode.

It is reported that smaller beam widths and lower side lobes lead to lower co-channel interference, which results in increased throughput. In addition, higher throughput performance can be achieved by having an adaptive null toward the interfering signal. On the other hand, network throughput drops and the packet delay increases rapidly with increasing training packet size. Furthermore training periods greater than 20% of payload reduce the throughput considerably while training periods lower than 6% of payload increase the throughput 3 times compared to the system where isotropic antenna is used instead of smart antennas [26].

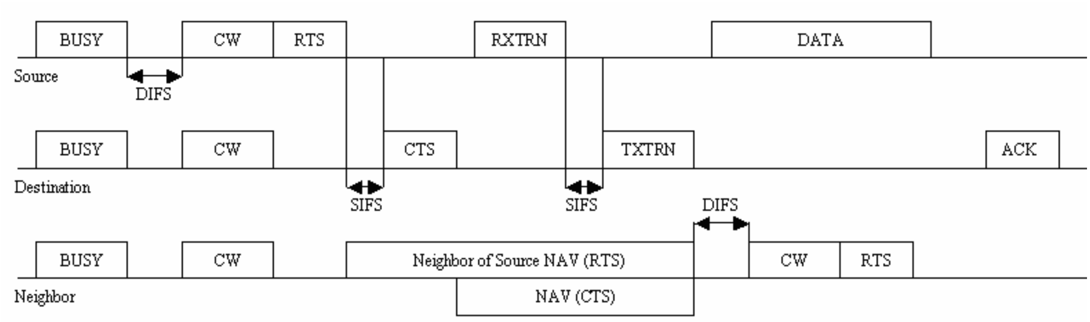


Fig.2.17 The proposed channel access protocol in [26]

For the application of beam forming in PCF based access, invoking a pilot tone from each remote user can be used to allow the base station to continuously adjust the weighting coefficients of its antenna array.

The proposed MAC scheme by Acampora et al, assumes frames of fixed length [25]. Each remote is polled exactly once in every frame where there is a polling segment and a data segment.

In [27], directional protocols that employ beam forming, with contention-based and contention-free polling methods to locate users are discussed. In reception mode, the base station uses packet preambles to obtain information about the spatial signatures of users. These preambles are used to adjust the antenna weights that effectively steer the beam towards the desired user. However, before transmission, the base station may not have the location information of the users. The access point is assumed to have only one transceiver. In contention-based polling, a polling message is sent where the polling message does not contain the address of the user. Users send Polling Acknowledgement (P_ACK) packets to inform the access point their spatial signatures. After getting this acknowledgement, access point is able to adjust the beam pattern. If a collision occurs, the nodes defer the transmission and then try again with probability p. On the other hand, in contention-free polling, polling messages include the address of the user. After receiving this packet, each user responds by sending a known sequence of bits and access point obtains information about the spatial signature of the intended user by this training sequence. It is reported by the authors that contention-free scheme has smaller delay than contention based one for low numbers of beams. However if the number of beams increase (i.e. AP has to poll more stations), the contention-free polling becomes time-consuming [27].

Multiple packet reception and transmission by a node using beam forming is considered in the work by Lal et al, where a node can receive more than one packet from spatially separated transmitter nodes [28]. Here, directional RTS and directional CTS messages are used for throughput enhancement over spatial sub channels, instead of omni directional RTS/CTS. To achieve multiple receptions at a time requires the synchronization of the transmitters in this scheme. However, transmitter nodes cannot synchronize their own transmissions to others, so the receiver initiates a handshake between transmitter nodes. The node that wants to initiate the reception sends an omni directional Ready To Receive (RTR) packet which contains a unique training sequence (Fig.2.18a). Each node replies with a directional RTS message that contains the size of their data packet (Fig.2.18b). After reception of the RTS packet, the receiver informs each of the potential transmitters with the maximum of all the packet sizes requested, by sending a directional CTS to each one, simultaneously (Fig. 2.18c). All the nodes pad their data packet size up to the negotiated value. Finally, data packets are transmitted directionally towards the receivers (Fig. 2.18d). After receiving the data packets, the receiver replies with simultaneous directional ACKs (Fig. 2.18e). Unfortunately, the RTR and RTS packets that are used in this scheme are longer than the typical size of a control packet in 802.11, because non-blind beam forming requires a unique training sequence that is reasonably orthogonal to all other sequences and using such a sequence increases the packet sizes. At low load, it is observed that IEEE 802.11 with omni directional antennas performs better than the proposed scheme. This is because of the extra overhead of RTR packets and the larger size RTR packets in the scheme. It is shown that there is a large performance gain when the load on the wireless channel is heavy. At high loads, for example with 10 nodes in a cell, the throughput of this scheme outperforms the 802.11’s throughput by a factor of 10.

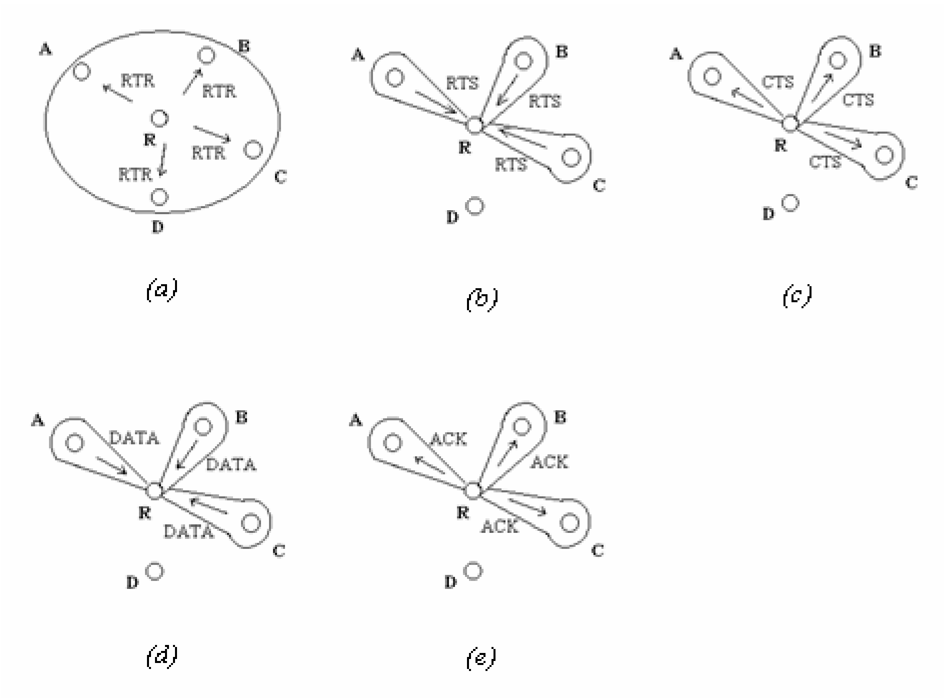


Fig.2.18 Multi reception of packets by a node [28]

If there is more than one user in the beam pattern region, their spatial signatures will be almost same. To separate these users, the beam width of the antenna pattern can be made narrower or a time slotted system can be used. By this way, every node will use the same beam region to transmit, but at different time slots. In [29], a similar system is proposed where there are N_s number of different beams, N_r number of data slots and N_c number of contention slots. The stations make reservation attempts at contention slots and the access point reserves the data slots for the winner nodes at the contention window as shown in Fig.2.19. In this work, it is suggested to use a scheduler to assign time slots fairly to users that are located at the same beam area. The spatial signatures are obtained in the contention period over the uplink channel, and this position information is used by the access point for transmissions over the downlink channel. In this protocol, the access point sends the station identifiers (IDs), available time-space slots, and it informs the stations about the change of the scheduled sequence in the next uplink frame, in a broadcast slot. Figure 2.19 shows three different beams. The users inside these beams transmit sequentially, but the users in different beams transmit simultaneously. If the number of space slots, N_s, increases say 4 times, the throughput increases 4 times, too, with a constant delay [29].

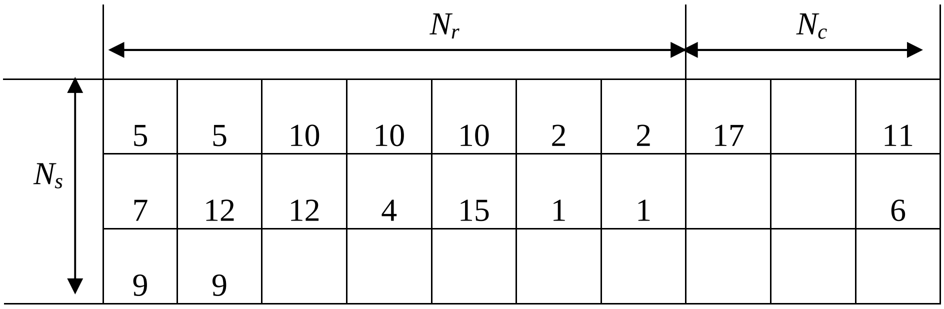


Fig.2.19 Channel access in the proposed protocol at [29]

Here N_s is the number of beams, N_r is the number of data slots and N_c is the number of contention slots. The numbers in the cells indicate the IDs of the users.

The simulation results of the above protocol show that there is a large performance gain over single user beam forming systems even though parallelism is exploited only in the reception process. The delay performance is also examined. The throughput increases and the delay decrease as the number of beams increases. If the beam number is 5, the throughput increases by a factor of 5 and the delay per frame decreases by a factor of 5.

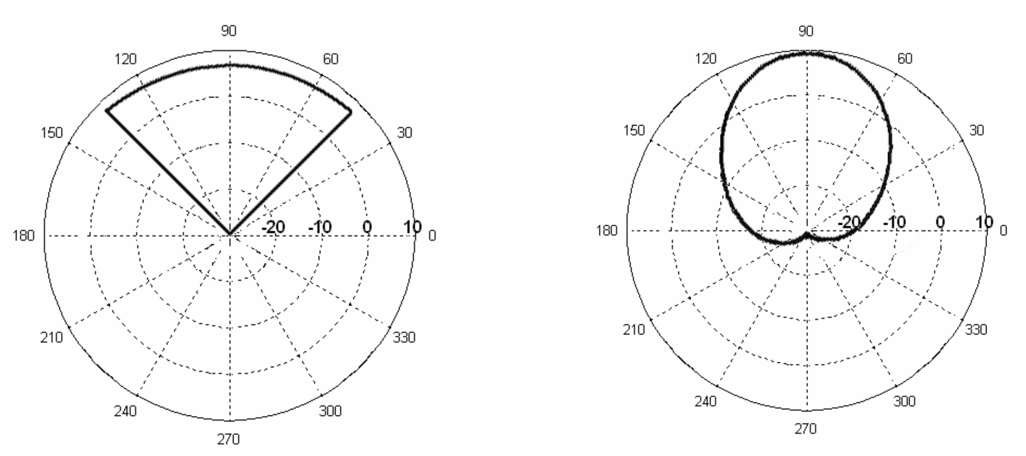
In this thesis, we concentrate on switched beam smart antenna systems. Existing MAC protocols proposed for wireless networks with switched beam antennas have limitations such as deafness, hidden nodes and dependence on topology. We propose a new protocol to overcome these limitations.

3 ANGULAR MAC PROTOCOL (AN-MAC)

In this thesis a new medium access protocol, the Angular MAC (AN-MAC), is proposed for enhancing the performance of Ad Hoc Wireless Local Area Networks (WLANs) by the use of switched beam smart antennas [30].

3.1 Station Properties

In our work, the beam patterns are predefined and fixed according to the radiation pattern of the directional antenna used.

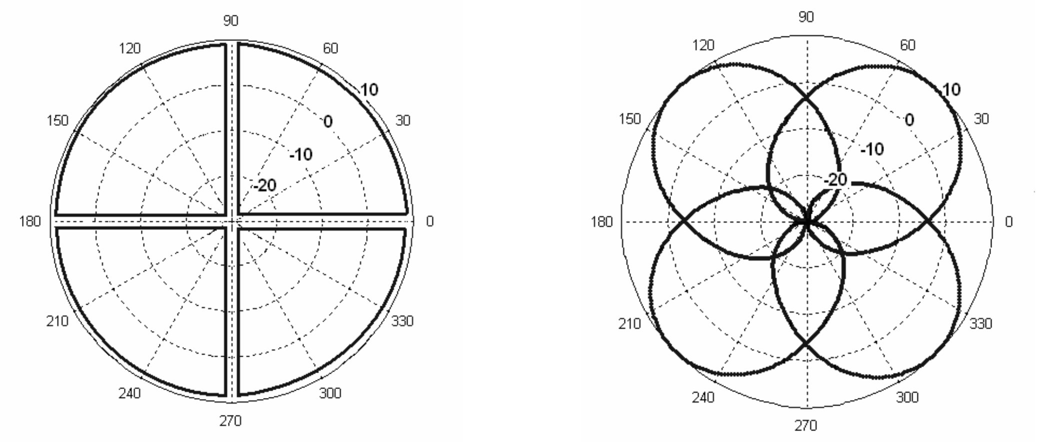


(a) ideal pattern (b) real pattern

Fig.3.1 Antenna patterns used by Angular MAC protocol

We consider two antenna patterns: The first antenna pattern we considered has 10 dBi of directional gain with 90^{o} half-power beamwidth and about 40 dB of front to back ratio. This pattern is assumed to have ideal shape with full reception in the desired direction and rejection in other directions as depicted in Fig. 3.1a. In practice, it is not possible to have a perfect beam shape antenna. Next, we consider a more realistic pattern with sidelobes as shown in Fig.3.1b. The second pattern has 10 dBi of directional gain with 40^{o} half-power beamwidth and about 40 dB of front to back ratio. For modeling this antenna, we used real patterns of commercially available antennas [31]. The four beams together are shown in Fig.3.2 for both ideal and realistic cases. Four antennas in the antenna model cover four different directions: North-East, North-West, South-East, and South-West

We assume that each station uses four individual beams in order to cover all directions and switch between these beams as directed by the ANMAC protocol.



(a) ideal beams

(b) realistic beams

Fig.3.2 Switched beam structure

The switching between beams is done via RF switches. Such RF switches are used to switch between beams in [32]. Stations can monitor the signal level on all beams, and choose the best one. The best beam is defined as the beam over which a station gets a signal with maximum SNR. We need 4 individual RF chips and 1 MAC chip in order to implement the ANMAC as shown in Fig.3.3.

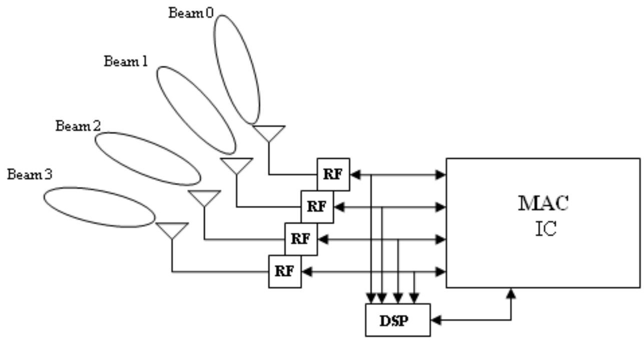


Fig.3.3 Transceiver architecture of the Angular MAC protocol

3.2 Proposed Protocol

3.2.1 Protocol Basics

In this section basic protocol operation will be discussed and the required elements of the protocol are given in detail.

3.2.1.1 Medium Access Table

My Address	Neighbor's Address	My Beam	Neighbor's Beam	Blocking			
				Beam 0	Beam 1	Beam 2	Beam 3

Field	Meaning
My Address	: Who am I?
Neighbor's Address	: Who is in the range of me?
My Beam	: My best beam to communicate with the neighbor in the list.
Neighbor's beam	: Neighbor's best antenna to communicate with me.
Blocking	: Which beams do I have to block?

Fig.3.4 The medium access table

In our protocol, every station uses a *medium access table* to keep the locations of neighboring nodes. The fields of the table are created for each neighbor in every node. The nodes get information about the communication around them both through packets and through the carrier sensing mechanisms to fill the appropriate fields of the medium access table. For example, the neighbor's address field is filled by getting packets from neighbors. The medium access table and meanings of the fields are as shown in Fig.3.4. The use of table will be explained in detail in the protocol operation. (The need for such tables was proposed in [22]. We have improved that approach by adding new table entries in order to overcome the problems of wireless media which will be discussed later.)

3.2.1.2 Packet Formats

In IEEE 802.11, RTS and CTS packets are used to warn other nodes about the next packet exchange between nodes to reserve the medium for a limited time as explained in Chapter 2. In our protocol, these packets are used not only to reserve the medium but also to give information about the locations of communicating nodes. For this reason, we have added new fields to these packets.

The format of the modified RTS, namely Angular RTS (AN-RTS), packet is shown in Fig.3.5. In addition to the existing fields of RTS, AN-RTS packet has an extra "Transmitter Beam Number" field.

