REPUBLIC OF TURKEY
ERCIYES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF COMPUTER ENGINEERING

PERFORMANCE ANALYSIS OF IEEE 802.11 PROTOCOL FOR DIFFERENT VALUES OF DATA LINK LAYER PARAMETERS

Prepared By
Göksenin ARIKAN

Supervisor
Assoc. Prof. Dr. Selçuk ÖKDEM

M.Sc. Thesis

March 2020
KAYSERİ

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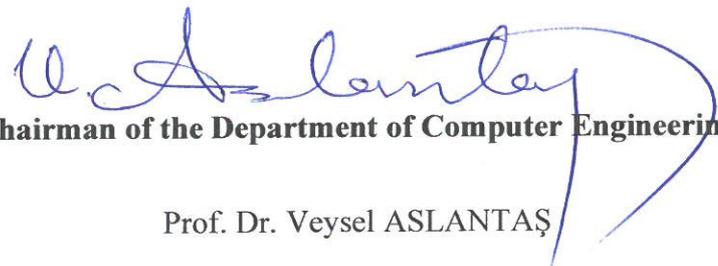
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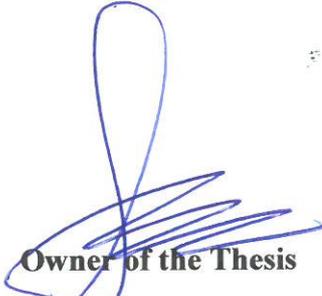
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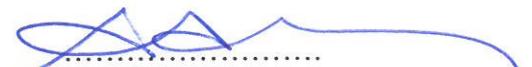
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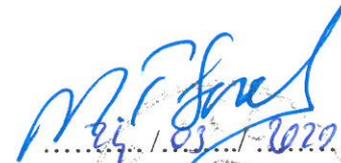Juror   : Assoc. Prof. Dr. Celal ÖZTÜRK

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I dedicate this dissertation to my father; whose support makes my way of success.

Göksenin ARIKAN

Kayseri, March 2020

VERİ BAĞLANTI KATMANININ FARKLI DEĞERLERİ İÇİN IEEE 802.11 PROTOKOLÜNÜN PERFORMANS ANALİZİ

Göksenin ARIKAN

Erciyes Üniversitesi, Fen Bilimleri Enstitüsü
Yüksek Lisans Tezi, Mart 2020
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ÖZET

IEEE 802.11, OSI referans modelinin ilk iki katmanı olan veri bağı ve fiziksel katmanlarında yer alan birçok protokol ve standartlardan oluşmaktadır. Veri bağı katmanının, alt katmanı olan ortam erişim kontrolü katmanında, kablosuz iletişim kalitesini etkileyen birçok parametre ve değişken bulunmaktadır.

Bu tez, kablosuz iletişimde net veri hızı, sinyal-gürültü oranı, paket hata oranı değerlerinin, veri bağı katmanına ait iletim gücü, mesafe, veri aktarım hızı, maksimum iletim birimi gibi parametrelerin değerlerine göre nasıl değiştiğini ve IEEE 802.11g standardının en iyi hangi değerlerde veya değer aralıklarında çalıştığını araştırmayı amaçlamaktadır.

Kablosuz iletim ortamı, kablolu ortama kıyasla fiziksel yapısı nedeniyle yüksek bir hata oranına sahiptir. Sinyal-gürültü oranı, paket hata oranı ve net veri hızı değerleri kablosuz iletişimin kalitesi hakkında bilgi veren önemli değerlerdir. Kablosuz iletişim ortamının, az gürültülü olması ve alıcının gönderilen sinyali yüksek güçle alması koşullarında, iyi bir sinyal-gürültü oranı elde edildiği gözlemlenmiştir. Ayrıca, modülasyon tekniklerinin sinyal-gürültü oranı üzerinde bir etkisi olmadığı, paket hata oranı yükseldikçe kablosuz iletişimin kalitesinin bozulduğu ve net veri hızında düşüşler yaşandığı, düşük veri aktarım hızlarının mesafeye daha az duyarlı, yüksek veri aktarım hızlarının mesafeye daha çok duyarlı olduğu tez kapsamında yapılan çalışmalarda tespit edilmiştir.

Yol kaybı modelleri, iletilen sinyal gücünün vericiden uzaklaştıkça ne kadar azaldığını hesaplamak için kullanılır. Tez kapsamında, iki ışınlı yer yansıması modeli kullanılmıştır. Bu modelde, alıcıya doğrudan yayılım ve yer yansıması ile iki dalga ulaşır.

Alt bölümlerde, IEEE 802.11b ve IEEE 802.11g için, IEEE 802.11 tarafından tanımlanan standartlar baz alınarak teorik veri hızı hesaplaması yapılmıştır. Üç yüzden fazla deney pratikteki veri hızını, sinyal-gürültü oranını, paket hata oranını ve bit hata oranını gözlemlemek için Omnet++ ve INET platformu kullanılarak gerçekleştirilmiştir. Sonuçlar ve bulgular tablo ve grafiklerde gösterilmiş ve yorumlanmıştır.

Anahtar Kelimeler: IEEE 802.11, Net veri hızı, Sinyal gürültü oranı, Veri aktarım hızı, Paket hata oranı, İletim gücü, Maksimum iletim birimi

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ABSTRACT

The IEEE 802.11 consists of several protocols and standards in data-link and physical layer, which are the first two layers of OSI reference model. Media access control layer is the lower layer of data-link layer in which has many parameters and variables that affects the wireless communication quality.

This thesis aims to investigate how throughput, signal-to-noise ratio, packet error-rate values of a wireless communication vary according to various data-link layer parameters such as transmission power, distance, bit rate, and maximum transfer unit size. And, it intends to find out values or value ranges of these parameters in which IEEE 802.11g wireless standard works most efficiently.

The wireless transmission has a high error-rate due to its physical structure compared to the wired media. The signal-to-noise ratio, packet error-rate, and throughput are crucial values that give information about the quality of wireless communication. It has been observed that a good signal-to-noise ratio is obtained with low noise and high receiving power, and if the packet error-rate increases, the quality of wireless communication and throughput deteriorates, and slower data transfer rates are less sensitive to distance, and faster data transfer rates are more sensitive to distance in the studies conducted within the scope of the thesis.

Path loss models are used to calculate how much of a transmitted signal power decreases as it moves away from the transmitter. Within the scope of the thesis, the two-ray ground reflection model was used as a path loss model in which two waves arrive at the receiver with direct propagation and ground reflection wave.

The theoretical throughput has been calculated based on standards defined by IEEE 802.11 for IEEE 802.11b and IEEE 802.11g. More than three hundred experiments have been run on the Omnet++ and INET framework to observe practical throughput, signal-to-noise ratio, packet error-rate, and bit error-rate. The results and findings are illustrated in tables and graphs and interpreted.

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ABBREVIATIONS

AP	:	Access Point
AODV	:	Ad hoc On-Demand Distance Vector
BER	:	Bit Error-Rate
BPSK	:	Binary Phase Shift Keying
BSS	:	Basic Service Set
BSSID	:	Basic Service Set Identifier
CCA	:	Clear Channel Assessment
CCK	:	Complementary Code Keying
CDM	:	Code Division Multiplexing
CDMA	:	Code Division Multiple Access
CRC	:	Cyclic Redundancy Check
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
DCF	:	Distributed Coordination Function
DIFS	:	Distributed Interframe Space
DQPSK	:	Differential Quadrature Phase Shift Keying
DS	:	Distribution System
DSSS	:	Direct Sequence Spread Spectrum
EIFS	:	Extended Interframe Space
ESS	:	Extended Service Set
FCS	:	Frame Check Sequence
FDM	:	Frequency Division Multiplexing
FDMA	:	Frequency Division Multiple Access
FHSS	:	Frequency Hopping Spread Spectrum
IEEE	:	Institute of Electrical and Electronics Engineers
IFS	:	Interframe Space
LAN	:	Local Area Network
LLC	:	Logical Link Control
MAC	:	Medium Access Control
MPDU	:	MAC Protocol Data Unit
MSDU	:	MAC Service Data Unit

MTU : Maximum Transfer Unit
NIC : Network Interface Card
NAV : Network Allocation Vector
OFDM : Orthogonal Frequency Division Multiplexing
OMNET++ : Objective Modular Network Testbed in C++
OSI : Open Systems Interconnection
PCF : Point Coordination Function
PER : Packet Error-Rate
PG : Process Gain
PHY : Physical Layer
PN : Pseudo-Noise
PIFS : Priority Interframe Space
PLCP : Physical Layer Convergence Procedure
PMD : Physical Medium Dependent
PPDU : PLCP Protocol Data Unit
PSDU : PLCP Service Data Unit
QAM : Quadrature Amplitude Modulation
QPSK : Quadrature Phase Shift Keying
RA : Receiver Address
RF : Radio Frequency
RTR : Ready to Receive
RTS : Request to Send
SIFS : Short Interframe Space
SNR : Signal-to-Noise Ratio
SS : Spread Spectrum
SSM : Single Sideband Modulation
TA : Transmitter Address
U-NII : Unlicensed National Information Infrastructure
WLAN : Wireless Local Area Network

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INTRODUCTION

Technological developments are progressing rapidly, and they change the lifestyle of individuals. Especially, the usage of wireless communication technologies is a milestone in our lives. Wireless communication is the transfer of information or energy between two or more points that are not connected by an electrical conductor. Electromagnetic waves use the air as a transmission medium in wireless communication. This is the main difference in wireless communication from other data communications.

Electromagnetic waves consist of discrete energy carrying particles, which are called photons. A photon contains a vibrating electric field (E) and a vibrating magnetic field (H). These components are perpendicular to each other and the direction of photon propagation. The electric and magnetic field components are displaced along the direction of the motion of the photon. The number of changes or vibrations per unit of time is called frequency. In other words, frequency is the number of waves that pass a fixed place in a given amount of time. Hertz (Hz) is the standard unit of measurement used for frequency calculations.

The wireless communication contains the following steps: mixing the original signal with high-frequency signal (modulation), spread with antenna, extracting original information through the modulated signal at receiving end. An unmodulated signal occupies immeasurably small space in a frequency spectrum. Signal spread to the spectrum if modulation occurs. This spread occupies certain radio frequency ranges in the spectrum, which is called the channel.

As the amount of information to be transmitted per unit time increases, the required channel capacity will also increase. The radio signal separated from the antenna will weaken inversely proportional to the distance. The signal must have strength above a specific threshold value in order to be detected on the receiving side. Natural or human-made obstacles cause weakening in the radio signal in the area where radio broadcasting

takes place. However, since there are no obstacles in the space gap, radio signals can be carried over long distances.

The electromagnetic signals do not reach the receiver only via a direct spread. Multipath is the propagation of radio signals to the receiving antenna by two or more paths. Reasons for multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from water bodies and terrestrial objects such as mountains and buildings. Generally, the signals with different phases suppress each other, which causes the original signal to be extinguished.

A signal can be defined by amplitude, frequency, and phase values. Modulation takes place by changing one or more of these three essential characteristics. These changes are used to recreate the signal transmitted at the receiving end. The required channel capacity varies depending on the modulation type used. In amplitude modulation, the channel width must be twice the highest frequency in the information signal (Nyquist Theorem). In frequency modulation, it must be several times the highest frequency in the information signal. Although frequency modulation causes inefficient use of the radio spectrum, the signals which spread over wide channels are much more resistant to any interference.

Digital signals can be transmitted by changing the characteristics of signals, just like analog signals. The first example of digital transmission is telegraph communication using the Morse code. However, the detection of transmitted zeros in digital communication is a problem that needs to be solved. The receiver side should be able to distinguish whether the received signal is zero or extinguished.

In modern digital transmission systems, combinations of frequency, phase, and amplitude modulations are used to carry more bits from the communication channel. The use of digital transmission techniques is common in today's wireless transmission systems. Digital signals are more immune to interference. Error detection and correction is possible in transmitted digital information. Additionally, digital information can be easily compressed and carried, and encryption can be performed more effectively.

The frequency spectrum is a finite source. Therefore, the transmitter terminals simultaneously share specific frequency ranges. There are several ways to divide the frequency spectrum and share it among many users. The simplest and clearest way is

Frequency Division Multiple Access (FDMA) method. With FDMA, the frequency spectrum is divided into non-overlapping sections in the frequency space. These sections are assigned to transmitter terminals. FDMA has been used extensively in analog systems.

Time Division Multiple Access (TDMA) is a digital transmission method that allows more than one digital signal on a single transmission path by interleaving frames of each signal in time. If the frames are repeated quickly enough, the terminals will not feel any interruption or delay during communication.

A third access method is Code Division Multiple Access (CDMA). This method is both modulation and an access method obtained by mixing time and frequency division access methods. For carrying the information signal in a distributed spectrum system, a wider frequency range than the bandwidth of the information signal must be used.

Spread Spectrum (SS) technology is one of the essential methods used by next-generation wireless local area networks for multiplexing and modulation. In terms of wireless local area network (WLAN), we can see two types of spread spectrum techniques. These are Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DHSS). It is the technology of placing the RF signal over a wide bandgap and processing the signal spread over this band by the transmitting and receiving devices. The modulation scheme determines the wireless local network standards. IEEE 802.11b standard expands the original IEEE 802.11 with Direct Sequence Spread Spectrum (DSSS) to operate up to 11 Mbps data rate in the 2.4-GHz unlicensed spectrum using complementary code keying (CCK) modulation technique [1].

Next-generation wireless local area networks use Orthogonal Frequency Division Multiplexing (OFDM) modulation technique. In this multiplexing and modulation method, the phase shift and amplitude-shift methods are applied simultaneously in a special way, and wide bandwidths can be obtained. OFDM is a frequency division multiplexing and modulation technique used to transfer large amounts of data over radio waves.

OFDM works by dividing the information signal into smaller sub-signals and transmitting it to the receiver at different frequencies simultaneously. OFDM decreases interference

in signal transmission and tolerates multipath delay propagation and channel noise. So, it is quite suitable for many wireless communication applications.

This thesis has been progressed within the following plan.

In the first chapter, basic information about wireless networks such as standards, architecture, modulation types, and access methods is explained.

In the second chapter, it is aimed to calculate theoretical throughput in IEEE 802.11 b/g wireless networks in ideal and non-collision environments with Distributed Coordination Function (DCF).

In the third chapter, Omnet ++ and Inet platforms are explained briefly. The experiments related to this thesis were performed on these platforms.

In the fourth chapter, effective data transfer rate, throughput, bit error-rate (BER), packet error-rate (PER) and signal-to-noise ratio (SNR) values are observed according to various data-link parameters like transmission power (Tx Power), distance, bit rate, maximum transfer unit (MTU).

The fifth chapter, as a final chapter, contains findings that are obtained in the previous chapter, and a short evaluation is made accordingly.

1. CHAPTER

WIRELESS LOCAL AREA NETWORK

1.1. Wireless Local Area Network

Wireless network devices were first developed to meet military needs and then used for civilian purposes. Wireless local area network (WLAN) created with these devices. It carries all the advantages of Ethernet technology in its own body without cable clutter. Wireless communication technology, in its simplest definition, is a point-to-point or network-based connection that uses air as a transmission medium.

While wireless communication increases the access of mobile users, it also reduces wiring costs for office and home users. Nowadays, information technologies are needed every day than before. Wireless local area networks have a crucial role in meeting these needs.

The first standard was the IEEE 802.11 release that was defined in 1997 and clarified in 1999 [2]. It had operated at a frequency of 2.400-2.483 GHz and had operating speeds of 1 and 2 Mbps.

The IEEE 802.11a standard was published towards the end of 1999 which uses a 5 GHz frequency band and supports data transfer rates of 54 Mbps with Orthogonal Frequency Division Multiplexing modulation.

Since the 2.4 GHz frequency band is unlicensed and free to use, it has caused studies to intensify on this frequency band. As a result, the IEEE 802.11g standard was published in 2003 using the 2.4 GHz frequency band and Orthogonal Frequency Division Multiplexing modulation technique.

1.2. Comparison of Wireless Local Area Network Standards

The IEEE 802.11 standard uses the FHSS (Frequency Hopping Spread Spectrum) modulation technique in the 2.4-2.4835 GHz band and achieves 2 Mbps data transmission rate with this technique [3]. In today's wireless local area networks, the Orthogonal Frequency Division Multiplexing (OFDM) technique is used, and the data rate can reach 54 Mbps in 2.4-2.4835 GHz frequency band which does not require a license. This band has several limitations. Since the band spacing is only 83.5 MHz, it is necessary to use the spread spectrum technique. Despite the limited bandwidth of the IEEE 802.11, it provides a robust and secure system infrastructure. Since the whole bandwidth and frequency hopping technique is used, the probability of being affected by the parasite is considerably reduced.

1.3. IEEE 802.11 Architecture

Wireless Local Area Network (WLAN) is a distribution system where devices use air to communicate with each other in a coverage area. A WLAN is ultimately connected to a wired network. Access Point (AP) is a device that accepts wireless signals from multiple devices and retransmits them to the rest of the network. AP may also be known as base stations. AP often includes routing function. Thus, they may also be called wireless routers or wireless gateways at home using. However, at the business level, APs and routers are separate devices in general. AP is a layer two device because it is like a bridge connecting two types of networks.

Basic Service Set (BSS) is a group of wireless network devices that are working with the same AP. Basic Service Set Identifier (BSSID) is the AP's physical (MAC) address which is a 48-bit long hexadecimal number just like PC's physical address. As a wireless user, we don't see BSSID. However, they are included in wireless packages/frames.

Extended Service Set (ESS) is a set of infrastructure BSSs, where the APs communicate among themselves to forward traffic from one BSS to another and to facilitate the movement of mobile stations from one BSS to another. The access points perform this communication via an abstract medium called the distribution system (DS).
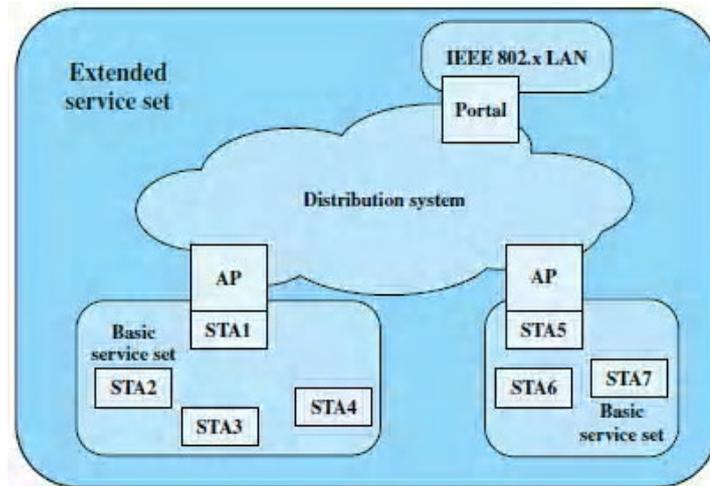
Figure 1.1: IEEE 802.11 Architecture [4]

1.4. IEEE 802.11 Layer Definitions

The IEEE 802.11 standards operate on the first and second tiers of the Open System Interconnection (OSI). Modulation types like FHSS and DSSS are related to the first layer of OSI. Other safety and transmission aspects are processed in the second layer.

1.5. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is a method where sender checks for traffic on a shared medium before sending any data. The purpose of this access method is to minimize the number of collisions in the network. This means that the nodes using 802.11 will retain the full bandwidth when they want to talk. While the channel already has a transmission, other users have to wait for it to start transmission. However, as new nodes are added to a network, contention increases to obtain channel. Significant time is spent to resolve conflicts in conversation. Therefore, the effective use of bandwidth decreases.

Unlike conventional wired Ethernet, WLAN terminals cannot detect collision during transmission because of the full-duplex transmission line is required to operate the collision detection algorithm.

Carrier sense means a node in the network can detect what is going on in the transmission medium. Multiple access means every node in the network has equal right to access and use the shared medium, but they must take turns.

Before a node transmits information, it checks or listens to the medium. When the medium is not busy, the node sends its information signal. If it detects the medium is used, it will backoff and wait for a random amount of time and try again.

1.6. Fragmentation and Reassembly

In a wireless local area network, small packets are used instead of large packets for several reasons. Reasons for using small packages are;

- High bit error-rate and the probability of corruption of large data packets due to the use of air as the transmission medium,

- Due to corruption in the packets, the use of the smallest packets imposes less burden on the sending process.

- In the frequency hopping system, the transmission medium is interrupted at certain intervals, so it is ideal for sending small packets with a delay.

There is a simple mechanism for fragmenting and reassembling frames. The logic of this algorithm is "Send and Wait". The transmitter does not send any new data until the following operations are performed.

- Receiving an ACK message or

- Deciding that the fragment was retransmitted too many times and drops the whole frame.
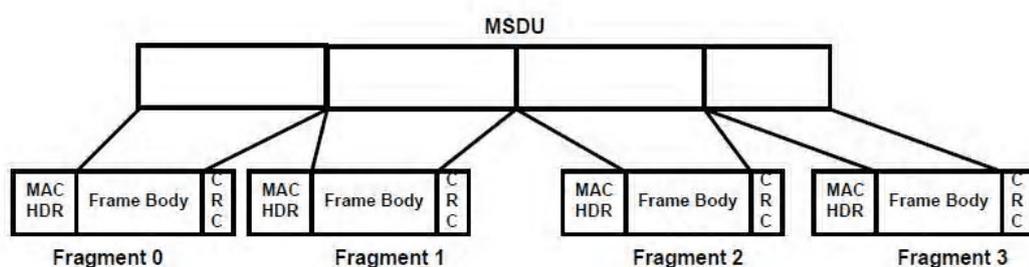
Figure 1.2: A frame is divided into several fragments [3]

1.7. Frame Types

Frames can be grouped under three main headings.

- Data frames: which are used in data transmission.

- Control frames: which are used to control access to a transmission medium (RTS, CTS, ACK)

- Management frames: which are used for exchanging management information. These frames are not forwarded to upper layers.

