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Abstract

The big evolution of modern applications in the wireless networks domain as the wireless videos remote access, big files transfer, streaming and downloading high definition videos etc, has led to using the mmWave technology (60 GHz for example) that represents an important solution for these applications because of the advantages presented by this frequency band such as the high data rate transmission up to multi gigabits, also the large bandwidth that goes up to 7 GHz.

The use of the mmWave technology requires a MAC protocol which ensures the channel sharing between users in a multi-node network, with directional antennas that increase spatial reuse and cover a wider area compared to the omnidirectional antennas.

Many access method approaches were used in order to resolve these problems, for instance, the methods that use a signaling channel, then methods that exploit directional antennas with directional frames, and those using beacons and many others....

In our project, we worked on the adaptation of the 'Busy –Tone' method using the 802.11 ad protocol with directional antennas in addition to a coordination between 2.4 GHz and 60 GHz.
This method offers a big solution to resolve the collisions of data and control packets that affect and reduce the network capacity and lead to data loss.

Simulation results showed the efficiency of this model by reducing collisions caused by hidden terminals, therefore, enhancing the performance of the network in terms of transmission delay, retransmission attempts and throughput.

Résumé

L'évolution des applications modernes dans le domaine des réseaux sans fils tel que l'accès à distance des vidéos sans fils, le transfert des gros fichiers, flux des vidéos à haute définition etc.…nécessite l'utilisation de la bande 60 GHz qui présente une solution très importante pour ces applications grâce aux avantages que présente cette bande tel que le taux de transmission des données qui atteint quelques Gigabits, et aussi grâce à la bande passante du canal qui est environ 7 GHz.

L'utilisation de cette bande de fréquence nécessite un protocole MAC qui assure le partage de canal entre les utilisateurs dans un réseau multi-nœuds. Ce protocole doit tenir compte les problèmes et les défis qui se produisent grâce à l'utilisation de la bande 60 GHz, tel que les problèmes des terminales cachées et exposées

Dans ce projet on a proposé une méthode qui se base sur l'adaptation de protocole 802.11ad avec la méthode 'Busy-Tone 'parce qu'elle représente la solution la plus efficace pour résoudre les problèmes des collisions des paquets de donnés et les paquets de contrôle qui sont causés normalement par la présence des terminales cachées et exposées.

L'approche proposée consiste aussi à utiliser les antennes directives qui augmentent la réutilisation spatiale et couvre une portée plus grande par rapport à l'antenne omnidirectionnelle. Ces antennes ont été utilisés à côté des antennes omnidirectionnelles avec une coordination entre les deux, alors les antennes omnidirectionnelles sont utilisées pour envoyer les signaux 'Busy-Tone ' tandis que les antennes directives sont utilisées pour envoyer les paquets de données.

Les résultats de la simulation ont montré une amélioration au niveau de la performance du réseau en terme du débit, du délai et les essaies de retransmission en comparant avec le standard 801.11ad.

Glossary of Abbreviations

MAC	Medium Access Control
HD	High definition
EIRP	Effective isotropic radiated power
Wlans	Wireless local area networks
Wpans	Wireless personal area networks
UWB	Ultra wide band
LOS	Line of Sight
NLOS	None Line of sight
OSI	Open Systems Interconnect
LLC	Logical Link Control
DCF	Distributed coordination function
HCCA	HCF controlled channel access
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
FDMA	Frequency Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
QoS	Quality of services
RF	Radio frequency
PN	Pseudorandom noise
CBP	Contention-based protocol
CSMA	Carrier Sense Multiple Access
CSMA/CD	CSMA with collision detection
CSMA/CA	CSMA with collision avoidance
MACA	Media Access with Collision Avoidance
MACAW	MACA for wireless networks
CTS	Clear to send
RTS	Ready to send

ACK	Acknowledgment
BTMA	Busy tone multiple access
DBTMA	Dual Busy Tone Multiple Access
CATA	Collision Avoidance Time Allocation Protocol
HRMA	HOP Reservation Multiple Access Protocol
SRMA/PA	Soft Reservation Multiple Access with Priority Assignments
RTMAC	Real-Time Medium Access Control
WIGIG	Wireless Gigabit Alliance
GHz	Gigahertz

Chapter 1
Introduction

1.1 Introduction

The mmWave technology opens the door on a big variety of potential applications that requires a large bandwidth as presented in the 60 GHz frequency band. Due to its huge unlicensed bandwidth (up to 7 GHz). Many new applications that require high data rate can be easily supported, such as Wireless HD, single and multi set uncompressed video streaming, office desktop data transfers, conference adhoc data transfer, and Kiosk file downloading.

Another factor that makes this technology so attractive is that 60 GH regulation allows much higher effective isotropic radiated power (EIRP) compared to other existing wireless local and personal networks (Wlans and Wpans). High EIRP is required to overcome the high path loss in the 60 GHz band.

On the other hand, using this physical layer demands an adaptation of the Medium Access Control (MAC) layer that respects its characteristics and properties and also enhances its performance. Furthermore, the main objective of Multiple Access Control (MAC) protocols is to schedule access of multiple competing nodes in communication networks to a shared channel.

This control has a role of preventing interference between the nodes in a multi-hop network and packets collisions which lead to data loss and bandwidth waste. One of the main reasons of packets collisions is the problem of hidden terminals. This problem occurs often in multi-hop networks where some terminals are considered “Hidden” from each other (either because they are out of sight or out of range).

1.2 Research objectives

The main objective of our research is to adapt a MAC protocol that overcomes the problems mentioned above; the most important problems in our research are the hidden and exposed terminals. Those problems occur a lot in multi-hop networks causing packets collisions and data loss which reduce the capacity and the performance of the network.

The MAC protocol used in this work is the 802.11 ad, this protocol is made for mmWave technology and it was derived from the standard 802.11 protocol for wireless LANs. In addition to 802.11ad, we used the ‘Busy-Tone’ method and directional antennas.

So this research was done in order to:

- Reduce the problem of hidden terminals.
- Increase the capacity and the throughput of the network.
- Decrease the collisions of data and control packets.
- Coordinate the use of directional and omnidirectional antennas.
- Guarantee a better medium access and control.

1.3 Structure of the thesis

This thesis is organized as follows:

In the first chapter we did a general introduction to the 60 GHz frequency and the MAC protocol; also in the chapter we defined our research objectives and the structure of this thesis.

The next chapter presents a mmWave wireless technology overview, the 60 GHz frequency in specific and its available spectrum for indoor wireless communications around the world and the reasons that makes this technology very attractive for modern applications, then we present the challenges and the properties of this channel and most importantly the benefits presented by this frequency band in wireless communications.

In chapter three we present our problematic, the main issue that we are working to solve which the collision problem is caused by hidden terminals and deafness, also we presented the problem of exposed terminals and how these problems affect the network performances in many aspects such as the throughput, transmission delay and retransmission attempts.

Chapter four presents a MAC protocol overview, it includes detailed explications about the data link layer, the medium access control sub layer and its role, then we explained what is a MAC protocol and its goals, also in this chapter you will find a detailed study about protocol MAC classification, the different types and the role of each one. Also we give an overview on the related works and the methods that have been proposed so far to deal with the same issues and what are the advantages and disadvantages of each method.

The following chapter presents the proposed method, in other words the idea that we proposed to solve the problem listed in chapter three. This method is based on the adaptation of the standard 802.11ad to be used with 'Busy-Tone' method in addition to the use of directional antennas in coordination with omnidirectional antennas.

In chapter six we present the modeling phase, or the model that we used and implemented using the software OPNET, the use of this software was based on the given results which are considered more realistic compared to other software such as network simulator. In this chapter we present the different phases and methods that were used to achieve our goal which creating a functional model to test our idea which will be shown in the simulation results and the interpretation. In the second part of this chapter we present the network model that we used in addition to the simulation parameters, then we show the simulation results and the interpretation of these results to show the efficiency of our proposed method and ho it affects the performance of the network

Finally in chapter seven, we give our conclusion and comments about the proposed method based on the simulations results, and how the method affected the network performance, then we talk about the perspective and possible future work based on the method we proposed such as using a dual busy tone method or exploits the use of directional antennas.

Chapter 2
The 60 GHz frequency band

2.1 MmWave Wireless Technology Overview

The need for very high data rate radio communications applications (1 Gbit/s or higher) makes the mmWave technology one of the most promising forms for multi-gigabit wireless communications for wireless networks due to its huge unlicensed bandwidth (up to 7 GHz). This huge bandwidth represents great potential in terms of capacity and flexibility, making 60 GHz technology very attractive for gigabit wireless applications. The fact that this band is unlicensed and largely harmonized across most regulatory regions in the world is a big advantage, in contrast to the meager spectrum available in the lower frequency bands for existing technologies such as Wi-Fi.

Figure 2-1 Available spectrum in 60GHz band for indoor wireless communication around the world

Another factor that makes this technology so attractive is that 60 GHz regulation allows much higher effective isotropic radiated power (EIRP) compared to other existing wireless local and personal networks (Wlans and Wpans). Table 1 shows examples of typical 60 GHz, UWB and IEEE 802.11systems that operate near the US Federal Communications Commission (FCC) regulatory limit [2].

Table 2.1 Comparison of the typical implementation of 60 GHz, UWB and 802.11n systems in terms of their output power, antenna gain and EIRP output

Technology	Frequency (GHz)	PA output (dBm)	Antenna gain (dBi)	EIRP output (dBm)
60 GHz	57.0–66.0	10.0	25.0	35.0
UWB	3.1–10.6	–11.5	1.5	–10.0
IEEE 802.11n	2.4/5.0	22.0	3.0	25.0

2.2 Challenges and properties of the 60 GHz channel

First, the propagation of the 60 GHz band is characterized by high levels of oxygen absorption and rain attenuation limiting the range of communication systems using this band; but it also offers interference and security advantages when compared to other wireless technologies.

Small beam sizes coupled with oxygen absorption makes these links highly immune to interference from other 60GHz radios, so two links with slightly different paths will not interfere, while oxygen absorption ensures that the signal does not extend far beyond the intended target, even with radios along the exact same trajectory. Hence, it will allow a high level of frequency re-use, and therefore, makes it attractive for a variety of short-range communication applications.

Secondly, 60GHz channel generally exhibits quasi-optical properties, meaning the strongest components tend to be Line of Sight (LOS). Non Line of Sight (NLOS) components do exist, but mostly in the form of reflection. 60 GHz band measurements [3] show that in general, the strongest reflected components are at least 10 dB below the line of sight (LOS) component.

Thirdly, one of the major challenges when using 60 GHz frequency band is the path loss factor. For example, the propagation loss of 60 GHz signals in free space is 22 dB higher than that of 5 GHz signals [4], also the signal at this frequency is very sensitive to obstacles, (e.g. human bodies, walls ,objects …),table 2.2 gives an idea about the transmission lost at 60 GHz and 2.5 GHz for different obstacles.

Table 2.2: Transmission loss at 60 GHz and 2.5 in dB

	Thickness (cm)	60 GHz	2.5 GHz
drywall	2.5	6.0	5.4
Office whiteboard	1.9	9.6	0.5
Clear glass	0.3	3.6	6.4
Mesh glass	0.3	10.2	7.7
Clutter	-	1.2	2.5

2.3 Advantages of 60 GHz

The 60 GHz frequency band offers a lot of benefits and has its great advantages in wireless communications.

1- Unlicensed operation, there is no need to spend lots of money and time to obtain a license from a telecom regulator.

2- One of the greatest advantages is the large bandwidth as mentioned above, this bandwidth can go up to 7 GHz comparing to <0.3 GHz in other unlicensed bands, allowing and presenting many modern applications that need such a bandwidth.

3- Highly secure and virtually interference operation; it is a result from short range transmissions due to oxygen absorption, narrow antenna beam width and limited use of 60 GHz spectrum.

4- Carrier-class communication links enabled, 60 GHz can be engineered to deliver “five nines” of availability if desired.

5- Channel access in 60 GHz will use directional communications, which will lead to exploit spatial reuse in 60 GHz and increase the spectrum efficiency.