Octets:	2	2	1	6	6	4
	Frame control	Duration	Transmitter Beam Number	Transmitter Address	Receiver Address	FCS

Field	Meaning
Duration	: Duration of the communication
Transmitter beam number	: The beam number of this signal at source node
Receiver address	: Destination node of the packet
Transmitter address	: Source node of the packet

Fig.3.5 AN-RTS Frame Format

In addition to the existing fields in IEEE 802.11's CTS packet, Angular CTS (AN-CTS) packet has transmitting address, receiver's best beam number, transmitter beam number, and transmitter's best beam number fields, as shown in Fig.3.6.

Octets:	2	2	6	6	1	1	1	4
	Frame control	Duration	Transmitter Address	Receiver Address	Transmitter Beam Number	Transmitter's Best Beam Number	Receiver's Best Beam Number	FCS

<u>Field</u>	<u>Meaning</u>
Duration	: Duration of the communication
Transmitter address	: Source node of the packet
Receiver address	: Destination node of the packet
Transmitter beam number	: The beam number of this signal at source node
Transmitter's best beam number	: Transmitter will send packets over this beam
Receiver's best beam number	: Receiver will accept packets over this beam

Fig.3.6 AN-CTS Frame format

3.2.1.3 Basic Protocol Operation

We describe the protocol operation and steps over an example scenario given in Fig.3.7. Suppose that node A wants to transmit a data packet to node B. Node A sends the AN-RTS (Angular RTS) packet in every direction. The format of this packet is shown in Fig.3.5. From now on, we will use the following notation for the AN-RTS frame: AN-RTS [source beam, source node, destination node].

After getting the AN-RTS packet that is sent from node A to node B and decapsulating it, every surrounding node will be aware of packet exchange between node A and node B. Each station reads the receiver address and if a node is the destination, it marks the maximum power received beam, which is in the direction of source node, to be used at data exchange. The nodes other than the destination node block their own beam at that direction (signal direction obtained from received beam as explained previously) so as not to be interfered by the data exchange between nodes A and B, and not to interfere with the communication between nodes A and B. (After getting the AN-CTS packet from node B, a node may remove the blocking condition on its beam in the direction of node A, if that beam does not interfere with A and B's communication). While blocking the beams, a timer is set after reading the duration field of the received AN-RTS packet. This was called Directional Network Allocation Vector (D-NAV) in [6], which is in fact similar to the NAV of 802.11 but this time, for a specific direction. The beams are released after this timer expires.

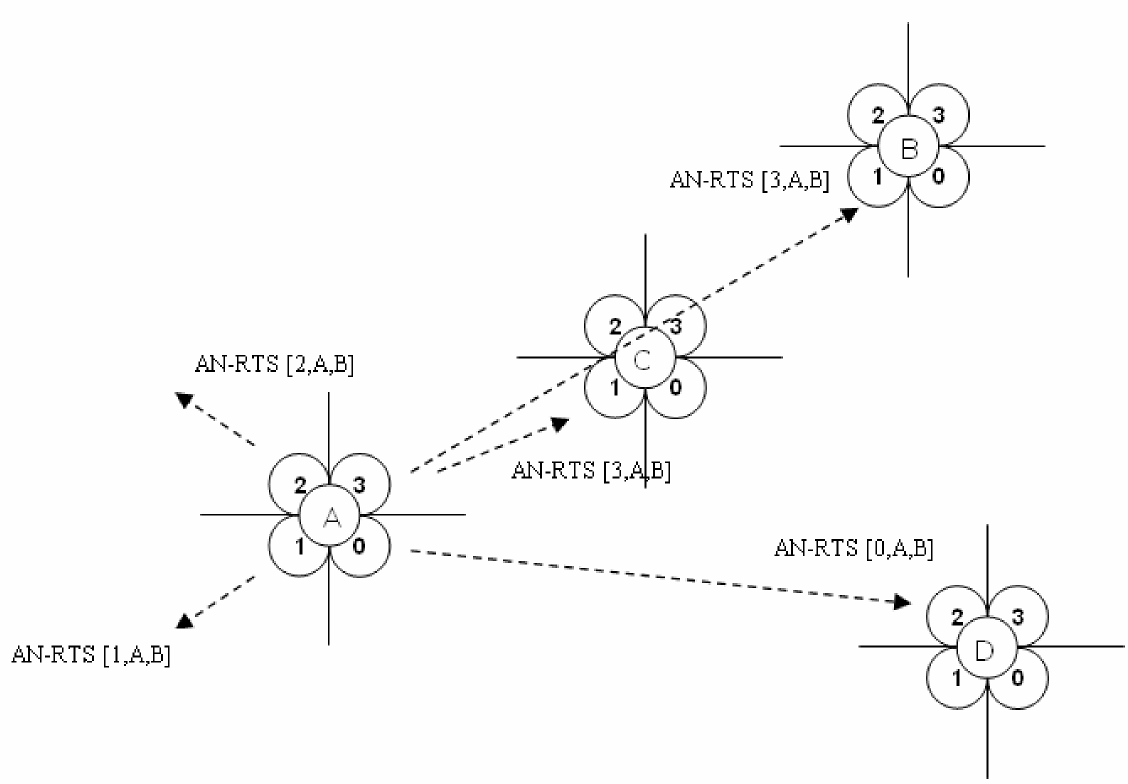


Fig.3.7 Sample topology of nodes

After getting the AN-RTS[3,A,B] packet, node B records the name of the station in its neighbors list, the index number of its receiver's best beam (beam numbered as 1 in Figure 3.7), which is to be used during communication between the two nodes. Node B also determines its best beam in the direction of node A, and records it in the appropriate field in its list. The best beam is defined as the beam over which a station gets a signal with maximum SNR. In this case, since the destination is node B, itself, it blocks all the beams except the best beam (beam 1).

Now, let us consider one of the surrounding nodes, node C in the same scenario. Node C gets the AN-RTS[3,A,B] packet, decapsulates it and records node A into its neighbors list while noting beam number of node A under neighbor's beam field and best beam of itself in the direction of node A, which is the beam with best reception with respect to A. Node C also marks 'no' to blocking field at that direction because at that moment it is unaware of the location of node B. After getting the AN-CTS from node B, node C will mark this field as 'yes' not to interfere with the data exchange. Fig.3.8 shows the configuration of the table at each node, after the AN-RTS packet is received from node A.

My Address	Neighbor's Address	My Beam	Neighbor's Beam	Blocking			
				Beam 0	Beam 1	Beam 2	Beam 3
B	A	1	3	yes	no	yes	yes
C	A	1	3	no	no	no	no
D	A	2	0	no	no	no	no

Fig.3.8 Complete list after getting AN-RTS from node A

AN-CTS frame is sent in all directions, like the AN-RTS frame by node B as shown in Fig.3.9. After getting the AN-CTS, node A finds out that medium is available for communication. However other nodes must not interfere with the communication between A and B, otherwise packets will collide. Along getting the AN-CTS, node A chooses its third beam, which is directed to node B, and it sends the data packet over this beam. When node C gets the AN-CTS packet, it sees that node B's first beam is facing to its third beam. In the AN-CTS packet, the transmitter's best beam field indicates that do not try to transmit to node B over this beam, which is the first beam of node B, otherwise packets will collide. Therefore node C blocks its third beam. On the other hand, node C reads the receiver's best beam field and detects that node A will communicate with node B over its third beam. If node C wants to transmit a data packet to node A, it will look at the medium access table and see that its first beam is directed to node A's third beam. Finally, if node C tries to send a packet during the communication between node A and node B, the packets will collide. To prevent these collisions, node C blocks its 1st beam and third beam as well. It is only allowed to transmit over beam 0 and 2. Beams stay blocked for the time that is read in the duration field of received packet. Node C updates the table with this information.

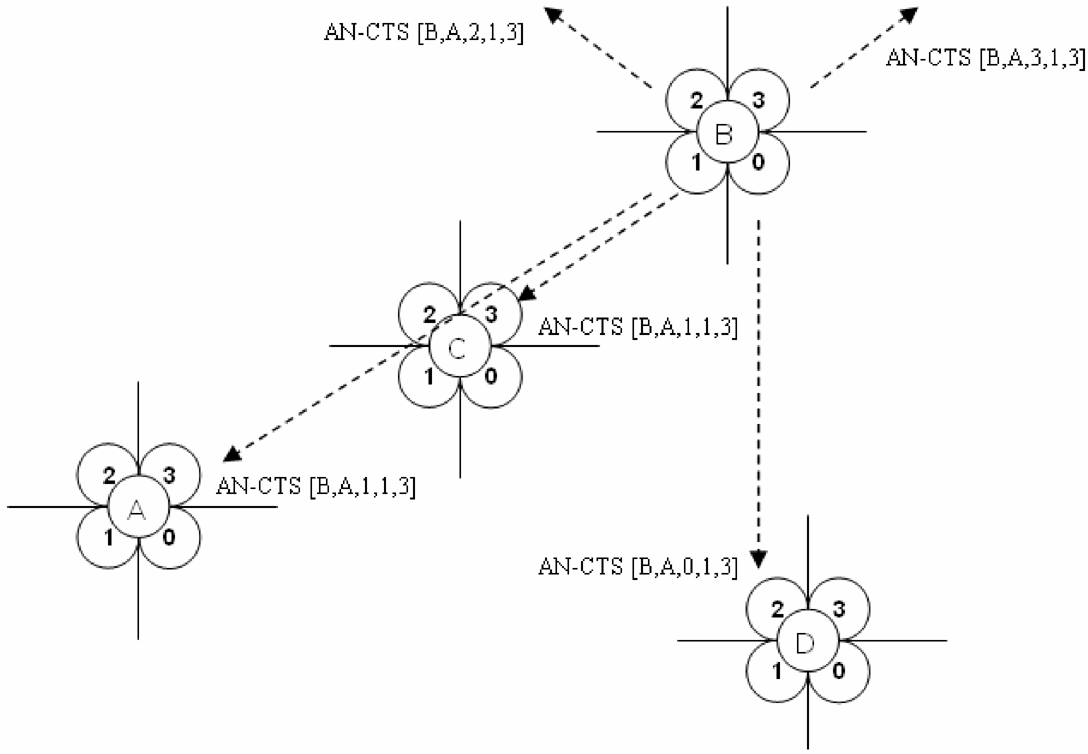


Fig.3.9 Response of node B to AN-RTS with AN-CTS packet

Node D gets the AN-CTS packet over its second beam. It checks the destination address field and notices that the destination node, node A, is in its list. As mentioned before, node A will communicate with node B over its third beam. Node D's second beam faces node A's 0th beam, which will be free during the communication. On the other hand, if node D sends a packet over its second beam, it will reach node B at beam number 0. This will not cause interference on the communication between node A and node B. Figure 3.10 shows the revised location tables at each node, after the AN-CTS frame.

After angular AN-RTS/AN-CTS handshake, node A sends the data over its third beam to node B gets the signal from its first beam. The directional data transmission will essentially reduce the interference and establish a reliable and high quality channel between communicating nodes. During the operation, we may need to mark the orientation of the nodes. In [20], Nasipuri suggested to use a compass. We can assume a similar solution.

My Address	Neighbor's Address	My Beam	Neighbor's Beam	Blocking			
				Beam 0	Beam 1	Beam 2	Beam 3
A	B	3	1	yes	yes	yes	no
B	A	1	3	yes	no	yes	yes
C	A	1	3	no	no	no	no
C	B	3	1	no	yes	no	yes
D	A	2	0	no	no	no	no
D	B	2	0	no	no	no	no

Fig.3.10 Complete list after getting AN-CTS from node B

3.2.2 SDMA Support

In the example scenario in Figure 3.7, suppose that node D wants to talk to node C, while node A is communicating with node B. Nodes have blocked their antennas in directions different from the destination node. Therefore, if the antennas and medium are available, a node can communicate with another node without interfering with the ongoing transmission. This is called Spatial Division Multiple Access (SDMA).

Node D sends a new AN-RTS packet over all unblocked beams. In this scenario, node D has no blocked antenna. Node C hears this AN-RTS packet and it responds with an AN-CTS. However in the list of node C, the blocking field indicates that the first and third beams have been blocked and it can not send any packet over these beams until the communication between node A and node B ends. Hence, node C sends an AN-CTS packet in all directions except to node A and node B. Node C selects beam 0 as best beam, blocks the beam 2 and updates the D-NAV of the previously blocked beams 1 and 3 by the new NAV read from duration field of AN-RTS packet sent from node D. Node D gets the AN-CTS packet from node C from its second beam and blocks beams 0, 1 and 3. After this handshake, node D sends the data packet over its second beam and waits for receiving ACK from node C (Fig.3.11). The network throughput is doubled where two data streams exist in the same basic structure set of nodes simultaneously. Spatial reuse is achieved and SDMA is possible now.

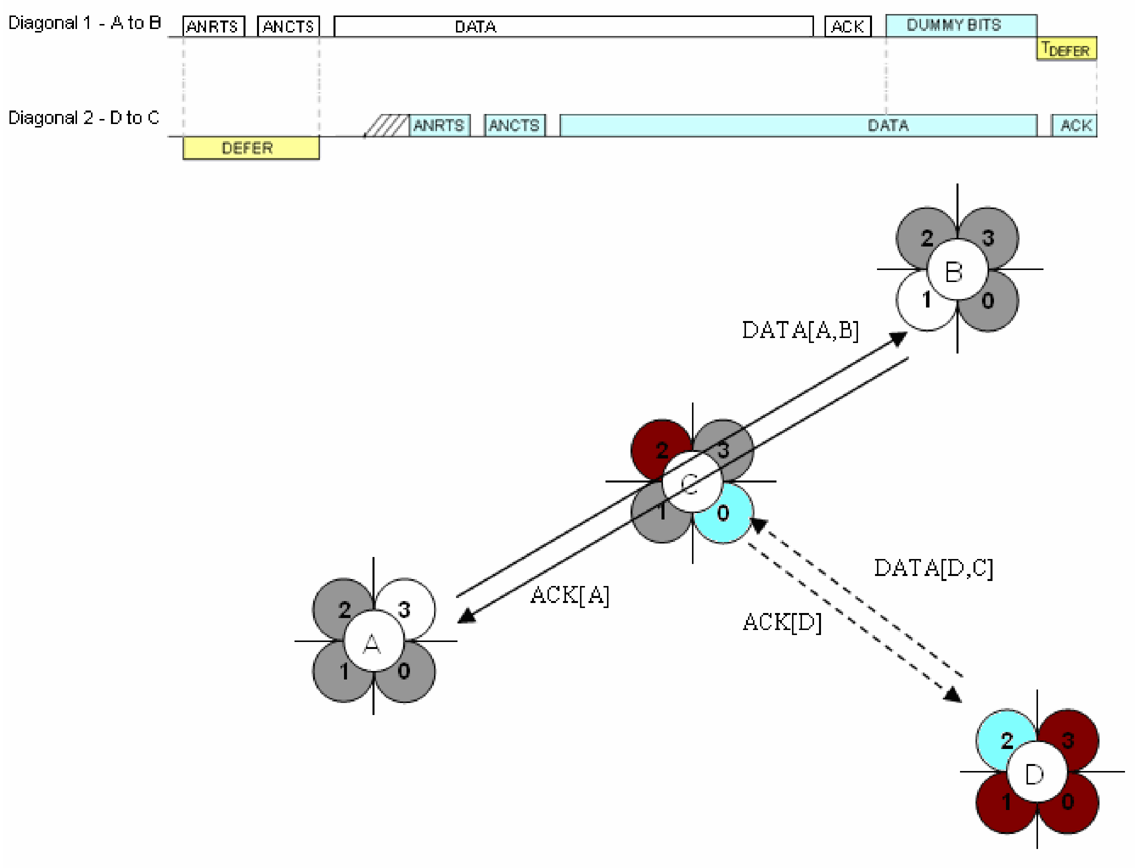


Fig.3.11 Achieving SDMA in the sample scenario

3.2.2.1 Location Based Packet Scheduler

SDMA performance is limited without using a location based smart scheduler. In ad hoc networks, every station may want to communicate with any of the others. In omni-directional WLAN systems, a station creates a packet and contends for the channel in all directions. A single user can capture the channel to communicate with another node and others wait for them to finish and avoid collisions. In case of directional transmission systems, spatial reuse of the channel is possible. This allows simultaneous transmissions between nodes without interfering with each other. However, nodes have to determine the idle stations and the idle sectors to achieve spatial reuse. If two nodes are communicating, another node must not attempt to send a packet to these nodes over its idle sectors. If a node has a packet at the head of its queue to any of the two communicating nodes, it has to enqueue this packet and process the second packet to check whether it is destined to an idle station or a busy one. If the packet is destined to an idle station, the node can try to send the packet to this destination while leaving the first packet in the queue. After completing the transmission, the node checks the availability of the destination of the unsent packet, and contends for the channel to send this packet. The state diagram of the scheduler is given in Fig.3.12.