All IEEE 802.11 frames are wrapped by the following components, as it is shown in Table 1.1.

Table 1.1: A frame with wrapped components

Preamble	PLCP Header	MAC Data	CRC

1.8. Multiplexing and Multiple Access

Multiple access is sharing of the available bandwidth of a transmission medium in time, frequency or code among different terminals simultaneously. In other words, multiplexing in networking means multiple signals are combined and thus travels simultaneously over one link. The purpose of multiplexing is that multiple information signals to share a larger transmission capacity. When sending more than one signal from a single channel at the same time, it is important that the signals are not mixed and that the desired signal can be re-parsed at the receiver.
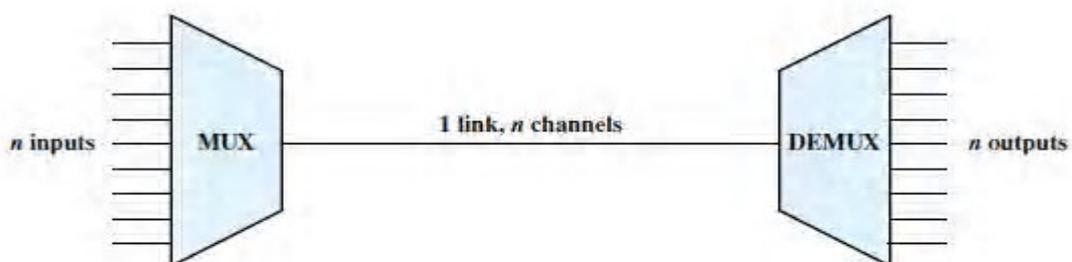
Figure 1.3: Multiplexing [4]

1.8.1. Frequency Division Multiplexing and Multiple Access

Frequency Division Multiplexing (FDM) and Frequency Division Multiple Access (FDMA) are intended for the frequency sharing of communication channels. FDM can be used mostly with analog signals. More than one information signal is carried simultaneously on the same transmission medium by allocating to each signal a different frequency band. Modulation equipment is needed to move each signal to the required frequency band, and multiplexing equipment is needed to combine the modulated signals [4].
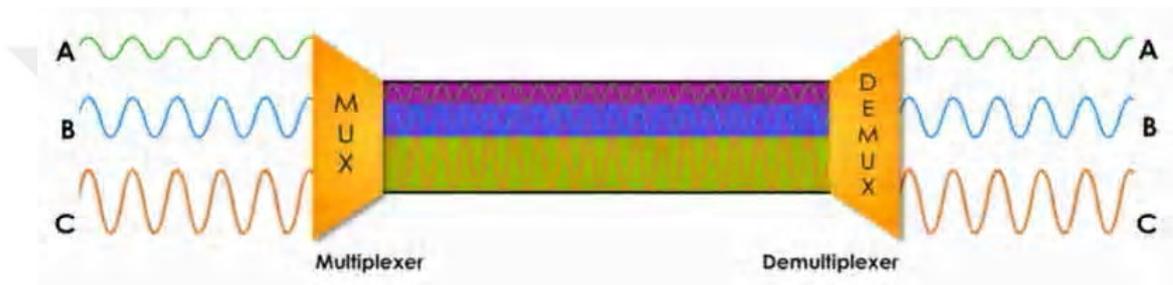
Figure 1.4: Three users are sending their data in FDMA [5]

FDM is possible when the bandwidth of the transmission medium exceeds the required bandwidth of signals to be transmitted [4]. The bandwidth of information signals to be multiplexed with FDM must be limited, so it is not possible to multiplex a sampled signal with FDM. A digital signal can only be multiplexed by FDM after it is converted to a continuous waveform.
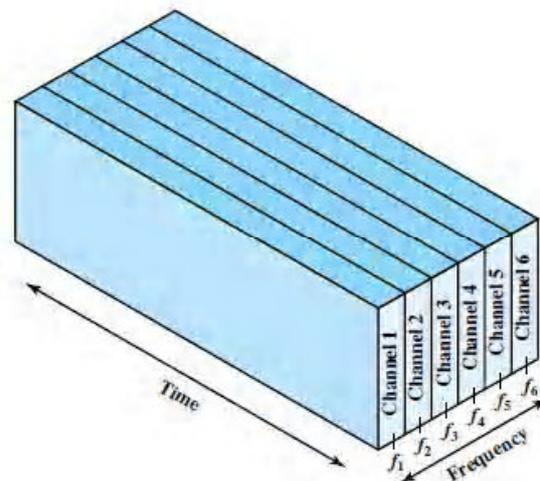
Figure 1.5: Frequency Division Multiplexing [4]

Single Sideband Modulation (SSB) provides an effective solution for multiplexing analog signals with FDM. Efficient transmission in terms of the frequency spectrum can be achieved after receiving the sideband of the modulated signal to the carrier frequency by the bandpass filter, and another sideband is discarded. Each receiver must know which information signal is sent to itself from which frequency band and also distinguish the signal which deals with the others by using a band-pass filter. For this reason, at the set-up stage of the communication link, the transmitter and receiver are notified of the frequency band allocated for transmission.

When multiplexing with FDM and FDMA, it is important to note that the carrier frequencies are sufficiently separated to prevent interference. Therefore, the distance between the two neighbouring carrier frequencies should be kept at least bandwidth of the least multiplexed signal. Even a guard band must be left between the two frequency bands. The FDM signal $s(t)$ has a total bandwidth B where $B > \sum_{i=1}^{n} B_i$ [4].

1.8.2. Time Division Multiplexing and Multiple Access

In this form of multiplexing, multiple digital signals from different users can be carried in repetitive frames on a single transmission path by interleaving portions of each signal in time. Each frame consists of a set of time slots, and each source is assigned one or more time slots per frame. The time-division multiplexing is possible when the achievable data rate of the medium exceeds the data rate of digital signals to be transmitted.
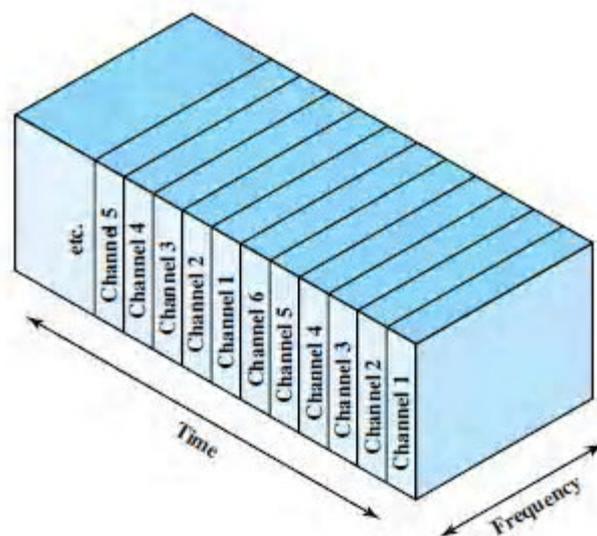
Figure 1.6: Time Division Multiplexing [4]

As shown in Figure 1.6, the time-space is divided into time-slots. Different periods are used for repetitive frames of each signal. As a result, the common use of communication resources is ensured while the confusion of the signals is prevented. In TDM and TDMA, multiplexing is not performed in the frequency band, and the entire available frequency spectrum is available for each signal. The guard bands should be reserved for possible minor synchronization errors between periods allocated for two consecutive signals.

When multiplexing the signals with TDM / TDMA, it is important to note that sampling frequencies of the signals must be equal to each other or multiple of each other, so that there is no conflict in the time domain.

All recipients need to know at what time the frames will be sent to it. In the installation phase of the communication link, timing synchronization is established between the sender and the receiver. That is, the sender and receiver are informed which period is allocated for their use.

1.8.3. Code Division Multiplexing and Multiple Access

Code Division Multiplexing (CDM) and Code Division Multiple Access (CDMA) are multiplexing methods obtained by mixing FDM and TDM. There is no division of the frequency and time domain in CDMA. Because the frequency spectrum of the sampled digital signals is unlimited in which time-space and frequency space division cannot be done. On the other hand, analog signals with limited frequency spectra are continuous in time so that no time division can be made. The basis of CDM/CDMA is the use of frequency space in a partitioned manner. Frequency bands are allocated to users for a certain period, and then frequency band sharing is re-arranged. During the specified time interval, users transmit from the bands allocated to them. At the end of this period, users who continue to transmit, change their frequency bands according to the new share. As a result of adding new users who want to transmit instead of the users whose transmission is finished, communication sources are evaluated effectively.

The transmission of signals by switching to different frequency bands at specific time intervals is called frequency hopping. When establishing the communication connection, a pseudo-noise (PN) code is given for each user, and it determines which frequency band will be used in which time interval.
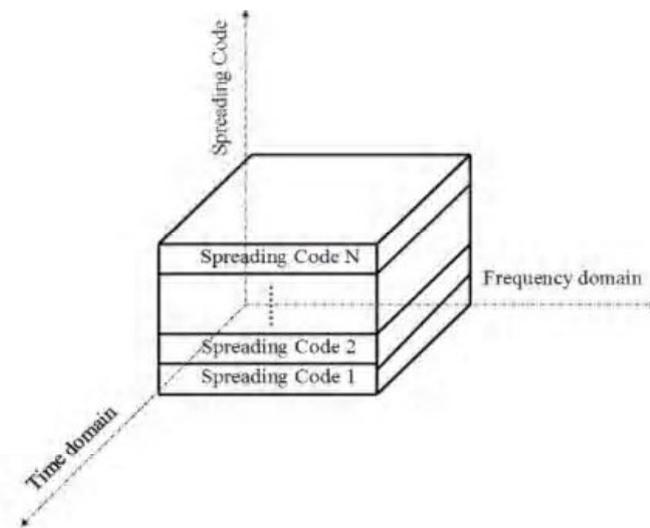
Figure 1.7: Code Division Multiplexing [6]

The PN code is reported to both the sender and receiver when establishing a connection. Since a different frequency band hopping occurs each time according to the PN code which specified separately for each transmission, CDM is particularly preferred to FDM and TDM methods for security reasons. Special functions are used in the determination of PN codes, and these functions prevent the transmission of more than one signal from the same frequency band.

Another benefit of code division multiplexing is that because every user jump between frequency bands during the transmission period, even if there are frequencies with poor communication quality due to environmental conditions, the reduction in communication quality will be temporary since the user will not stay at these frequencies for a long time.

When performing a frequency hopping, the information signal uses a wider band than own bandwidth for transmission. All of the methods that extend the frequency band of a signal is called Spread-Spectrum (SS) in literature.

Table 1.2: Code Division Multiple Access example

(a) User's codes

User A	1	-1	-1	1	-1	1
User B	1	1	-1	-1	1	1
User C	1	1	-1	1	1	-1

(b) Transmission from A

Transmit (data bit=1)	1	-1	-1	1	-1	1	
Receiver codeword	1	-1	-1	1	-1	1	
Multiplication	1	1	1	1	1	1	= 6

Transmit (data bit=0)	-1	1	1	-1	1	-1	
Receiver codeword	1	-1	-1	1	-1	1	
Multiplication	-1	-1	-1	-1	-1	-1	= -6

(c) Transmission from B, receiver attempts to recover A's transmission

Transmit (data bit=1)	1	1	-1	-1	1	1	
Receiver codeword	1	-1	-1	1	-1	1	
Multiplication	1	-1	1	-1	-1	1	= 0

(d) Transmission from C, receiver attempts to recover B's transmission

Transmit (data bit=0)	1	1	-1	1	1	-1	
Receiver codeword	1	1	-1	-1	1	1	
Multiplication	1	1	1	-1	1	-1	= 2

(e) Transmission from B and C, receiver attempts to recover B's transmission

B (data bit=1)	1	1	-1	-1	1	1	
C (data bit=1)	1	1	-1	1	1	-1	
Combined Signal	2	2	-2	0	2	0	
Receiver codeword	1	1	-1	-1	1	1	
Multiplication	2	2	2	0	2	0	= 8

1.9. Modulation Techniques

The transmitted signal is distorted due to changes in the external world and interference caused by other signals. There are also some restrictions imposed by the transmission medium. Therefore, some operations are performed on the signal to minimize the distortion of the signal. It is challenging to send very low-frequency signals (e.g. audio) over very long distances. Therefore, the low-frequency signal can be added to a high-

frequency carrier signal to carry it over long distances. This event is called modulation. Different techniques are used for modulation of analog and digital signals. One of the essential criteria for determining the modulation technique is the frequency of the signal. For example, an audio signal consists of components below 1000 Hz. However, since the modulation allows the transmission of the signal at the desired frequency, it provides effective communication. The frequency range of the signal determines the amount of information that a signal can carry. For example, a transmission system with a frequency of 5 GHz can carry ten thousand times more information than a 500 kHz transmission system. However, transporting information at higher frequencies causes higher costs. Frequency Hopping Spread Spectrum, Direct Sequential Spread Spectrum, and Orthogonal Frequency Division multiplexing modulations are used in wireless IEEE 802.11 standards [7].

1.9.1. Modulation Method Used in IEEE 802.11b Standard

IEEE 802.11b was published in September 1999. IEEE 802.11b extends the original IEEE 802.11 direct sequence spread spectrum (DSSS) standard to operate up to 11 Mbps in the 2.4 GHz unlicensed spectrum using Complementary Code Keying (CCK) modulation [8].

The aim of the development of IEEE 802.11b is to less affected data transmission by interference, increasing security and the data transmission up to 11 Mbps. It was a significant improvement in the conditions of that time.

The first IEEE 802.11 standard uses Spread Spectrum technology and digital carrier modulation. While the original 802.11 standard uses both Frequency Hopping Spread Spectrum and Direct Sequence Spread Spectrum, the IEEE 802.11b standard uses only Direct Sequence Spread Spectrum. In digital carrier modulation, it uses Differential Quadrature Shift Keying (DQSK) modulation. In the IEEE 802.11b standard, DBSK (Differential Binary Phase Shift Keying) coding methods for 1 Mbps and DPSK (Differential Quadrature Phase Shift Keying) for 2 Mbps coding methods are used. For higher data rates of 5.5 and 11 Mbps, CCK (Complementary Code Keying) is used. The main disadvantage of the IEEE 802.11b is the frequency band is common and interference from other networking technologies such as Bluetooth, cordless phone, and so on.

1.9.1.1. Differential Quadrature Phase Shift Keying

Differential Quadrature Phase Shift Keying (DQPSK) is a modulation technique where the phase shift of one symbol is performed relative to the previous symbol. The relative phase is the phase of the current symbol minus the phase of the previous symbol [9]. There are four possible phase states $(0, -\frac{\pi}{2}, +\frac{\pi}{2}, \pi)$. Each of the four possible phases corresponds to a unique pair of information bits [10]. DQPSK is used for transmission 2, 5.5 and 11 Mbps in the IEEE 802.11b standard [3].
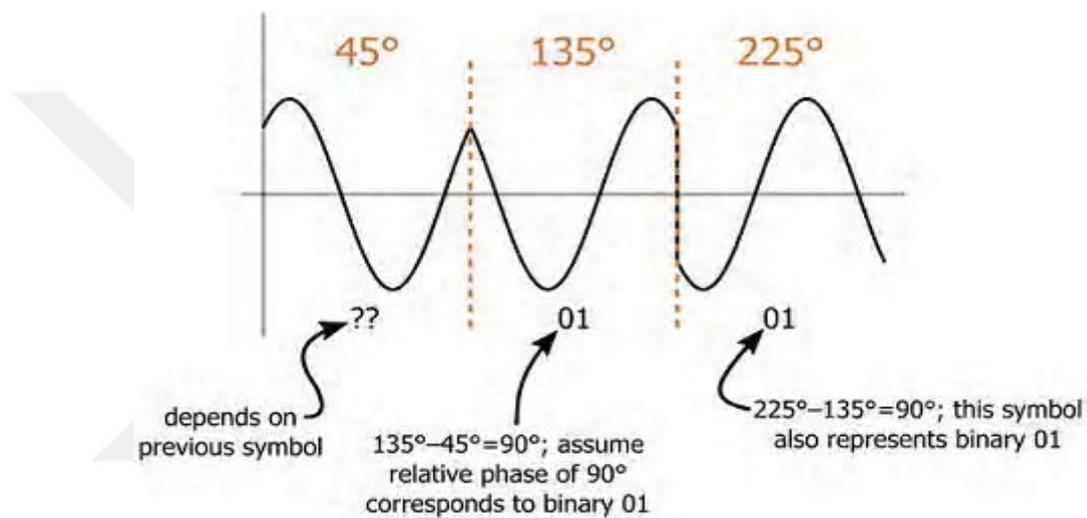
Figure 1.8: Differential Quadrature Phase Shift Keying Example [9]

Table 1.3: Carrier / Phase change in DQPSK

Data	Phase Change
00	0
01	$\frac{\pi}{2}$
11	π
10	$-\frac{\pi}{2}$

1.9.1.2. Complementary Code Keying

Complementary Code Keying (CCK) comprises a pair of identical finite-length sequences having the property that the number of pairs of like elements with any given separation in one series is equal to the number of pairs of unlike elements with the same separation

in the other [11]. CCK uses code words to carry information signals. CCK modulation is employed to achieve data rates of 5.5 Mbps and 11 Mbps.

The IEEE 802.11 complementary spreading codes have a code length of 8 and a chipping rate of 11 MChips/s. The 8 complex chips comprise a single symbol [12]. The symbol rate is 1.375 MS/s.
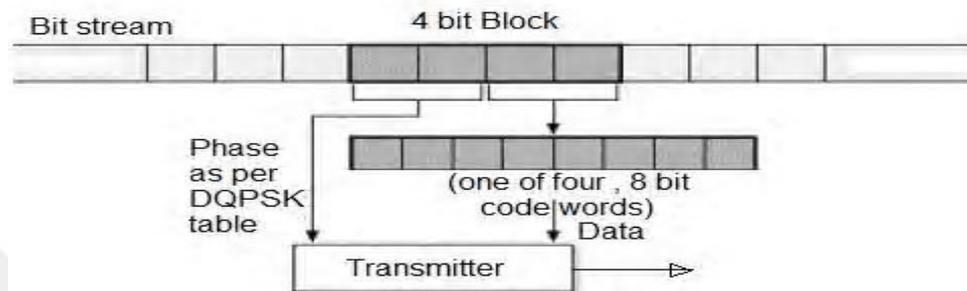
Figure 1.9: CCK Transmitter for IEEE802.11b at 5.5 Mbps [13]

For 5.5 Mbps transmission in IEEE 802.11b, information bits are first grouped to blocks of 4 bits each. The first 2 bits are mapped as per Table.1.4(a), and the rest of the two bits are mapped as per CCK sequence is shown in the following Table1.4(b). In other words, it spreads the data signal. Several phase angles are typically used to generate complex codeword of 8 bits.

Table 1.4: Carrier / Phase change for 5.5 Mbps in Cck

Dibits	Phase		Bit Sequence	Cck Code Word
00	0		00	+i, +1, +i, -1, +i, +1, -i, +1
01	$\dfrac{\pi}{2}$		01	-i, -1, -i, +1, +1, +1, -i, +1
11	π		11	+i, -1, +i, 1, -i, +1, i, 1
10	$-\dfrac{\pi}{2}$		10	-i, +1, -i, -1, -i, 1, +i, 1
	(a)			(b)

Data rate = 4 bits/symbol * 1.375 MS/s = 5.5 Mbps
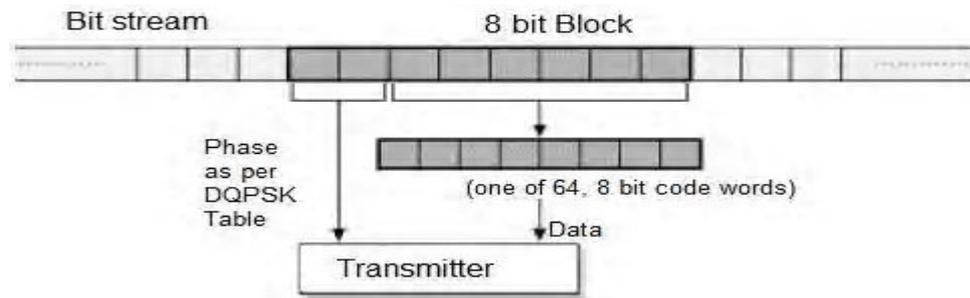
Figure 1.10: CCK Transmitter for IEEE 802.11b at 11 Mbps [13]

For 11 Mbps transmission in IEEE 802.11b, information bits are first grouped to blocks of 8 bits each. Then out of these 8 bits, 2 bits are encoded by a phase shift of transmitted symbol relative to the previous symbol. The rest of the 6 bits are encoded using CCK. One out of 64 codewords is mapped to these 6 bits each.

Table 1.5: Carrier / Phase change for 11 Mbps in CCK

Dibits	Phase (even symbol)	Phase (odd symbol)
00	0	π
01	$\dfrac{\pi}{2}$	$-\dfrac{\pi}{2}$
11	π	0
10	$-\dfrac{\pi}{2}$	$\dfrac{\pi}{2}$

Data rate = 8 bits/symbol * 1,375 MS/s = 11 Mbps

Table 1.5 is used to map the appropriate phase as per dibits in the information for 11 Mbps rate as per odd and even symbols in the transmitted data. The first symbol in the frame is taken as even.

1.9.1.3. Direct Sequence Spread Spectrum

Direct Sequence Spread Spectrum (DSS) is a modulation technique in which a message signal is spread over a bandwidth that is typically much greater than that required for reliable communications [14]. In DSSS, the transmitter and receiver contain identical pseudo-random sequence generators producing a pseudo-noise (PN) signal [15]. DSSS is

implemented by multiplying the modulated signal, which is ready for transmission with a digital signal called pseudo-noise (PN). We can say it is a second modulation. This allows the original signal to be placed over a wider bandwidth.