2.4 Potential applications

With the 7 GHz bandwidth allocated in most countries, the 60 GHz frequency band has become the technology enabler for many gigabits transmissions applications that are constrained at lower frequencies. Many indoor applications are presented such as:

1- Uncompressed high definition (HD) video streaming that enables users to wirelessly display content to a remote screen with wired equivalent quality/experience.

2- ‘Synch and go’ file transfer that enables gigabytes of file transfer in a few seconds.

3- Wireless docking stations that allow multiple peripherals (including an external monitor) to be connected without the need for frequent plugging and unplugging.

4- Wireless gigabit Ethernet that permits bidirectional multi-gigabit Ethernet traffic.

5- Vehicular applications which are partitioned into three classes: intra-vehicle wireless networks, inter-vehicle wireless networks and vehicular radar.

6- LAN-to-LAN connections (LAN bridges), buildings in a campus environment can be connected together with wireless links that offer high bandwidth, excellent data security availability.

2.5 Adapted 60 GHz MAC protocol

Working at the 60 GHz frequency band require a modified MAC protocol to serve its characteristics, and to overcome all the challenges in order to present a better quality of service which lead to a better network performance. In the following chapter, we explain what is a protocol MAC and what are his functionalities and also what types of protocols exist.

Chapter 3
MAC protocol Challenges

3.1 Introduction

As we mentioned previously, using the 60 GHz frequency band requires a special adapted MAC protocol to serve its characteristics and respect its properties. So many challenges that we can find in the MAC layer when working with mmWaves like the robustness of the link, because of the high attenuation by obstructions, hence, the 60 GHz link is much more likely to break in comparison with 2.4 or 5 GHz. Therefore, it is important to design a MAC protocol that can handle link failures efficiently.

Another challenge in 60 GHz MAC is that it must support a high number of directions relative to the number of associated devices. Most, or all, directional MAC protocols proposed for 2.4 / 5 GHz are concentrated on the support of eight independent directions to each device. However, creating a standard for the mmWave technology requires the support of 32 (and in some cases 64) independent directions so that a higher gain antenna can be obtained.

Supporting a high number of directions represents big challenges for the protocol; the most important one among them is probably the use of omnidirectional transmissions, so the communication becomes extremely expensive as the throughput should fall roughly proportionally to the number of supported directions.

Therefore, the design of the MAC needs to minimize the use of omnidirectional transmissions at low rates and exploit the high rate directional communication, not only for data transmission but also for control functions and management.

Another major challenge is the requirement of an effective mechanism of a contention-based random access method. The following table shows a comparison between WLAN parameters for 5 and 60 GHz.

Table 3.1 shows the different parameters used in both 5GHz and 60 GHz frequencies where:

- EIRP (equivalent isotropically radiated power) represents the amount of power that a theoretical isotropic antenna (which evenly distributes power in all directions) would emit to produce the peak power density observed in the direction of maximum antenna gain. EIRP can take into account the losses in transmission line and connectors and includes the gain of the antenna. The EIRP is often stated in terms of decibels over a reference power emitted by an isotropic radiator with equivalent signal strength.
- E_b/N_0 or (SNR: signal to noise ratio), it is especially useful when comparing the bit error rate (BER) performance of different digital modulation schemes without taking bandwidth into account.
- The penetration loss indicates the fading of radio signals from an indoor terminal to a base station due to obstruction by a building.
- Beamforming represents a signal processing technique used in sensor arrays for directional signal transmission or reception. This is achieved by combining elements in a phased array in such a way that signals at particular angles experience constructive interference while others experience destructive interference

Table 3.1 : WLAN parameters for 5 GHz and 60 GHz

	5GHz	60GHz
Number of antennas	4	36
Maximum EIRP (FCC)	30dBm + 6dBi (antenna gain)	40dBm
Transmit power/antenna (P_t)	24dBm	4dBm
Transmit beamforming gain (G_t)	0	15dB
Power combining gain (G_c)	0	15dB
Receive beamforming gain (G_r)	0	15dB
Modulation coding scheme	64QAM 5/6	BPSK 3/4
Minimum E_b/N_0 @ 10e-5	19dB	10dB
Aperture loss @ 1m	-48dB	-68dB
Penetration loss/drywall (L_w)	4.7dB[12]	8.8dB[13]
Penetration loss/person (L_p)	5dB[15]	14.5dB[14]

3.2 The Hidden-Terminal problem

Recently, research interest in the performance analysis of wireless networks was revived. An issue of utmost importance in this class of networks, classified as one of the severest reasons for the degradation of their performance, is the hidden terminal problem.

Nodes usually work in a half-duplex mode in wireless ad hoc networks and cannot transmit and receive at the same time. Hence, nodes are not able to detect collisions during transmissions. When a collision occurs, the source node continues transmitting the complete packet. When the packet is large, the radio resources are wasted greatly due to the corrupted packets.

In a multi-hop environment, collisions are much more serious than those in a single-hop environment due to the existence of hidden terminals; therefore, degrade the network throughput significantly [12].

Hidden terminals in a wireless network refer to nodes that are out of range of other nodes or a collection of nodes. To explain this problem in a more detailed way see figure 3-1.

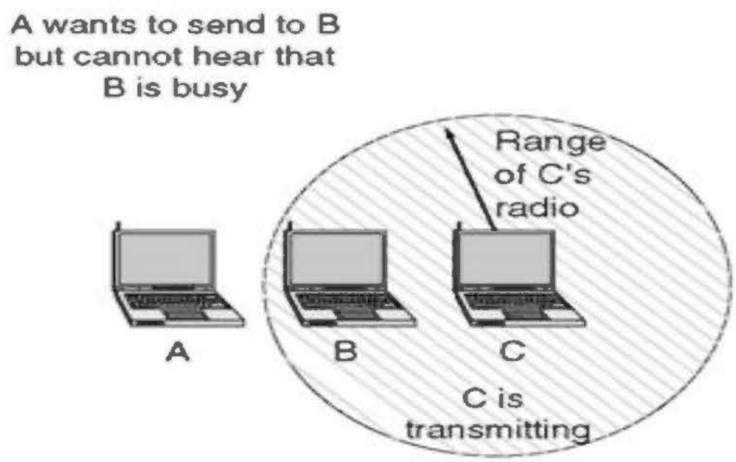


Figure 3-1: The Hidden-Terminal problem

Since not all stations are within radio range of each other, transmissions going on in one part of a cell may not be received elsewhere in the same cell. In this example, station *C* is transmitting to station *B*. If *A* senses the channel, it will not hear anything and falsely conclude that it may now start transmitting to *B*.

To address the collisions caused by this problem, many solutions have been proposed. The first and simplest solution was the RTS/CTS (Ready to Send / Clear to Send) method, this handshake between the transmitter and the receiver has a role in preventing data collisions by reserving the channel before transmitting. However, this solution was not a complete solution because RTS/CTS packets themselves are subject to collisions as figure 3-2 shows.

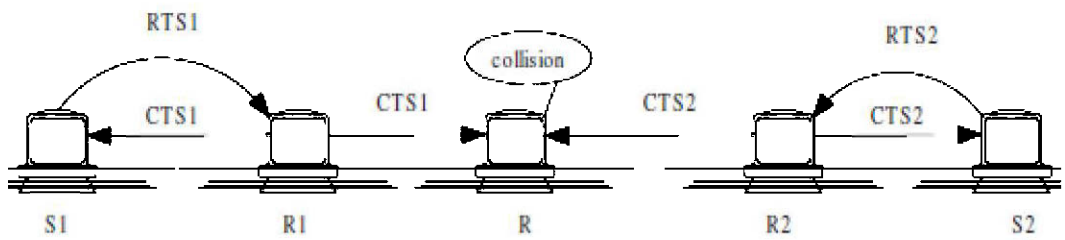


Figure 3-2: CTS collision

When the traffic load is heavy, DATA packets may still experience collisions with a high probability due to the loss of RTS or CTS packets [13]. In order to overcome this problem the 'Busy-Tone' method was introduced, this solution was proposed to protect the data packets as well as the control packets (RTS/CTS) and prevent their collisions.

3.3 The Exposed Terminal problem

RTS/CTS handshake mechanism was introduced to wireless MAC layers to eliminate the hidden terminal problem. However, this mechanism introduces a new problem termed the exposed terminal problem [14]. In wireless networks, the exposed node problem occurs when a node is prevented from sending packets to other nodes due to a neighboring transmitter. To understand this issue see figure 3-3.

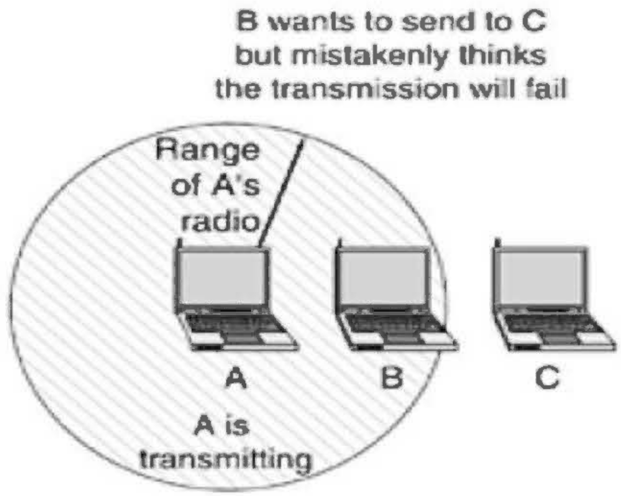


Figure 3-3: The Exposed Terminal Problem

Here B wants to send to C so it listens to the channel. When it hears a transmission, it falsely concludes that it may not send to C, even though A may be transmitting to D (not shown). In addition, most radios are half duplex, meaning that they cannot transmit and listen for noise bursts at the same time on a single frequency [5].

The RTS/CTS mechanism can help solving this issue only if the terminals are synchronized and packet sizes and data rate are the same for both transmitting terminals. When a node hears an RTS from its neighbor, but not the corresponding CTS, that node can deduce that it is an exposed node and is permitted to transmit to other neighboring nodes.

If the nodes are not synchronized (or if the packet sizes are different or the data rates are different) the problem may occur that the sender will not hear the CTS or the ACK during the transmission of data of the second sender.

The major effects of the exposed terminal problem are the underutilization of the channel and the low effective throughput.

3.4 The Deafness problem

This problem is basically created when using directional antennas, a node using a directional antenna is considered deaf in all the directions except for the directions in its main beam [15]. Figure 3-4 shows a simple example of the deafness.

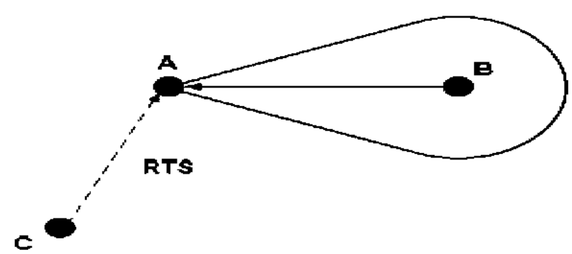


Figure 3-4: The Deafness problem.

To understand more this problem, we consider that there is a communication between nodes *A* and *B* with the main beam of *A* is pointed toward *B*; node *C* cannot hear the ongoing communication between those two nodes so it attempts to transmit packets to *A* by sending out a RTS. Since the main lobe of node's *A* antenna is not in direction of Node *C*, it does not hear RTS packets sent by *C*, which results in timeouts in Node *C*. Furthermore, the deafness problem can start a chain effect throughout the network and cause low performance, unfairness, and deadlock.

Deafness does not only affect the MAC layer, but also the performance of higher layers. For example, when a node send a RTS packet and does not receive its CTS, it backoffs and tries to send its RTS another time. This leads to excessive wastage of network capacity in control packet transmission. Larger backoff intervals also result into unfairness wherein a flow completely captures the wireless shared medium [16].