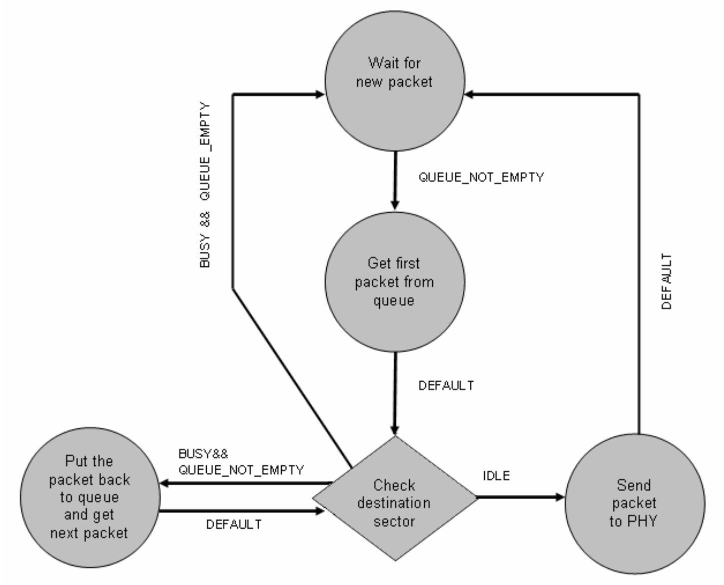


Fig.3.12 Location based scheduler state diagram

The scheduler also provides self-learning of the neighbor nodes' locations. To determine whether a node can send a data packet to another node or wait, the node needs to check the medium access table. If the destination is not in the list, the node will send an AN-RTS packet over all unblocked beams because it is unaware of the location of destination node. Surely, the node looks for the destination node in the medium. But if the station has recorded the destination node in the table before, it can make a decision for sending a packet. With these enhancements unsuccessful, consecutive retries will be avoided and unnecessary queue waiting times will be avoided and the capacity increase obtained with SDMA will be maximized.

3.2.3 Deafness Problem and the Proposed Solution

Deafness is due to the nodes that are unaware of communication of other nodes with directional transmission. With the help of SDMA support, while node A is communicating with node B, nodes C and D can initiate a new data exchange between them (Fig.3.11). There are two possible consequences of this:

i. If the length of the data packet of node D is less than the length of data packet that is transmitted from node A, the data exchange between C and D will be completed before data exchange between A and B. After expiration of the D-NAVs in neighboring nodes and NAV in communicating nodes, the nodes will back-off and re-contend for the channel. By sending a new AN-RTS packet in all directions, the nodes that are going to communicate will inform the other nodes for the next coming data exchange.

ii. If the length of the data packet of node D is greater than the length of the data packet that is transmitted from node A, the data exchange between C and D will be completed after A and B exchange. However, because of deafness, node A and node B will be unaware of the communication between C and D, both nodes will sense the packet from their 0^{th} beam, which has been transmitted from the second beam of node D. These dummy bits will give no information to nor node A neither node B. However, since CSMA/CA algorithm is employed, the signal will be sensed the nodes will defer their communication during the ongoing communication between node C and node D without decoding the packet. After receiving of the dummy bits, the nodes will wait defer some amount of time;

$$T_{DEFER} = SIFS + ACK\_DURATION + DIFS \tag{3.1}$$

to protect the ACK of node D that is destined to node C, so that collisions at node D are avoided as shown in the timing diagram in Fig.3.11. After deference, nodes A and node B will recheck the medium.

Consider the case that data is to be transmitted from node C, although nodes A and B sense the medium, because of the directional transmission, they will both be unaware of the ongoing communication between C and D. At this time, if node A wants to transmit a new data packet, it will send a new AN-RTS packet in all directions because it didn’t block any of its beams. Sending a signal from the 0th beam of node A will interfere the node D’s second beam because it is receiving the data packet over it. If the signal is powerful, the packets will collide and than node D will want to retransmit the same data packet, which will degrade the overall performance of the network.

As considered above, the performances of the medium access protocols that are designed to work with directional antennas are limited to some scenarios because of the deafness problem. However, by the addition of new precautions in our protocol, these problems can be prevented.

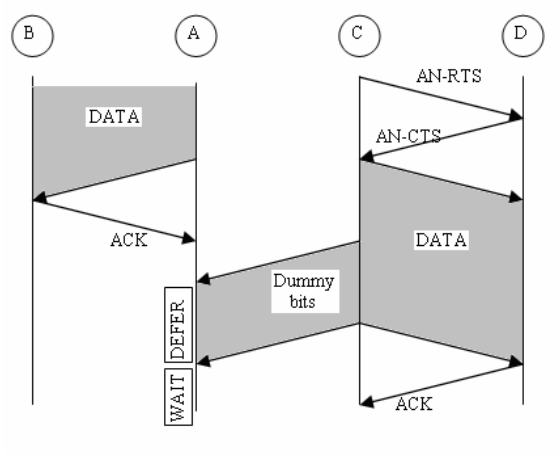


Fig.3.13 Node C warns node A because of its ongoing transmission

In Fig.3.13, if a user (like node C) wants to send a data packet during communication of others (A and B) and if it knows that A and B are communicating (as in our sample scenario), it will calculate the required time to initiate a new transmission and data exchange of its own. Then it will compare the remaining time of D-NAV duration and the required time to transmit a data frame. If it is enough to complete the data exchange in this remaining time, it will send an AN-RTS packet over its unblocked antennas. Doubtless, node C will finish transmission before A to B communication, node A and B will not interfere with the ongoing transmission between C and D. Then all nodes will re-contend for the channel. If the calculated time is greater than the remaining time, node C may wait for the completion of the A to B communication and then it will contend for the channel. If the back-off of node C is smaller than node A, node C will gain the channel and will start its transmission. This will decrease the expected network capacity with the use of directional antennas and give the same performance of omni directional system of current WLANs. On the other hand if the calculated time is greater than the remaining time, node C may send data to D as explained in section 3.2.2. After the completion of A to B communication, D-NAV in node C will expire. Node C may inform A and B by a simple method. After the expiration of D-NAV, node C will open all blocked antennas and send power from those antennas, too (Fig.3.13). Only sending the remaining part of the data packet over all antennas via RF switches [32]. By this way, the surrounding nodes will be aware of the ongoing transmission. These nodes only get dummy bits but this will make them to defer their transmissions because of carrier sensing mechanisms and additionally wait for T_{DEFER} (Equation 3.1) time to protect ACK. At the end of communication between C and D, all nodes will back-off and re-contend for the channel.

3.2.4 ANMAC with *M* Beams

The ANMAC protocol and framework can be generalized to work with any number of antennas. The same rules and packet formats will be applied. If the nodes have 2 antennas and the orientation of nodes is fixed, there will be only one diagonal that the users will communicate and SDMA cannot be achieved. As in our protocol, when the users have 4 antennas, the space can be divided into two diagonals, which can be used for simultaneous communication through SDMA. The number of diagonals will be increased to three, with 6 beams, and to four with 8 beams. (More than 8 beams is not realistic for implementation).

As an example, considering the case with 6 beams, we can extend the timing scenario in Fig.3.11. By the use of ANMAC protocol, while two nodes are using a diagonal, other nodes can now use two free diagonals and start a new communication. After the first or second transmission is completed, both will need to wait until the end of the transmission of the third pair, which can result in performance degradation. Also the third diagonal may not start if there is not enough time for deferral. Therefore, full SDMA requires large packets, in other words packet concatenation. Even larger concatenation size will be necessary when 8 beams are used in a node to enable SDMA for four diagonals. Using large number of antennas in the nodes can give better angular precision for determining the position of neighboring nodes. However, the need for packet concatenation and synchronization are two major limitations. In this thesis, we provide the analysis for 4 beams. The performance of ANMAC in larger number of beams is left out of the scope of this thesis.

3.2.5 Selection of Contention Window Size

As explained in section 2.1.4, 802.11 MAC uses the exponential backoff algorithm for contention resolution. The backoff time is chosen randomly for every packet in a range of [0,W] where W is the current Contention Window (CW) size, and it depends on the number of the transmissions failed for the packet. At the first attempt of the transmission, W is set to W_{min} and if collisions occur, the W is doubled upto CW_{max}. The CW_{min} and CW_{max} are specified in the standard. In 802.11 standard, after each successful transmission, the CW is set to CW_{min}. If we consider a crowded network, setting to CW to a small value may cause collisions and force stations to increment their contention window size, so some amount of time will be wasted due to collisions, and after a while successful transmission can be possible. On the other hand, if the network is lightly loaded, backoff due to CW_{min} may be too long for a small network, where contention is low. To adapt the stations to network conditions, we should determine the best contention window size for the density of the network. In [bianchi] an optimum CW_{min} (W_{opt}), which provides maximum throughput, is derived, for a given number of users in the network;

$$W_{opt} = n\sqrt{2T_c} \tag{3.2}$$

where T_c is the total time spent during a collision and n is the number of stations contending for the medium. In our work, in both omni 802.11 and ANMAC-LS, we use RTS/CTS handshake. Therefore the value for T_c is calculated for RTS collisions that is:

$$T_c = RTS\_DURATION + DIFS + PropDelay \tag{3.3}$$

Generally, stations are unaware of the number of the stations in the network, and the network state needs to be estimated. For this purpose, we propose an algorithm to adapt the CW according to collision and success statistics. The stations can keep track of the number of collided packets, N_c, via carrier sensing and number of successful packets, N_s, by counting ACKs. By finding an optimal ratio between the collided packets and the successfully delivered packets, namely the *success ratio* (N_c/N_s), and relating this ratio to optimal CW, the stations can adjust their CW_{min} values so as to operate at the optimal conditions. The optimum value has been found analytically as follows:

Through a two dimensional Markov chain model, Bianchi obtained the throughput performance of the 802.11 MAC protocol [33]. We use the event probabilities derived in that analysis to find the success ratio, N_c/N_s.

In [33], τ is the probability that a station transmits in a randomly chosen slot time, obtained as

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)} \tag{3.4}$$

p is the probability that a transmitted packet encounters a collision, found as

$$p = 1-(1-\tau)^{n-1} \tag{3.5}$$

P_{tr} is the probability that at least one transmission occurs in a slot time, given by

$$Ptr = 1-(1-\tau)^n \tag{3.6}$$

Ps, the probability that exactly one station transmits, in other words, the probability of successful transmission is given by

$$Ps = \frac{n\tau(1-\tau)^{n-1}}{Ptr} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{3.7}$$

Our *success ratio*, *SR,* can be found as

$$Success\ Ratio = \frac{Nc}{Ns} = \frac{Number\ of\ collided\ packets}{Number\ of\ successful\ packets} = \frac{p}{Ps} \tag{3.8}$$

where n is the number of active stations, m is the superscript of maximum value in 2^m for backoff window and W is the minimum backoff window size in the above equations. In [33] τ and p are solved together to obtain Equation (3.2). Substituting the number of stations to find the W_{opt} and performing Equations (3.4)-(3.7), we can obtain the optimal success ratio, SR_{opt}. If we are to set CW as a binary exponential, the closest power of 2 to W_{opt} should be selected.

Through simulations under the conditions that will be explained in Chapter 4, we found W_{opt} and SR_{opt} for networks of different sizes. For this purpose, we analyzed the effect of CW_{min} on the throughput performance of omni 802.11. The CW_{min} is set to 7, 15, 31, 63, 127, 255 and 511 respectively and the throughput performance is investigated. For a network of 10 nodes, the maximum throughput is reached when the CW_{min} is 63 so W_{opt}=63. The success ratio for this CW is observed to be 0.20. For a network of 40 nodes, the maximum throughput is reached when the CW_{min} is 255, i.e., W_{opt}=255, and the success ratio is obtained as 0.21. When we plug in these values in the above formulas, for the network with 10 nodes, the success ratio is calculated as 0.2177; for the network of 40 nodes, the analytical results showed that the success ratio has to be 0.2279.

This study showed that maintaining the success ratio around 0.2 and adjusting the window size accordingly provides the best throughput performance independent of the number of the nodes in the network. These results were also confirmed by ANMAC-LS analysis and simulations.

3.2.5.1 Dynamic CW Adaptation

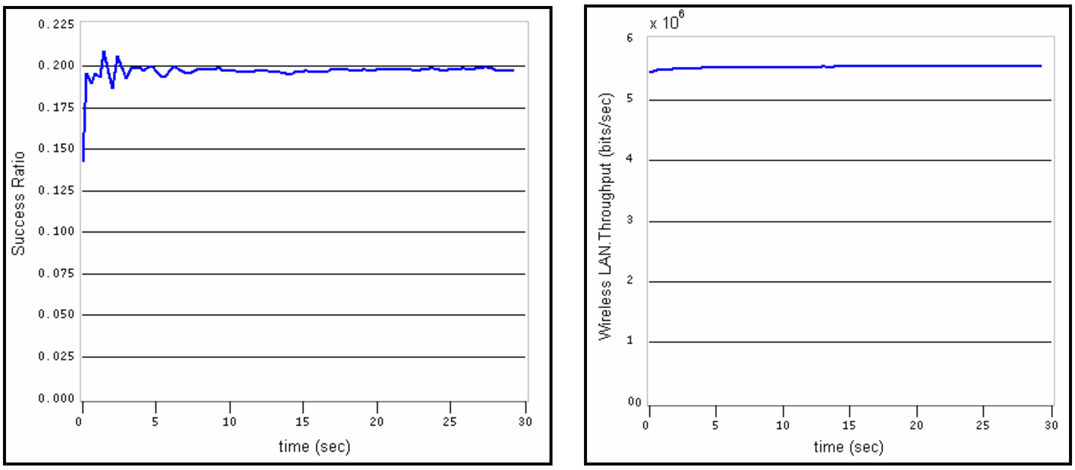
Having determined the optimal *SR* as 0.2, we have designed an iterative algorithm that calculates success ratio dynamically in each node and adapts CW_{min} accordingly. This way, CW_{min} approaches W_{opt}, and eventually *SR* approaches SR_{opt}.

The instantaneous value of *SR* is monitored through N_c and N_s measurements, through collisions in carrier sensing and received ACK packets, respectively. The following algorithm is proposed to update CW_{min}:

```
Initialize CWmin=31;
Measure average(Nc) and average(Ns) over Ts seconds;
if ((SR=Nc/Ns) > 0.2)
      CWmin=CWmin/2;
else
      CWmin=CWmin*2;
```

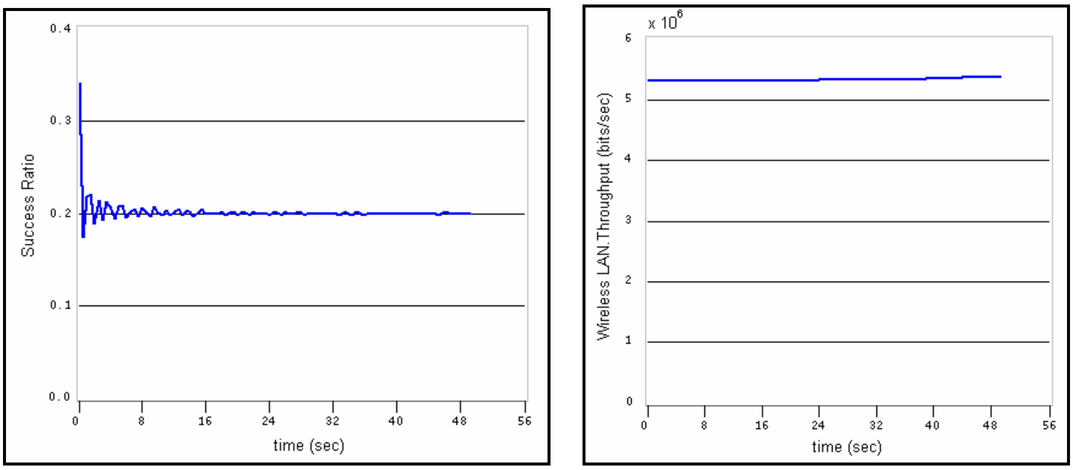
This dynamic CW adaptation algorithm can be applied to ANMAC-LS with a simple modification, since in ANMAC-LS we have two diagonals. Each diagonal can have different number of contending stations in each sector, so each diagonal should have separate collision (N_c) and success (N_s) counters, which can result in different contention window sizes.

The results of the simulations with the dynamic CW adaptation algorithm in omni 802.11 prove the validity of our heuristics. As it can be seen in Fig.3.14a and Fig.3.15a, the success ratio is observed to remain close to 0.2 in a network of 10 stations and 40 stations, respectively. In Fig.3.14b and Fig.3.15b, it is depicted that the throughput always stays at its maximum value.



(a) (b)

Fig.3.14 Performance of the network with 10 nodes with dynamically CW adaptation



(a) (b)

Fig.3.15 Performance of the network with 40 nodes with dynamically CW adaptation

4 SYSTEM MODEL AND SIMULATION ENVIRONMENT

4.1 Introduction

OPNET Modeler, or OPtimized Network Engineering Tool [34], is a network simulation software, providing a comprehensive development environment for the specification, simulation and performance analysis of communication networks, computer systems and applications, and distributed systems. In this chapter, an overview of wireless network simulation with OPNET Modeler is given and the models created to simulate our work are explained.