DSSS adds redundant bits of data known as chips to the data to represent binary 0s or 1s. The ratio of chips to data is known as the spreading ratio: the higher the ratio, the more immune to interference the signal is because if part of the transmission is corrupted, the data can still be recovered from the remaining part of the chipping code [16].
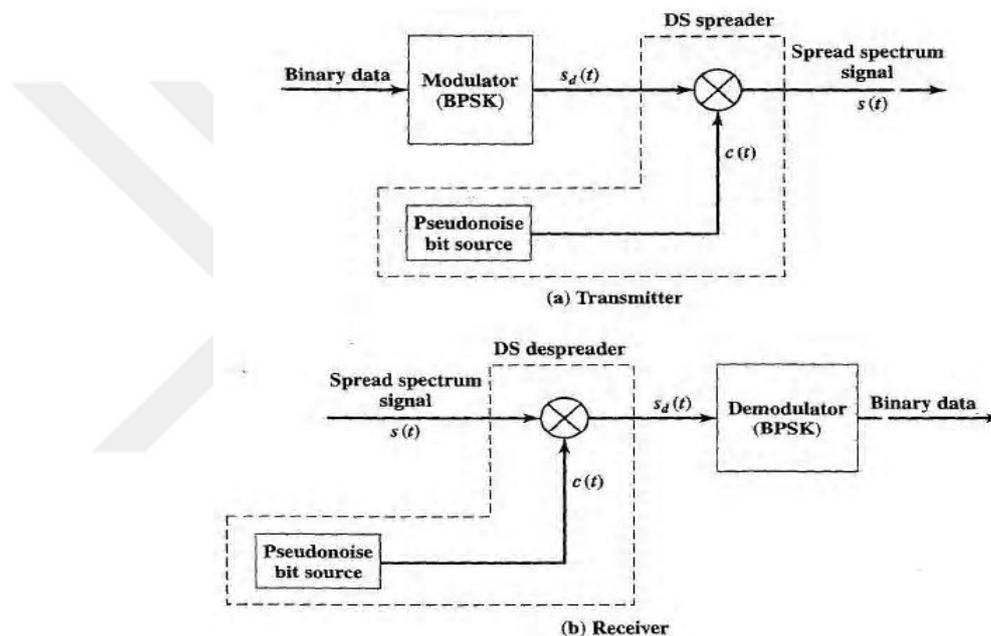
Figure 1.11: Direct Sequence Spread Spectrum [17]

One technique for direct sequence spread spectrum is to combine the digital information stream with the spreading code bitstream using an Exclusive-Or (XOR) [17]. For direct sequence spread spectrum (DSSS), each bit in the original signal is represented by multiple bits in the transmitted signal [17]. Pseudo-noise (PN) code has always much higher bit rate than the original signal. At the receiving end, transmitted signals are demodulated with the identical PN code, and the original data are restored.

To better understand the system, let's assume the transmission is done on the baseband. Let the information signal is R(t), and the PN is C(t). Modulation means the multiplication of two signals on the time axis and convolution on the frequency axis. We can convert a signal defined in the time axis to the frequency axis by taking the Fourier Transform. If a

narrowband signal is multiplied by a wideband signal, the result is a signal close to the bandwidth of the wideband signal. According to this definition, the PN code plays the role of a broadband signal. When our signal is modulated with PN code, $K(t) = R(t).C(t)$ signal is obtained. This signal is amplified and transmitted by an antenna. During transmission, this signal interferes for various reasons. If we indicate this interference with $I(t)$, the signal detected by the receiver is $A(t) = K(t) + I(t)$.
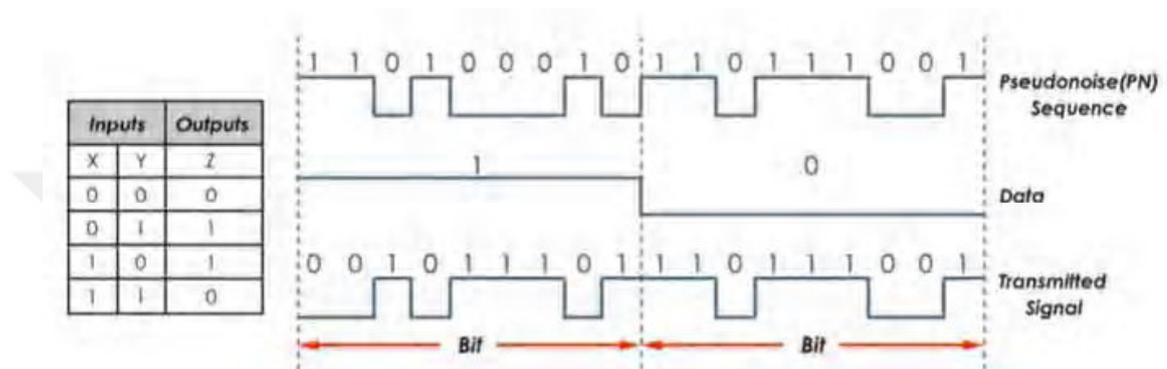
Figure 1.12: Direct Sequence Spread Spectrum Example [18]

DSSS compatible receiver multiplies the incoming signal by the same PN code on the receiving side to obtain the signal $Z(t) = C(t)^2 \times R(t) + C(t) \times I(t)$. Since the PN code is a signal between -1 and +1, the square of this signal is always one ($C(t)^2 = 1$). Thus, the signal obtained at the receiver consists of an information signal itself and interference multiplied by the PN code. As it is known, multiplication of interference with wideband PN code is also a wideband signal. The original signal is narrowband. Since these events take place on the baseband, most of the interference can be filtered with a Low Pass Filter (LPF). As can be seen, protection against interference exists in the natural structure of DSSS. Process Gain (PG) is defined as the ratio of the spread signal bandwidth to the un-spread signal bandwidth. It is usually expressed in decibels (dB). Since the interference is inversely proportional to PG, the length of the PN code must be increased to resist intentional and unintentional interference. Just as against parasites, protection against obstructions is provided by unpredictable carrier signals. A system with indistinguishable data and carrier modulation offers privacy and security.

1.9.1.3.1. DSSS Physical Layer Convergence Protocol

Physical Layer Convergence Procedure (PLCP) defines a method of mapping 802.11 MAC layer protocol data units (MPDUs) into a framing format suitable for sending and receiving user data and management information between two or more stations using the physical medium dependent sublayer (PMD) [17].

A brief description of the fields of the PPDU follows as it is shown in Figure 1.13.
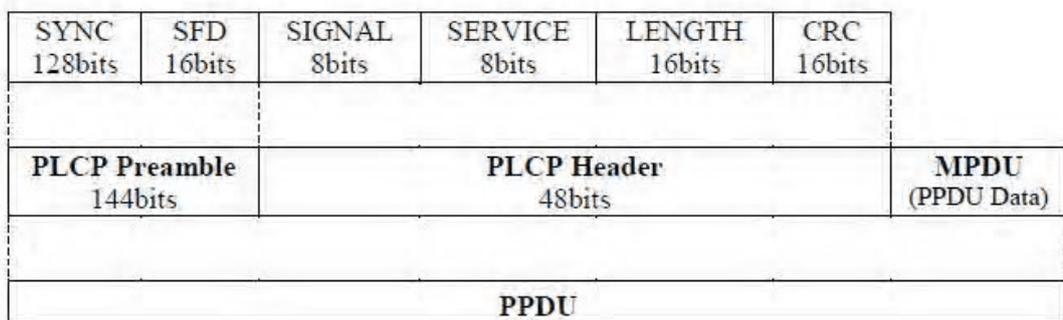
Figure 1.13: PLCP frame format (PPDU). The MPDU is the PPDU data field [3]

- The SYNC filed consists of 128 bits in length and contains a string of 1s which is scrambled before transmission and is used for synchronization at the receiver.

- The SFD is a 16-bit field, whose function is to indicate the start of PHY dependent parameters within the PLCP preamble.

- The SIGNAL field indicates the modulation that shall be used for the transmission and reception of the MPDU.

- The 8-bit SERVICE field is reserved for future use.

- The 16-bit LENGTH field is an unsigned 16-bit integer indicating the number of microseconds required to transmit the MPDU;

- The CRC field is a 16-bit frame check sequence, which protects the SIGNAL, SERVICE, and LENGTH fields.

1.9.2. Modulation Method Used in IEEE 802.11 a/g Standard

IEEE 802.11a/g standards have a fast data rate compared to 802.11 and 802.11b standards. The most significant difference of 802.11a operates in the 5 GHz band called Unlicensed National Information Infrastructure (U-NII) in the United States. With increasing frequency, the available bandwidth of the system is 300MHz. The IEEE 802.11g standard was standardized in 2003. While IEEE 802.11b uses only DSSS technology, IEEE 802.11g uses DSSS, OFDM, or both at the 2.4 GHz ISM band to provide high data rates of up to 54 Mbps [19]. Some features of some IEEE 802.11 standards are summarized in Table 1.6.

IEEE 802.11b network is easily influenced by multipath propagation because in operation in DSSS, but IEEE 802.11a and IEEE 802.11g use OFMD technology, it transmits information in multiple sub-channels hence reduces the impacts of multipath.[8].
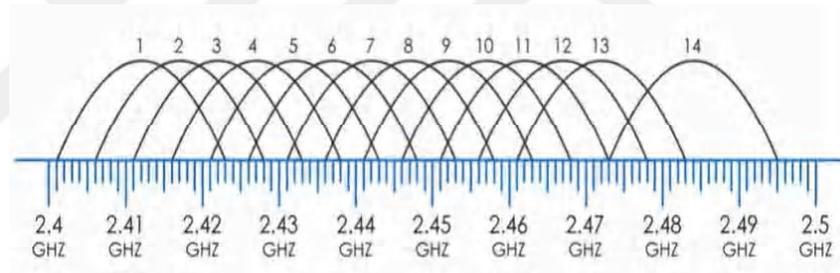
Figure 1.14: Wi-Fi: 2.4 GHz band [20]

In IEEE 802.11g, there are three channels (frequencies) that do not overlap with each other for simultaneous operation in the frequency band 2.4 to 2.4835. The 2.4 GHz band is divided into 14 fixed frequency channels. Each channel is 20 MHz wide. In some countries, channels 13 and 14 are not legal. Channel 14 is beyond the 2.4 GHz band; thus, it is not used except in Japan. Only 11 channels are free to use. The gap between adjacent channels is 5 MHz wide. There are many overlaps among these 11 channels. For this reason, only three channels can be active at any one time. When more channels are used, interference and interference are likely. There are several groups of three nonoverlapping channels like Channel [1, 6, 11], Channel [3, 8, 13].

Table 1.6: Summarization of IEEE 802.11 standards [8]

	802.11	802.11a	802.11b	802.11g
Date	July 1997	September 1999	September1999	June 2003
Bandwidth	83 MHz	300 MHz	83 MHz	83.5MHz
Frequency	2.4-2.4835 GHz DSSS, FHSS	5.15-5.35 GHz OFDM 5.725-5.825 GHz OFDM	2.4835 GHz DSSS	2.4-2.4835 GHz DSSS, OFDM
Data Rate	1, 2 Mbps	6, 9, 12, 18, 24, 36, 48, 54 Mbps	1, 2, 5.5, 11 Mbps	1, 2, 5.5, 6, 9, 11, 12, 22, 24, 33, 36, 54 Mbps
Modulation Type	DQPSK (2 Mbps DSSS) DBPSK (1 Mbps DSSS) 4GFSK (2 Mbps FHSS) 2GFSK (1Mbps FHSS)	BPSK (6,9 Mbps) QPSK (12,18 Mbps) 16-QAM (24,36 Mbps) 64-QAM (48,58 Mbps)	DQPSK/CCK (11,5.5 Mbps) DQPSK (2 Mbps) DBPSK (1 Mbps)	OFDM/CCK (6,9,12,18,24,36,48,5) OFDM (6,9,12,18,24,36,48,5) DQPSK/CCK (22, 33, 11, 5.5 Mbps) DQPSK (2 Mbps) DBPSK (1 Mbps)
Compatibility	802.11	Wi-Fi 5	Wi-Fi	Wi-Fi ≤ 11Mpbs below

1.9.2.1. Orthogonal Frequency Division Multiplexing

Frequency Division Multiplexing (FDM) is a multiplexing method used to divide a channel into many non-overlapping sub-channels. FDM allows multiple users to share one single transmission medium. Orthogonal Frequency Division Multiplexing (OFDM) is a variation of FDM which is very popular used for many of the latest wireless and telecommunication channels. OFDM is a frequency-division multiplexing (FDM) scheme utilized as a digital multi-carrier modulation method. The main feature of OFDM modulation in the IEEE 802.11 standard is to provide modes with different code rates and modulation schemes due to excellent performance on highly dispersive channels that are selected through link adaptation [21].

Firstly, let us compare the FDM and OFDM [22]. FDM allows multiple users to share one link by dividing available bandwidth into different non-overlapping sub-channels. A guard band (a narrow frequency range) is inserted between adjacent sub-channels so that different signals travel separately and simultaneously without interfering with each other. In OFDM, on the other hand, those sub-channels are closely spaced. There is no guard band between them; hence they are overlapped. OFDM would allow more data transmission than FDM.
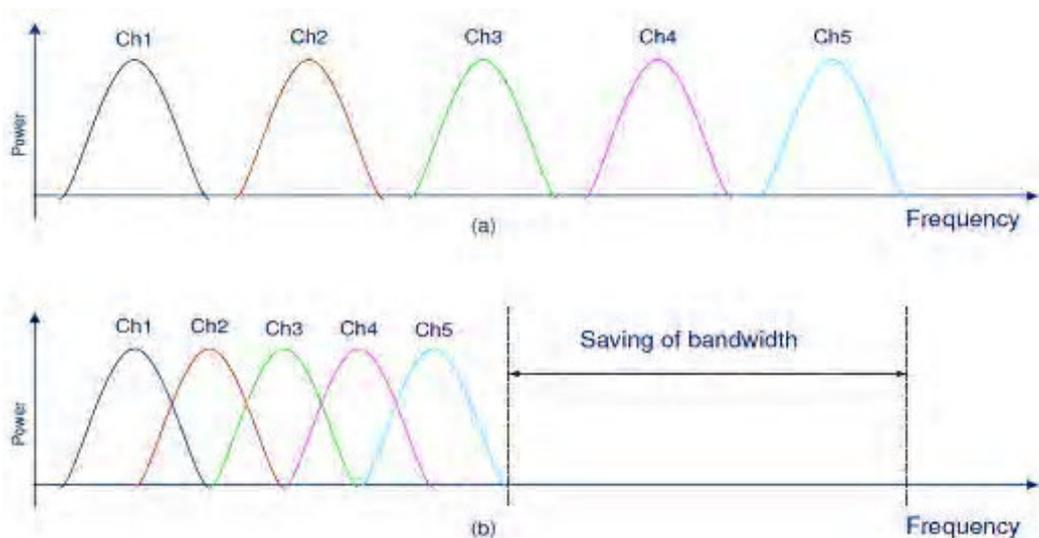
Figure 1.15: Comparison between conventional FDM and OFDM [22]

However, a question may come to mind. How OFDM prevent interference while multiple sub-channels overlap each other? OFDM combine multiple signals closely together in a

way that they are orthogonal each other. When a signal reaches its peak, the highest point, its two neighbors are at their zero (0) point or at null. Therefore, orthogonal means signals are multiplexed in a way that the peak of one signal occurs at null of the other neighbors' signals, as shown in Figure 1.16. At the receiving end, the demultiplexer separates them on this orthogonal feature.

OFDM would better utilize the available bandwidth, thus offering higher data transmission data rates than FDM. Orthogonal Frequency Division Multiplexing (OFDM) is an efficient technique that increases speed, range, reliability and spectral efficiency for wireless systems [23].
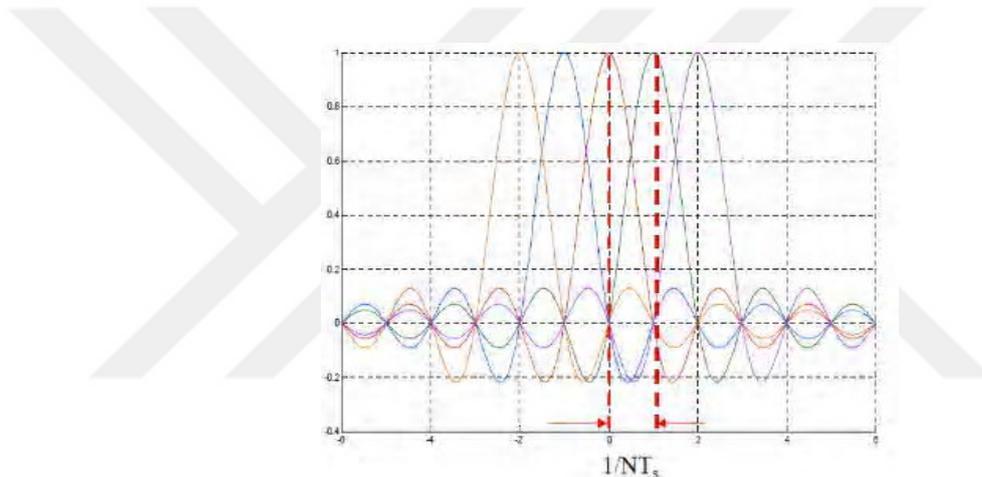
Figure 1.16: Orthogonality property for five subcarriers [23]

1.9.2.2. Binary Phase Shift Keying

Phase specifies the location of a point within the wave cycle. The locations on a wave cycle can be specified as an angle in either radian or degree as well as in fractions of a cycle.
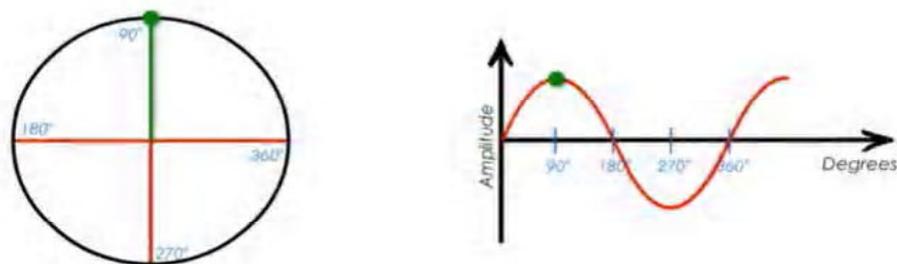
Figure 1.17: The locations on a wave [24]

The phase of the carrier is varied to represent binary ones and zeros which is used to transmit data via changing and modulating a carrier wave is called Phase Shift Keying, and if the phase shift uses two phases differing by 180° to represent binary digits, the modulation is called BPSK [8]. Figure 1.18 shows an example of DPSK.

Table 1.7: Input-output relationship in BPSK modulation

INPUT	OUTPUT
Logic 0	-1
Logic 1	1

The equation of BPSK as following:

$$s(t) = \begin{cases} A\cos(2\pi f_c t) \\ A\cos(2\pi f_c t + \pi) \end{cases} = \begin{cases} A\cos(2\pi f_c t) \; , & binary\ 1 \\ -A\cos(2\pi f_c t) \; , & binary\ 0 \end{cases} \qquad 1.1$$

A phase shift of 180° (π) is equivalent to shifting the sine wave or multiplying it by -1 [17].
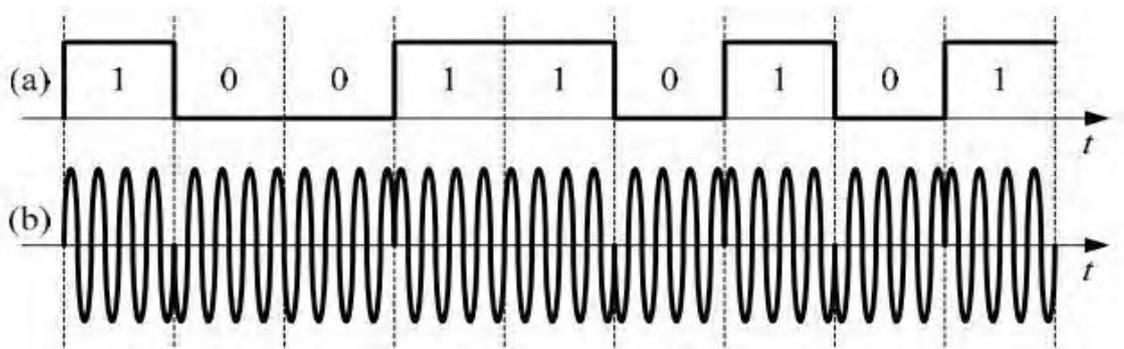
Figure 1.18: BPSK modulation example (a) binary signal (b) modulated signal [25]

1.9.2.3. Quadrature Phase Shift Keying

Efficient use of bandwidth can be achieved if each signaling element represents more than one bit. [17]. QPSK is also known as 4-QAM. Each symbol consists of two bits and signal transmits among the phases that are separated by 90 degrees but used only one bit per

channel [8]. QPSK uses phase shifts separated by multiples of $\frac{\pi}{2}$ (90°) instead of a phase shift of 180° as allowed in BPSK.