The impact of this problem is also severe on the routing layer because each consecutive unsuccessful transmission of a packet (RTS or DATA) at the MAC causes the increment of a variable called Short Retry Limit (SRL) which results in considerable network performance degradation, as route request packets are often flooded [16].

Finally, deafness may also impact the performance of the transport layer. Deafness may preclude a node from receiving a TCP ACK, for example. Clearly, this negatively impacts TCP performance as it may continuously enter its congestion control mechanisms [16].

The deafness problem can be solved by sending the RTS and CTS omni-directionally, while the data packets are sent via directional antennas. However, this solution has its disadvantages the RTS and CTS packets can collide which will lead to more data loss while comparing to busy tone, the signal is sent for one time and it keeps the channel busy as long as the data transmission procedure is taking place [17].

Chapter 4
MAC protocols overview

4.1 Introduction

This chapter presents a MAC protocol overview, it includes detailed explications about the data link layer, the medium access control sub layer and its role, then we explained what is a MAC protocol and its goals, also in this chapter you will find a detailed study about protocol MAC classification, the different types and the role of each one. Also we give an overview on the related works and the methods that have been proposed so far to deal with the same issues and what are the advantages and disadvantages of each method.

4.2 The data link layer

It is the second layer in the Open Systems Interconnect (OSI), this layer provide data transmission control, it handles the moving of data in and out across the physical layer in a network. It also ensures that incoming data has been received successfully by analyzing bit patterns at special places in the frames.

The data link layer has many specific functions [5]:

- It provides a well-defined interface to the network layer.
- It deals with transmission errors.
- It regulates the flow of data so that slow receivers are not swamped by fast senders.

This layer is divided into two sublayers: the Medium Access Control (MAC) and the Logical Link Control (LLC).

4.3 The Medium Access Control sub layer

This layer contains all the protocols that are used to determine who uses next a multi-access channel. The main function of this layer is to regulate the use of the medium through a channel access mechanism, this mechanism presents a way to divide the main channel between nodes, and this operation of channel sharing is controlled by the MAC protocol, it tells each node when to transmit its packets and when it is expected to receive packets.

The main objective of the MAC protocol algorithm is to ensure a secure data transmission, and to prevent collisions that happen occasionally in the network for many reasons, depending on the type of the network that is used and its topology, also many problems that we will talk about and explain later, such as the deafness problem, the hidden and exposed terminals problems…All of these problems are main reasons for causing collisions and data loss, which reduce the performance of the network entirely.

4.4 MAC protocols goals

Medium Access control techniques are designed to achieve the following goals [8]:

- Initialization: The technique enables network stations, upon power-up, to enter the state required for operation.

- Fairness: It should treat each station in a fair way regarding the waiting time until the station gains entry to the network, access time and transmission time.

- Priority: Giving priority of channel access and communication time to some stations over others depending on the types of needed services.

- Limitations to one station: the transmission should be done by one station at a time.

- Reception: The technique should ensure the reception of the packets, also ensure that there is no duplication and the packets are received in the right order.
- Error limitation: The capability of encompassing an appropriate error detection scheme.

- Recovery: In case of packets collisions, the method should be able to recover, which means being able to halt all the transmissions and select one station to retransmit.

- Reconfiguration: The technique should enable a network to accommodate the addition or deletion of a station with no more than a noise transient from which the network station can recover.
- Reliability: By enabling the network confine operating despite of a failure of one or several stations

4.5 Conventional MAC protocols

There are generally two types of MAC: contention-free and contention-based. The first type protocols include IEEE 802.11 DCF (distributed coordination function) and 802.15.3 contention access and are currently the dominant MAC in use. The second type protocols include 802.11e HCCA (HCF controlled channel access) and 802.15.3 channel time allocation, where channel access is centrally allocated in a TDMA fashion, also in the contention based protocols, there is another category which is the contention based with reservation mechanism.

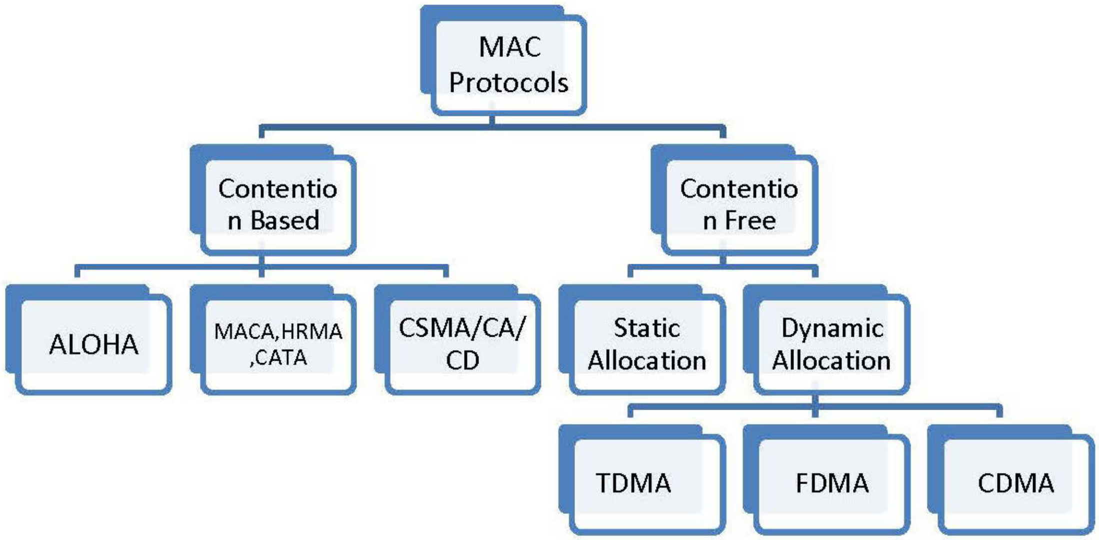


Figure 4-1: MAC protocols classification

4.5.1 Contention-free protocols

In these protocols, the nodes are following some particular schedule which guarantees collision free transmission times. Typical examples of such protocols are: Time Division Multiple Access (TDMA); Frequency Division Multiple Access (FDMA); Code Division Multiple Access (CDMA) [6].

This three protocols that we mentioned can be also combined together to create or adapt another protocol that can be more efficient like the FDMA/CDMA hybrid MAC protocol called (HYMAC) [25].

4.5.1.1 Time Division Multiple Access (TDMA)

TDMA consists of a network that contains a base station in addition to other nodes; the base station has a role of coordinating those nodes in the network, the principle of this mechanism is to divide the channel into fixed size time slots. Each node of the network is allocated a certain number of slots where it can transmit. Slots are usually organized in a frame, which is repeated on a regular basis.

The organization of the frame is normally specified by the base station by sending a control frame or a management frame that's called a beacon, so all the node has to follow the instructions of the base station. The frame is organized as downlink (base station to node) and uplink (node to base station) slots, and all the communications are done through the base station.

TDMA is very popular in the technologies that are sensitive to QoS (Quality of Service) including WiMAX and cellular networks, TDMA also provides good support for power saving. When applying TDMA to 60 GHz use, we find it very suitable for applications such as wireless display (compressed or not) and large file transfers in sync-and-go.

4.5.1.2 Frequency Division Multiple Access (FDMA)

It is one of the simplest and oldest mechanisms, it consists of dividing the frequency band into several lower frequencies or channels, FDMA is like any other multiple access systems; it coordinates access between multiple users.

However, it is not very efficient because a channel could be wasted if no one is talking in that channel; also the cost of a base station for FDMA is high with very limited capacity. Due to these limitations, very few wireless systems use FDMA at present. Most applications of FDMA are in satellites applications [7].

4.5.1.3 Code Division Multiple Access (CDMA)

CDMA is a form of multiplexing, which allows numerous signals to occupy a signal transmission channel, optimizing the use of the available bandwidth. It uses a technology called direct sequence spread spectrum to provide more conversations for a given amount of bandwidth and digital service.

It uses unique digital codes rather than separate RF frequencies or channels to differentiate subscribers, those codes are shared by both the mobile station and the base station, and they are called “Pseudo-random Code Sequences”. And all users share the same range of radio spectrum.

There are different codes used in CDMA such as the Walsh orthogonal codes that provide a means to uniquely identify each user on the forward link, and the Pseudorandom Noise (PN) codes that uniquely identify users on the reverse link. The PN codes used in CDMA yield about 4.4 trillion combinations of code which makes the CDMA so secure.

The advantages of this method are represented by the improved call quality and reduced audible effects of multipath fading, it also provides great coverage for a low cost, and it improves security and privacy along with increasing the data throughput.

The only disadvantage to CDMA is that it is not used as widely as GSM so roaming can be a problem, especially internationally.

4.5.2 Contention-based protocols

A contention-based protocol (CBP) is a communications protocol for operating wireless telecommunication equipment that allows many users to use the same radio channel without pre-coordination. Contention techniques are suitable for bursty nature of traffic.

Contention-based MAC protocols are also known as random access protocols, requiring no coordination among the nodes accessing the channel. There is no centralized control and when a node has data to send, it contends for gaining control of the medium.

Colliding nodes back off for a random duration and try to access the channel again. The "listen before talk" operating procedure in IEEE 802.11 is the most well known contention-based protocol.

The principle advantage of contention techniques is their simplicity. They can be easily implemented in each node. The techniques work efficiently under light to moderate load, but performance rapidly falls under heavy load [8].

4.5.3 Contention-based protocols types

So many protocols and methods have been defined under this category.

4.5.3.1 Aloha

It is one of the oldest methods that were found, in order to solve the channel allocation problem; this method has been extended by many researchers since then. There are two versions of Aloha; pure and slotted.

i. *Pure Aloha*

The basic idea of this method is very simple; the users transmit whenever they have data to be sent, of course, this will cause collisions and frame damaging. However, due to the feedback property of broadcasting, a sender can always find out whether its frame was destroyed by listening to the channel [5].

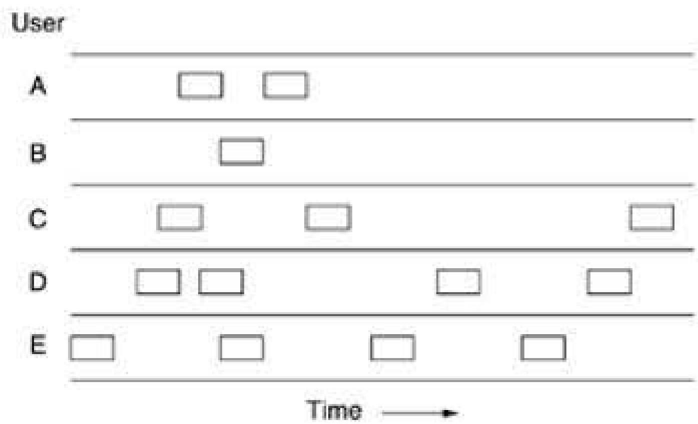


Figure 4-2: In pure ALOHA, frames are transmitted at completely arbitrary times.

ii. *Slotted Aloha*

This method was published to double the capacity of an Aloha system. The principle was to divide time into discrete intervals, each interval corresponding to one frame. A computer is not permitted to send whenever data is ready to be sent. Instead, it is required to wait for the beginning of the next slot. Thus, the continuous pure Aloha is turned into a discrete one [5].

4.5.3.2 Carrier Sense Multiple Access (CSMA)

It is a probabilistic Media Access Control protocol in which a node verifies the absence of other traffic before transmitting on a shared transmission medium, "Carrier Sense" describes the fact that a transmitter uses feedback from a receiver that detects a carrier wave before trying to send.

It tries to detect the presence of an encoded signal from another station before attempting to transmit. If a carrier is sensed, the station waits for the transmission in progress to finish before initiating its own transmission. In other words, CSMA is based on the principle "sense before transmit" or "listen before talk".

"Multiple Access" describes the fact that multiple stations send and receive on the medium. Transmissions by one node are generally received by all other stations using the medium.