4.2 Network Modeling with OPNET

OPNET has been designed to support the modeling and simulation of a large range of communication systems from a single LAN to a global satellite network. Discrete event simulations are used as the means of analyzing system performance and their behavior. This sophisticated package comes complete with a range of tools which allows us to specify models in great detail, identify the elements of the model of interest, execute the simulation and analyze the generated output data.

OPNET is an object oriented tool, where each object has a defined set of attributes. In addition, OPNET is a hierarchical system that has three separate domains to describe any communication network. Higher levels use models developed in lower levels. By this way, different generic models can be used under many different scenarios. Library models enable designers to use and modify existing communication processes, protocols, and networks.

OPNET is a discrete event simulation package. The model's progression over simulation time is decomposed into events. An event is executed by the simulation. Multiple events can execute simultaneously (i.e. in simulation time) and can affect different parts of the complete system. An OPNET simulation can be described as a set of states that evolve over time. In this instance, the time is not real time but simulation time. The simulation maintains a variable to record the time and its value has no relationship with real time. This concept ensures that the same results are obtained from a simulation executed on a slow workstation as when the simulation is executed on a more powerful workstation.

4.2.1 Wireless LAN Module

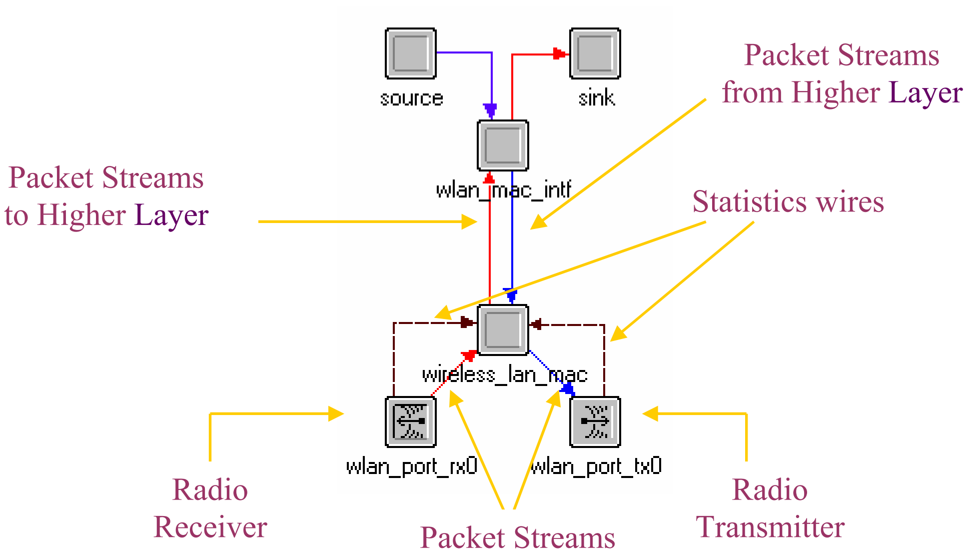


Fig.4.1 Wireless LAN module in OPNET

The Wireless LAN module of OPNET is shown in Fig.4.1. In the model, there are two kinds of connections between processors. The first one is the packet stream line. It is utilized in packet-based communication and used for information exchange between subsystems. The packets in these streams are sensed via interrupts generated by data sensing which is organized by simulation kernel. The second one is the statistics wires. They are used for exchanging values between the attached source/destination ports and for physical carrier sensing that are invoked by simulation kernel. The values are passed to processors to keep track of changes in the transmitter/receiver status.

4.2.2 Communication Channel Model

The wireless communication channel in OPNET is modeled by 13 pipeline stages including antenna gains, propagation delay, signal-to-noise ratio, calculation of background noise and interference noise, transmission delay, etc. The pipelines stages can be found in detail in Appendix-A.

The transmitter power of stations is 100 mW. Antenna gains are included per angle basis at the *receiver antenna gain* and *transmitter antenna gain* pipeline stages. The path loss, which represents signal attenuation, is defined as the difference between the effective transmitted power and the received power. We assume the free space propagation model for the path loss [35]. In Equation (4.1), λ is the wavelength and d is the distance.

$$PL = \frac{\lambda^2}{(4\pi)^2 d^2} \tag{4.1}$$

The background noise is the in-band noise from both background and thermal sources. We set the noise figure of the receiver and calculate effective receiver temperature. We can also set the background temperature. Receiver channel bandwidth is defined at the beginning of the simulation (in Hz). As a result we calculate background noise as follows [35];

$$N = k * T * B \tag{4.2}$$

where k is the Boltzmann's constant, T is the sum of Rx temperature and Background temperature and B is the bandwidth in Equation (4.2). We neglected the multi-path fading. We assume no mobility.

Signal to interference plus noise ratio (SINR) is calculated with interfering packets and background noise. In Equation (4.3), I represents the power received from interfering packets, n includes all interferers, and N is the background noise power.

$$SINR = \frac{Pr}{\sum_{j=1}^{n} I_j + N} \tag{4.3}$$

4.2.3 Antenna Models

Antennas are used in a wireless system for improving the gain of a transmitted signal. An antenna pattern defines the gain on a per-direction basis. Certain wireless systems make use of directional antennas, which provide high gains within a concise region. In the event that the communicating entities are stationary, the antenna can be pointed in a direction to achieve maximum gain. In the event the system contains mobile components, it might be of interest to alter the antenna pointing direction periodically to maximize the gain.

4.3.2.1 Antenna Pattern Usage

Antenna patterns consist of a set of gain values that vary as a function of direction in three dimensions. Thus, from the point of view of a source that is transmitting, its antenna provides a gain value with respect to every other point in space. The same is true of a receiver's antenna, and for a given transmission, the gains of both the transmitter and receiver antennas, with respect to each other, are typically taken into account. Physically, an antenna pattern can be thought of as a three-dimensional object whose shape indicates the relative magnitudes of gain in each direction. The simplest case is a sphere, which represents an antenna pattern known as isotropic. An isotropic pattern radiates (or captures) power equally in all directions. Its gain is equal to 0 dB at all points as shown in Figure 4.2.

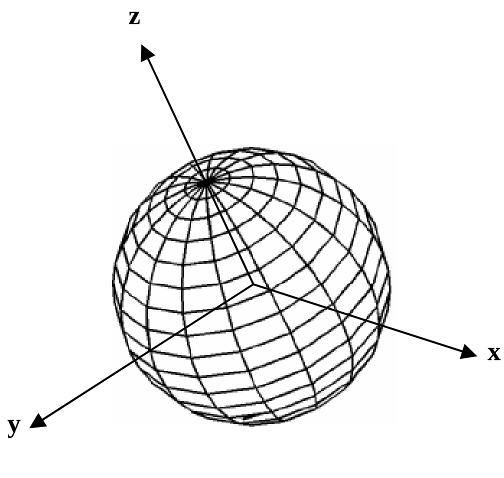


Fig.4.2 Isotropic antenna pattern

Other patterns can be thought of as deformations of the sphere which represents an isotropic pattern, with areas stretching further from the center corresponding to directions of higher gain. Regions of the pattern that are relative maxima of the gain function are called lobes. Likewise, other areas can be compressed toward the center of the sphere, indicating a gain less than unity. Where the gain reaches a relative minimum, the antenna pattern is said to have a null as shown in Figure 4.3.

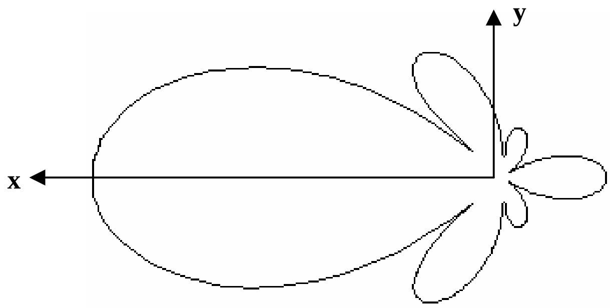


Fig.4.3 Antenna pattern with side lobes

Antenna patterns are defined in a context that is separate from the one in which they are deployed. This is due to the fact that a single pattern can be assigned to multiple antennas in different subnets and with variable pointing requirements. Because a pattern maps gain to all directions in a three dimensional space, it can be represented as a function of two angle variables called Φ and θ (Phi and theta). As shown in the following diagram, the angle Φ varies from 0 to 180 degrees and the variable θ varies from 0 to 360 degrees. Together they uniquely specify all directions in terms of vectors departing from the center of the pattern as depicted in Figure 4.4.

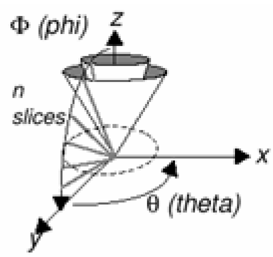
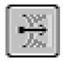
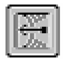
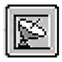


Fig.4.4 Antenna pattern representation in OPNET [34]

OPNET offers users the ability to define the representation of an antenna pattern using the antenna pattern editor. The antenna pattern can be associated with a radio transmitter and/or receiver to provide the gain defined by the pattern using an antenna module in the node editor. This module provides an attribute called "pattern" that allows for the specification of the pattern.

It might be required to define a point on the antenna pattern that will be used as a reference point for pointing the antenna. There exist two attributes of the antenna module that define this pointing direction. These attributes are called pointing ref. phi and pointing ref. theta. There exist three additional attributes that define the target location for which the antenna pointing reference can be pointed. These attributes are called target latitude, target longitude and target altitude.

The Figure 4.5 shows the antenna module and its associated attributes:

Radio transmitter	Allow packet to be sent outside of the node's boundary via radio link	
Radio receiver	Allow packet to be received from other nodes via radio link.	
Antenna	Optionally can be used to exchange packet with other nodes, when antenna directionality or gain need to be modeled.	

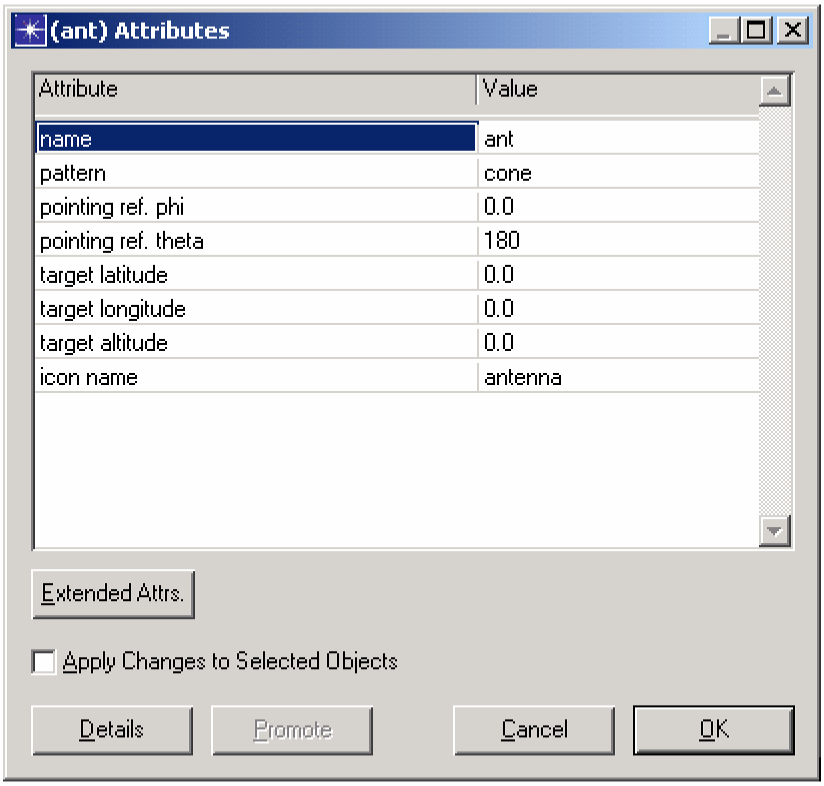


Fig.4.5 Antenna Model Attributes

4.2.3.2 Pointing the Antenna Pattern

To point an antenna pattern, an arbitrary point on the antenna pattern needs to be chosen to serve as the point of reference. Creating an initial pointing reference for an antenna pattern is done by setting the attributes of the antenna node so that pointing ref. phi and pointing ref. theta are set to the point on the antenna pattern which will serve as the aim for the antenna (generally the max gained point-boresight). This aim can change throughout the simulation as desired by the user. The aim of the antenna can be then pointed at a target by setting the targeting attributes with values for target latitude, target longitude, and target altitude. This target of the antenna can also change during a simulation as well, as desired by the user.

Since both point of reference of the antenna pattern and aiming the antenna pattern are attributes of the model, they can be accessed and changed during the simulation. This can incorporate phenomena like an antenna tracking a target or rotation of an antenna attached to a mobile node such as a plane, train, automobile or ship. The attributes can be accessed using kernel procedures like op_ima_obj_pos_get() to attain a location of a mobile node and op_ima_obj_attr_set() to dynamically change the value of an attribute like the target latitude, or pointing reference.

In OPNET, to get location information of the other node, we need its object ID. All nodes register these IDs in a global array that is accessible to all process models. We use a process model called pointing processor which can retrieve the node object ID of the other node from global array by using the kernel procedure op_ima_obj_pos_get() and update the node antenna's target location. It includes longitude in degrees, latitude in degrees, altitude in meters. (0,0) is the reference point to all global variables. If we select a 10 kmx10 km topology while constructing a project, the mid-point (5km,5km) will be set to (0,0) point while calculating the target latitude and target longitude. The altitude is measured from the center of the earth. A node's altitude is the summation of its height above the sea level and the earth's radius that is 6378 km as shown in Figure 4.6.

Antenna patterns in OPNET have been implemented so that users can conveniently create antenna patterns, point them at a target, and dynamically change either their point of reference or aiming direction. This capability accommodates cases where an antenna is rotating or tracking a target. In either case, or many other scenarios, the antenna references as well as its pointing direction can be altered throughout the simulation.

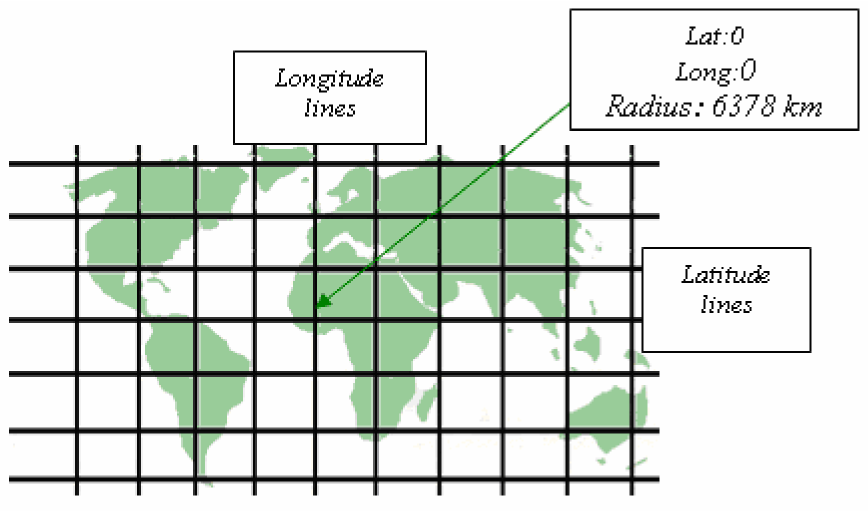


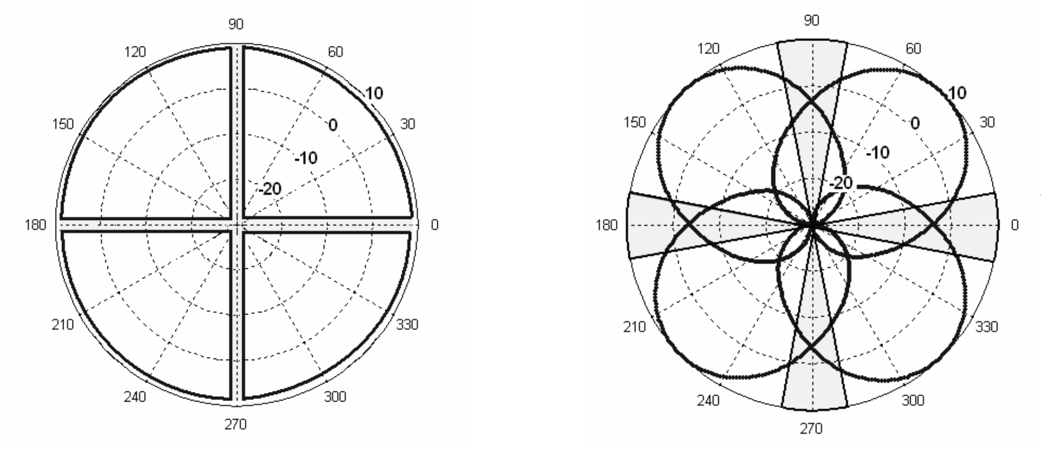
Fig.4.6 Longitude and Latitude lines of the Earth

4.2.3.3 ANMAC Antenna Model

In our work, we modeled antenna patterns by the pattern editor of OPNET and we designed an antenna pointer model that directs the beams in specific directions or dictated by ANMAC.