Table 1.8: Input-output relationship in QPSK modulation

I	Q	Phase Shift I+Q
0	0	45°
0	1	135°
1	0	225°
1	1	315°
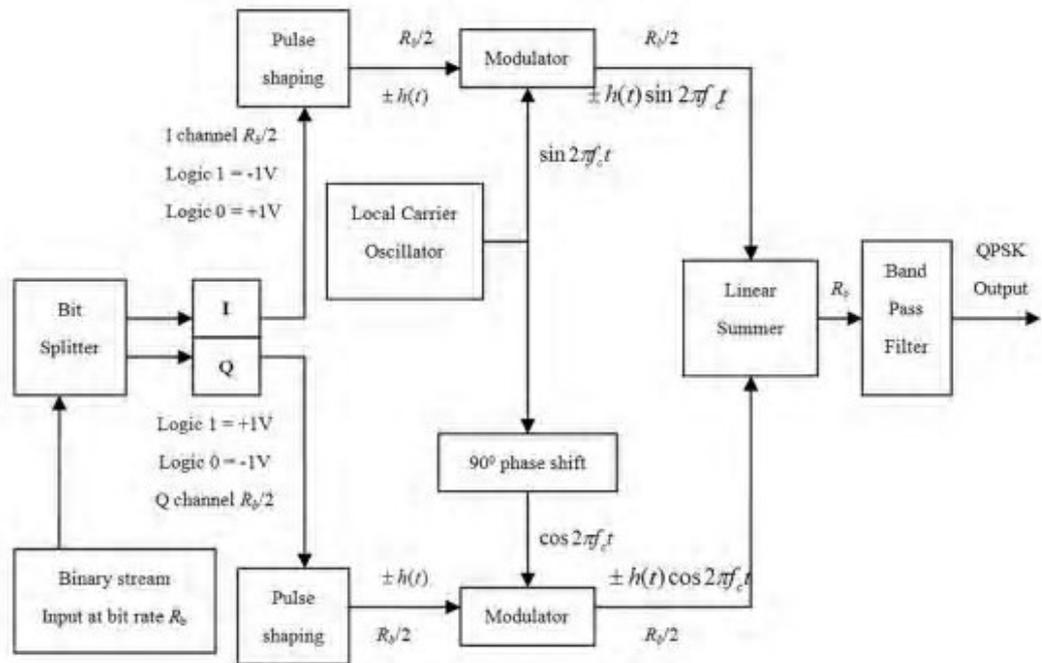
Figure 1.19: Schematic diagram of a QPSK modulator [26]

The equation of BPSK as following:

$$s(t) = \begin{cases} A\cos\left(2\pi f_c t + \dfrac{\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t + \dfrac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \dfrac{3\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t - \dfrac{\pi}{4}\right) & 10 \end{cases} \qquad 1.2$$
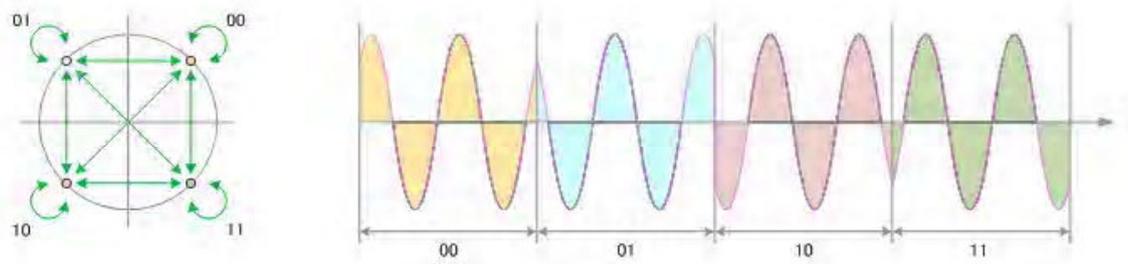
Figure 1.20: QPSK constellation and the transition of the information signal [27]

1.9.2.4. 16 Quadrature Amplitude Modulation

Four different phases and four different amplitudes are used in this modulation. Every symbol contains 4 bits, so there are $2^4=16$ symbols.
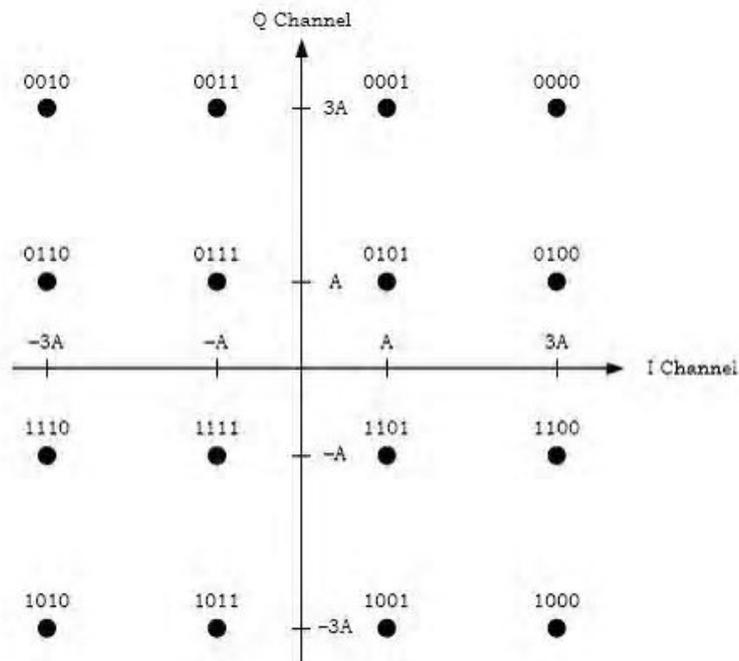
Figure 1.21: Signal Constellation for 16-QAM Modulation [28]

1.9.2.5. 64 Quadrature Amplitude Modulation

In case of a 64-QAM modulation, a group of 6 bits is mapped into a single constellation symbol with real and imaginary parts $m_I(k)$ and $m_Q(k)$. The signal constellation is shown in Figure 1.22.
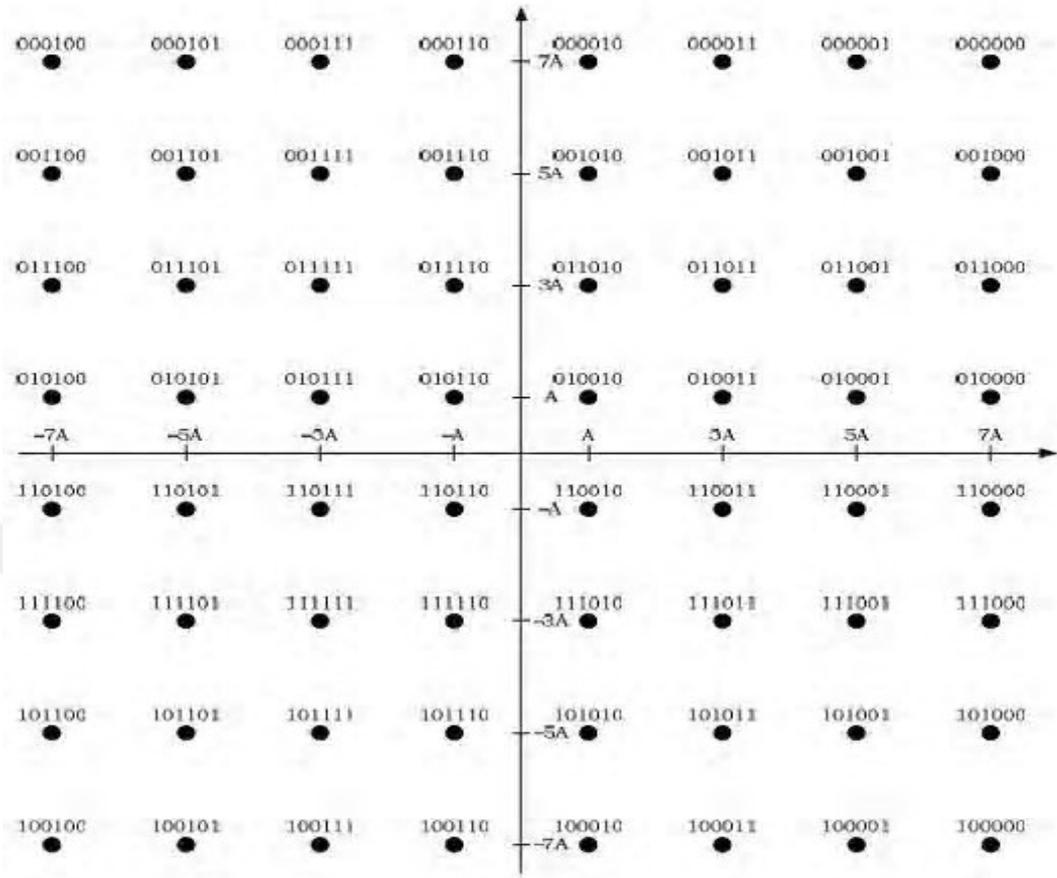
Figure 1.22: Signal Constellation for 64-QAM Modulation [28]

2. CHAPTER

MODELING THROUGHPUT IN WIRELESS LOCAL AREA NETWORK

Bandwidth is often related to the maximum amount of data transfer per second. For example, if we say "Gigabit Ethernet can provide bandwidth up to 1 Gbps", in this context, it means capability. Bandwidth also means a range of frequencies used to transmit signals. In this case, it is measured in hertz (Hz). Throughput is an actual amount of data passing through media or a connection. If bandwidth what it is possible in a perfect world, or theory, throughput is what it is in a non-perfect world or practice. A network connection is like a bridge, and each bit of data is like a vehicle. If the bridge can handle 1000 vehicles per hour at its full capacity, then we are talking about the bridge's bandwidth. Suppose every vehicle must stop to pay the crossing fee, and the actual number of vehicles passing the bridge would be decreased to 100 vehicles per hour. Now, we are talking about the bridge's throughput.

This chapter investigates how much of a transmission channel can be used efficiently with a data rate of 54 Mbps. Also, factors that are affecting the throughput of a transmission medium will be examined in IEEE 802.11 architecture. The theoretical throughput will be calculated based on standards defined by IEEE 802.11 for IEEE 802.11 b and IEEE 802.11 g.

2.1. Carrier Sense Multiple Access with Collision Avoidance

The 802.11 MAC layer protocol provides shared access to a wireless channel. The Distributed Coordination Function (DCF) is the primary access method, as shown in Figure 2.1, which provides contention-based shared access to the medium. DCF is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) [29]. CSMA/CD (Carrier Sense Multiple Access with Collision Detection) is used in Ethernet technology.

When using the DCF, a station, before initiating a transmission, senses the channel to determine if another station is transmitting [30]. If the channel is busy, it will defer its transmission and wait for the channel to empty. If the channel is detected to be empty, the transmission starts. Such protocols are very efficient since they give users a chance of transmission with minimum delay when the transmission channel is not used extensively. However, there is always a possibility that more than one user will perceive the channel as empty and start transmitting at the same time, which causes collisions. If a collision occurs, the MAC layer allows retransmission of the packets, but this causes significant delays. If the transmitting station does not receive the acknowledgement packet, a collision is assumed, and the random exponential back off algorithm is used to retransmit the packet [31].

The Collision Detection mechanism, which works very well in wired computer networks, cannot be used in wireless systems for two main reasons:

- To implement the collision detection mechanism, a full-duplex transceiver is required to enable simultaneous reception and reception. This requirement increases costs significantly. At the same time, it is quite challenging to apply simultaneous reception when neighbouring frequencies are full.

- In wireless systems, all users cannot see each other. (Basic working principle of collision detection mechanism). A hidden node in a network is a device that is visible to the access point but not visible to other nodes attached to the access point [32].

To overcome these problems with DCF in wireless systems, acknowledgement frames are used with collision avoidance mechanism.

A station that wants to transmit firstly listens to medium. If the medium is sensed not empty, the transmission is delayed. The station can proceed with its transmission if the medium is determined to be idle for a time interval of Distributed Interframe Space (DIFS). After a data frame is successfully received at the destination, the receiver must send an acknowledgement frame (ACK), because the transmitter cannot determine whether a frame has been faithfully delivered to its destination by merely listening to the channel [29].
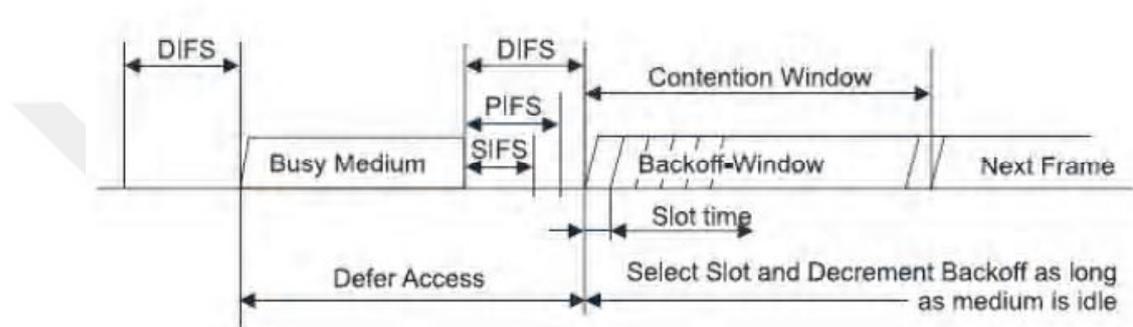
Figure 2.1: IEEE 802.11 Basic Access Method [3]

Carrier sensing is not enough alone because all users do not see each other. To reduce the possibility of collision between two users, the IEEE 802.11 standard defines a virtual carrier sensing mechanism.

- The user who wants to transmit first sends a small packet of signals, called RTS (Request to Send). RTS frame contains source and destination address, transmission duration (time required for transmission of the packet + time for receiving the ACK message)

- The receiving user will respond to the RTS frame with a control message called CTS (Clear to Send) if the channel is empty. CTS frame contains the same transmission duration information.

The other neighbour terminals read RTS or CTS frames which contain transmission duration field and set their Network Allocation Vector (NAV). NAV is a counter for how long other terminals must defer from accessing to medium. No medium access is permitted during the blocked NAV duration [33]. RTS and CTS messages also eliminate

additional loads arising from collisions. Figure 2.2 shows transmission between two users and NAV settings of their neighbours.
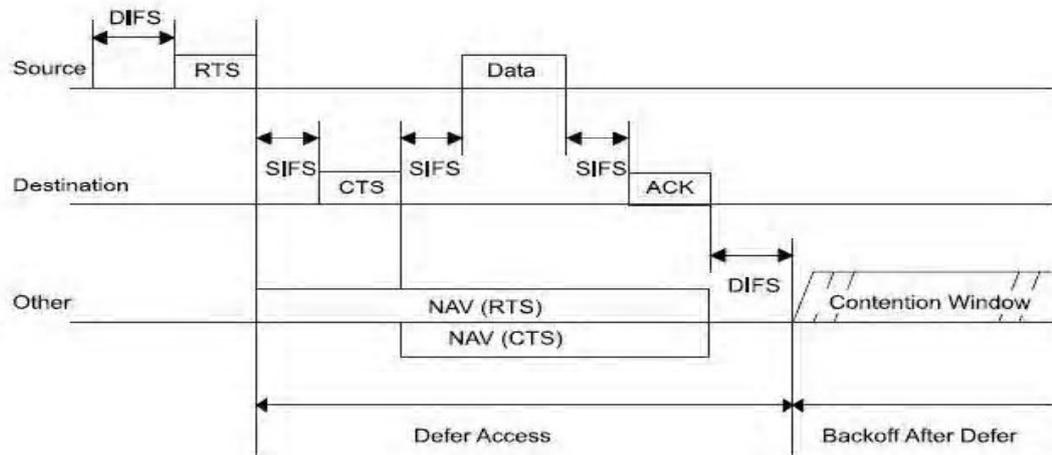
Figure 2.2: RTS/CTS/Data/ACK and NAV setting [34]

The hidden node problem occurs in wireless networks due to coverage or lack of information on terminals. This is specific to wireless networks and is not seen in other network types [35]. The hidden node problem is a case in IEEE802.11, where a transmitting node does not know about the existence of another node while transmitting to a third node, which is within the range of both nodes. Since the node does not know when the hidden node is transmitting, typical collision avoidance is not sufficient, and their transmissions will often collide at the third node. The hidden node problem reduces channel utilization and damages network performance.

Packets are likely to fail because of high bit error-rate (BER) in wireless networks. The overhead on the network will increase as the corrupted frames will be retransmitted until received in a healthy way. The 802.11 MAC protocol allows for simple packet fragmentation and reassembly mechanism for this situation.

2.2. Interframe Space (IFS)

The time interval between frames is called IFS [3]. The length of the interframe space determines when the channel can be accessed. Thus, interframe spacing is used to set prioritized access to the channel. There are four types of interframe spaces, Short

Interframe Space (SIFS), PCF Interframe Space (PIFS), Distributed Interframe Space (DIFS) and Extended Interframe Space (EIFS) [36].

IEEE 802.11 is a Time Division Duplex (TDD) system, only one transmission can happen at a time, and both the signal travel time and Transmit (Tx) to Receive (Rx) switching should be considered in the system timing. Several timers called IFS (Interframe Space) are specified with this purpose [37].

2.2.1. Slot Time

Slot Time (ST) is the basic unit of the backoff algorithm that time required for a station to sense the end of the frame, start transmitting, and beginning of the frame to propagate to others. The backoff interval is defined in multiples of the slot time.

ST = CCA (Clear Channel Assessment) Time + RxTx turnaround time + Air propagation time + MAC processing delay [38]   2.1

- Clear Channel Assessment is a technique for determining whether the medium is idle or not. CCA includes carrier sensing and energy detection. Carrier sense detects and measures the signal strength of the IEEE 802.11 frames. Energy detection measures the power of all RF energy in the channel.
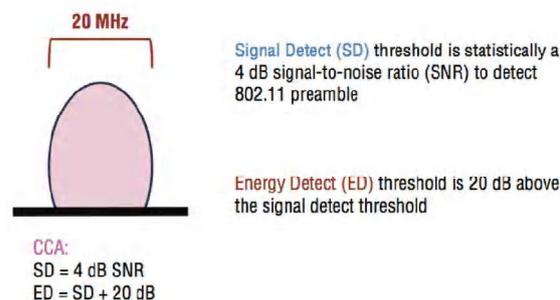
Figure 2.3: Clear Channel Assessment [39]

- RxTx turnaround time: maximum time (in microseconds) that the PHY requires to change from receiving to transmitting the start of the first symbol [3].

- Air propagation time: Twice the propagation time (in microseconds) for a signal to cross the maximum distance between the most distant allowable STAs that are slot synchronized [3].

- MAC processing delay: Concise period for MAC to process a frame and prepare an answer.

2.2.2. Short Interframe Space (SIFS)

SIFS is the shortest interframe space, which is the time interval required by a wireless device in between receiving a frame and responding to the frame. In other words, the recipient station transmits the ACK frame after a prescribed time interval SIFS (short interframe space) [40]. The duration of SISF is usually 10 μs and is calculated by the formula below:

$$\text{SIFS} = Rx_{Rf} \text{ delay (receiver radio front end delay)} + Rx_{PLCP} \text{ delay (receiver PHY layer delay)} + Rx_{MAC} \text{ processing delay} + \text{RxTx turnaround time [38]}$$

2.2

- Rx_{Rf} delay: Nominal time (in microseconds) between the end of a symbol at the air interface to the issuance of a PMD_DATA.indication primitive to the PLCP [3].

- Rx_{PLCP} delay: Nominal time (in microseconds) that PLCP uses to deliver the last bit of a received frame from the PMD receive path to MAC [3].
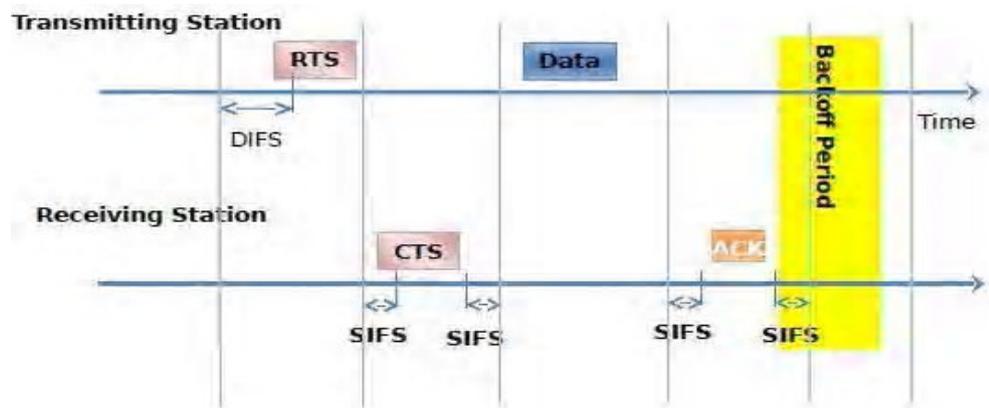
Figure 2.4: Short Interframe Spacing in DCF [41]

2.2.3. Point Coordination Interframe Space (PIFS)

PIFS is used by Access Point (AP) in Point Coordination Function (PCF) mode to access channel before other users. PIFS time is SIFS + Slot Time.

2.2.4. Distributed Interframe Space (DIFS)

The DIFS is used to initiate transmission by a user who wants to transmit. The user waits for the DIFS period to determine if the channel is empty before the transmission begins. DIFS time is SIFS + 2.Slot Time [3].

2.2.5. Extended Interframe Space (EIFS)

The EIFS is a longer frame space-time that is defined for a user receiving a corrupted packet. It is used to avoid a collision for users who cannot read transmission duration information in RTS and CTS frame and set its NAV.