There are three variations of this basic scheme as outlined below [5]:

i. 1-persistent CSMA

In this case, if the node has packets to send it starts sending if it founds the channel idle, if not it waits until the channel is sensed free then it sends its packets.

ii. Non-persistent CSMA

In this case, if the channel was sensed free, the node starts sending its data otherwise it waits for a random amount of time then it start sensing the channel.

iii. p-persistent CSMA

Also in this case the node starts sending if it senses the channel free, if not, the node continues to monitor until the channel is free and then it sends with probability p.

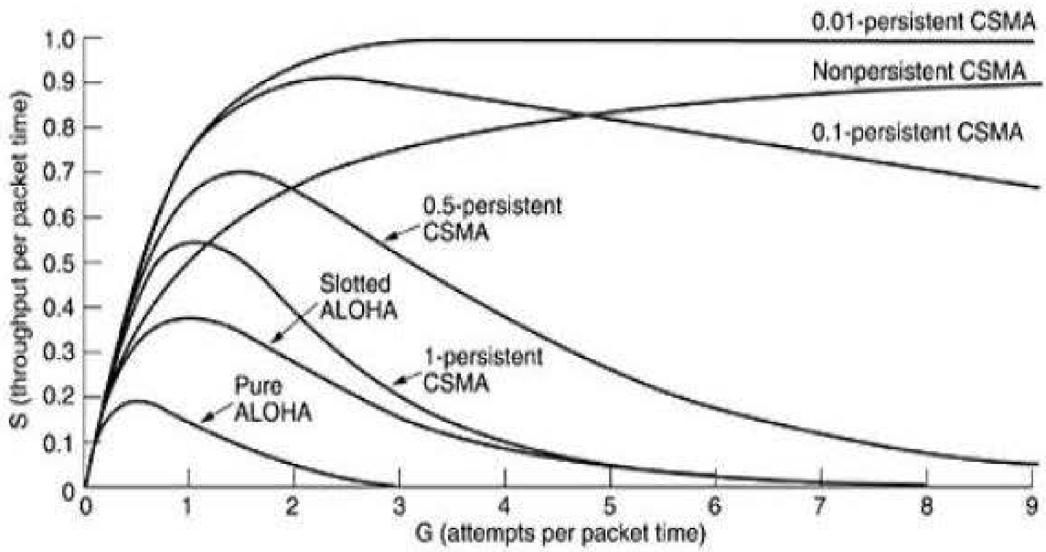


Figure 4-3: Comparison of the channel utilization versus load for various random access protocols [5].

4.5.3.3 CSMA/CD (CSMA with collision detection)

It is used to improve CSMA performance by terminating transmission as soon as a collision is detected, and reducing the probability of a second collision on retry. In a more detailed way, if a collision is detected during transmission of a packet, the node immediately ceases transmission and it transmits jamming signal for a brief duration to ensure that all stations know that collision has occurred, then it waits for a random amount of time and then transmission is resumed [8].

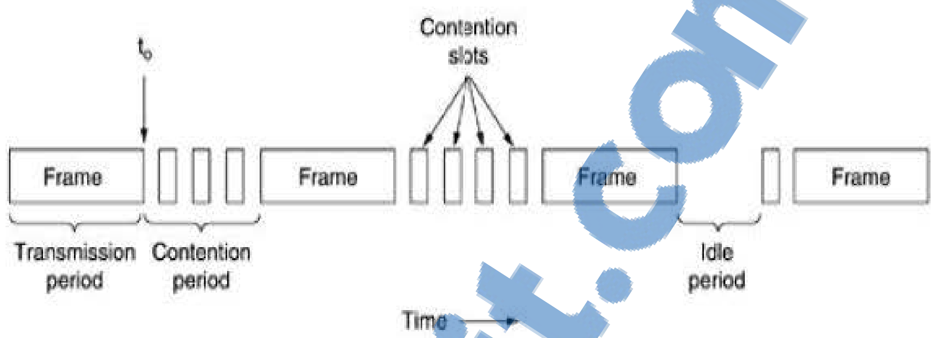


Figure 4-4: CSMA/CD can be in one of three states: contention, transmission, or idle.

4.5.3.4 CSMA/CA (CSMA with collision avoidance) or Media Access with Collision Avoidance (MACA)

It is also used to improve the performance of CSMA by attempting to be less "greedy" on the channel; if the channel is sensed busy before transmission then the transmission is deferred for a "random" interval, if it finds the channel free, it does not send its packets immediately, instead it sends a signal indicating that it is about to send data. This reduces the probability of collisions on the channel.

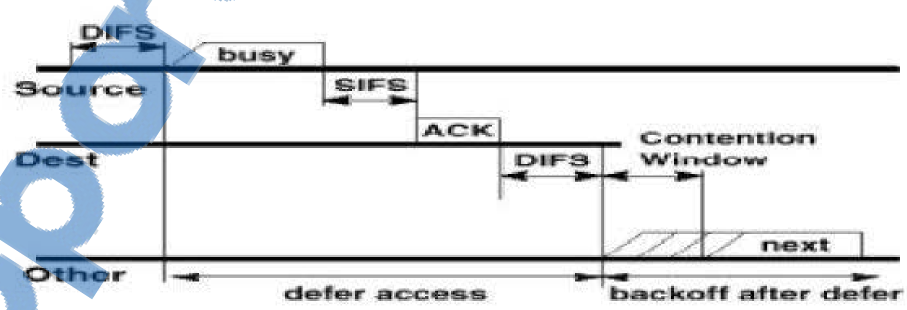


Figure 4-5: CSMA/CA

To explain this figure in a simple way we have to take both sender and receiver in count. The sender senses the channel if its idle for a random time called DIFS (DCF Interframe Space) then transmit entire frame, if it senses that the channel is busy, if performs a binary backoff [4].

A host which has experienced a collision on a network waits for a amount of time before attempting toretransmit. A random backoff minimises the probability th at the same nodes will collide again, even if theyare using the same backoff algorith m. Increasing the backoff period after each collision also helps toprevent repeated co llisions, especially when the network is heavily loaded

From the receiver side now, if the frame was received the receiver waits a random amount of time called SIFS (Short Interframe Space) then it sends a frame called acknowledgment (ACK)

4.5.3.6 MACA for wireless networks (MACAW)

It is based on the MACA protocol with a modified back-off algorithm, the node that wants to transfer data checks back-off counter and selects packets with minimal waiting time, new control packets are introduced in this protocol such as the acknowledgment packets (ACK), data sending (DS) and request for request to send packets (RRTS).

4.5.3.7 Busy Tone Multiple Access (BTMA)

The method offers the first solution to the hidden terminal problem, it consists of two channels, one for the data transmission and the other is for the tone signal transmission. The role of the busy tone signal is to inform other nodes that the transmission channel is busy so nodes can defer their transmissions using a back-off mechanism.

So any node wants to transmit data, it checks the “busy-tone” channel instead of checking the data transmission channel, if it finds it busy it, defers its transmission and wait for a backoff. Otherwise, it sends its data.

After a node sends the data via the transmission channel, it also has to send a "busy-tone" signal into the "busy-tone" channel to set it ON so other can see its actual situation.

4.5.3.8 Dual Busy Tone Multiple Access (DBTMA)

It is an extension of BTMA; in this case, there are two channels for the "busy-tone" signal, the first channel is used by the transmitter (BTt), and the other is used by the receiver (BTr), the BTt channel indicates that the transmitter is sending packets on the data channel. And the BTr shows that a node is receiving packets on the data channel [22].

The two "busy-tone" signals are sine waves at two different frequencies with enough spectral separation. The busy tone, which is set up by the transmitter, provides protection for the RTS packets, increasing the probability of successful RTS reception and, consequently, increasing the throughput.

4.5.4 Hybrid Protocols

These are contention based protocols with reservation mechanism; these protocols provide bandwidth reservation ahead. Even though these protocols are contention-based, the contention takes place only during the bandwidth reservation phase; therefore, they can provide QoS support. These can be further subdivided into:

- Synchronous protocols: there is time synchronization among all nodes in the network; the nodes in the neighborhood are informed of the reservations;

- Asynchronous protocols: no global synchronization is needed. Relative time is used for the reservations [10].

4.5.4.1 Distributed Packet Reservation Multiple Access Protocol (D-PRMA)

This method is based on TDMA; it divides the channel into fixed frames along the time axis; so every frame consists of several minis lots, and each minislot contains two control fields, RTS/BI – Request To Send / Busy Indication and CTS/BI – Request To Send / Busy Indication.

The competition for slots is done in a way that a certain period of time at the beginning of every slot is reserved for carrier-sensing. The nodes compete for the first minislot, and then the winning node sends a RTS packet through the RTS/BI part of the first minislot, after that the receiver responds by sending a CTS packet through the CTS/BI field. Thus, the node is granted all the subsequent minislots [11].

4.5.4.2 Collision Avoidance Time Allocation Protocol (CATA)

In this protocol, time is divided into frames and each frame into slots. Each slot is also divided into 5 minislots. The first four are for control (CMS) and the last one is longer than the others, it is used for data transmission (DMS).

This method is based on dynamic topology dependent transmission scheduling; it supports broadcast, unicast and multicast. CATA has two basic principles [10]:

- The receiver of a flow must inform other potential source nodes about the reservation of the slot, and also inform them about interferences in the slot.
- Negative acknowledgements are used at the beginning of each slot for distributing slot reservation information to senders of broadcast or multicast sessions.

4.5.4.3 HOP Reservation Multiple Access Protocol (HRMA)

It represents a multichannel MAC protocol based on FHSS (frequency-hopping spread spectrum); it can be viewed as a time slot reservation protocol where every time slot has a separate frequency, each time slot assigned a separate frequency channel.

A handshake mechanism is used for reservation to enable node pairs to reserve a frequency hop, thus providing collision-free communication and avoiding the hidden terminal problem, after the handshaking is over, the two nodes communicate by sending data and ACKs on the very same frequency channels [11].

4.6 MAC protocol 802.11

Our work in this theses and the adapted protocol that we talked about earlier and we explain in details later in the coming chapters is based on this protocol (802.11). It is considered one of the most deployed protocols in the world, it applies to wireless LANs and provides 1 or 2 Mbps transmission in the 2.4 GHz band using either frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS).

IEEE 802.11 is a set of media access control (MAC) and physical layer (PHY) specifications for implementing wireless local area network (WLAN) computer communication in the 2.4, 3.6, 5 and 60 GHz frequency bands. They are created and maintained by the IEEE LAN/MAN Standards Committee (IEEE 802). The base version of the standard was released in 1997 and has had subsequent amendments. The standard and amendments provide the basis for wireless network products using the Wi-Fi brand. While each amendment is officially revoked when it is incorporated in the latest version of the standard, the corporate world tends to market to the revisions because they concisely denote capabilities of their products. As a result, in the market place, each revision tends to become its own standard.

4.7 Protocols for 60 GHz

Previous works attempted to adapt or create new methods in order to guaranty a better communication and to resolve medium access control issues when using mmWaves. Many authors worked on the directivity issue and how to use directional antennas to increase the communication range and guaranty a better connectivity. For example in [18] the authors proposed a directional medium access control (DMAC) algorithm for wireless communication networks operating in the 60 GHz bands, this method presents an efficient approach to determine the presence of a direct path between transmitter and receiver, which will be used to determine if the environment is LOS or non-LOS.

In [19] they investigated spatial interference statistics for multigigabit outdoor mesh networks operating in the unlicensed 60-GHz “millimeter (mm) wave” band. Also in [20], Fan proposed a network architecture for 60 GHz wireless personal area networks (WPANs) using directional antennas, which describes protocols for neighbor discovery, medium access, and multi-hop route establishment that exploit directional antennas to improve network performance and maintain connectivity [20].

Another group of researches worked in the signaling channel part where we can easily recognize the Busy-Tone method; this method depends on using a channel to send control packets other than the original channel where the data are sent. The most important works we can find in this domain and which were helpful for our research were ‘Busy-Tone’ methods for WLans, for example in [21], they proposed a ‘Busy-Tone’ based cooperative MAC protocol for wireless local area networks called BTAC. In this technique, different nodes in a wireless network are allowed to share their resources and cooperate through distributed transmission, forming multiple transmission paths to the destinations.