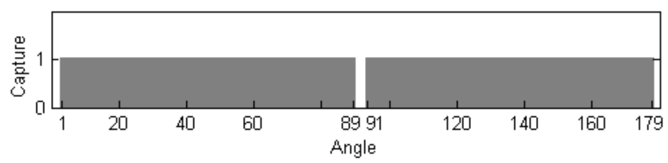
It is worthwhile to note that there must be some difference between power levels of two simultaneously arriving packets in order to capture the more powerful packet from one beam and to avoid collisions. This rejection threshold typically ranges from 1 to 20 dB [36], and we used 10 dB as rejection threshold in our physical model.

Despite being ideal, four perfect antennas can cause overlap regions of total 2^o at the beam edges as shown in Fig.4.7a.These overlap regions are blind angles where packet reception, i.e. capture, is not possible. We simulated packet capture events with ANMAC via our ideal antenna model, and by keeping one of the nodes fixed and rotating the other node around the fixed node, we measured the effective aperture of the ideal antenna pattern. Fig. 4.8a shows the packet capture as a function of angle of arrival ranging between 0 and 180 degrees. This experiment proved that the effective aperture of the ideal antenna pattern is 88^o. In other words, if two nodes are within up to 88^o with respect to each other, they can communicate; otherwise the packets will be lost. The overlapping regions between beams in realistic case are shown in Fig 4.7b. Again, the darken zones indicate the blind regions. The packet capture experiment is repeated for this realistic case as well. Fig. 4.8b shows the packet capture with respect to angle of arrival. For the realistic antenna pattern, the effective aperture per beam is measured as 70^o.

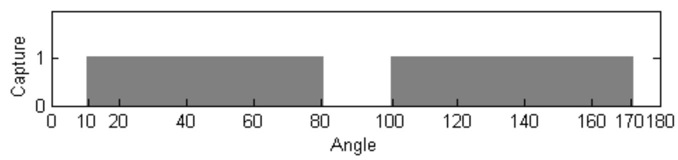


(a) ideal beams (b) realistic beams

Fig.4.7 Switched beam structure of Angular MAC protocol



(a) Packet capture of ideal pattern vs. angle



(b) Packet capture of real pattern vs. angle

Fig.4.8 Relation between packet capture and angle of arrival

These experiments show that the orientation and positioning of nodes with respect to each other is important for successful packet capturing with directional antennas. In this manner, in our topologies for our simulations, we assumed that the nodes are deployed in such a way that they face each other from non-blind angles. The nodes are fixed so that their positioning does not change.

4.3 Modeling ANMAC with OPNET

4.3.1 Node Model

We have modified the existing 802.11 MAC model to implement our new MAC protocol and to provide all necessary interfaces with the antenna models. The designed model is shown in Figure 4.9. Four antennas, each covering different zones, are attached to the MAC processor. The antenna pointer in the node model provides the pointing of the main beam lobe to desired angle. By this way, we can either set the direction of the main lobe or change it during the simulation. Surely, setting the angle to a fixed value enables us to design switched beam systems and changing the angle leads to adaptive systems. Four antennas in the antenna model cover four different directions: North-East, North-West, South-East, and South-West.

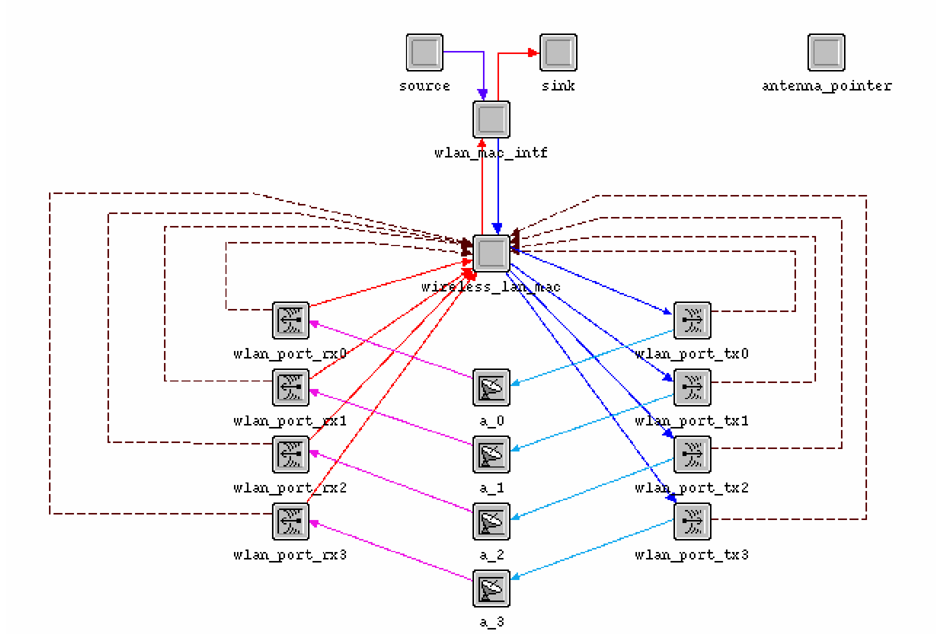


Fig.4.9 OPNET Model of the Angular MAC protocol

4.3.2 Process Model

The MAC process model stores the main code of our model and shown in Figure 4.10. The code is placed in functions and states. During its operation, it observes interrupt types and executes required state transitions. There are two types of interrupts; the stream interrupts occur at either higher layer data arrival or lower (physical) layer data arrival. On the other hand, self interrupts are user defined interrupts which are issued during DCF to be informed for deference (SIFS, DIFS, and EIFS time intervals), back-off elapses, contention window elapses and frame timeouts. In our work we added the interrupts for switching between beams, enabling and disabling (blocking) the beams, checking the sectors and etc.

The Process Model has many states. During simulation, it performs transitions between these states and executes appropriate functions. In **INIT** state, WLAN process registration is completed, all state variables and MAC auto-addressing are initialized. In **BSS_INIT** state, MAC auto-addressing is completed, network configuration is validated and for PCF enabled networks, a list of CF-pollable stations is formed. In **IDLE** state, transmission buffer is emptied and wait for appropriate interrupts. In **DEFER** state, receiver status and network allocation vector (NAV) is checked, if busy, wait until it gets idle and if idle, wait for inter-frame spacing (SIFS, PIFS, DIFS, or EIFS) before advancing to the next state. In **BKOFF_NEEDED** state, decide whether back-off is needed, if needed, check whether starting a new back-off or resuming and compute total back-off duration. In **BACKOFF** state, wait for the completion of back-off period and if the back-off is suspended, compute the remaining back-off duration. In **TRANSMIT** state, transmit Data/Control/Dummy packets and detect collisions if any packet is received during transmission. In **FRM_END** state, detect collisions if any packet is received during transmission. In **WAIT_FOR_RESPONSE** state, wait for the response message until the expected ACK or any type of message is received, or ACK-waiting timer expires. The key functions used to perform operations in the states are given in Appendix-B.

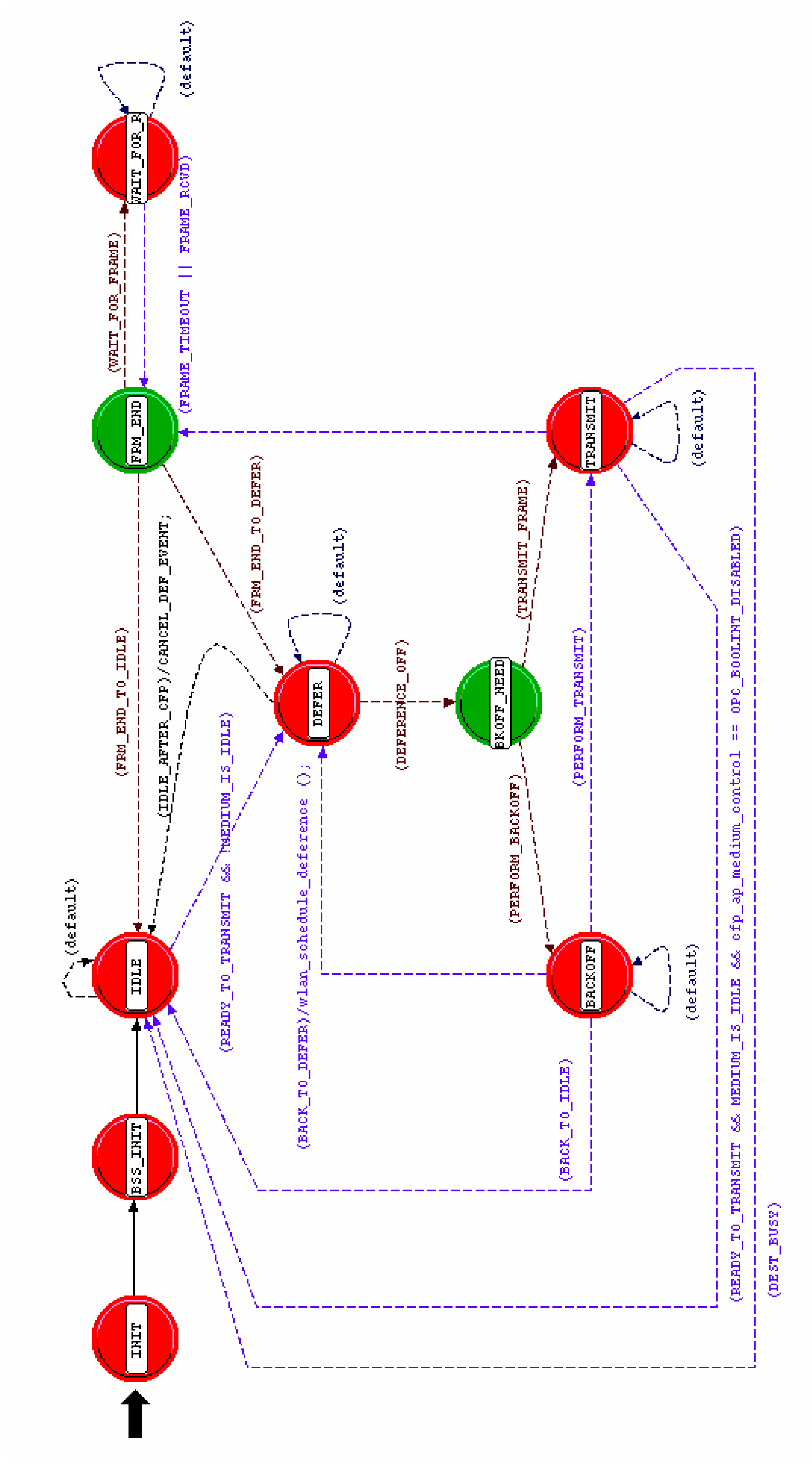


Fig.4.10 Process Model of ANMAC

5 PERFORMANCE ANALYSIS

5.1 Numerical Results

5.1.1 Numerical Omni 802.11b Performance

In this section the maximum throughput of 802.11b obtained by a single station is calculated. The specifications are taken from the 802.11b standard [36] and shown in Fig.5.1. Fig.5.2 shows the total communication sequence in order to send a data packet successfully by the use of RTS/CTS mechanism. We assumed that all packets are sent at link rate of 11 Mbps.

$T_{preamble}$	144 μs
$T_{phyheader}$	48 μs
CW_{min}	31
T_{slot}	20 μs
T_{sifs}	10 μs
$T_{difs} = 2*T_{slot} + T_{sifs}$	50 μs
τ_p (maximum propagation delay)	1 μs

Fig.5.1 802.11b specific parameters

$$T_{data} = T_{preamble} + T_{phyheader} + \frac{(34+L)*8}{(11*10^6)} \qquad T_{rts} = T_{preamble} + T_{phyheader} + \frac{20*8}{(11*10^6)}$$

$$T_{ack} = T_{preamble} + T_{phyheader} + \frac{14*8}{(11*10^6)} \qquad T_{cts} = T_{preamble} + T_{phyheader} + \frac{14*8}{(11*10^6)}$$

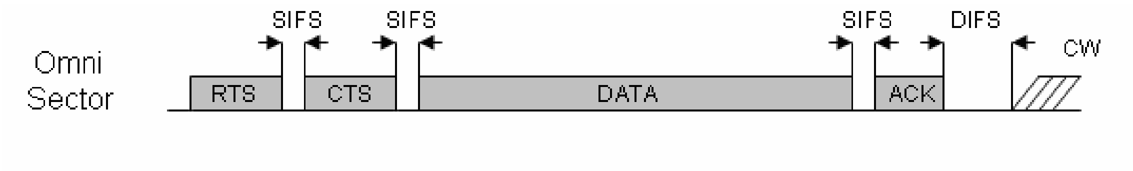


Fig.5.2 RTS/CTS handshake with omni directional antennas

$$S = \frac{8 * L_{data}}{T_{rts} + \tau_p + T_{sifs} + T_{cts} + \tau_p + T_{sifs} + T_{data} + \tau_p + T_{sifs} + T_{ack} + \tau_p + T_{difs} + (\frac{CW_{min} * T_{slot}}{2})}$$

$$S_{max} = 5.1*10^6 \quad \text{bps}$$

This result is used to verify the boundary condition on 802.11 omni performance.

5.1.2 Numerical AN-MAC Performance

In this section the throughput of ANMAC-LS is analyzed analytically. The specifications are taken from the 802.11b standard [36] as shown in Fig.5.1. Figure 5.3 shows the total communication sequence in order to send simultaneous data packets successfully by the use of RTS/CTS mechanism in two sectors. We assumed that all packets are sent at link rate of 11 Mbps.

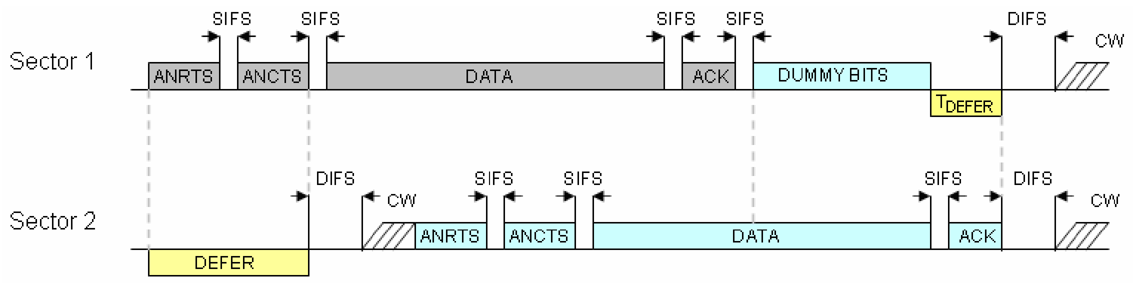


Fig.5.3 ANRTS/ANCTS handshake for achieving SDMA. Deafness is prevented by sending dummy bits.

$$CycleTime_{802.11} = T_{rts} + T_{cts} + T_{data} + 3*T_{sifs} + T_{ack} + 4*\tau_p + T_{difs} + (\frac{CW_{min}*T_{slot}}{2})$$

$$S = \frac{8*L_{data}}{CycleTime_{802.11} + DUMMY_{time} + T_{DEFER}}$$

$$S = \frac{8*L_{data}}{CycleTime_{802.11} + \left[T_{rts} + \tau_p + T_{sifs} + T_{cts} + \tau_p + T_{sifs} + T_{difs} + \left((\frac{CW_{min}*T_{slot}}{2}) - T_{difs}\right)\right]}$$

$$S_1 = 3.85*10^6 \text{ bps}$$
$$S_2 = \text{Network Throughput} = 2*S_1 \quad \text{(two sectors)}$$
$$S_2 = 7.7*10^6 \text{ bps}$$

5.2 Simulations

We have performed extensive simulations to analyze ANMAC protocol in a number of scenarios. We employed the OPNET models described in Chapter 4. In all scenarios, it is assumed that all stations can communicate with each other i.e. they are all in the same coverage area.

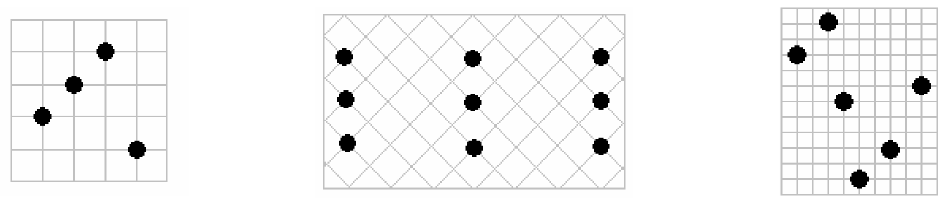
5.2.1 ANMAC vs. Previous Protocols

In this section, we examine ANMAC's performance through network throughput and medium access delay measurements and we compare it with other protocols from literature. The packet size is chosen as 1450 bytes. The simulated protocols are;

- ANMAC
- ANMAC with location based scheduler (ANMAC-LS)
- Directional CSMA (D-CSMA) proposed in [8]
- D-CSMA with Location based scheduler (D-CSMA-LS)
- IEEE 802.11 Omni

In the omni system, the stations use omni directional antenna and initiate communication one by one. D-CSMA is based on simultaneous sensing of carriers in different sectors. However, D-CSMA is incapable of avoiding deafness. ANMAC performs directional carrier sensing, as D-CSMA, but also prevents the deafness problem by modified RTS/CTS messages, medium access tables and dummy bits. ANMAC-LS and D-CSMA-LS are enhanced versions of the two algorithms that involve a smart packet scheduler.