2.3. Exponential Backoff Algorithm

The random backoff interval is the final timer by an 802.11 station before it transmits. Back off is a well-known algorithm used to resolve the contention of different users to access the channel. Each user holds a random number from a range called Contention Window (CW) and waits for that expiry of backoff interval to access channel. The random backoff interval utilized in the IEEE 802.11 standards is defined as multiples of a specific unit-interval called a Slot Time, up to a specified maximum number of such units constituting the contention window [40].

$$\text{Backoff interval} = \text{Random} ([0, \text{CW}]) \times \text{Slot Time} \qquad 2.3$$

$$CW_{min} \leq CW \leq CW_{max} \qquad 2.4$$

The IEEE 802.11 standard backoff algorithm works as follows. If the medium is busy, the transmission is deferred, and the station uses an Exponential Random Backoff mechanism by choosing a random backoff interval from [0, CW], where CW is the Contention Window. If no ACK occurs, the station doubles its CW. At the first transmission, $CW = CW_{min}$, and this value is doubled at each retransmission up to CW_{max} [42]. When the channel is sensed as empty, back off timer operates and reduced. The

backoff timer is stopped while the channel is busy. After a successful transmission, CW is synchronized to CW_{min}.
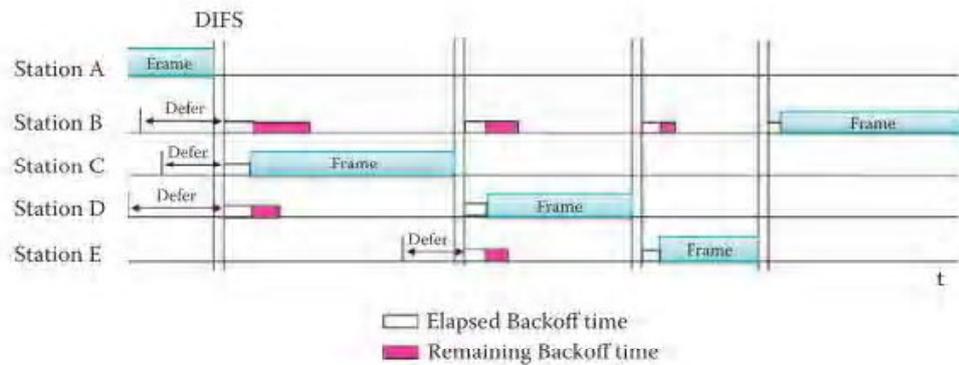
Figure 2.5: Backoff Illustration [42]

Figure 2.5 is an illustration of the backoff mechanism when several stations are sending data on a shared transmission medium. The process starts with sending a frame of the station A. The other stations (B, C, D) defer their transmission because they detect the presence of station A's frame on the medium. The stations (B, C, D) select a random number for the backoff period. After completing the DIFS period, they start counting down to complete the randomly selected backoff period. Firstly, station C completes its backoff period, and since the medium is now not used, it starts to send its frame. At this point, stations B and D stop counting in their backoff period and save the remaining portion of their backoff period. The station E is added to the stations that want to send data. However, it defers its transmission because station C is sending its frame at the same time. Station E starts its backoff period after completing the DIFS period. By the way, firstly the station D completes its backoff period, so it starts to send its frame. When the station D completed its transmission, the remaining two stations (E, B) begin the DIFS interval again. Then, firstly station E completes its backoff period, and it starts to send its frame. After the last DIFS interval, the remaining backoff time for station B expires, and then station B sends its frame [42].

2.4. Physical Layer Architecture

The IEEE 802.11 physical layer has two sublayers: Physical Layer Convergence Protocol (PLCP) and Physical Medium Dependent (PMD). The PLCP sublayer receives a frame

for transmission from the MAC sublayer and creates the PLCP Protocol Data Unit (PPDU). The MAC Protocol Data Unit (MPDU) that is delivered to the physical layer is referred to as the PLCP Service Data Unit (PSDU. When the PLCP layer receives the PSDU from the MAC layer, the appropriate PLCP preamble and header are added to the PSDU to create the PPDU. The PMD sublayer then modulates and transmits the data as bits. When transmitting data, the transmitting station provides the receiving station with special synchronization sequences at the beginning of each transmission [43].
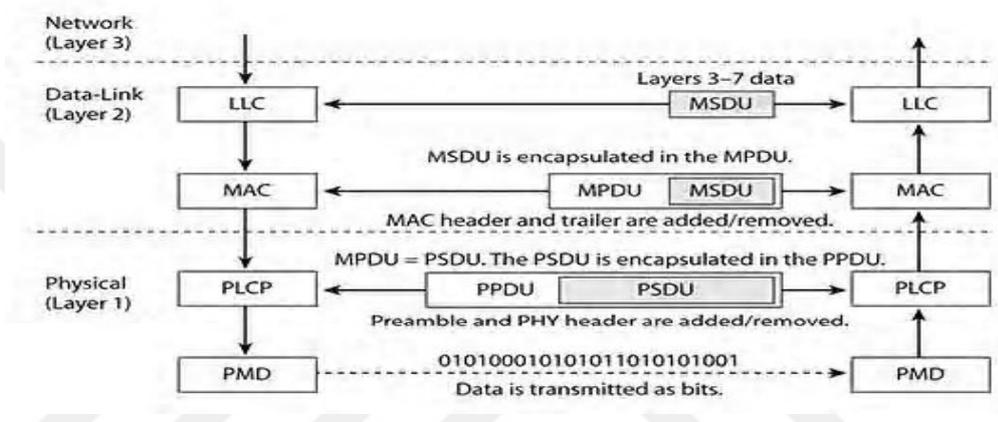
Figure 2.6: OSI and IEEE 802.11 protocol relationships [44]

2.4.1. MAC Frame Format

The MAC frame format comprises a set of fields. The format of the frame is defined as in Figure 2.7.
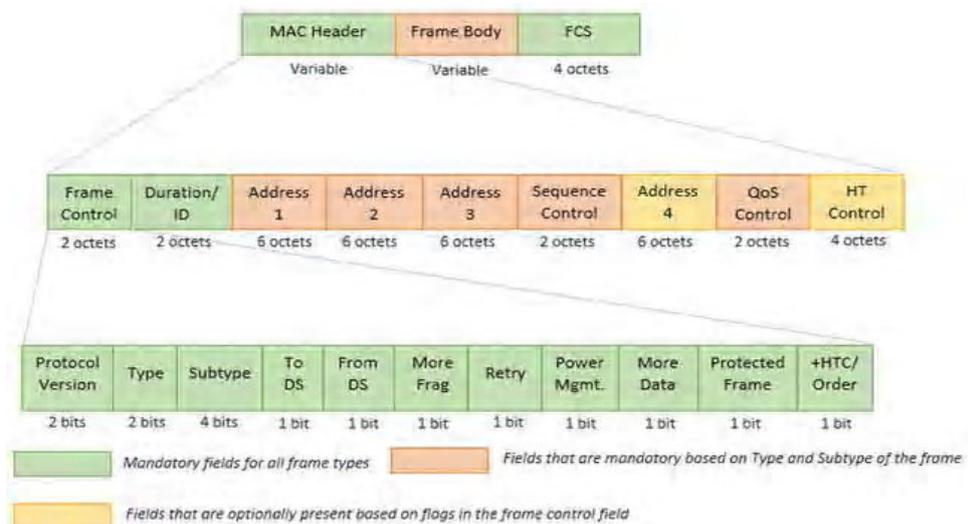
Figure 2.7: Mac frame format [45]

- Frame Control: It is a 2-byte long field. It identifies the type of wireless frame and contains subfields for protocol version, frame type, address type, power management, and security settings.

- Duration/ID: It is a 2-byte long field. It contains a value indicating the remaining duration needed to receive the next frame transmission (in µs).

- Address 1: It is a 6-byte long field. It usually contains the MAC address of receiving wireless devices.

- Address 2: It is a 6-byte long field. It usually contains the MAC address of transmitting wireless devices.

- Address 3: It is a 6-byte long field. It usually contains the MAC address of destination such as router interface (default gateway) to which AP is attached.

- Address 4: It is a 6-byte long field. It is only used by wireless bridges and is therefore relatively uncommon.

- Sequence control: It is a 2-byte long field. It contains two subfields which are Sequence Number (12 bits) and Fragment number (4 bits). Since acknowledgement frames may be duplicated, hence a sequence number is used to filter duplicate frames.

- Data: It is a variable-length field that contains data for transmission.

- Frame Check Sequence: It is a 4-byte long field that contains a 32-bit CRC error detection sequence to ensure an error-free frame.

2.4.2. RTS Frame Format
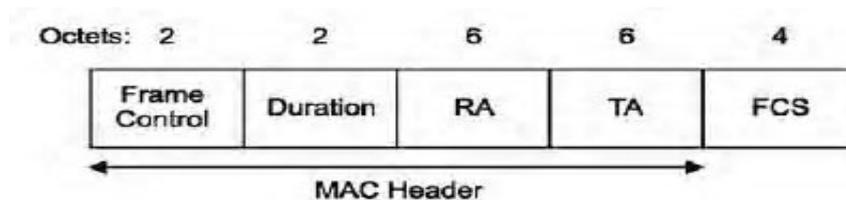
Figure 2.8: RTS frame format [3]

The frame format for the RTS frame is as defined in Figure 2.8.

- Frame Control: frame subtype is set to 1011 to indicate an RTS frame [34].

- Duration: contains a period for how long the channel will be occupied. It is equal to Data transmission time + CTS frame + ACK frame + 3xSIFS time [34].

- RA: receiver address.

- TA: address of the sender of the RTS frame.
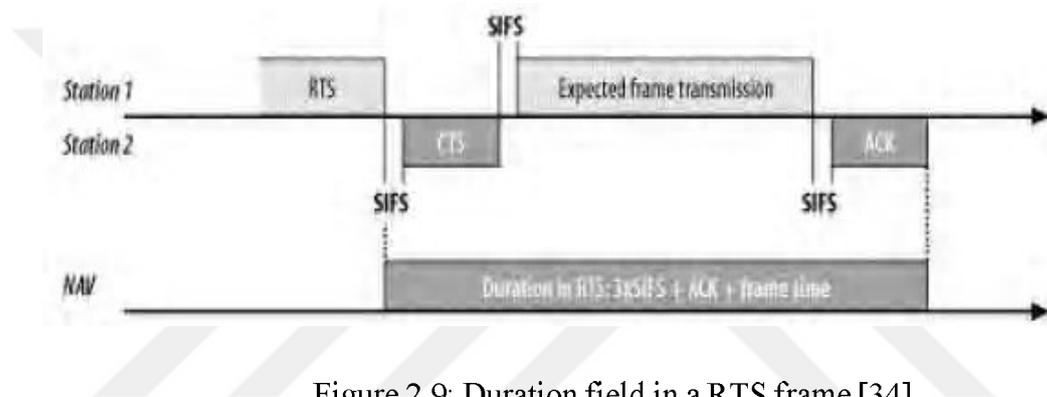
Figure 2.9: Duration field in a RTS frame [34]

2.4.3. CTS Frame Format
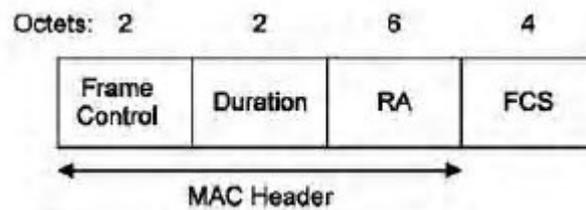
Figure 2.10: CTS frame format [3]

- Frame Control: frame subtype is set to 1100 to indicate a CTS frame [34].

- Duration: since the CTS frame is transmitted, the sender of the CTS frame subtracts one CTS frame and Short Interframe Space (SIFS) durations from the RTS frame, and places the result of calculation in Duration field [34].

- RA: it is a copy of TA information in the previous RTS frame.
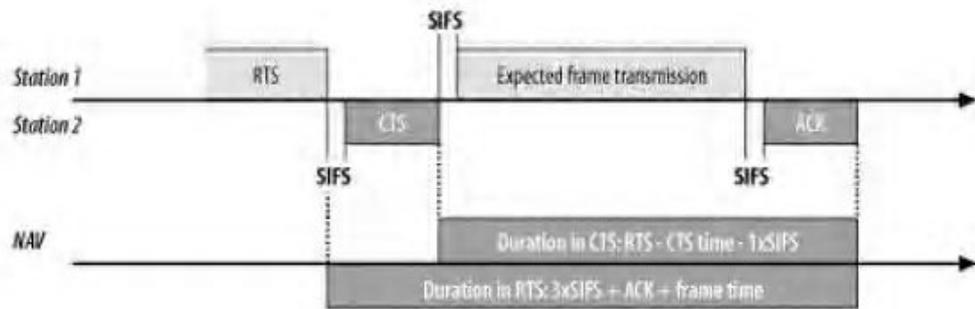
Figure 2.11: Duration in CTS [34]

2.4.4. ACK Frame Format
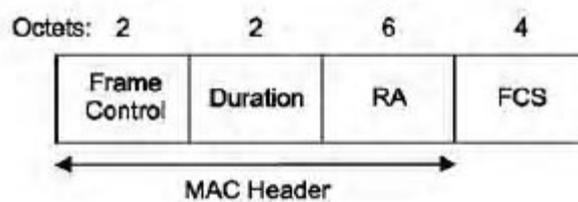
Figure 2.12: ACK frame format [3]

- Frame Control: frame subtype is set to 1101 to indicate an ACK frame [34].

- Duration: if More Fragments bit is 0, the transmission is complete. Thus, the duration is set to 0. If the More Fragments bit is 1, the time required to transmit the ACK and its short interframe space is subtracted from the duration in the most recent fragment [34].

- RA: indicates recipient of ACK message (it is a copy of Address 2 field.)
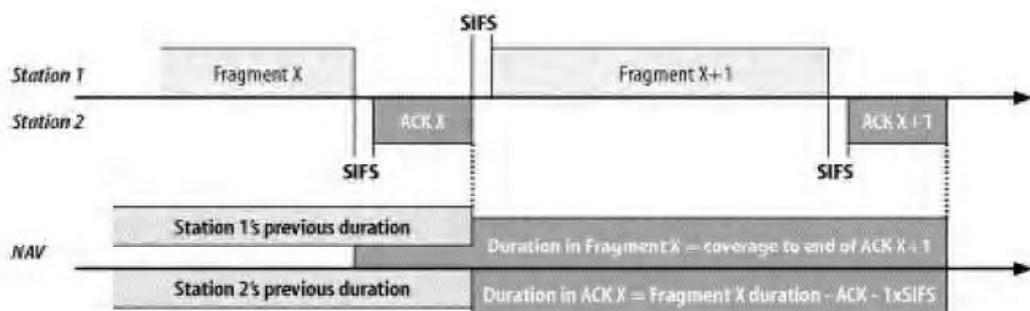
Figure 2.13: Duration in non-final ACK frames [34]

2.5. Point Coordination Function (PCF)

The IEEE 802.11 MAC may also incorporate an optional access method called a PCF, which is only usable on infrastructure network configurations [3]. PCF is used for time-bounded data services such as voice, data, video [42]. Access Points (APs) are used as point coordinators in PCF.

PCF uses a central Point Coordinator (PC), which manages access to wireless medium and polls stations during a Contention Free Period (CFP). A station only can start transmitting after it is polled [46]. During CFP, access to the medium is governed and assigned to stations by Point Coordinator, but during the Contention Period (CP), there is no central authority, and all the stations contend for access to the medium [36].

2.6. Ad Hoc Architecture

Stations that use the same frequency band and situates in the transmission range of each other may form an Independent Basic Service Set and communicate directly. There is no need for Access Point (APs) in this architecture. Some of the operations performed by APs are made by stations like creating beacon frames, synchronization. On the other hand, some functions of APs are not supported at all.
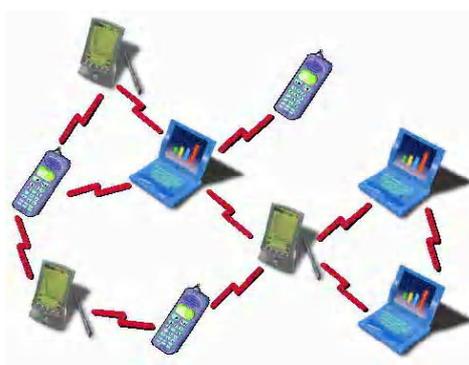
Figure 2.14: An ad hoc wireless network [47]

2.7. Path Loss Model

In a communication model, in its purest form, there is a transmitter and a receiver. In wireless systems, communication is through electromagnetic waves. As a signal propagates through space, its power density decreases. Path loss models are used to compute the decrease in the power of a radio signal as it propagates away from the

transmitter. It is usually expressed in decibel (dB). Two path loss models are commonly used in the transmission of electromagnetic waves.

The first of these is the free-space path loss model where communication takes place only one clear line-of-sight path in the absence of obstacles, reflections, or shadowing. In two-ray ground reflection models, two waves arrive at the receiver with direct propagation and ground reflection wave [48]. In literature, the free space model is preferred for communication at less than cross-over distance (d_{snir}) value and two-ray ground reflection model is preferred at distances greater than d_{snir} value [49]. Equation 2.5 indicates the formula for d_{snir} [50].

$$d_{snir} = \frac{4.\pi.\sqrt{L}.h_a.h_g}{\lambda} \qquad 2.5$$

where L is the loss factor of the system, h_a is the height of the receiving antenna, h_g is the height of receiving antenna, λ is the wavelength of the carrier signal. The formula used in communications less than d_{snir} is given in Equation 2.6 [50].

$$P_a(d) = \frac{P_g.A_g.A_a.\lambda^2}{(4.\pi.d)^2.L} \qquad 2.6$$

where P_a is power at receiver, P_g is power at the transmitter, d is the distance, A_g is transmitter antenna gain, A_a is receiver antenna gain, L is system loss, λ is the wavelength of the carrier signal.

Figure 2.15 shows the power transmission in short distance ($d < d_{snir}$) using the free space model, Figures 2.16 and 2.17 show the power transmission in long-distance using two-ray ground reflection model.
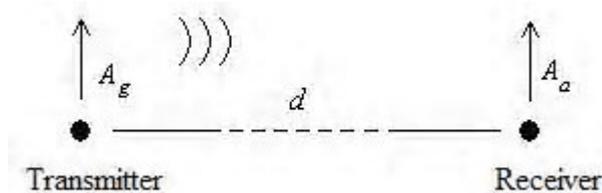
Figure 2.15: The power left on the receiving antenna within a short, clear and accurate field of view [50].

In Figure 2.16, transmitted power on receiving antenna is equal to the sum of the power of direct transmitted (E_d) and reflected from the ground (E_y). (Equation (2.7) [50])

$$E_T = E_d + E_y \qquad\qquad 2.7$$
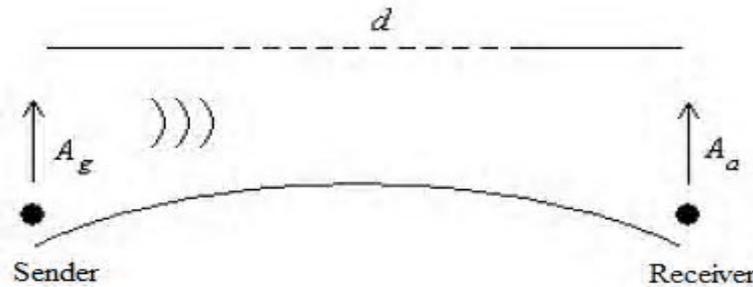
Figure 2.16: The power left on the receiving antenna within a long-range field of view with possible reflections [50].

If communication distance d is greater than d_{snir} value, the two-ray ground reflection model should be used. The formula for the two-ray ground reflection model is given in Equation 2.8 [50].

$$P_a(d) = P_g \cdot \frac{h_g^2 \cdot h_a^2}{d^4} \cdot A_a \cdot A_g \qquad\qquad 2.8$$

where P_a is power at receiver, P_g is power at the transmitter, d is the distance, A_a is receiver antenna gain, A_g is sender antenna gain, h_g is sender antenna height, h_a is receiving antenna height. The main difference between these two models is the ratio of received signal strength to distance. In the first model, received signal strength is inversely proportional to the square of the distance, whereas, in the second model, signal strength is inversely proportional to the fourth force of distance since signals from different paths fade each other.

Both models have signal attenuation. As given in Equation 2.9 [50], gain in decibels is the logarithmic ratio of transmitted signal level (P_g) to received signal level (P_a).

$$G_{dB} = 10 \cdot \log_{10}\left(\frac{P_g}{P_a}\right) \qquad\qquad 2.9$$
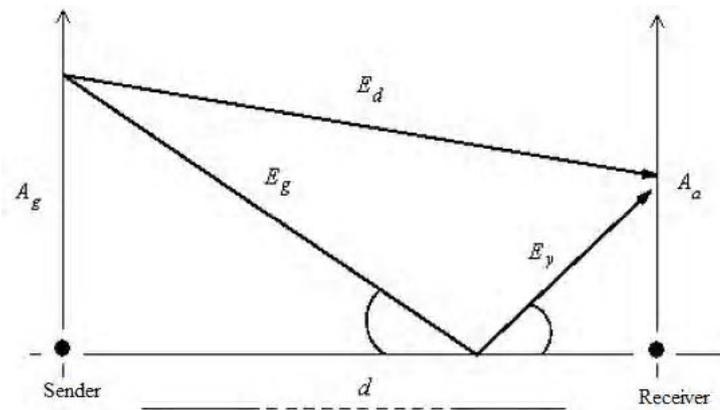
Figure 2.17: The power left on the receiving antenna in case of ground reflection [50]

The effect of environmental conditions on the transmission of radio waves is quite complicated. Therefore, it is difficult to determine the radio transmission range of a transmitting device. Radio transmission range is the maximum distance between two communicating devices under normal operating conditions. This distance is directly dependent on the power of the transmitter and receiver device and receiver sensitivity. The transmit power is the power of a transmitter device to emit radio waves. Receiver sensitivity is the lowest radio signal value in decibels that a receiving device can detect. If received signal power is below this threshold, reception is not possible. This value also determines the performance of a receiver device. Lower receiver sensitivity value indicates that proper hardware is used. This value is generally between -80 and -90 dBm in industrial applications. The gain in the free-space path loss model can be expressed as given in Equation 2.10 [50].

$$\frac{Pg}{Pa} = \frac{(4.\pi.d)^2}{\lambda^2} = \frac{(4.\pi.f.d)^2}{c^2}$$

2.10

where c is the speed of light, f is transmission frequency.

In transmission with power Pg by a transmitter at distance d, power falling on the antenna for a receiver to receive this signal in a healthily way must be at least $RX_{sensivity}$ as given in Equation 2.11 [50].

$$P_a^{min} = RX_{sensivity}$$

2.11

2.8. Calculating Theoretical Throughput

Theoretical throughput can be calculated using Equation 2.12.

$$Throughput\ (Mb/s) = \frac{Amount\ of\ Data\ (bits)}{Transmission\ Time\ (\mu s)}$$

2.12

In calculations, it is assuming that the application layer of the sender device sends a UDP data packet of 1470 bytes to a receiver device in ad hoc architecture. At the transport layer, 8 bytes UDP header is added to application data, and it is called a segment. When the segment reaches the network layer, 20 bytes TCP/IP header is added to the segment, and it is called a packet, so a total amount of 1498 bytes.