In [22], the authors proposed a ‘Busy-Tone ‘solution for collision avoidance in wireless ad hoc networks, the idea was to use two ‘Busy-Tone’ channels, one for the transmitter and the second is for the receiver, this method was mainly proposed to avoid collisions (Data collisions and RTS collisions) and to resolve the exposed terminal problem incurred by the increased carrier sense range of the transmitter busy-tone channel.

We can find many other works in the domain; we mentioned the ones that we find relevant to our work.

In our research we combined the use of directional antennas along with the‘Busy-Tone’ method which will be explained later in further chapters with details

Chapter 5
Proposed method

5.1 Introduction

This chapter presents the proposed method, in other words the idea that we proposed to solve the problem listed in chapter three. This method is based on the adaptation of the standard 802.11ad to be used with 'Busy-Tone' method in addition to the use of directional antennas in coordination with omnidirectional antennas; also we present the float chart of the proposed scheme with a detailed explanation for the different states and phases, also we explain the TPC method and how we used this principal to execute our proposed idea to be able to do the combination between 2.4 GHz and 60 GHz.

5.2 The Proposed MAC Algorithm

The proposed method contains three essentials parts, the first part is obtaining a protocol MAC that works under the 60 GHz frequency band by modifying the CSMA protocol that already exists in OPNET using the 802.11 ad parameters, the second part is the implementation of the 'Busy-Tone' method in a way that respects the properties and characteristics of the modified protocol, and thirdly the implementation of directional antennas that are necessary for 60 GHz communications adding the combination with omnidirectional antennas and the 2.4 GHz channel. These three parts are explained in details in the coming sections. Figure 5-1 shows the float chart of the algorithm.

As we mentioned above the basic idea of our proposed scheme is using the busy tone method combined with directional antennas, the protocol MAC that we used is the standard 802.11 ad, which was made for mmWaves and short range communications.

The frequency bands used in our method are 2.4 GHz and 60 GHz, the 2.4 GHz channel is used for neighbor discovery and sending busy tone signals using omnidirectional antennas, while 60 GHz is used to send data packets using directional antennas.

The protocol MAC used in our approach is 802.11 ad, in order to get this protocol with the right parameters, we used the CSMA/CA protocol that already exists in OPNET Modeler and modified it to get the properties and characteristics that we needed.

It begins with the *idle* state, the purpose of this state is to wait until the packet has arrived from the higher or lower layer, when data arrives from the application layer, and it is directly inserted in the queue. If the receiver is not busy, then it sets *deference* to DIFS (DCF Inter Frame Space) and changes state to *defer* state. Then it sets Backoff if it is needed.

After the packet arrives and placed in the queue, the second step is to transmit it. But before transmitting the data directly, the process enters in the *deference* state. This state defer until the medium is available for transmission. If the medium was found busy then a backoff procedure is executed after deference. The medium we are talking about contains the data channel and the 'Busy-Tone' channel and both should be idle in order to consider that the medium is idle.

The next step is to determine whether a backoff is necessary for the frames we are trying to transmit. It is needed when the node is preparing to transmit and it discovers that the medium is busy or when a collision is detected. A backoff is not needed when a node is responding to the frame. A backoff is also performed following a successful packet transmission.

Now in case of a needed backoff, the node checks if it completed its backoff in the last attempt, if not then it resumes the backoff from the same point, otherwise it generates a new random number for backoff slots.

After determining if the node needs to perform a backoff and it is ready to transmit the frame, it prepares the transmission by setting appropriate fields in the data frame. After a data frame is transmitted via directional antennas on the 60 GHz channel, also a 'Busy-Tone' packet is generated and sent on the 2.4 GHz channel to set the medium as busy, and inform other nodes that are trying to communicate that there is a communication already taking place so they can defer their transmissions.

The Generated 'Busy-Tone' packet is a short packet with respect to the necessary delays. So the Busy-Tone delay = DIFS time + SIFS time + Ack Time + Data time. In other words, the busy tone signal sent, its flag is set to ON state for a time equal to the packet sending time plus the acknowledgment time in addition to both DIFS and SIFS times.

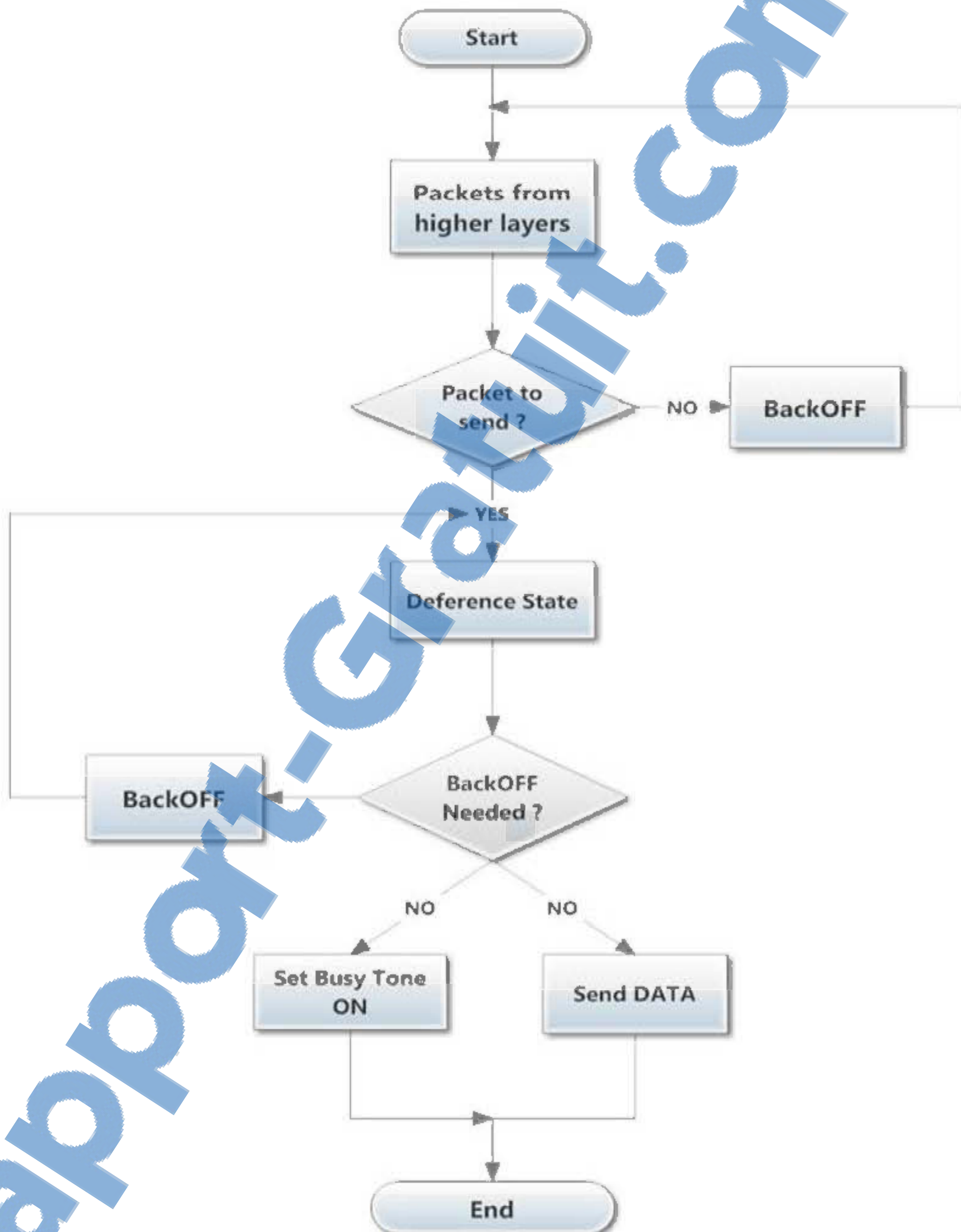


Figure 5-1: The proposed algorithm Float Chart

5.3 The standard 802.11 ad

It is also known as WiGig 1.0, the complete version of its specification was announced in December 2009, and it was created in May 7 of the same year. The 802.11 ad is a proposed specification in the 802.11 family applicable to WLANs (wireless local area networks). It represents an extension or update of the current 802.11a standard.

The 60 GHz spectrum is also known as the "oxygen absorption band." That means radio waves at those frequencies are actually degraded by the presence of oxygen in the air. For this reason, 60 GHz was considered only appropriate for point-to-point, outdoor applications using highly-directional antennas (e.g., wireless links between two networks) until recently. It could also be used in outer space for inter-satellite communications where oxygen is obviously not a problem, or for indoor short-range applications, such as linking device docks with wireless interconnects

The enhancements supported by 802.11ad will facilitate simultaneous streaming of HD (high definition) video to multiple clients in large office environments, as well as faster wireless synchronization and backup of large files [23].

802.11 ad presents new features and enhancement to 802.11 a [23]:

- Native 802.11a/b/g/n/ac support.
- Seamless switching between 2.4, 5, and 60-GHz bands.
- Bandwidth up to 2160 MHz.
- Throughput of up to 6.7 Gbps (gigabits per second).
- Working range of 10 meters or more.
- Improved functionality for mobile devices.
- Built-in support for wired connections.

- Advanced security features.
- Support for power management.

In addition to the tabulated details, the system uses a MAC layer standard that is shared with current 802.11 standards to enable session switching between 802.11 Wi-Fi networks operating in the 2.4 GHz, and 5 GHz bands with those using the 60 GHz WiGig bands. In this way, seamless transition can occur between the systems. However the 802.11ad MAC layer has been updated to address aspects of channel access, synchronization, association, and authentication required for the 60 GHz operation

The 802.11ad PHY supports three main signals with different modulation.

- Control PHY, CPHY: Providing control, this signal has high levels of error correction and detection. Accordingly it has a relatively low throughput. As it does not carry the main payload, this is not an issue. It exclusively carriers control channel messages.
  The CPHY uses differential encoding, code spreading and BPSK modulation.
- Single Carrier PHY: The SCPHY employs single carrier modulation techniques: BPSK, QPSK or 16-QAM on a suppressed carrier located on the channel centre frequency. This single has a fixed symbol rate of 1.76 Gsym/sec. A variety of error coding and error coding modes are available according to the requirements.
- Orthogonal Frequency Division Multiplex PHY, OFDMPHY: As with any OFDM scheme, the OFDMPHY uses multicarrier modulation to provide high modulation densities and higher data throughput levels than the single carrier modes.

The modulation format SQPSK is Spread QPSK and involves using paired OFDM carriers onto which the data is modulated. The two carriers are maximally separated to improve the robustness of the signal in the presence of frequency selective fading.

- Low Power Single Carrier PHY, LPSCPHY: This 802.11ad signal uses a single carrier as the name implies, and this is to minimize the power consumption. It is intended for small battery devices that may not be able to support the processing required for the OFDM format.

5.4 The combination between 2.4 GHz and 60 GHz

Working in the 60 GHz frequency band demands the respect of new properties and characteristics due to the sensitivity of this band. The most important factor is that the wave length that is very short, and requires the use of directional antennas to increase the range of communication.

So for these reasons, it was necessary to implement the directional antenna in the node model. Its role is to send and receive data packets that are sent on the 60 GHz channel. The other channel which is the 2.4 GHz channel is used only to send 'Busy-Tone' packets. These packet are sent in an omnidirectional way in the purpose to protect the 60 GHz data communication from collisions and interferences by reserving a larger space as figure 5-2 shows.

In the figure 5-2 we see a representation to the range covered by both antennas (directional and omnidirectional) and how the two type of antennas coordinate to be able to cover the same distance in order to provide a maximum protection when the data transmission starts between two nodes. To execute this procedure we used a method based on the idea of the Transmission Power Control (TPC).

The Transmit Power Control or sometimes called Dynamic Power Control (DPC) is a mechanism used in radio communications to reduce the power of a radio transmitter to the minimum necessary to maintain the link with a certain quality. TPC is normally used to avoid interference into other devices and/or to extend a battery life [26].