Throughput performance of the network depends on the network topology, because the SDMA conditions occur when there is an additional diagonal which should not interfere with the ongoing communication. Different algorithms discussed in the simulations can give the same performance if the spatial locations of the stations do not cause deafness. The destinations may be fixed and the difference between algorithms does not matter. However our algorithm is designed to work for almost every situation including random destinations and random distribution of stations over a region.



(a) Topology #1 (b) Topology #2 (c) Topology #3

Fig.5.4 Topologies

The first simulation scenario we consider is the example scenario referred in section 2 (shown as Topology #1 in Fig.5.4). The four nodes in the network choose their destinations randomly. Figure 5.5 shows the throughput values measured for varying traffic load. Both D-CSMA and ANMAC have performances close to (even lower than) the omni directional system, because of randomly chosen destinations. A node can wait for a long period of time, inefficiently, due to the activity in the destination node or sector. Therefore, the advantage of spatial re-use cannot be exploited. D-CSMA has the worst performance due to the deafness problem, which can cause collisions on already communicating nodes. The effect of a location-based scheduler can be easily seen through the performance of ANMAC-LS that outperforms the throughput of omni 802.11 by 55%. The performance of D-CSMA is also enhanced by the scheduler; however, its throughput is still below omni 802.11 because of deafness. Figure 5.6 shows the medium access delay with respect to measured throughput. ANMAC-LS has the best delay performance with maximum throughput.

Secondly, we examine the Topology #2 shown in Fig. 5.4. There are 9 nodes deployed on a 3x3 grid. Figure 5.7 shows the throughput values for varying traffic load. ANMAC and D-CSMA, where there is no scheduler, have lower throughput than omni directional system because of crowded network topology, which causes too many collisions and long delays. ANMAC-LS outperforms omni 802.11 by 80%, and D-CSMA-LS by 30%. However, D-CSMA-LS has closer performance to ANMAC-LS because of using the location-based scheduler in the grid topology. Location based scheduler prevents stations from sending packets through busy sectors, and this avoids deafness in some cases. As mentioned before, throughput performance depends on the network topology. Figure 5.8 shows the medium access delay vs. throughout performance of topology 2. We can easily find out that the performance of delay in ANMAC-LS is better than all other schemes.

Topology #3 in Figure 5.4 is examined next. There are 6 nodes that are deployed randomly in the network. D-CSMA, ANMAC, Omni 802.11 and D-CSMA-LS schemes have lower throughput than ANMAC-LS. We can see the effect of deafness again because of the network topology. D-CSMA and ANMAC have closer performances to the omni system, similar to topology 1. In this topology, although D-CSMA-LS has a scheduler, the deafness conditions occurred more frequently and decreased the performance of D-CSMA-LS. However ANMAC-LS has 45% better performance than the omni system, and 55% better performance than D-CSMA-LS.

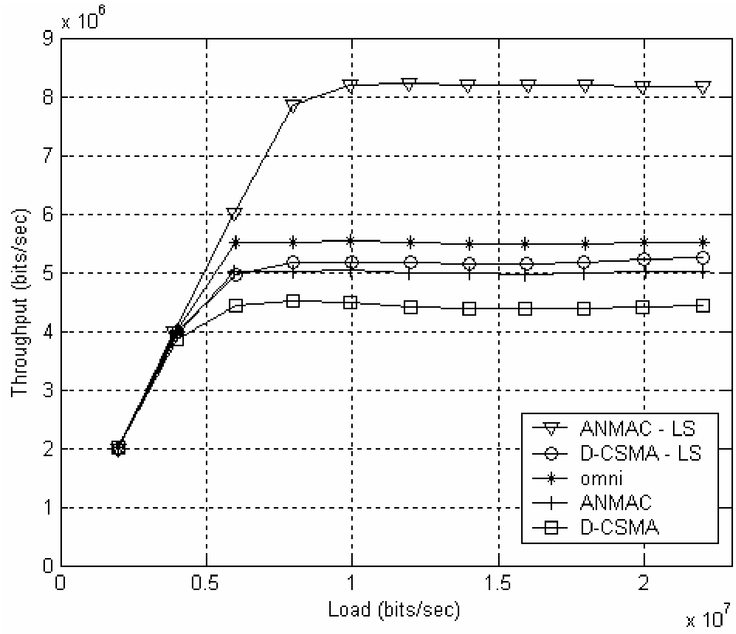


Fig.5.5 Throughput vs. load performance of scenario #1

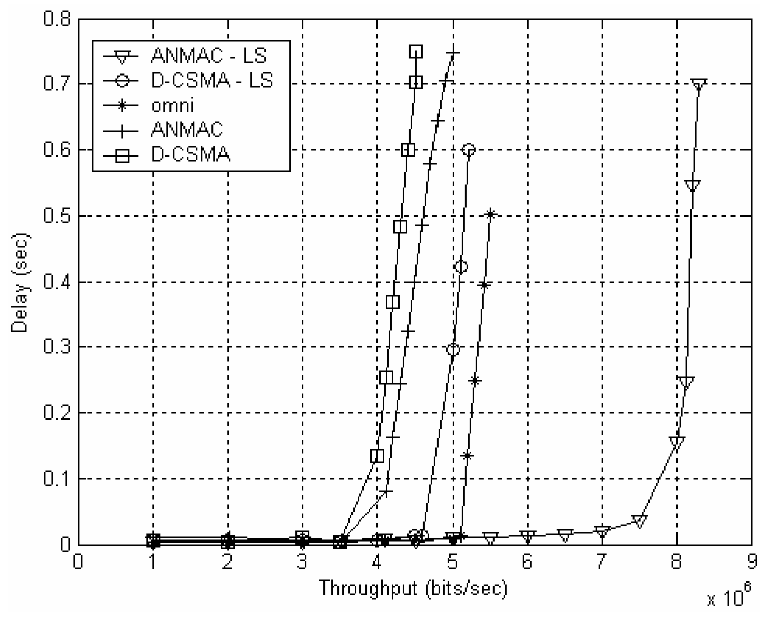


Fig.5.6 Delay vs. throughput performance of scenario #1

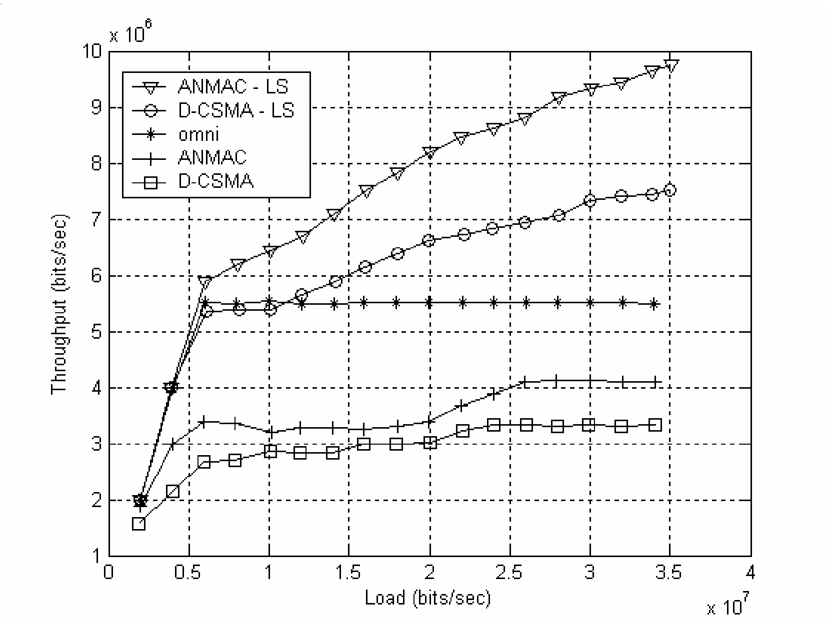


Fig.5.7 Throughput vs. load performance of scenario #2

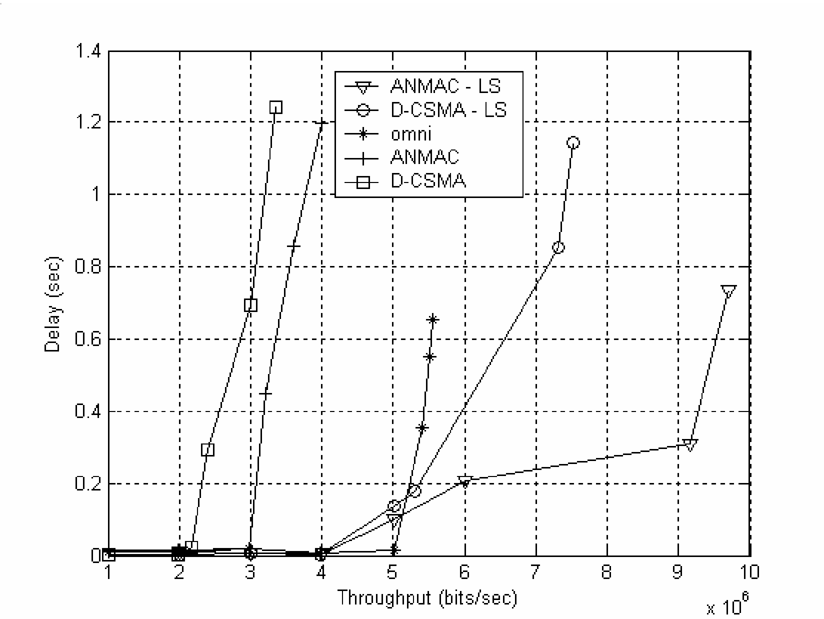


Fig.5.8 Delay vs. throughput performance of scenario #2

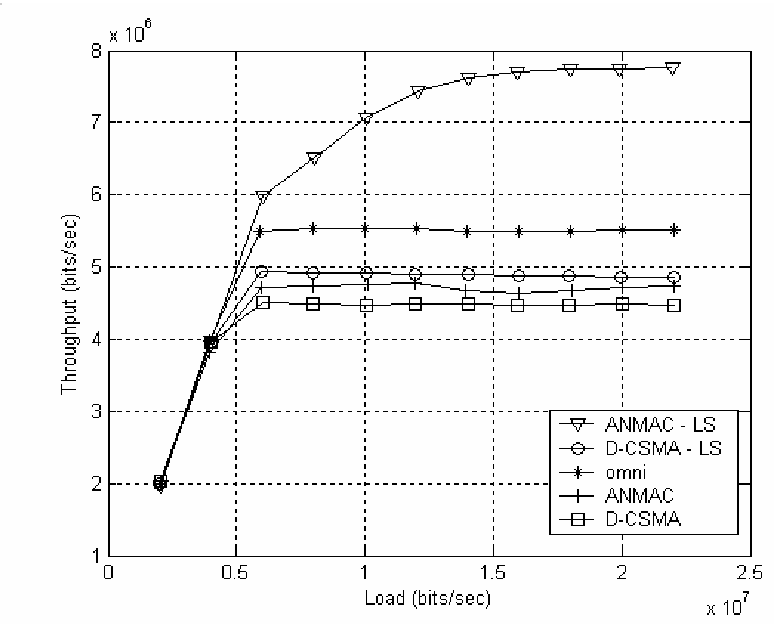


Fig.5.9 Throughput vs. load performance of scenario #3

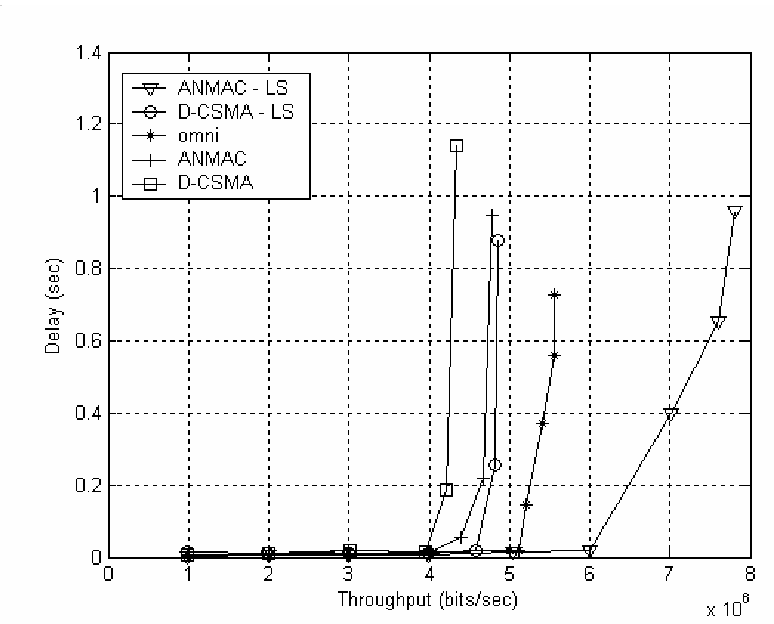


Fig.5.10 Delay vs. throughput performance of scenario #3

5.2.2 Performance of ANMAC-LS

5.2.2.1 Effect of Packet Length

We have further analyzed the performance of ANMAC-LS with different packet lengths and compared it with omni 802.11. In simulations we have used a Topology #1 in Fig.5.4. We first set the packet length to 64 bytes. The throughput performance for various network loads is shown in Fig.5.11. As shown in the Fig.5.11, the Omni 802.11 and ANMAC-LS performances are the same because SDMA cannot be applied. ANMAC-LS can start using the idle diagonal if there is enough time for handshaking (i.e. RTC/CTS exchange) to initialize a data packet transmission. The length of the 64 byte packet is not long enough to complete the handshake between other stations in order to achieve SDMA. If the packet length is chosen to be 512 bytes, the performance of ANMAC-LS starts to exceed the performance of omni 802.11 as shown in Fig.5.12. The packet length in this scenario gives enough time for handshaking at the unused diagonal, which enables SDMA. ANMAC-LS has gained %30 better throughput performance over omni 802.11. The delay performance can be seen in Fig.5.13.

In fact, every packet carries a header. Each header has a pre-defined length and this length may become comparable with the length of the actual data carried by that packet if the packet is so small. Combining two 512 byte packets into a 1024 byte packet will reduce the time spent for header transfer in case of sending these two packets separately. As shown in Fig.5.14, if the packet length is chosen to be 1450 bytes, the performance of ANMAC-LS exceeds the performance of omni 802.11 by 50%. The delay performance can be seen in 5.15. Then we increase the packet length to 4000 bytes, and as shown in figure 5.16, the throughput performance of ANMAC-LS is 75% better than omni 802.11. As explained before if small packets are concatenated into longer packets, the performance of the system increases because of the reduced overhead. The delay performance can be seen in 5.17.

Finally we have used a realistic packet size distribution by employing an empirical model obtained through measurements in a LAN [37]. The real life IP traffic has a distribution as shown in figure 5.18. As shown in Fig.5.19, the throughput performance of ANMAC-LS is 21% better than omni 802.11. The SDMA is achieved rarely because of packet size distribution.