Table 2.1: Order of frames in 802.11 b /g transmission

DIFS	BACKOFF	PHY	MAC	DATA	FCS	SIFS	PHY	ACK	FCS

Table 2.1 indicates the order of a general 802.11 b/g transmission procedure. However, there are many differences between IEEE 802.11 b and IEEE 802.11 g standards, so it is better to analyze them separately.

2.8.1. Theoretical Throughput in IEEE 802.11 b

$$T_{DIFS} = T_{SIFS} + 2.T_{SLOT} = 10\mu s + 2*20\mu s = 50\mu s$$

$$T_{BACKOFF} = 15.5 * 20 = 310\ \mu s\ \text{(Assumed no collision and random CW = 15.5)}$$

PLCP preamble can be long (144bits) or short (72 bits). Long preamble is used in DSSS mode, while short is used preamble in HR/DSSS mode. It is sent at 1Mbps in both cases. PLCP header is 48 bits. It is sent at 1Mbps in DSSS. It is sent at 2Mbps in HR/DSSS.

$$T_{PHY_{DSSS}} = \frac{144\ bits}{1Mbps} + \frac{48\ bits}{1Mbps} = 192\mu s$$

$$T_{PHY_{HR/DSSS}} = \frac{72\ bits}{1Mbps} + \frac{48\ bits}{2Mbps} = 96\mu s$$

MAC header is 24 bytes without QoS, Address 4, Ht Control fields. The selected data rate is 11 Mbps.

$$T_{MAC} = \frac{(24 * 8\, bits)}{(11\, Mbps)} = 17.45\, \mu s$$

$$T_{Data} = \frac{Data_{APP} + H_{UDP} + H_{IP} + H_{LLC}}{11\, Mbps} = \frac{(1470 + 8 + 20 + 8) * 8}{11 Mbps} = 1095.27 \mu s$$

After data, FCS is appended to frame body, which is 4 bytes, and it is sent at a data rate of 11Mbps.

$$T_{FCS} = \frac{4 * 8\, bits}{11\, Mbps} = 2.91 \mu s$$

The sender completed its transmission. After a SIFS period, the receiver sends the acknowledgment frame.

$$T_{SIFS} = 10 \mu s$$

$$T_{PHY_{HR/DSSS}} = \frac{72\, bits}{1 Mbps} + \frac{48\, bits}{2 Mbps} = 96 \mu s$$

$$T_{ACK} = \frac{14 * 8\, bits}{11\, Mbps} = 10.19 \mu s$$

Summing all transmission durations for 11 Mbps obtained previously,

$$T_{TOTAL} = 50 + 310 + 96 + 17.45 + 1095.27 + 2.91 + 10 + 96 + 10.19$$

$$= 1687,82 \mu s$$

$$Throughput_{APP} = \frac{1470 * 8\, bits}{1687.82\, \mu s} \cong 6.97\, Mbps$$

2.8.2. Theoretical Throughput in IEEE 802.11 g

IEEE 802.11 g standard has a new PHY specification which is Extended Rate PHY (ERP). Slot Time (ST) is decreased to $9\mu s$ in IEEE 802.11 g standard.

$$T_{DIFS} = T_{SIFS} + 2.T_{SLOT} = 10\mu s + 2 * 9\mu s = 28\mu s \text{ (Slot Time)}$$

$$T_{BACKOFF} = 15.5\ \mu s * T_{SLOT} = 15.5 * 9 = 138.5\ \mu s \text{ (Assumed no collision and random}$$
CW = 15.5)
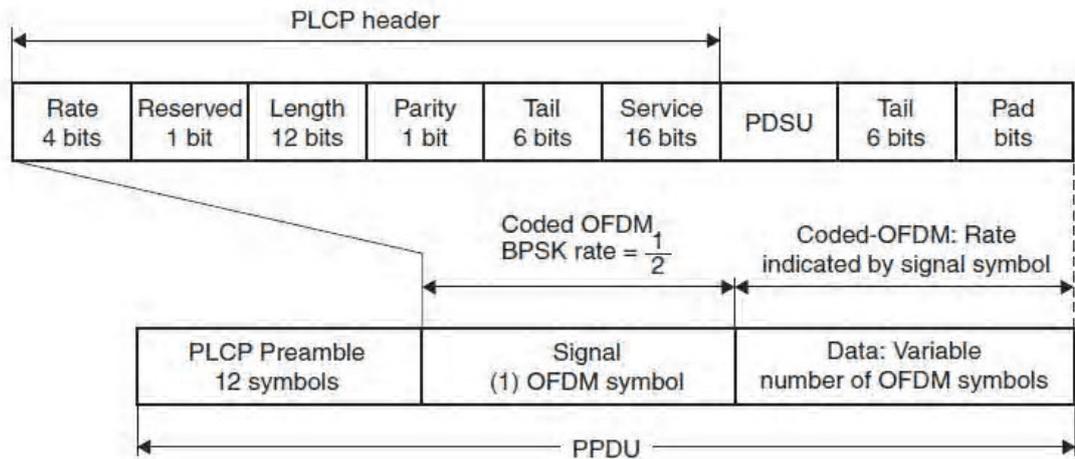
Figure 2.18: OFDM PLCP preamble, header, and PSDU [51]

The PHY header changes completely in pure g mode. It does not have long/short preambles anymore. The PLCP preamble consists of 12 symbols, 10 of which are short, and 2 of which are long, which takes $16\mu s$ to be sent. The PLCP preamble and the signal fields are always transmitted at 6 Mbps [51]. Then, the PLCP header made of 40 bits. The first 24 bits are sent at 6 Mbps, so they take a fixed amount of time of $4\ \mu s$. The total time of the PHY header:

$$T_{PHY_{ERP}} = T_{PREAMBLE} + T_{HEADER} = 16 + 4 = 20\mu s$$

Service field which is 16 bits, MAC header which is 24 bits, data which is 1506 bytes, FCS which is 4 bytes and Tail which is 6 bits are sent at data rate 54 Mbps.

$$T_{SERVICE} = \frac{16\ bits}{54\ Mbps} = 0.3\ \mu s$$

$$T_{MAC} = \frac{24\ bits}{54\ Mbps} = 3.56\ \mu s$$

$$T_{Data} = \frac{Data_{APP} + H_{UDP} + H_{IP} + H_{LLC}}{54\ Mbps} = \frac{(1470 + 8 + 20 + 8) * 8}{54\ Mbps} = 223.11\ \mu s$$

$$T_{FCS} = \frac{4 * 8\, bits}{54\, Mbps} = 0.59\, \mu s$$

$$T_{TAIL} = \frac{6\, bits}{54\, Mbps} = 0.11\, \mu s$$

Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})	Data rate (Mb/s) (20 MHz channel spacing)	Data rate (Mb/s) (10 MHz channel spacing)	Data rate (Mb/s) (5 MHz channel spacing)
BPSK	1/2	1	48	24	6	3	1.5
BPSK	3/4	1	48	36	9	4.5	2.25
QPSK	1/2	2	96	48	12	6	3
QPSK	3/4	2	96	72	18	9	4.5
16-QAM	1/2	4	192	96	24	12	6
16-QAM	3/4	4	192	144	36	18	9
64-QAM	2/3	6	288	192	48	24	12
64-QAM	3/4	6	288	216	54	27	13.5

Figure 2.19: Modulation dependent parameters [3]

To calculate pad bits, which is the number of data bits per OFDM symbol, refer to Equation 2.13. 16 and 6 represent service and tail bits[52]. N_{DBPS} value is 216 for 54 Mbps which can be found in Figure 2.19.

$$N_{SYM} = \left\lceil \frac{16 + 8 * Length + 6}{N_{DBPS}} \right\rceil$$

2.13

$$N_{DATA} = N_{SYM} * N_{DBPS}$$

$$N_{PAD} = N_{DATA} - (16 + 8 * Length + 6)$$

where $Length = Payload + Mac\, Header + FCS = 1506 + 20 + 8 = 1534\, bytes$

$$N_{SYM} = \left\lceil \frac{16 + 8 * 1534 + 6}{216} \right\rceil = 57$$

$$N_{DATA} = 57 * 216 = 12312$$

$$N_{PAD} = 12312 - (16 + 8 * 1534 + 6) = 18\ bits$$

$$T_{PAD} = \frac{18\ bits}{54\ Mbps} = 0.33\mu s$$

T$_{SIGNAL}$=6μs (T_{SIGNAL} is added which is supplementary time)

The sender completed its transmission. The receiver sends the acknowledgement frame after a SIFS period.

$$T_{SIFS} = 10\mu s$$

$$N_{SYM} = \left\lceil \frac{16 + 8 * 14 + 6}{216} \right\rceil = 1$$

$$N_{DATA} = 1 * 216 = 216$$

$$N_{PAD} = 216 - (16 + 8 * 14 + 6) = 82\ bits$$

$$T_{ACK} = T_{PHY} + \frac{10 * 8}{54\ Mbps} + T_{PAD} = 27\mu s + \frac{80\ bits}{54\ Mbps} + \frac{82\ bits}{54\ Mbps} = 30\mu s$$

Summing all total transmission durations for 54 Mbps obtained previously,

$$T_{TOTAL} = 28 + 138.5 + 20 + 0.3 + 3.56 + 223.11 + 0.59 + 0.11 + 0.33 + 6 + 10 + 30$$

$$= 460.5\ \mu s$$

$$Throughput_{APP} = \frac{1470 * 8\ bits}{460.5\ \mu s} \cong 25.54\ Mbps$$

3. CHAPTER

OMNET++ AND INET

This section of the study describes the simulation tools, methods, and techniques used in this thesis.

3.1. What is Omnet++

Objective Modular Network Testbed in C++ (Omnet++) [40] is an open-source and C++ and component-based discrete event simulator for modeling communication networks, multiprocessors, and other distributed or parallel systems [41]. Figure 3.1 shows the Omnet++ simulation environment. It has two versions. One of them is free to use for academic purposes. The other version is for commercial use, which is called Omnest. Omnet++ is not just network simulation software; however, it won a reputation as a network simulation platform in the academic community. The components inside Omnet++ are also called modules. These components can be reassembled into larger components and models. The main modules of Omnet++ are;

- Simulation kernel library (C++)
- The NED language
- IDE (based on the Eclipse)
- Interactive simulation runtime GUI (Qtenv)
- Command-line interface for simulation execution (Cmdenv)
- Utilities (makefile creation tool, etc.)
- Documentation, sample simulations, etc.

Figure 3.1: Omnet++ simulation environment

3.1.1. Installation of Omnet++

Omnet++ can run on Windows, macOS, and Linux operating systems. The installation of Omnet++ is described here for the Windows operating system since the studies in this thesis were done on a computer with the Win10 operating system. Omnet++ supports 64-bit versions of Windows 7 and 10 [53].

Figure 3.2: Omnet++ download page

Firstly, the zip file that contains the Omnet++ source code must be downloaded from *http://www.omnetpp.org* as it is displayed in Figure 3.2. Then, the zip file must be extracted to the directory where to want to install the software. Then, open *mingwenv.cmd* file (located in the extracted directory) by double-clicking it. It will bring a command shell screen. Before starting the installation, we will be warned with a message, as shown in Figure 3.3. You must press any key to unpack some required files on the tools directory.

Figure 3.3: MinGW toolchain

When the previous step is completed, ./configure and make commands must be run on the shell consecutively for building simulation libraries, as it is shown in Figure 3.4.

Figure 3.4: Building simulation libraries

When the installation is completed, the Omnet++ IDE can be started by writing *omnetpp* and then pressing enter on the command shell.

3.1.2. INET Framework

The INET Framework is built on Omnet++, which is an open-source simulation model library. It provides communication possibilities with other modules or hosts in wired and

wireless network simulations. Besides, the INET framework includes several protocol implementations such as IEEE 802.11, TCP, UDP, IPv4, IPv6, Ethernet, MANET, etc.

3.1.2.1 INET Installation

The latest versions of Omnet++ can download and install the INET framework. If it is skipped, INET can be installed by following the steps below.

Firstly, we have to open the Omnet++ IDE. Then, go to "*Help -> Install Simulation Models*". The dialogue screen with available INET versions appears as it is displayed in Figure 3.5. Then, we must select the version of INET, which will be installed from the list and click the "Install Project" button. The Omnet++ IDE will do the rest and install the selected INET version.
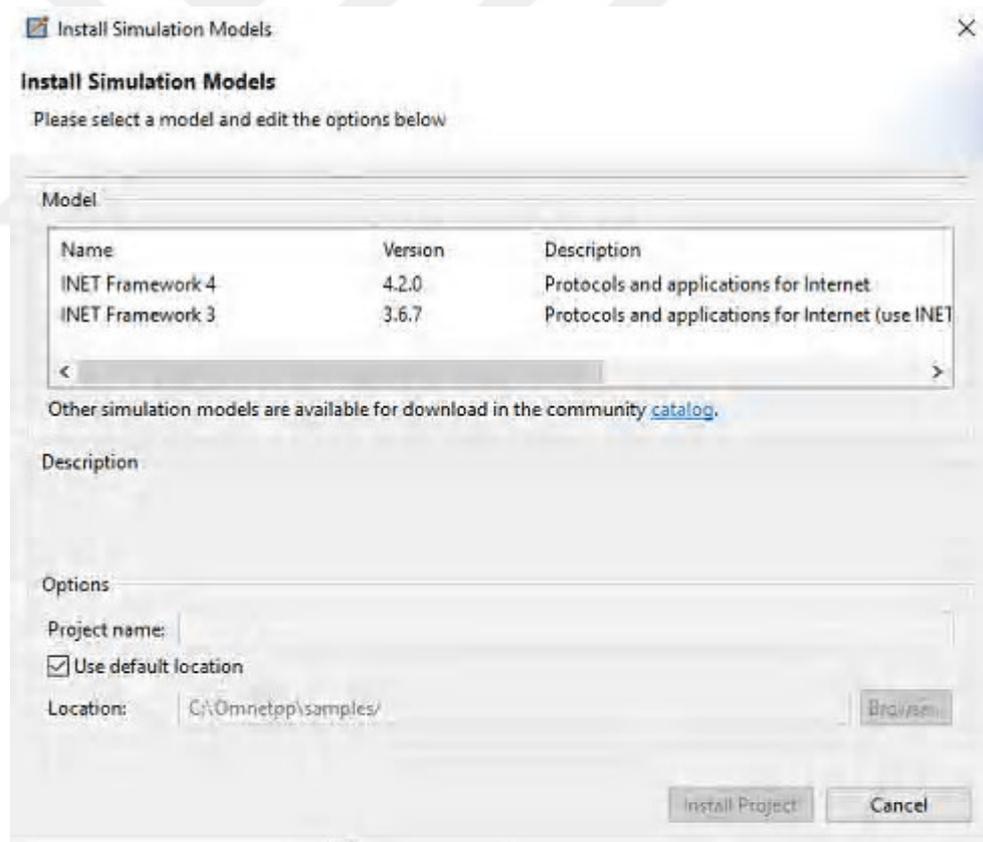
Figure 3.5: Installing INET simulation tool

3.1.3. The Component Model

Omnet++ is made of modules that can talk with each other. The component model can be grouped into four main categories, which are connections, parameters, simple, and compound modules. The active components are called simple modules, which are defined with the simple keyword. Simple modules are written in C++ and using the simulation class library. Simple modules can be merged to create compound modules. Figure 3.6 shows the structure of the Omnet++ component model. Compound modules may also be merged to create new compound modules. Hierarchy levels can be infinite. The connections are used between modules when they are communicating with each other. Modules have input and output interfaces so that we can call them gates. Modules send messages via gates to communicate with other modules or hosts. Messages are sent via input gates and arrive via output gates. A connection can link an input and output gate. The whole system's name is the network.
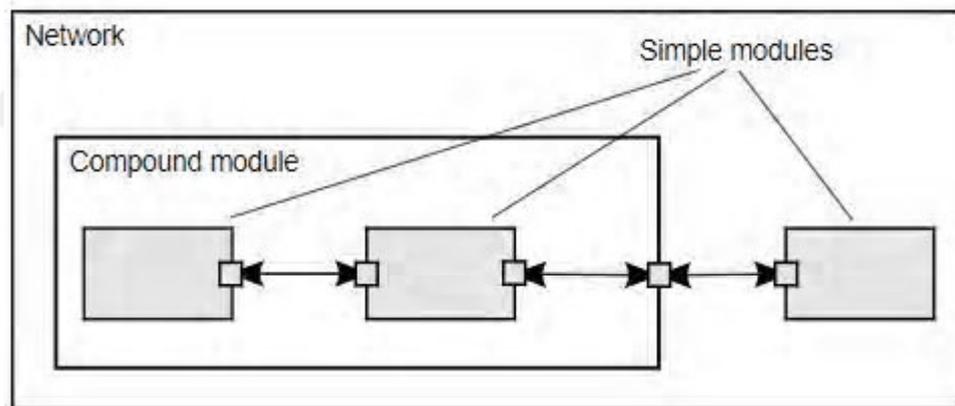
Figure 3.6: Simple and compound modules [54]

3.1.4. The NED Language

The topology description language of Omnet++ is Network Description (NED) that lets the user define simple modules, and merge them into compound modules. Compound modules can be labeled as networks. In other words, the user builds the structure of the simulation environment in the NED language.

Figure 3.7 shows the NED codes of the simulation environment in this thesis study. The most basic NED types used in this study will be explained briefly in the following subchapters.

```
network Wireless
{
    parameters:
        @display("bgb=650,500;bgg=100,1,grey95");
        @figure[title](type=label; pos=0,-1; anchor=sw; color=darkblue);
    submodules:
        visualizer: IntegratedCanvasVisualizer if hasVisualizer() {
            @display("p=580,125");
        }
        configurator: Ipv4NetworkConfigurator {
            @display("p=580,200");
        }
        physicalEnvironment: PhysicalEnvironment {
            @display("p=580,335");
        }
        radioMedium: Ieee80211ScalarRadioMedium {
            @display("p=580,275");
        }
        hostA: AodvRouter {
            @display("p=50,325");
        }
        hostB: AodvRouter {
            @display("p=450,325");
        }
}
```

Figure 3.7: NED codes of the simulation environment

3.1.3.1. AodvRouter

The hosts can have different NED types. The StandardHost is the default NED type of hosts in INET that has comprise of protocols such as TCP, UDP, IP, various network interfaces (NICs). The WirelessHost is another host NED type of host's for wireless network scenarios. The AodvRouter type is very similar to the WirelessHost type. When the AodvRouter type is used as a host type, the hosts additionally contain the AodvRouting submodule. This difference converts each host into a router.

In Ad hoc On-Demand Distance Vector (AODV) routing protocol, communication paths established as they are needed. Once installed, the communication path is used by the needy host as long as it is needed. After a while, redundant communication paths are cleaned in the routing tables.

The network is silent until the sender terminal needs a route to the receiver host. The network terminal that requires a route broadcasts the route request message. Other terminals direct the route request message to their neighbor terminals and save the needy host, generating temporary routes back to the needy host. When a host receives the route

request message and already has a route to the desired host, it sends a message back through the temporary route to the needy terminal. The needy terminal then begins to use the route with the least number of hops through other nodes.

If a network uses AODV as a routing protocol, the defined message types are Route Request (RREQ), Route Reply (RREP), and Route Error (RERRs). The communication path is created or not with these messages at the start of the simulation.

3.1.3.2. Ipv4NetworkConfigurator

The Ipv4NetworkConfigurator is an INET module that assigns IP addresses to hosts. It is not sufficient to know the destination IP address to communicate. The hosts also need to know each other's MAC addresses, which is handled by per-host with the GlobalArp module. The configurator can assign IP addresses to hosts either automatically or manually.

3.1.3.3. StationaryMobility

The hosts also have a submodule for mobility purposes. There are different mobility types for different needs in INET. The StationaryMobility is a mobility type in INET that needs the hosts' (x, y, z) positions are defined in the configuration file at the beginning of the simulation and cannot be changed during the simulation. If hosts' positions are stationary during simulation, how do we talk about the mobility feature of hosts? We can use parameter values for the mobility feature of hosts, as it is shown below. The distance parameter of host A takes values from 10 to 100, with an increase of 10 in each run in the following code snippet. As a result, the simulation runs ten times. This is an example of how to configure batch simulation in Omnet++.

*.hostA.mobility.initialX = ${distance=10..100 step 10}m

3.1.3.3. Ieee80211ScalarRadioMedium

A radio medium module takes care of the transmission and reception of frames on the shared physical medium, which is necessary for all wireless simulations at INET. The radio medium module also has responsibilities for signal propagation, interference,

attenuation. The Ieee80211ScalarRadioMedium type has many sub-modules for background noise, path loss, obstacle loss, and more.