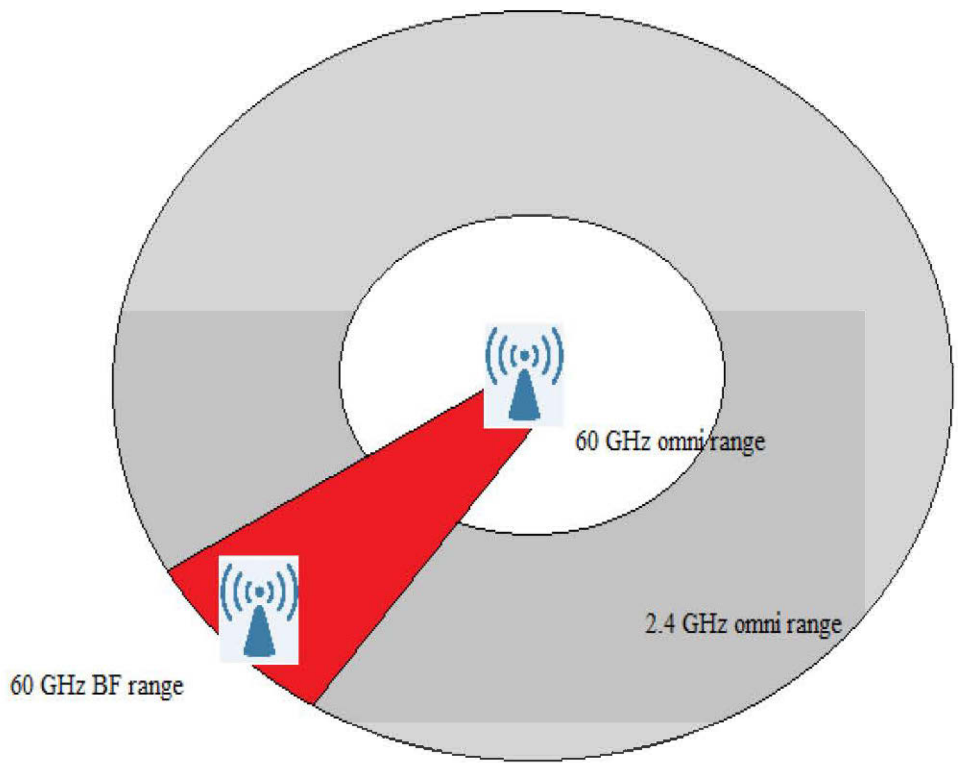


Figure 5-2 : Coordination between 2.4 GHz and 60 GHz

Chapter 6

OPNET Modeling and Simulation results

6.1 Introduction

In this six we present the modeling phase, or the model that we used and implemented using the software OPNET, the use of this software was based on the given results which are considered more realistic compared to other software such as network simulator. In this chapter we present the different phases and methods that were used to achieve our goal which creating a functional model to test our idea which will be shown in the simulation results and the interpretation. In the second part of this chapter we present the network model that we used in addition to the simulation parameters, then we show the simulation results and the interpretation of these results to show the efficiency of our proposed method and ho it affects the performance of the network.

6.2 OPNET Modeler

Modeler is a network simulator that provides a comprehensive development environment supporting the modeling of communication networks and distributed systems. Both behavior and performance of modeled systems can be analyzed by performing discrete event simulations.

The OPNET Modeler environment incorporates tools for all phases of a study, including model design, simulation, data collection, and data analysis.

Between all the features presented in OPNET, our work was mainly on two basic levels. The first level is the node model and the second one is the process model.

6.2.1 The Node Model

In this part we created our own node characteristics using the node editor that allows us to define the behavior for each network object. Behavior is defined using different modules; each is modeling some internal aspect of node behavior such as data creation, data storage, etc. Modules are connected through packet streams.

A network object is typically made up of multiple modules that define its behavior. In another way, at this level, we can see all the layers of the node (physical layer, MAC layer, network layer…..).

The node model we created contains 6 parts as figure 6-1 shows:

- Source: It is for traffic generation.
- Sink: It is for packet reception and storrage .
- Wlan-mac-intf : This module presents an interface between higher and lower layer to determine if the arriving packets are from the MAC or the Application layer.
- Wireless-lan-mac: This module contains the protocol MAC that is used.
- Wlan-port-tx-0: This module is used to send data packets via 60 GHz frequency band.
- Wlan-port-rx-0:This module is used to receive packets via 60 GHz frequency ban.
- A-0: This module represents the directional antenna used to send and receive data packets using the 60 GHz channel.

- Tx-busytone: This module represents the transmitter of the 'Bus-Tone" signal sent via 2.4 GHz channel
- Rx-busytone: This module represents the receiver of the 'Bus-Tone" signal received via 2.4 GHz channel.
- Bt-manage:this Module was created to manage the received 'Busy-Tone' signals.
- P_6: The role of this module is to create and control the antenna pattern coordination.
- The lines represent the packet streams between the different layers.

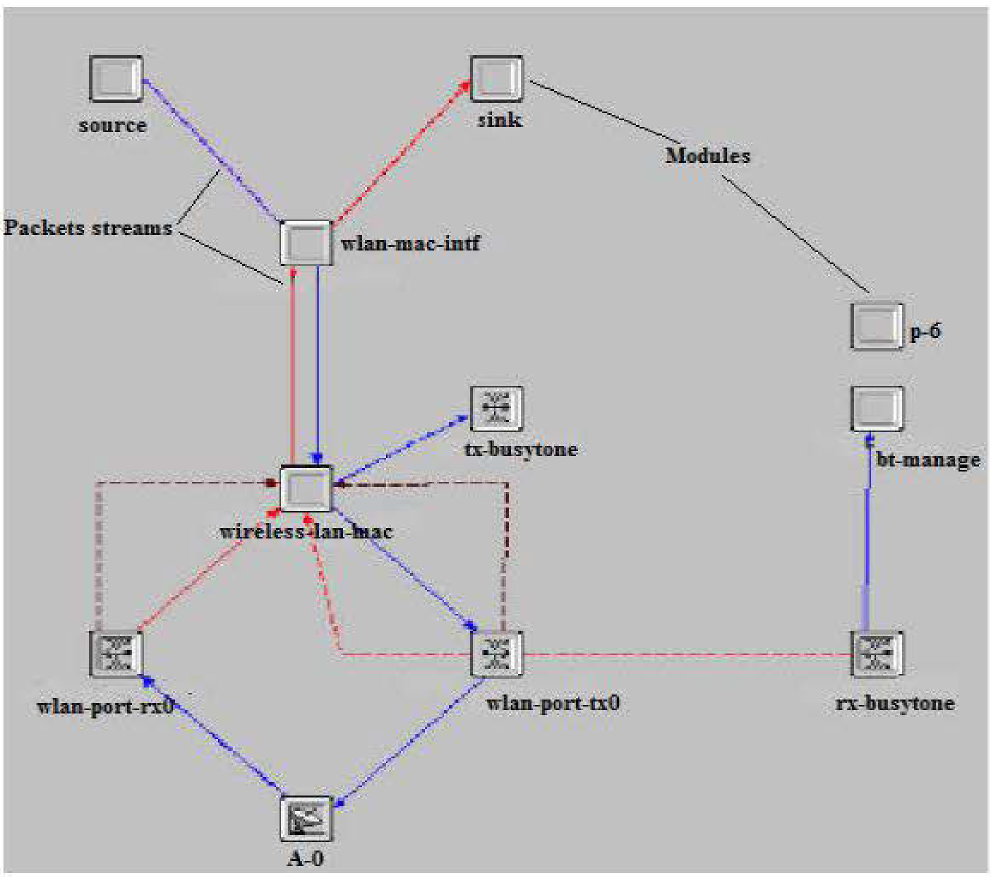


Figure 6-1: Node Model

6.2.2 Directional Antenna

The directional antenna is an antenna which radiates greater power in a specific direction in order to increase the performance on transmission and reception, and to reduce interference caused by different transmissions from different nodes.

6.2.2.1 Antenna module

The antenna module specifies the antenna properties for radio transmitter or receiver. The fact that these properties are specified externally to the transmitter or receiver modules enables us to specify the same set of properties for multiple transmitter or receiver within a single node. So in our case, we used the same antenna for every node with the same parameters and properties but with a different pointing.

In other words, every antenna for a single node that is used by a pair of transmitter and receiver has different coordinates and pointing. The coordinates are generated in a random way to create a nearly real case scenario. Figure 6-2 and 6-3 show the antenna pattern in 3D viewer and polar plots respectively.

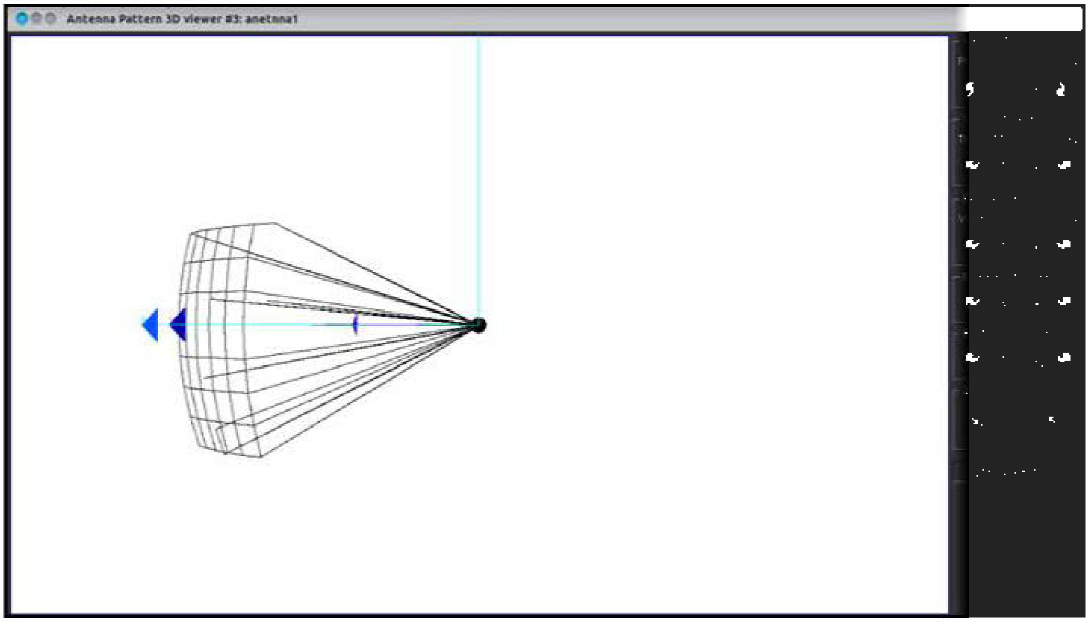


Figure 6-2: Antenna Pattern in 3D viewer

6.2.2.2 Antenna pattern

The antenna pattern is modeled separately from the antenna module and is associated with the antenna module by specifying its name as the value of the module's pattern attribute. It was created using the antenna pattern editor in OPNET Modeler.

The antenna is represented as a function of two angle variables called *polar* and *azimuth* as shown in figure 6-4. These coordinates represent the pointing and the elevation of the antenna which were generated randomly in our nodes. The gain of the used antenna is 30 dB.