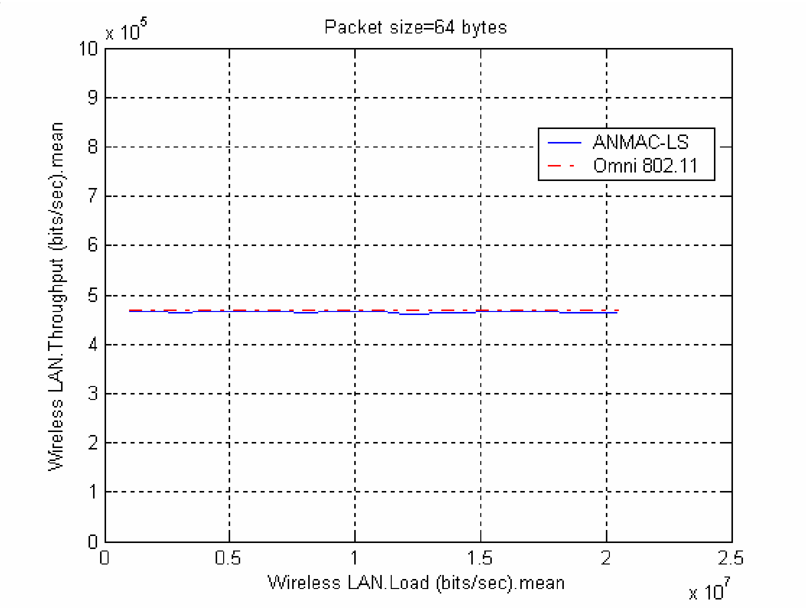


Fig.5.11 Throughput vs. load performance when the packets are 64 bytes

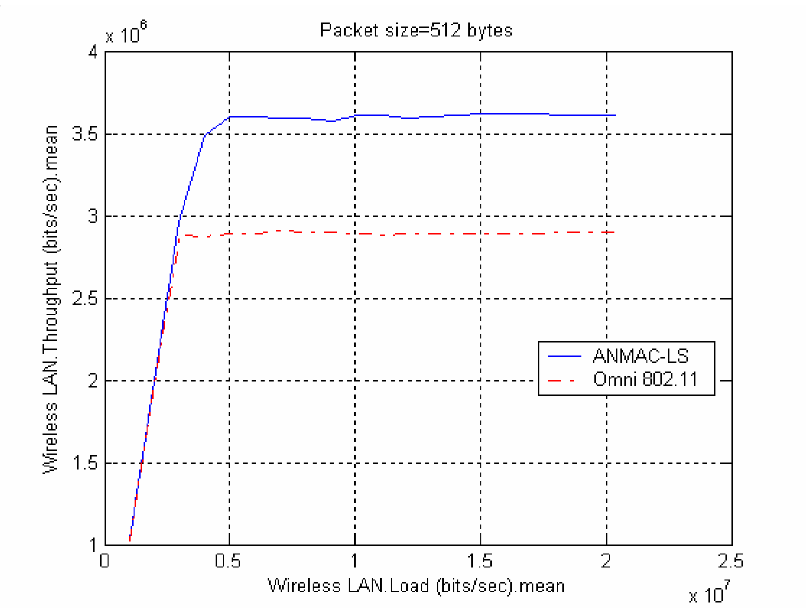


Fig.5.12 Throughput vs. load performance when the packets are 512 bytes

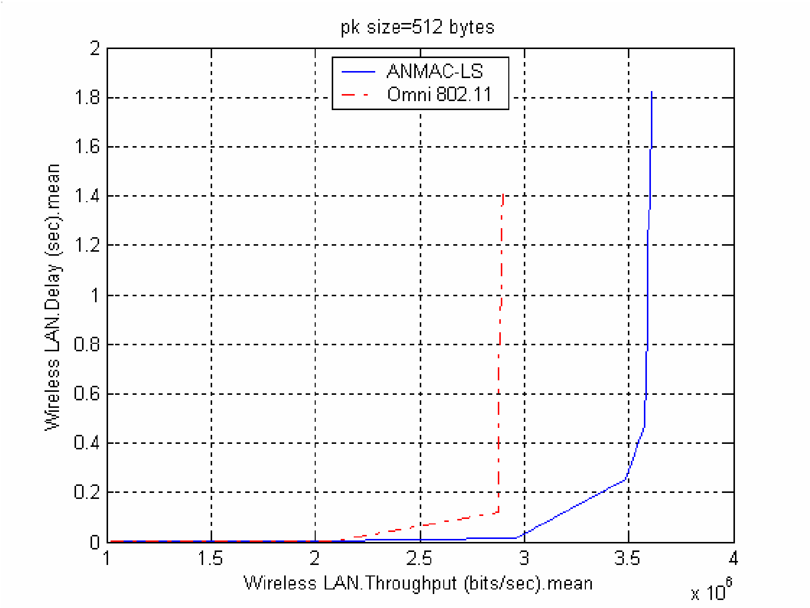


Fig.5.13 Delay vs. throughput performance when the packets are 512 bytes

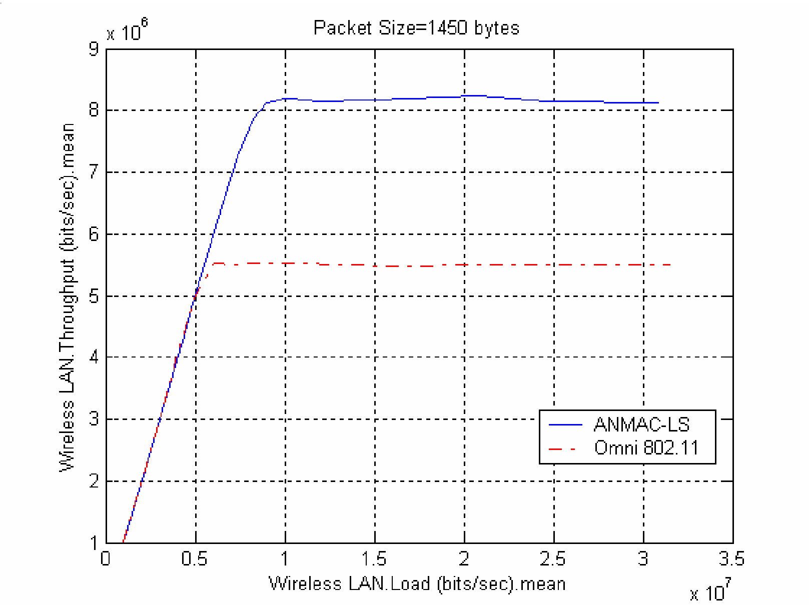


Fig.5.14 Throughput vs. load performance when the packets are 1450 bytes

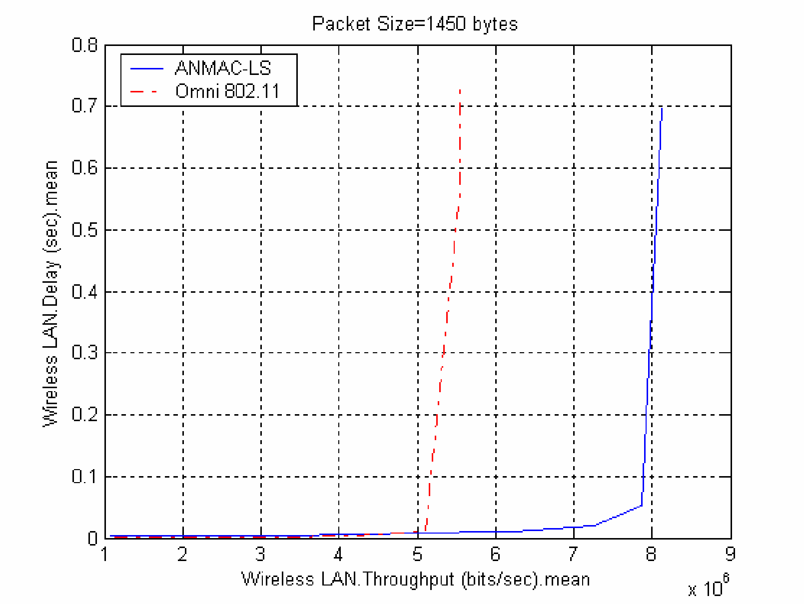


Fig.5.15 Delay vs. throughput performance when the packets are 1450 bytes

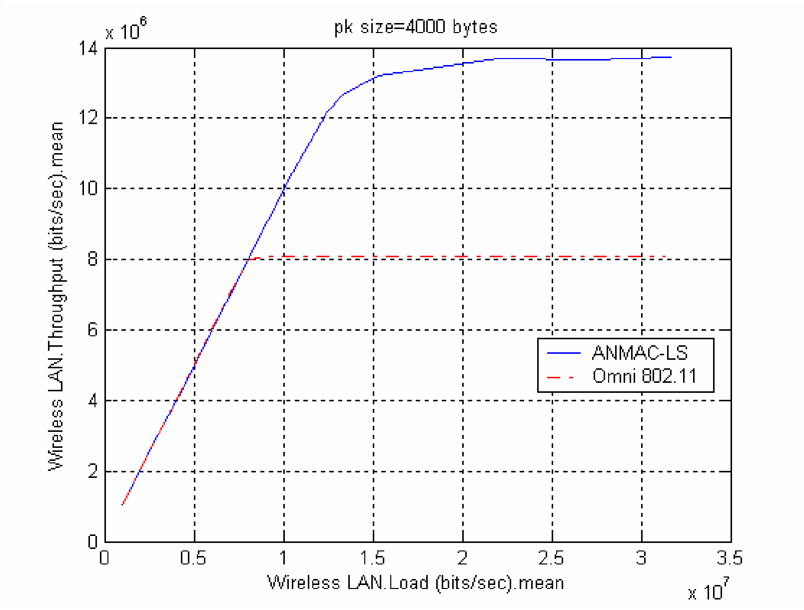


Fig.5.16 Throughput vs. load performance when the packets are 4000 bytes

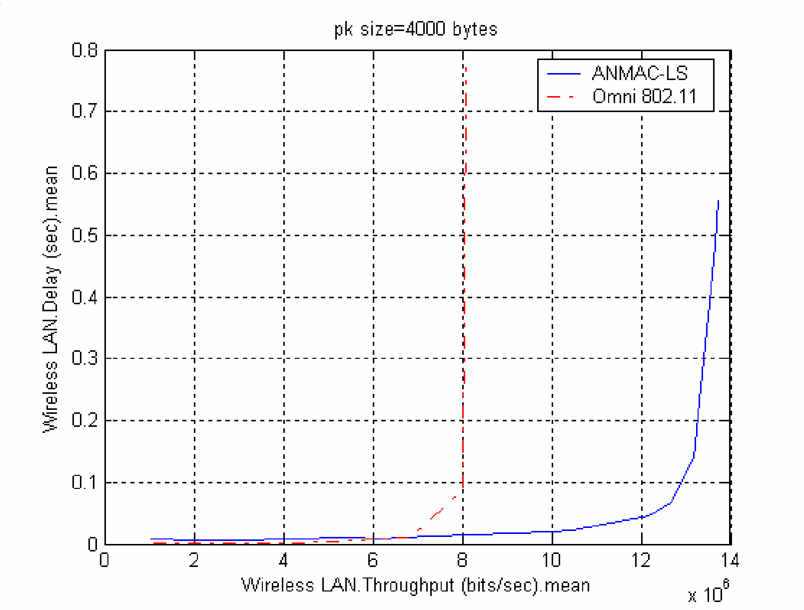


Fig.5.17 Delay vs. throughput performance when the packets are 4000 bytes

Packet Size(bytes)	64	128	256	512	1024	1518
Probability	0.6	0.06	0.04	0.02	0.25	0.03

Fig.5.18 IP Traffic: Message size distribution

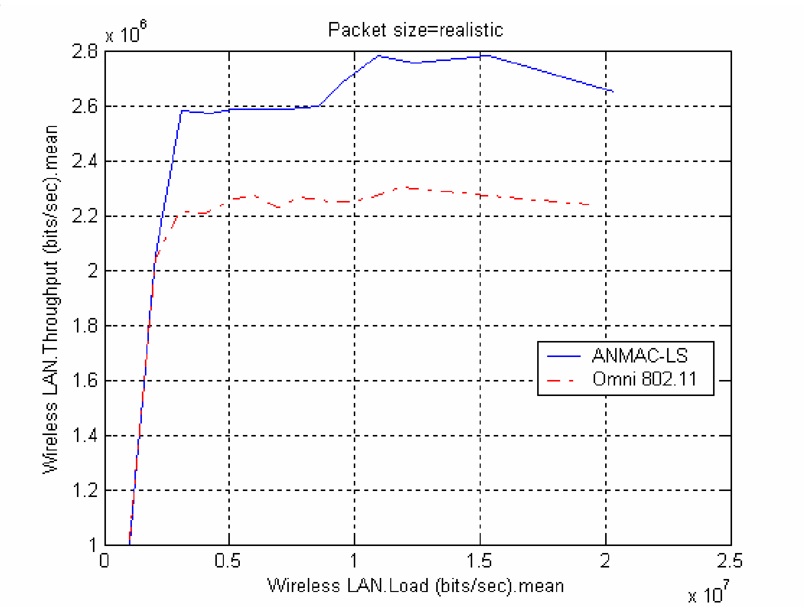


Fig.5.19 Throughput vs. load performance (realistic packet size distribution)

5.2.2.2 Self-Learning

Here, through an example scenario, we demonstrate the self-learning stage for location determination. We simulated the ANMAC-LS protocol in a crowded network where 30 stations transmit packets and choose the destination randomly (Fig.5.20). In the analysis, we assume that we operate in saturation conditions, i.e., the transmission queue of each station is assumed to be always nonempty. In Figure 5.21, the network throughput increases for 2.5 seconds and than stays constant. At the beginning of the simulation, the locations of the nodes are not known by each other. Upon receiving packets from different nodes, every station fills the adequate fields of their medium access tables as explained in section 3.2.1.1. The self-learning of the neighbors' locations takes some time. In the crowded topology shown in Figure 5.20, the self-learning period is 2.5 seconds as can be seen in Figure 5.21. Then by the use of fully filled medium access table and the location based scheduler, the retries are prevented.

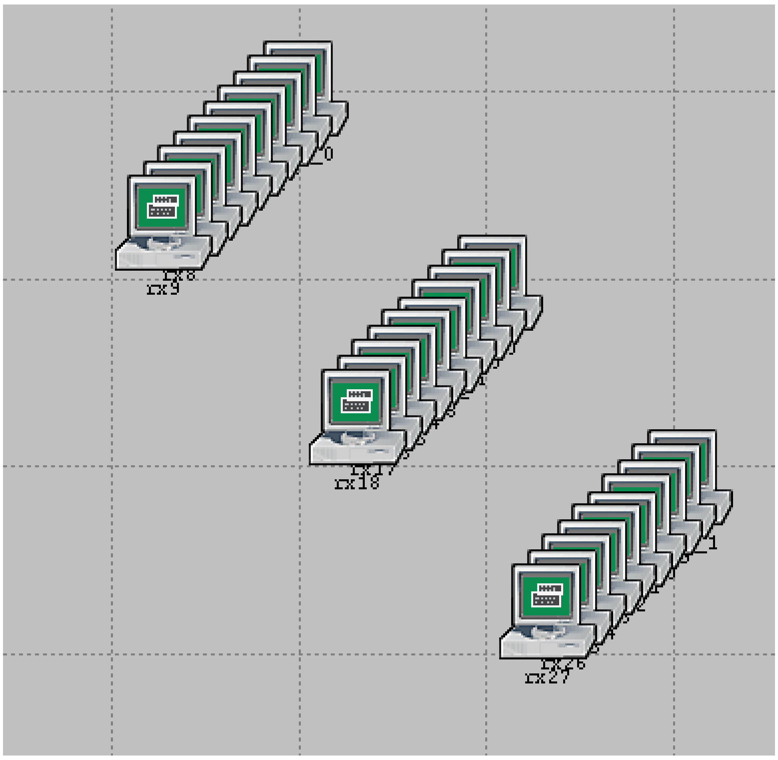


Fig.5.20 Network with 30 nodes

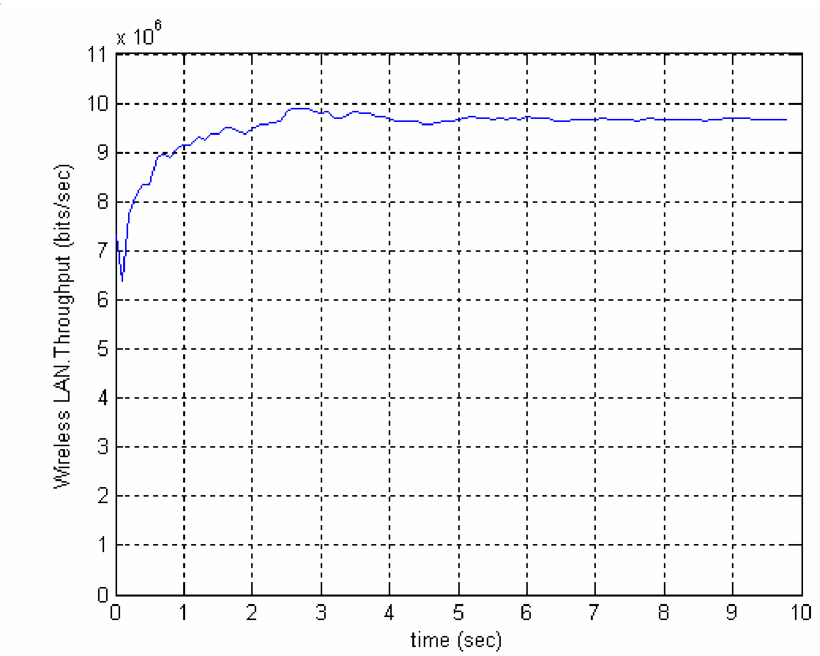


Fig.5.21 Throughput performance of Network in figure 5.20 for 10 seconds

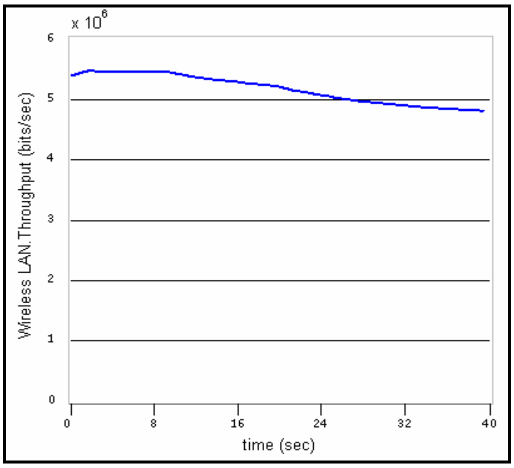
5.2.2.3 Dynamic CW Adaptation

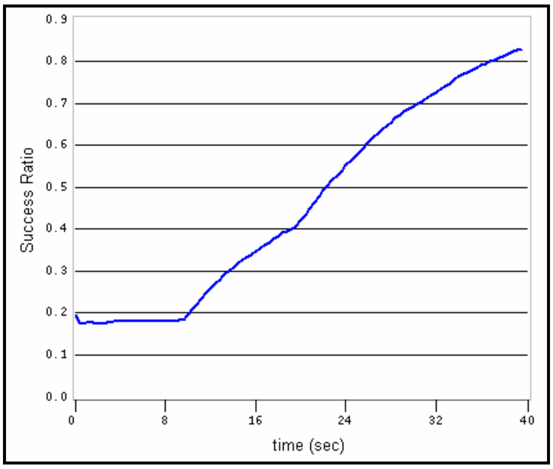
In section 3.2.4.1, we have proved that if the success ratio is near 0.2, we will get the maximum throughput. In this set of experiments we changed the number of stations in the network, and observed the variability of success ratio and throughput, using a constant CW and dynamic CW algorithm. In the first 10 seconds, there are 10 active stations in the network. From 10 seconds to 20 seconds active stations are increased to 20, and from 20 to 40 seconds there exists 80 nodes.