The Ieee80211ScalarRadioMedium module uses the free-space path loss model by default, which supposes a line-of-sight path, with no obstacles, reflection, diffraction. The two-ray ground reflection model is more accurate than the free-space path loss model. That is why it was used in this study. The two-ray ground model utilizes the heights of the receiver and the transmitter antennas from the ground as input.
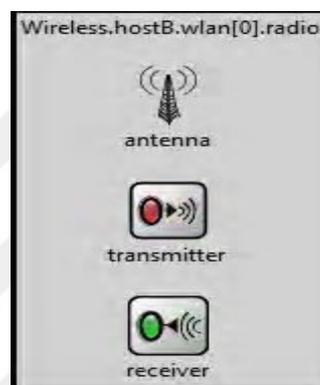
Figure 3.8: IEEE 80211 Scalar Radio Module in INET

3.1.3.4. Ieee80211Interface

The Ieee80211Interface s is plugged into hosts as a network interface card (NIC). It has two crucial subparts. These are the MAC and radio parts. The Mac part represents the data-link layer, and the radio part represents the physical layer in the OSI model. Figure 3.8 shows the radio part of the hosts. Figure 3.9 shows the MAC part of the hosts.
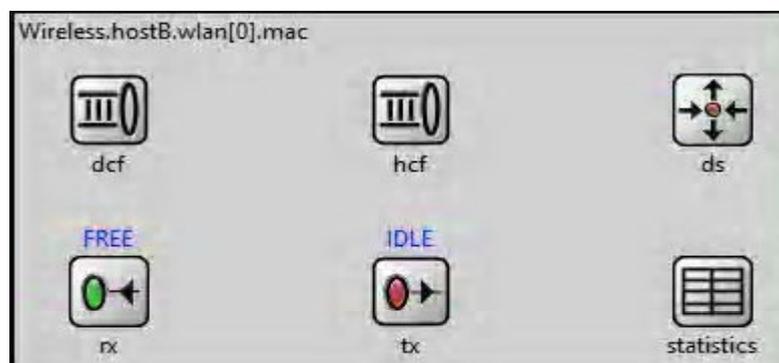
Figure 3.9: IEEE 80211 MAC Module in INET

3.1.5. Configuration File

The simple modules, compound modules, and application itself can have different parameters and settings. These settings are composed of key-value pairs and must be saved to a configuration file with the .ini extension, called INI files. The configuration file defines how the simulation will run. The simulation will not run without this file. Figure 3.10 shows a piece of the whole configuration file used in this study.

```
[General]
network = Wireless
sim-time-limit = 10s
# Arp
*.host*.ipv4.arp.typename = "GlobalArp"
# Mac
*.host*.wlan[0].opMode = "g(erp)"
*.host*.wlan[0].mac.dcf.originatorMacDataService.fragmentationPolicy.fragmentationThreshold = 2304B + 28B
# Configure path loss model
*.radioMedium.pathLoss.typename = "TwoRayGroundReflection"
*.physicalEnvironment.ground.typename = "FlatGround"
# Radio
*.host*.wlan[0].radio.transmitter.power = 10mW
# Transmission Medium
*.radioMedium.backgroundNoise.power = -86dBm
*.radioMedium.mediumLimitCache.carrierFrequency = 2.4GHz
# mobility
*.host*.mobility.typename = "StationaryMobility"
*.host*.mobility.initFromDisplayString = false
*.hostA.mobility.initialX = 0m
*.hostB.mobility.initialX = 0m
*.host*.mobility.initialY = 325m
*.host*.mobility.initialZ = 1.5m
**.constraintAreaMinX = 0m
**.constraintAreaMinY = 0m
**.constraintAreaMinZ = 0m
**.constraintAreaMaxX = 1000m
**.constraintAreaMaxY = 1000m
**.constraintAreaMaxZ = 1.5m
# for Aodv routing, disable static routing
*.configurator.addStaticRoutes = false
```

Figure 3.10: The configuration file

4. CHAPTER

EXPERIMENTAL STUDIES

In Chapter 2.8, we have calculated the theoretical throughput based on the standard defined by IEEE 802.11 in wireless networks. In this chapter, we will measure practical throughput using Omnet ++ and INET IDEs. Also, we will examine how signal-to-noise ratio, packet error-rate, effective data transfer rate values of a wireless transmission vary according to various data-link layer parameters like transmission power, distance, bit rate, maximum transfer unit (MTU) size.

4.1. Analyzing Simulation Environment

The measurement results were obtained by using the Omnet++ 5.5.1 and the INET 4.2.0 platforms. The network contains two wireless hosts in the simulation environment where they can communicate with each other directly, so there is no centralized access point (Ad hoc mode). Host A acts as a traffic source; on the other hand, host B acts as a traffic sink. In this study, we perform measurements by changing the values of the transmission power, distance, bit rate, maximum transfer unit in each simulation in an IEEE 802.11g wireless network. The common parameter values for each experiment are given in Table 4.1.

The Omnet++ allows us the opportunity to simulate the experiment for the desired duration and helps us to analyze results. It has a powerful result analysis tool. It can visualize the results in scalar, vector and histogram format. The diagrams in this thesis

study have been created with the result analysis tool of the Omnet++ IDE, and ten seconds was chosen as the simulation time.

Table 4.1: The common simulation parameters for each experiment in this study

Operation Mode	IEEE 802.11g (erp) Ad Hoc mode
Background Noise	-86 dBm
Path Loss Model	Two Ray Ground Reflection
Carrier Frequency	2.4 GHz
Antenna Heights	1.5 m
Antenna Gains	0 dBm

4.2. Measurements Using Various Distance and Data Transfer Rate Values

In this experiment, the distance and data transfer rate variables take the values, respectively, which are given in Table 4.2. The data transfer rate parameter has 8 and the distance parameter has 30 different values. Since these parameters have different values in each time, there are 240 different simulation runs.

Table 4.2: The parameters used in distance and data transfer rate experiment

Data Send Interval	1s
Message Length	56 Byte (At Application Layer)
Transmitter Power	10mW (-20 dBm)
Data Transfer Rate	6,9,12,18,24,36,48,54 Mbps
Distance Between Hosts	10,20,30….280,290,300 m (Each distance value in the range takes all of the data transfer rate values above.)
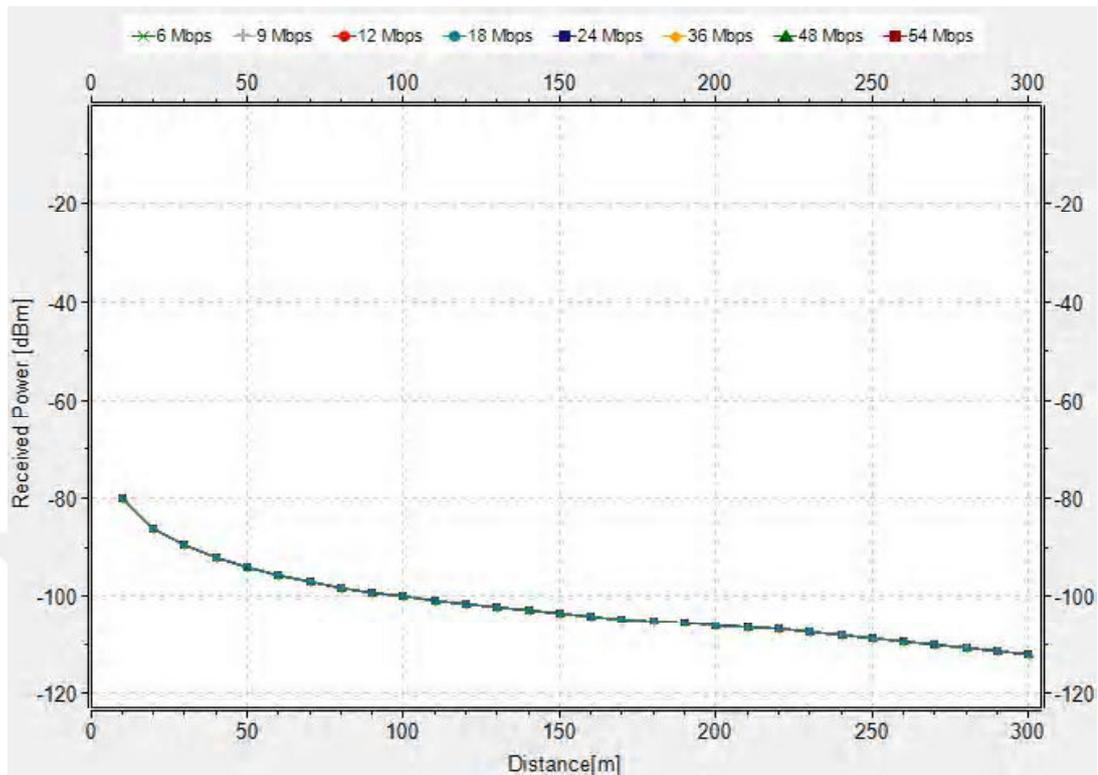
Figure 4.1: Received signal power against distance at different data transfer rates

The receiver host records some data about the transmission. One of them is the received signal power. The received signal power against distance is given in Figure 4.1 for different transfer rates. In the beginning, when the distance is 10 m, the received signal is about -80 dBm. When the distance value reaches to 100 m, the received signal falls to about -100 dBm. At the final distance value, which is 300 m, the received signal is measured by about -112 dBm. We can conclude that the distance and received signal power are inversely proportional to each other in exponentially.

The other saved record is the signal-to-noise ratio (SNR), which can provide information about the quality of transmission. The SNR is related to received signal power and noise power. Figure 4.2 shows the relationship between SNR and distance, depending on the different data transfer rates. Since the SNR is directly proportional to the received signal power, the SNR exponentially decreases with the increase of distance, as it is shown in Figure 4.2. In detail, we see that the SNR decreases in a sharp way. There is a drop after a certain distance for each data transfer rate, but it is gradually. The SNR curves are the same for all data transfer rates. We can conclude that modulation techniques have no major effects on the SNR.
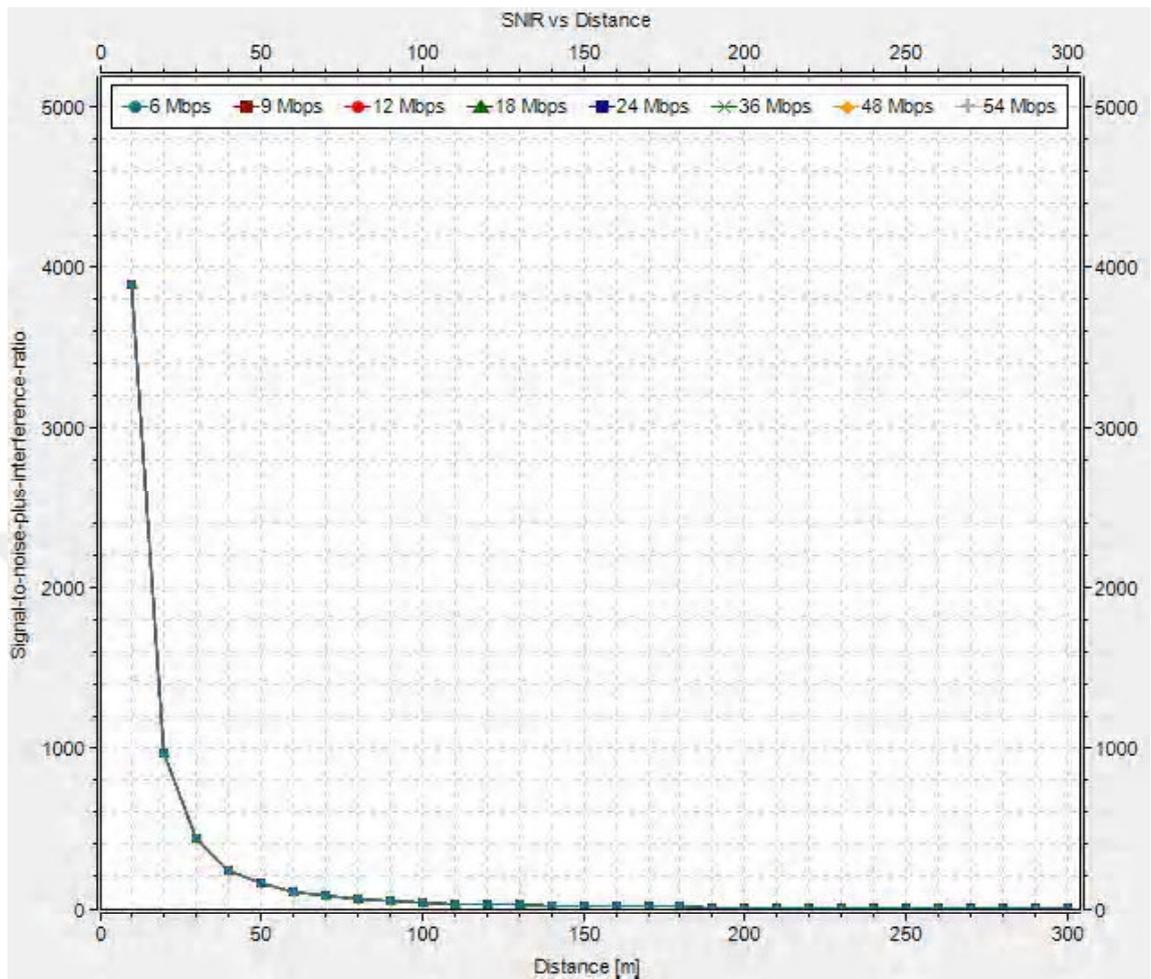
Figure 4.2: SNR against distance at different data transfer rates

Figure 4.3 plots the packet error-rate (PER) against distance, depending on the different data transfer rates. We observe that the packet error-rate increases with the increase of distance for each data transfer rate. The recovery of corrupted data bits is successful within a certain distance range for each data transfer rate, so PER increases very slowly, even we can say it does not change. However, when the distance value comes out of that range, the increase in PER is accelerating because of the modulation techniques are weakened in the recovery of corrupted data bits. The modulation techniques and coding rates used in IEEE 802.11g modes are given in Table 4.3.

Slower data transfer rates utilize simple modulation techniques like BPSK; on the other hand, faster data transfer rates utilize more complex modulation techniques. As a result, PER starts to increase at long distances for slower data rates; on the other side, it starts to increase at short distances for higher data transfer rates

Table 4.3: The different transmission modes with multiple data rates [55]

Mode	Data Rate (Mbps)	Modulation Technique	Coding Rates (R)
1	6	BPSK	1/2
2	9	BPSK	3/4
3	12	QPSK	1/2
4	18	QPSK	3/4
5	24	16-QAM	1/2
6	36	16-QAM	3/4
7	48	64-QAM	2/3
8	54	64-QAM	3/4
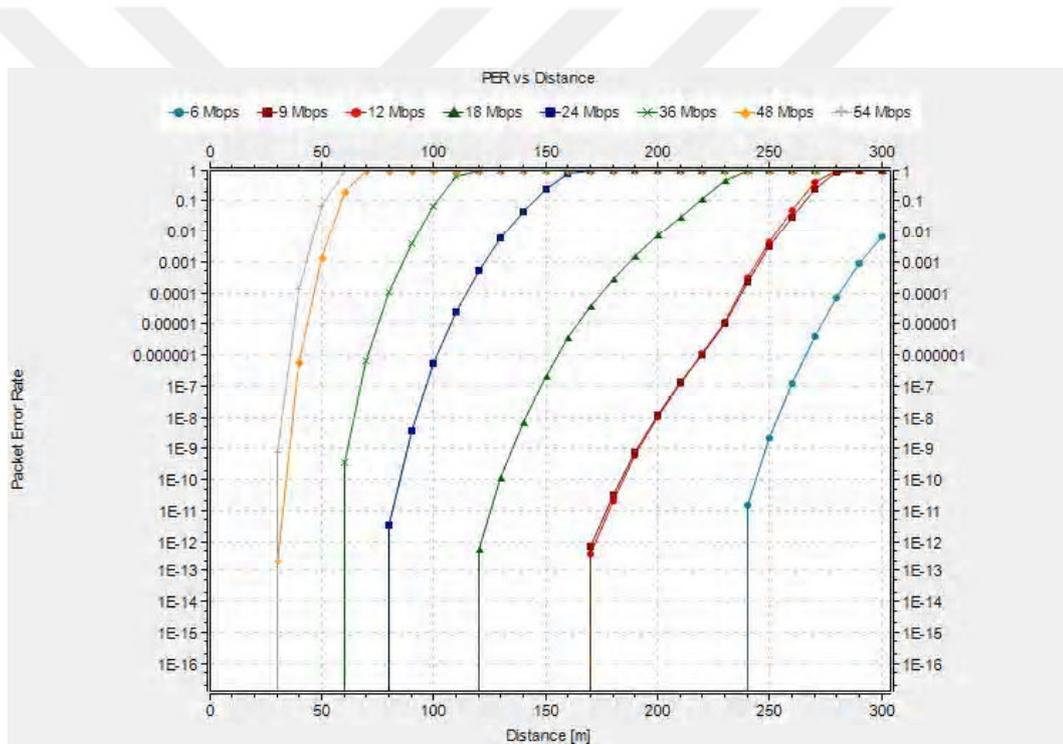
Figure 4.3: PER against distance at different data transfer rates

The next graph is about the relationship between PER and SNR. If the PER value rises, the transmission quality deteriorates. Inversely, If the SNR rises, the transmission quality improves. Based on the idea, as can be seen in Figure 4.4, The SNR and PER are inversely related to each other. For 6 Mbps (light green), the packet error-rate is nearly 0,0068 when the SNR value is about 2.49, and it is decreasing rapidly with the increase of SNR until the SNR reaches nearly 6.08. At that point, PER is 1.51×10^{-11}. After that point, PER is decreasing with very slow acceleration.

All measurement values about SNR and PER obtained in this experiment are given in Appendix [1-8].
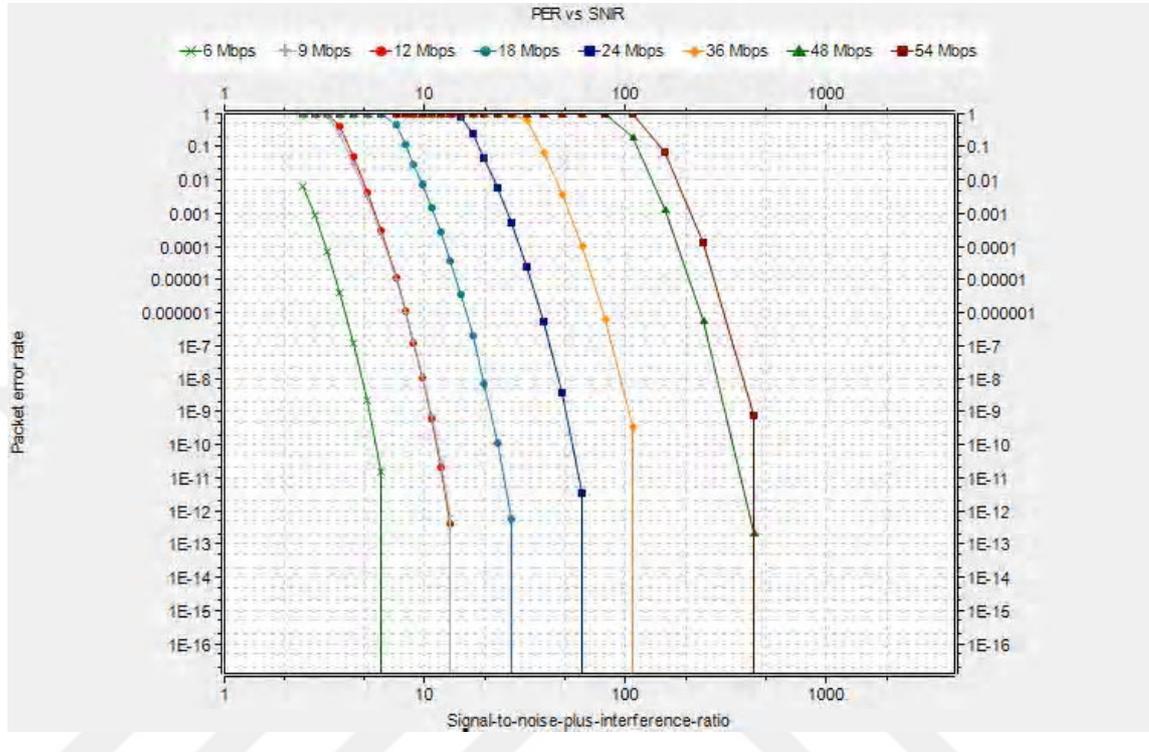
Figure 4.4: PER against SNR at different data transfer rates

The effective data transfer rate on the receiver host is equal to the nominal data transfer rate if there is no packet error-rate on the transmission. Otherwise, the effective data transfer rate is falling depend on the packet error-rate. We can formulate this as in Equation 4.1.

$$Effective\ Data\ Transfer\ Rate = (1 - PER) * Data\ Transfer\ Rate \qquad 4.1$$

The effective data transfer rate against distance is plotted in Figure 4.5. Here we can observe again; higher data transfer rates are more sensitive to distance. As we mentioned before, the packet error-rate increases as the distance increases. If we look at the 54 Mbps, it can maintain the data transfer rate up to only 40 meters. After that distance, critical falls are occurring in the data transfer rate. When the distance is kept at 50 m, it is falling from 54 Mbps to 50 Mbps. The significant decrease can be observed at a distance of 60 m. When the distance is at 60 m, data transfer rate is observed about 0.045 Mbps, and it is almost unusable.