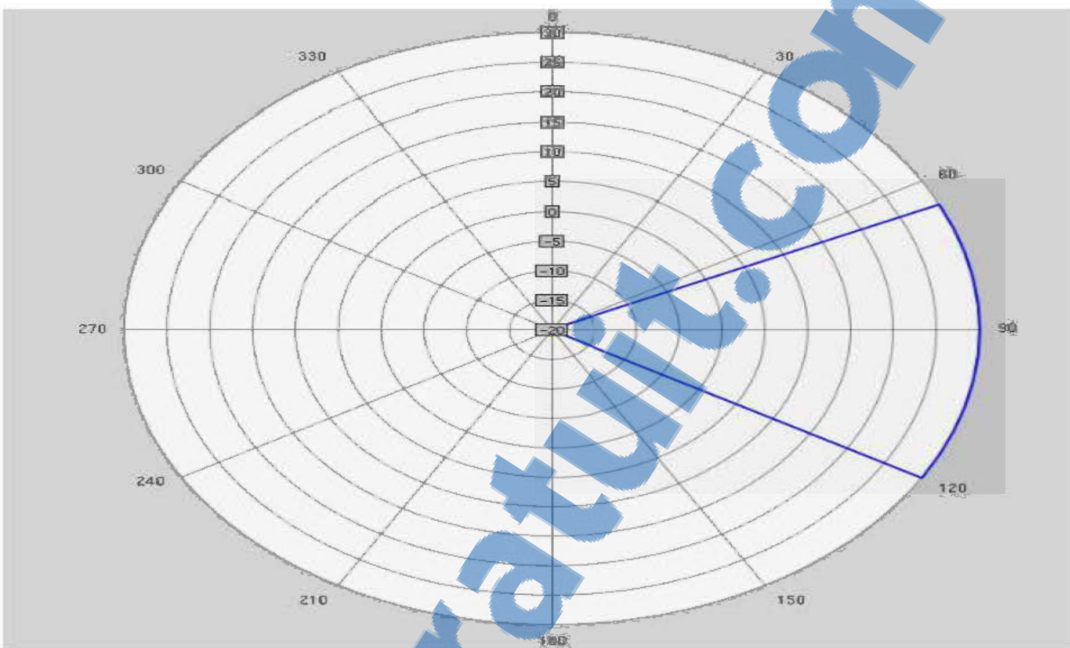


Figure 6-3: Antenna Pattern polar plots

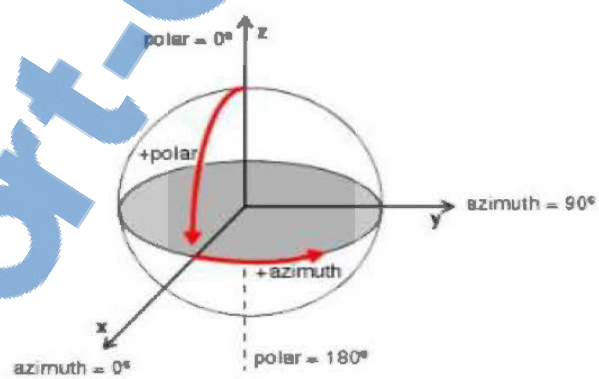


Figure 6-4: Polar, Azimuth coordinate system used to represent Antenna Patterns

6.2.3 The Process Model

In simple words, the process model is the part that represents the heart of a node, where all the functions and the variables are defined and executed, in this case the process model represents our MAC protocol. The process model is made using the process editor in OPNET Modeler. The protocol MAC that we implemented was based on the CSMA protocol already existing in OPNET process models.

6.2.3.1 The Process Model Editor

The Process Editor develops process models, and the process models control modules behavior. Using this editor allowed us to create process models, which control the functionality of the node models created in the Node Editor. The Process Model developer defines the model's interfaces, which determines what aspects of the process model are visible to its user. This includes the attributes and statistics of the process model.

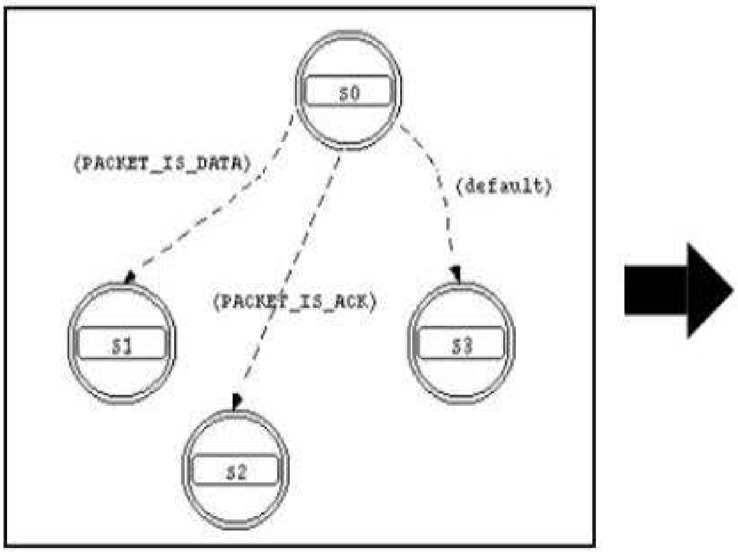
Process models are represented by finite states machines (FSMs), and are created with icons that represent states and lines that represent transitions between states. Operations performed in each state or for a transition are described in embedded C or C++ code blocks.

The process model is basically composed of states and transitions between those states. There are normally three types of states: the *initial state* where execution begins in a process, the *forced states*, and the *unforced states*. In OPNET Modeler, the forced states are represented in a green color while the other two types are represented by red as figure 6-5 shows.

Figure 6-5: The different types of states

6.2.3.2 State connections – Transitions

Transitions describe the possible movement of a process from one state to another and the conditions allowing such a change. Figure 6-6 shows a simple example of transitions between states with the equivalent pseudo-code.




```
if (PACKET_IS_DATA)
    jump_to_state (S1)

else if (PACKET_IS_ACK)
    jump_to_state (S2)

else jump_to_state (S3)
```

Figure 6-6: Pseudo-Code equivalent of multiple transitions

To explain the float chart presented in chapter five, it is better to show the process model in details with the different states and transitions. See figure 6-7.

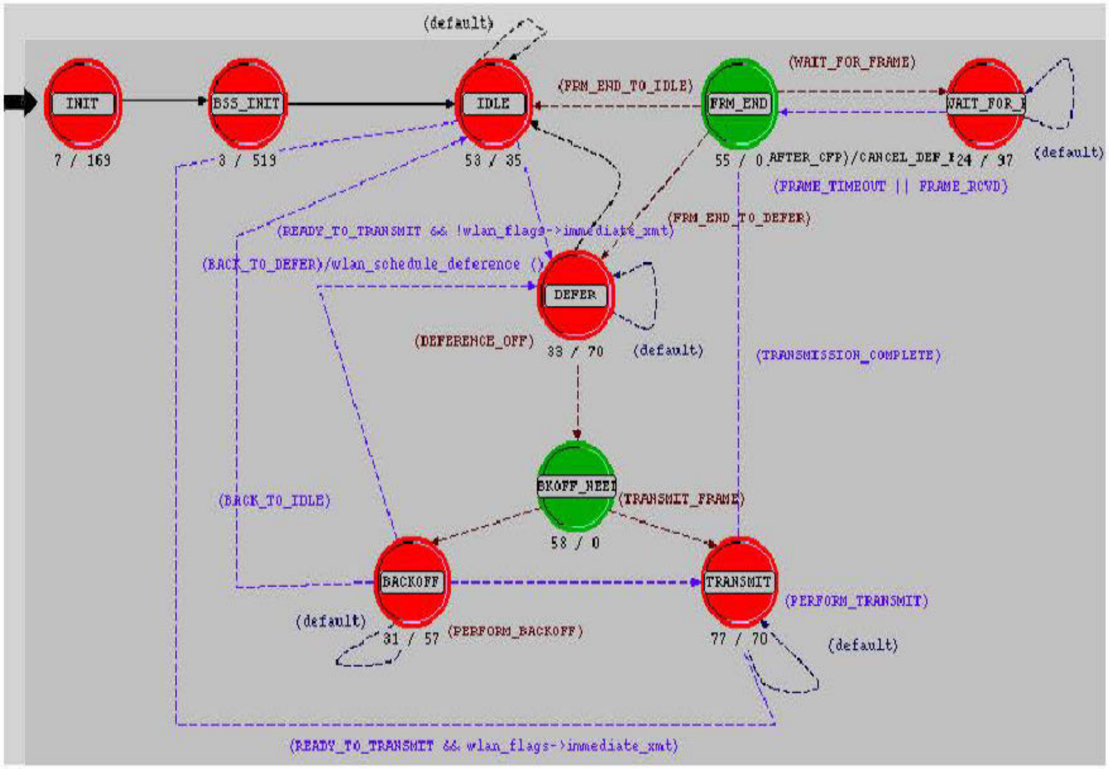


Figure 6-7: Process Model in OPNET Modeler

The first two states of the process model are set to initialize the process model and to load all the attributes of the model. In the following section we explain in details how the process model works from the beginning when the data is prepared to be sent to the phase where it reach its destination, with an explanation of the work of each state and its functionalities.

6.3 The Network Model

To simulate our model we used a linear network which was created in the network editor in OPNET Modeler. The network contains 8 nodes with the same node model and characteristics. The difference was in the packet generation parameters λ and the antenna coordinates which were generated randomly.

The choice of a linear topology is due to the importance of the hidden terminal problem in such topologies where it is most effective on the network performance.

Also as we mentioned in the chapter before, we used the principal of the TPC method to create the coordination between the two frequency ranges, to test this theory in our implemented model and to define the ranges we used the Friis formula in free space that is represented with the following equation.

$$P_R = \frac{P_T G_T G_R c^2}{(4\pi R f)^2}$$

Where *Pt* is the transmission power, *Gt* and *Gr* the antenna gain at both ends (transmitter and receiver respectively is the distance or the antenna range, *f* is the channel frequency.

6.3.1 Simulation parameters

As we mentioned earlier that this protocol was modified in order to respect the 801.11ad standard parameters. Table 6.1 shows the different use parameters for the network simulation.

Table 6.1: 802.11ad simulation parameters

Detection Threshold	-68 dBm
SLOT TIME	3 USEC
SIFS TIME	3 USEC
CW-MIN	15
CW-MAX	1023
PLCP-OVERHEAD-CONTROL	1745 NSEC
PLCP-OVERHEAD-DATA	3564 NSEC
DATA RATE	385 MB/S
CONTROL RATE	27.5 MB/S
BANDWIDTH	1.76 GHz
Air Propagation Time	<< 1 USEC

With the data rate representing the speed with which data are transmitted from one device to another through the channel, control rate represents the transfer speed of the control packets or in this case the busy tone signal. The bandwidth is the amount of data that can be transmitted through the channel between devices.

Second, the random backoff contention window further specifies how long a station must continue to wait if attempting to transmit a frame after detecting a busy medium. If the medium was busy when the station deferred access and queued a frame for transmission, there is a high likelihood that other stations also deferred access and have frames to transmit as well. Without a random backoff timer, multiple stations would then attempt to transmit frames at the exact same time, leading to a very high probability of collisions and degradation in network performance. The deferral of access due a busy medium serves to align the transmission of subsequent frames and increases the probability of collisions on the network.

By implementing a random backoff contention window on a per-station basis, frame transmissions are no longer aligned in most instances and allow for proper access by only one station to reserve the medium and transmit a frame; all other stations will recognize the beginning of a new transmission and pause their backoff timers and defer access to the new transmission. Additionally, should a collision still occur if two stations pick the same random backoff timer and no positive acknowledgment of the transmitted frame is received, the stations will increase the contention window range allowing for more possible random values to be selected and decrease the likelihood of subsequent collisions.

The contention window ranges from zero up to CWmin initially, with the potential to grow and range from zero to CWmax. Each subsequent collision (detected through a lack of acknowledgment in return) results in the station doubling the contention window size, up to the maximum value. Contention window values are decremented by one for every slot time that passes without detecting another station transmitting [24].

6.4 Simulation results

In the simulated scenario we studied the performance and the efficiency of the model with a comparison with the 802.11ad standard at 60 GHz, in terms of three statistics: the throughput, the transmission delay and the retransmission attempts. The throughput is the traffic received by the receiver, the transmission delay is the time for the packets to arrive to their destinations, and the retransmission attempts is number of retransmission of packets in case of a collision or packet destruction.