In Fig.5.21a, the throughput performance can be seen when CW_{min} is fixed as 31. As the number of stations increase in the network, it can be easily seen that the throughput performance of the network degrades. Fig.5.21b shows the success ratio during the simulation.

In Fig.5.22a, the CW_{min} is updated dynamically. The throughput always stays at its maximum value and the success ratio is close to 0.2.

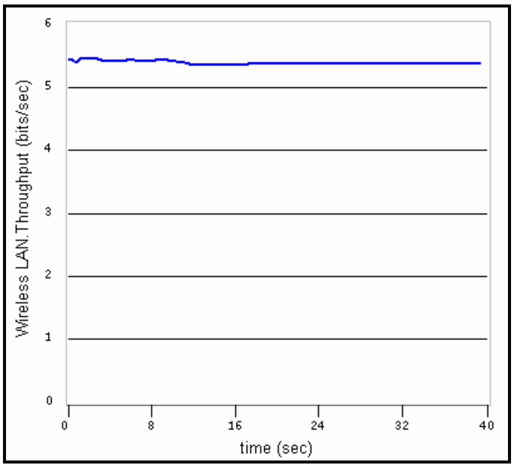
The optimal CW setting and dynamic CW adaptation algorithms were also simulated for omni 802.11 and ANMAC-LS scenarios with 30 stations. The throughput performance has been observed for two fixed CW values, 31 (specified by the 802.11 standard) and CW_{opt} (that provides optimal success ratio), and dynamic CW adaptation algorithm. As depicted in Fig.5.24, optimized CW provides a higher throughput, and dynamic CW achieves the performance of optimized CW in both omni 802.11 and ANMAC-LS.

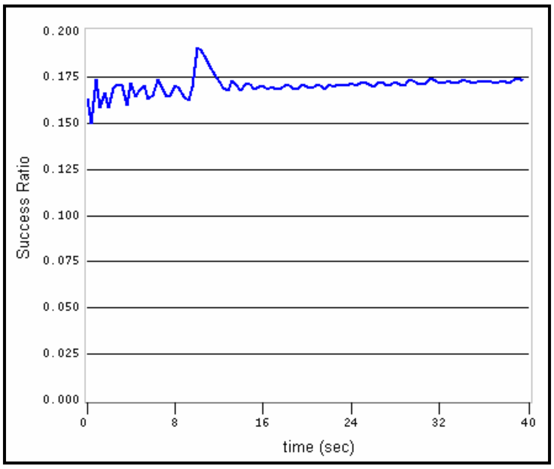




(a) (b)

Fig.5.22 Throughput performance when CW_{min} is static





(a) (b)

Fig.5.23 Throughput performance when CW_{min} is dynamic

	CW=31	CWopt	CWdyn
Omni 802.11	5.1	5.45	5.45
ANMAC-LS	9.6	10	10

Fig.5.24 Static vs. Dynamic CW

6 CONCLUSIONS

6.1 Contributions

In this thesis, we have proposed a new MAC protocol, Angular MAC (ANMAC) that includes location finding. The stations exchange modified RTS/CTS messages, which are sent in all directions to warn other nodes. Angular RTS/CTS messages are used to construct a medium access table to track the locations of not only the destination nodes but also all communicating neighbors. We proved that ANMAC introduces SDMA capability into the wireless ad hoc network by performing physical and virtual carrier sensing in a directional sense. We observed that performance depends on packet destinations. Next, we improved ANMAC performance by location scheduling (ANMAC-LS). The stations use the location information of other nodes to determine the busy destinations and busy sectors to avoid collisions and congestions in the network. As shown in our simulations, the advantage of SDMA can be obtained with ANMAC-LS while still avoiding deafness and hidden terminals.

We evaluated the performance of ANMAC and ANMAC-LS in detail, against regular omni 802.11 stations and other proposed schemes from literature via simulations. In addition to modeling the MAC layer, we modeled antenna characteristics, location based scheduler and the wireless channel in detail to reflect interference scenarios accurately. Our results promise significant enhancements over omni 802.11, with throughput gains 45-80%. The extent of the performance improvement depends on the network topology. ANMAC can result in higher throughput if the network topology has parallel diagonals, where nodes in each diagonal try to reuse the channel again and again. We also evaluated the performance of ANMAC-LS with different packet sizes. Our conclusion was that if small packets are concatenated into longer packets, the performance of the system increases because of achieving SDMA.

Last but not least, we proposed an optimization scheme for the contention window and an algorithm for dynamic adaptation of contention window to maximize total network throughput, at any network size. Simulations and analytical results prove the validity of this approach and how quickly the system can respond to changes in the number of stations. Optimizing contention window not only reduces delays and enhances the throughput, but also provides energy savings as well, due to reduction in back off time. Our results can be applied to wireless sensor network applications where the number of contending active stations are not known.

It is worthwhile to note that we assumed immobile nodes in this study. ANMAC protocol can be applied in nomadic applications, where users rarely change their positions and they remain in the new location for a long period of time. The existing handshake mechanism of ANMAC can be readily used to inform all the neighboring nodes about the new location, so that the new best beams are determined and the location table is updated. In the case of high mobility, however, an additional handoff mechanism between beams is required so as to enable uninterrupted communication.

With the assumption of low mobility, performance of ANMAC has been evaluated in AWGN channel with multiple user interference, not taking multi path fading into account. In a multi path environment, signals from different paths can be captured by different beams of an ANMAC node, and reflected signals can interfere with other beams. Since directive beams are employed, the number of reflected paths will be less than omni transmission; however, the strength of the reflected signals can be higher than omni reflections. At this point, ANMAC can make use of the thresholds for packet capture to distinguish between the power levels of two simultaneously arriving packets. ANMAC nodes can communicate in a multi path scenario, as long as the difference between power levels of multi path signals is larger than10 dB. The performance of ANMAC protocol in a fading channel yet needs to be investigated separately, which is left out of the scope of this thesis.

The contributions of ANMAC protocol proposed in this thesis can be summarized as follows:

- Medium access table is constructed for location determination and self-learning of locations of neighboring nodes is performed.
- Location based scheduler is proposed for allowing spatial channels while avoiding blocking and providing efficient scheduling.
- SDMA support is accomplished leading to increased throughput.
- Deafness is prevented through dummy bits that are sent at the end of SDMA period until the end of the continuing data packet to inform surrounding nodes.
- Theoretical optimal CW size for maximum throughput has been verified for different network sizes and a distributed algorithm for dynamic CW adaptation is proposed.

ANMAC operation comes with the following tolerable costs and limitations:

- Packet overhead is slightly increased due to the necessity of AN-RTS/AN-CTS exchange before every transmission.
- Station complexity is increased due to forming and maintaining the location table and additional hardware for extra RF chips and energy comparison, both of which require simple and cheap implementations.
- Placement and orientation of the antennas must be such that nodes are within the effective aperture of the antennas.
- During dummy bit transmission, some amount of RF power is exhausted by all antennas similar to the omni transmission system. In a heavy load situation, where the network is operated at saturation, the duration of dummy bits is proportional to the handshake period of the two nodes in the second diagonal. Nevertheless, energy cost of ANMAC directional system is lower than omni transmission.

With these costs and limitations we envision that the AN-MAC-LS protocol will be most appropriate for wireless bridges interconnecting networks of buildings, where the extra complexity costs for nodes and antenna deployment would be affordable, orientation of nodes can be fixed at installation, and the nodes will be immobile.

6.2 Future Work

Using smart antennas in wireless networks enables users to divide medium into sectors and communicate individually in each sector. Our scheme has been proposed for non-mobile users. The evaluation of smart antenna protocols showed that switched beams are not suitable for mobile users. Adaptive arrays seem to be the unique solution, which is an active research area. On the other hand, the problems of spatial usage have to be fully solved in order to reach the expected capacity with smart antenna systems.

The performance improvement of smart antenna systems depends on the network topology. By investigating different and complex topologies, the MAC protocols can be characterized more efficiently. The final step might be to use all available antennas together without interfering each other, which leads us to MIMO systems.

Finally, using an efficient routing algorithm can interconnect users that are out of each other's coverage areas. ANMAC can readily be applied a cross-layer approach and work with a routing algorithm that takes location information/antenna selection into account.

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APPENDIX-A

The wireless communication channel in OPNET is modeled by 13 pipeline stages including antenna gains, propagation delay, signal-to-noise ratio, calculation of background noise and interference noise, transmission delay, etc. The execution sequence is shown in Fig.A.1 and the functions of each stage are given below. Stages (0-5) are associated with Radio Transmitter and stages (6-13) are associated with Radio Receiver.

Stage (0) Receiver Group

- Exclude your own receiver
- Exclude the receivers in different OPNET subnets (an optional feature for faster simulation run)

Stage (1) Transmission Delay

- Retrieve the transmission data rate from the packet

Stage (2) Link Closure

- Line-of-sight is true for all receivers

Stage (3) Channel Match

- Match conditions are based only on the transmitting and receiving frequency and bandwidth

Stage (4) Tx Antenna Gain

- Gain is calculated from the antenna pattern for each direction

Stage (5) Propagation Delay

- Warning message added to “Simulation Log” if the distance between the transmitter and receiver exceeds 300 meters

Stage (6) Rx Antenna Gain

- Gain is calculated from the antenna pattern for each direction

Stage (7) Received Power

- In addition to the default behavior,
- Mark a received packet as "Noise" if the
  - Receiver is busy
  - Received power is lower than the threshold specified
- Monitor the beacons for channel evaluation

Stage (8) Background Noise

- Background noise is modeled as AWGN

Stage (9) Interference Noise

- Interference noise is calculated from other packets in the medium

Stage (10) Signal-to-Noise Ratio

- SNR is calculated from dividing received packets signal to sum of Background and Interference Noises

Stage (11) Bit Error Rate

- Computes the processing gain by itself using the data rate information conveyed in the packet

Stage (12) Error Allocation

- Optimized approach:
  - If the packet already has enough bit errors for rejection, don't find all the bit errors
- Retrieve the data rate from the packet

Stage (13) Error Correction

- Force the simulation kernel to always accept packets even in the event of collision
- Later drop the bad packets at the MAC layer

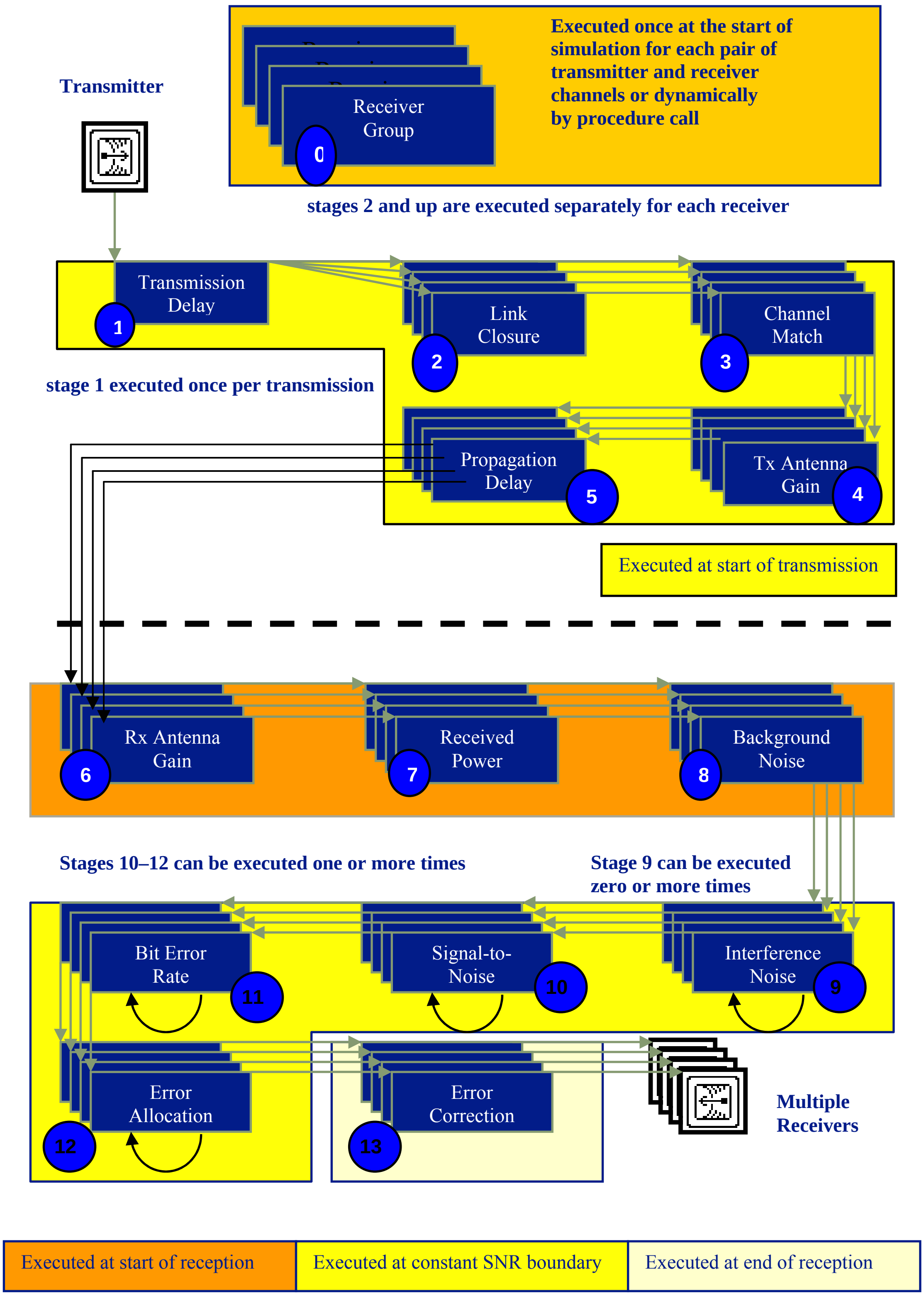

Fig.A.1 Pipeline stages of OPNET Modeler for Radio Simulation and execution sequence for one transmission

APPENDIX-B

Key WLAN Functions

Wlan_mac_sv_init (): State variable initialization, read the "Wireless LAN Parameters" configuration. The memory allocation for medium access table variables is completed. RX and TX channels are set for each transmitter because we have 4 individual RX and TX processors.

Wlan_higher_layer_data_arrival (): Packet queuing, In the DCF mode, all packets inserted into the hld_list_ptr, Location based Scheduler operates here.

Wlan_interrupts_process (): Handles the appropriate processing needed for each interrupt. Switching between beams are executed. If the stream interrupt is coming from unblocked antenna, it is decapsulated. However if it is coming from a blocked antenna, it is destroyed. Because OPNET needs to destroy all unwanted packets in order to use memory efficiently.

Wlan_prepare_frame_to_send () & wlan_frame_transmit (): Update the packet fields with the required information. Save a copy of the packet being transmitted, if required. Segmentation of higher layer data packets, if required. The new fields in packets are included and the packet is capsulated.

Wlan_physical_layer_data_arrival (): Process the frames received by the station from the lower layer. Course of action taken depends on the packet received. Update the medium access table. Determine which beams to block by carrier sensing and information gathered from the received packet. Set the NAV.

Wlan_data_process (): Handle the de-fragmentation process. Data sent to higher layer if the receiver is the destination of the packet.

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