6.4.1 Performance of the network throughput

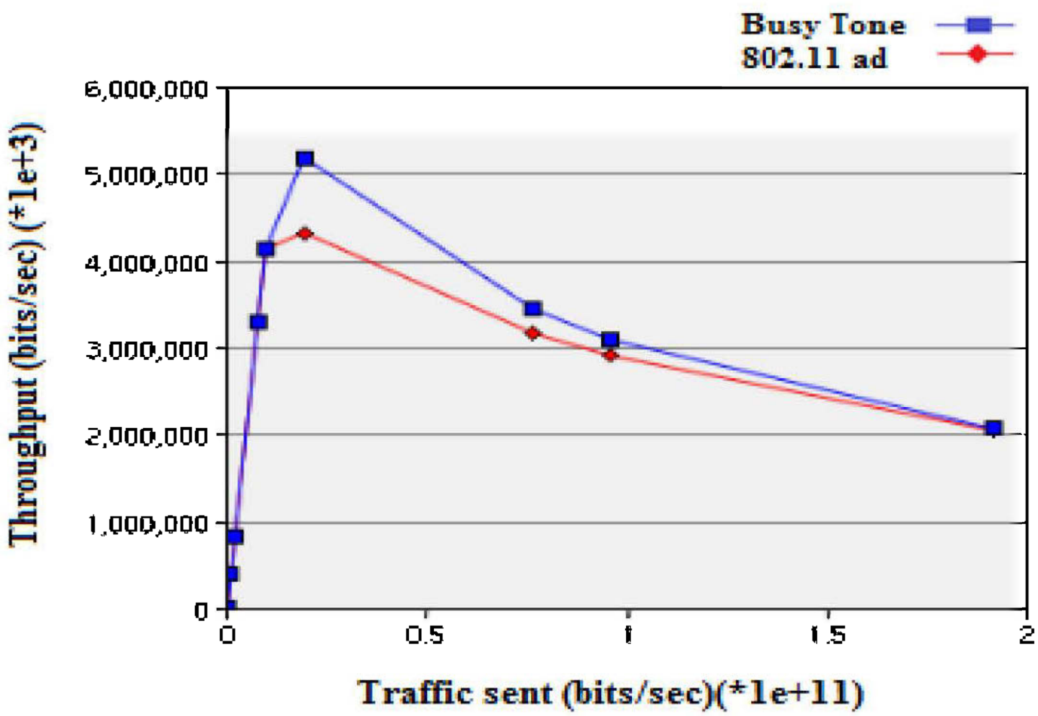


Figure 6-8: Wireless LAN Throughput

Figure 6-8 shows the average total throughput for the 802.11 ad standard (red line) and the proposed 'Busy Tone' method (blue line), the horizontal axis represents the traffic sent by the source with a variation of the parameter Lambda λ and the vertical axis represents the average wireless LAN throughput of the network entirely. The results show the efficiency of the proposed MAC as the number of received bits is bigger using busy tone which means less number of collisions resulting in reducing the hidden terminal problem.

One of the goals of the use of 802.11ad is to get multi gigabits throughput which we can see clearly in the results where the maximum throughput achieved was nearly 5.5 Gbps with a possibility of a maximum of 7 Gbps depending on the network model and the number of nodes we are using

6.4.2 Performance of the packet retransmission

The other statistic is packet retransmission, figure 7-2 shows the average retransmission attempts for both methods, the horizontal axis represents the traffic sent and the vertical axis represents the average retransmission attempts in packets. As the graph shows, in the 802.11 ad method the number of attempts is considered high and increases to over 200 packets per second when the traffic sent is nearly one million packets while by using busy tone approach, the number of attempts is decreased to nearly 120 packets at the same traffic generation level. This means that the 'Busy-Tone' method was very efficient in protecting the communication and data transmission from collisions that lead to data loss, also this represents the efficiency of our algorithm and our backoff procedure in terms of monitoring the status of the channels to be able to detect when they are busy and preventing collisions to occur.

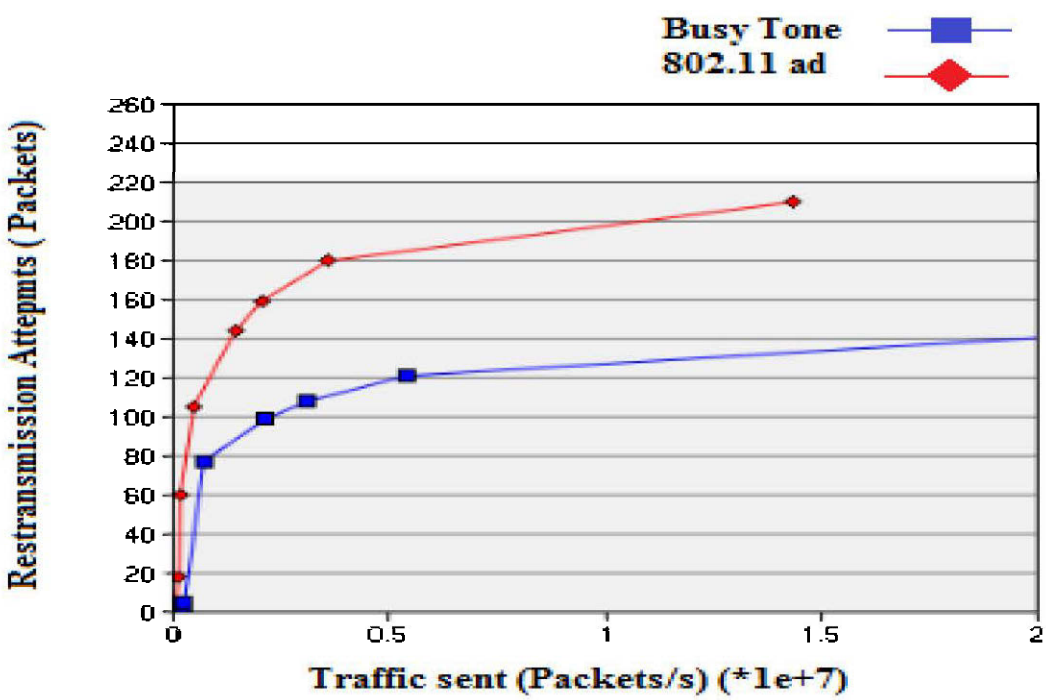


Figure 6-9: Packets retransmission

6.4.3 Performance of the network delay

The last studied statistic was the transmission delay. Figure 6-9 shows the average wireless LAN transmission delay for both methods, the horizontal axis represents the traffic sent, and the vertical axis represents the average delay in seconds. The results show an important decrease for the transmission delay using the busy tone method in comparison to 802.11ad.

It clearly shows that the delay is bigger in the 802.11 ad protocol, and it is increasing faster than the transmission delay in busy tone which has a lower delay. For example at a traffic equal 1.5 Gbs/secs we can see that the delay goes to nearly 500 seconds in 802.11 ad while it is about 400 seconds using the busy tone model.

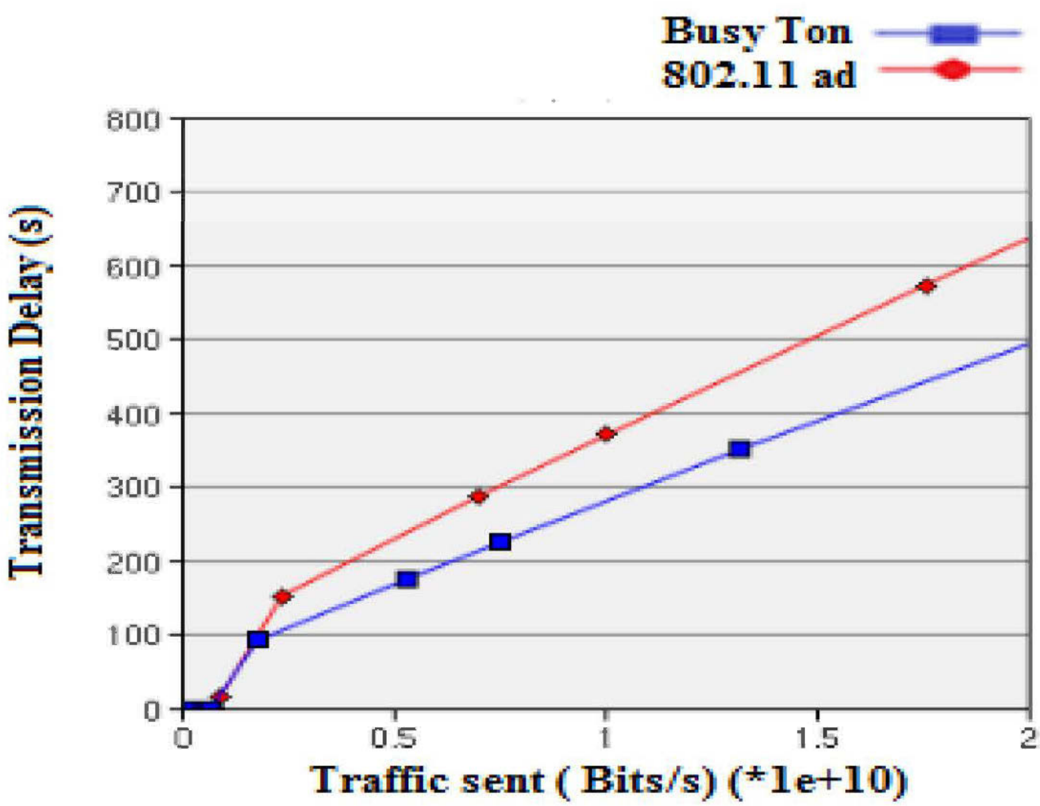


Figure 6-10: Transmission delay

The decreasing delay signifies a more efficient use of the bandwidth; hence we are decreasing the loss in terms of bandwidth and giving a faster communication between the nodes in the network.

6.5 Conclusion

In this chapter we presented the modeling phase of our work, and how we implemented our proposed method in the software OPNET, we showed all the phases and details used in this software what were mainly two phases (Node model and Process model), also how we created a directional antenna model to use it in coordination with the omnidirectional antenna. The second part of this chapter presented the simulation parameters and the simulation results that show the efficiency of the proposed method in terms of three statistics which are: the throughput, network delay, and retransmission attempts, the results show the improvement of the network performance when using the busy tone method comparing to 802.11 ad .

Chapter 7
Conclusion and perspectives

7.1 Conclusion

In this project, a busy tone protocol MAC was proposed to reduce the problem of hidden terminals, and improve the communication between the nodes in a multi hops network. When using directional antennas to send data packets, the simulation results showed the efficiency of the proposed scheme when compared to 802.11 ad standard in terms of throughput that went up to hit multi gigabits, also the retransmission attempts that are decreased when using the busy tone method which means a reduction in the number of collisions, and finally in term of the transmission delay of the network that is much lower when using busy tone, hence a better control of the medium and data protection , and less interferences.

This indicates the efficiency of the method 'Busy-Tone' which may be considered one of the most important solutions that were ever proposed to solve or reduce the problem of hidden terminals. Using the 60 GHz band obligates the use of a protocol MAC that serves its characteristics, due to the sensitivity to this frequency band and the increased probability of interferences between signals.

The other important factor was the use of directional antennas, which is necessary when using 60 GHz because of the short wavelength. Directional antennas are considered the most efficient solution in the modern technologies in order to increase the transmission range and deliver the signal to its destination.

7.2 Perspectives

The network domain when using 60 GHz is a very wide domain with many aspects. The method of "Busy-Tone" is a well know method in this part of research.

It has been an efficient solution to solve the hidden terminal problem and to reduce data and control packets collision.

In this approach, we used this method and modified it in order to be used in a MAC protocol made specifically for 60 GHz with directional antennas.

Many ideas can be suggested to future works, for example, the idea of using two 'Busy-Tone' signals, one for the transmitter and another for the receiver. This method provides an important solution with a great efficiency to guarantee a high secured communication between the nodes.

Another important solution is to exploit the use of directional antennas and eliminate the omnidirectional ones, which leads to directional neighbor discovery by sending busy-tone signals via directional antennas as same as the data packets. This method is an advanced version of our method that we can call "Smart Busy-Tone' where directional antennas control all kind of communication. This way we eliminate the hidden terminal problem even more and guarantee a better medium control and well distributed resources between all nodes.

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