If we look at the smallest data transfer rate used in this study, which is 6 Mbps, we can see that it can maintain its data transfer rate at almost the end of the simulation. When we use 6 Mbps as the data transfer rate, it is nearly 5.95 when the distance is 310 m between the transmitter and the receiver.
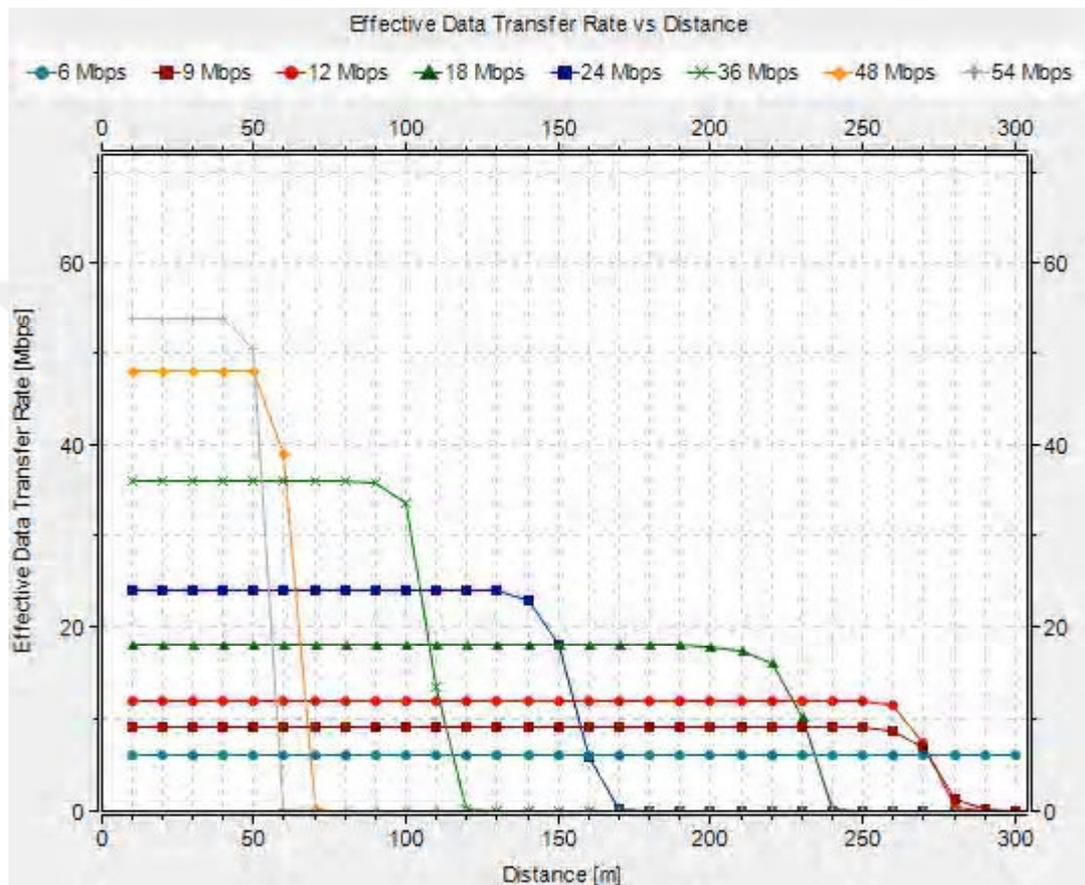
Figure 4.5: Effective data transfer rate against distance at different data transfer rates

Figure 4.6 tells us the relationship between throughput and distance at different data transfer rates. The throughput of the fastest data transfer rate, which is 54 Mbps, exponentially decreases over 50 m. When the distance is 60 m, the throughput falls to zero, and the transmission between the hosts becomes impossible. Table 4.4 gives the crucial measurement values, and at what distance the throughput of a data transfer rate drops to zero.

Table 4.4: Throughput and distance measurement values for each data transfer rate

Distance / Bit Rate	6 Mbps	9 and 12 Mbps	18 Mbps	24 Mbps	36 Mbps	48 Mbps	54 Mbps
10 m	0.00039	0.00039	0.00039	0.00039	0.00039	0.00039	0.00039
60 m	0.00039	0.00039	0.00039	0.00039	0.00039	0.00039	0
70 m	0.00039	0.00039	0.00039	0.00039	0.00039	0	0
120 m	0.00039	0.00039	0.00039	0.00039	0	0	0
170 m	0.00039	0.00039	0.00039	0	0	0	0
240 m	0.00039	0.00039	0	0	0	0	0
280 m	0.00039	0	0	0	0	0	0
300 m	0	0	0	0	0	0	0
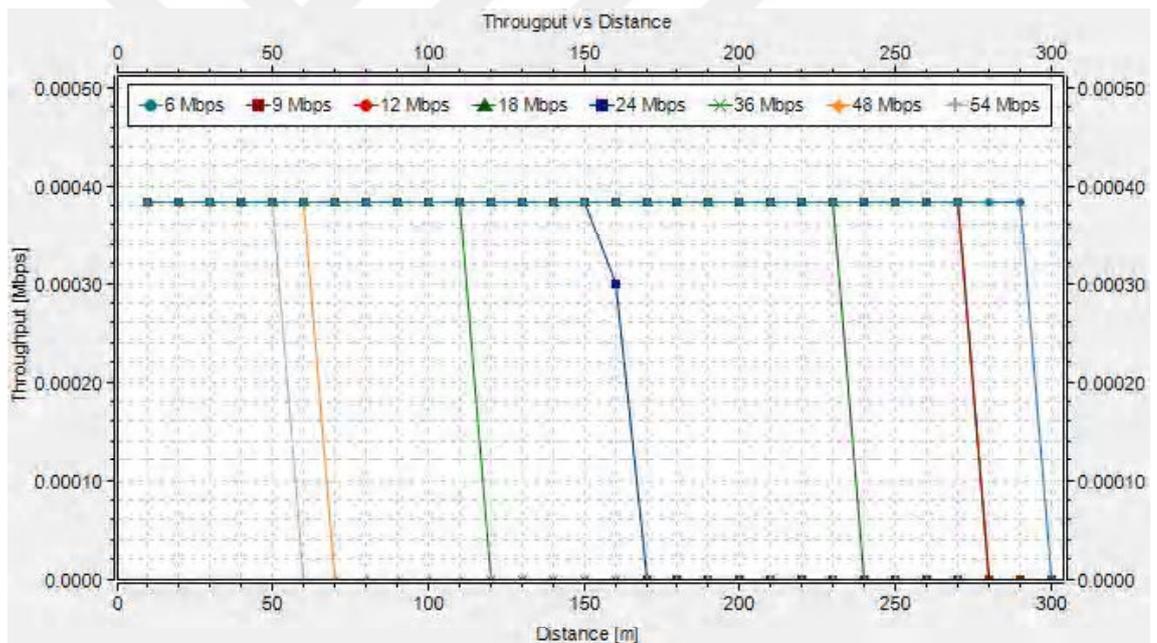
Figure 4.6: Throughput against distance at different data transfer rates

4.3. Measurements Using Various Transmitter Power and Distance Values

In this experiment, the transmitter power and distance variables take the values, respectively, which are given in Table 4.5. The transmitter power parameter has 20 and the distance parameter has 6 different values. Since the parameters have different values in each time, there are 120 different simulation runs. Figure 4.7 shows the relationship

between the transmitter and receiver power. The transmitter signal propagates on the air through to the receiver host and loses its power.

The power strength of a signal decreases as distance increases. Even as we mentioned in Equation 2.8, the received signal strength is inversely proportional to the fourth force of distance in the two-ray ground reflection model.

Table 4.5: The parameters used in transmitter power and distance experiment

Data Send Interval	1s
Message Length	56 Byte (At Application Layer)
Data Transfer Rate	6 Mbps
Transmitter Power	0.5, 1.0, 2.5,….,8.5, 9.5, 10.0 mW
Distance Between Hosts	50,100,150,200,250,300 m (Each distance value in the range takes all of the transmitter power values above.)
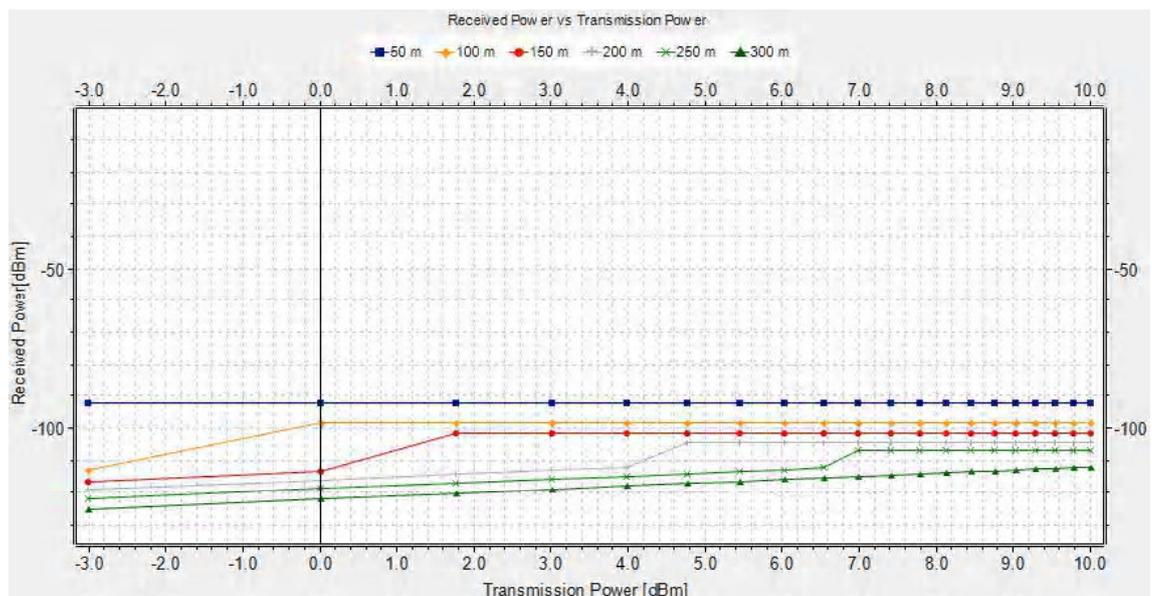
Figure 4.7: Received power against transmission power at different distances

Let us analyze Figure 4.7; if the transmitted signal power is about -3 dBm (0.5 mW), the received signal is about -100 dBm (3.92×10^{-10} mW) at a distance of 50 m. If we increase the distance to 300 m, the received signal power is approximately -125 dBm.

At this time, if we set the transmitted signal power to 10 dBm (10 mW), the received signal is approximately -94 dBm (3.92×10^{-10} mW) at a distance of 50 m. If we increase the distance to 300 m, the received signal power is approximately -112 dBm.

The received signal power values are the same for all transmitted signal power values for the distance of 50 m. For the other distance values, the received signal power values are too small ($\leq$ -113 dBm) at the beginning of the chart. The small increases occur in the received signal power with the increase of the transmission power. We cannot observe big differences in the received power value because the units are in dBm. All measurement values about the received power obtained in this experiment are given in Appendix [9-12].
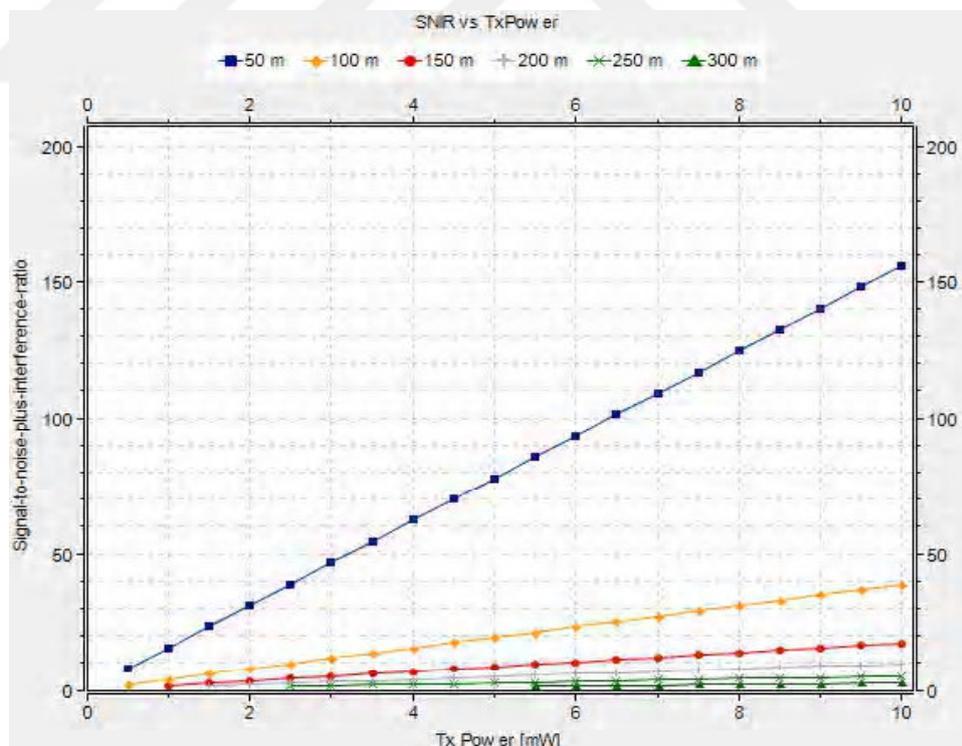
Figure 4.8: SNR against transmission power at different distances

We know that the received signal strength will increase as the distance decreases. As the received signal strength increases, the SNR value will increase as much. Figure 4.8 shows

the relationship between SNR and the transmitted power, depending on the distance values. The SNR exponentially increases with the increase of transmitted signal power at a distance of 50 m. For other distances, the SNR is increasing slowly. Table 4.6 indicates the threshold values for a significant change of transmission power at different distances. If the transmission power for the respective distance is less than the given value in the table, there will be very low SNR. All measurement values related to SNR obtained in this experiment are given in Appendix [13-16].

Table 4.6: Transmit power and distance values where the signal-to-noise ratio starts in a significant way

Distance (m)	Transmission Power (mW)
150	1
200	1.5
250	2.5
300	5.5
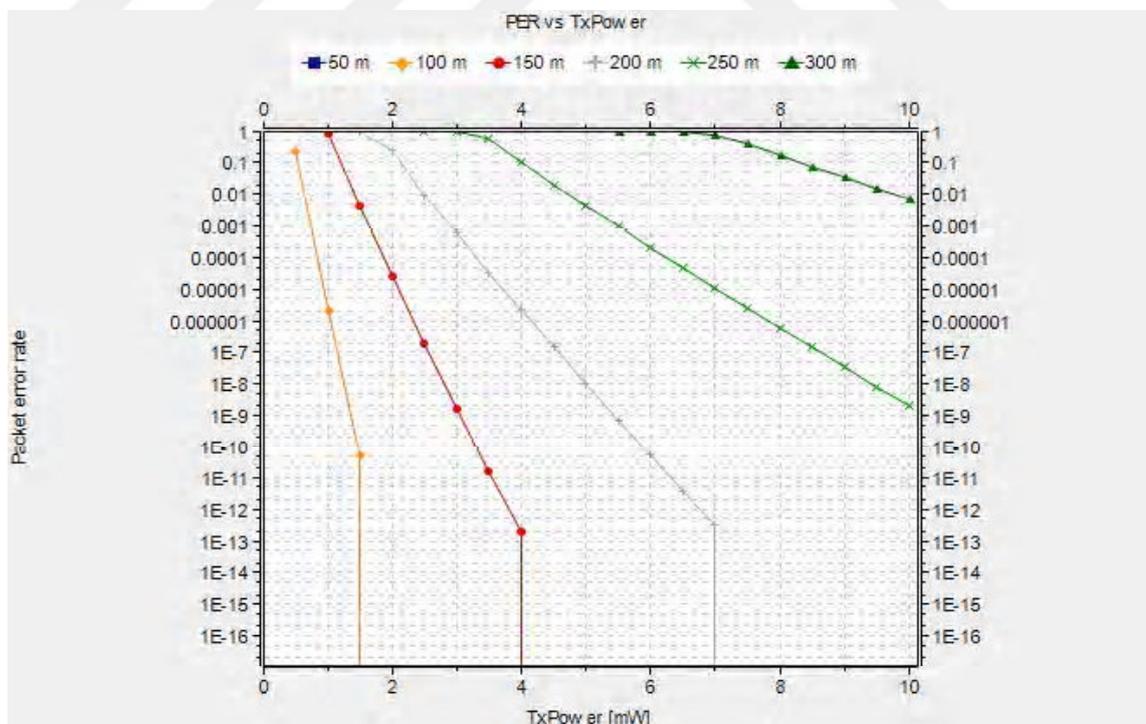
Figure 4.9: PER against transmission power at different distances

Figure 4.9 shows the relationship between PER and the transmitted power, depending on the distance values. We can observe from the figure that the PER decreases as the transmitted power increases. There is no detected PER for a distance of 50 meters. For the other distances, the obtained measurement values are given by grouping in Table 4.7. All measurement values related to PER obtained in this experiment are given in Appendix [17-20].

Table 4.7: Summary of the relationship between PER and transmission power at different distances with the data transfer rate of 6 Mbps.

Distance (m)	PER	Transmission Power (mW)
100 m	Exponentially decrease	$[0.5 - 1.5]$ mW
	Gradually Decrease	> 1.5 mW
150m	$\cong 1.00$	< 1 mW
	Exponentially decrease	$[1 - 4]$ mW
	Gradually Decrease	> 4 mW
200 m	$\cong 1.00$	< 1.5 mW
	Exponentially decrease	$[1.5 - 7]$ mW
	Gradually Decrease	> 7 mW
250 m	$\cong 1.00$	< 3 mW
	Exponentially decrease	$[3 - 10]$ mW
300 m	$\cong 1.00$	< 7 mW
	Exponentially decrease	$[7 - 10]$ mW

The relationship between throughput and transmission power is plotted in Figure 4.10. The throughput is the same for all different transmission power values at a distance of 50 m. There is no throughput for all values of the transmission power at 300 m because of transmitter power is not enough to be sensed at the receiver. For other distances, the throughput is increasing exponentially with the small increase of the transmission power up to a point. This point corresponds to a different transmission power value for each distance.

The obtained measurement values are given by grouping in Table 4.8. All measurement values related to throughput obtained in this experiment are given in Appendix [21-24].

Table 4.8: Summary of the relationship between throughput and transmission power at different distances with the data transfer rate of 6 Mbps.

Distance (m)	Throughput	Transmission Power (mW)
50m	3.85×10^{-4}	$[0.5 - 10]$ mW
100m	Exponentially increase	$[0.5 - 1]$ mW
	3.85×10^{-4}	> 1 mW
150 m	Exponentially increase	$[1.0 - 1.5]$ mW
	3.85×10^{-4}	> 1.5 mW
200 m	Exponentially increase	$[2.5 - 3]$ mW
	3.85×10^{-4}	> 3 mW
250 m	Exponentially increase	$[4.5 - 5]$ mW
	3.85×10^{-4}	> 5 mW
300 m	$\cong 0.00$	$[0.5-10]$ mW
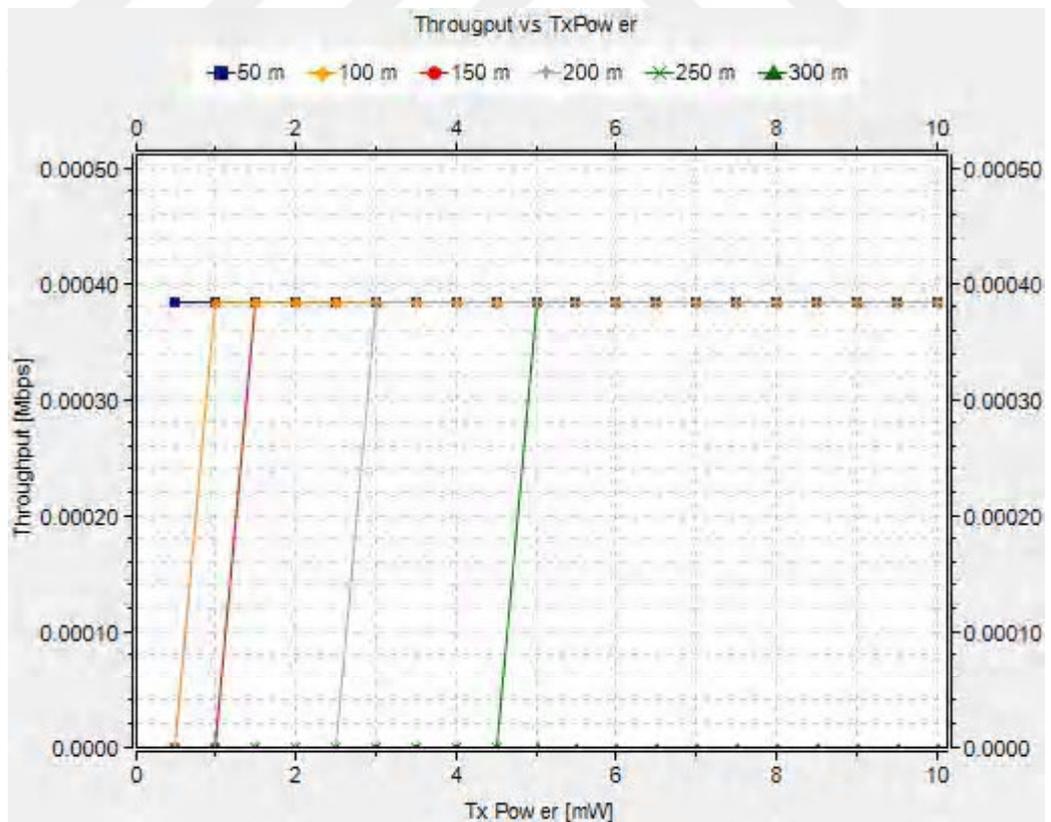
Figure 4.10: Throughput against transmission power at different distances

4.4. Measurements Using Various MTU and Data Payload Size

As the name suggests, the maximum transfer unit (MTU) stands for the largest protocol data unit length that can be carried in a single transmission. It works by dividing the bigger data from MTU value into a series of shorter pieces of data, thereby enhancing the chances of successful data transmission. A larger data frame has a higher probability of corruption than a smaller one. The error correction mechanism can correct some incorrect bits in a received frame, but as the bit error-rate increases, the probability of correcting bit errors is less likely.

Table 4.9: The parameters used in MTU and data payload size experiment

Data Send Interval	0.5 ms
Distance	100 m
Data Transfer Rate	6 Mbps
Transmission Power	5 mW
MTU	250, 500, 750,…,1500, 1750, 2000 Byte
Data Payload Length	10000, 15000, 20000 Byte (Each length value in the range takes all of the MTU values above.)

The downside of switching small MTU values can increase overhead, and thus causes lower throughput and medium utilization. Since more packets each containing a TCP and IP header will be sent and, it will bring an additional load to the network. Also, each frame transmission can be followed by a contention period and an ACK frame. Even, it increases delay, because the full package reaches the destination only when all its parts are received.

In this experiment, MTU and data payload size variables take the values, respectively, which are given in Table 4.9. The MTU parameter has 8 and the data payload length parameter has 3 different values. Since the parameters have different values in each time, there are 24 different simulation runs. The data payload length and MTU parameter values

had been chosen appropriate values for dividing large frames to a number of shorter frames. Additionally, according to IEEE Standards [3], the maximum MSDU size is 2304 before encryption. WEP will add 8 bytes, WPA-TKIP 20 bytes, and WPA2-CCMP 16 bytes.
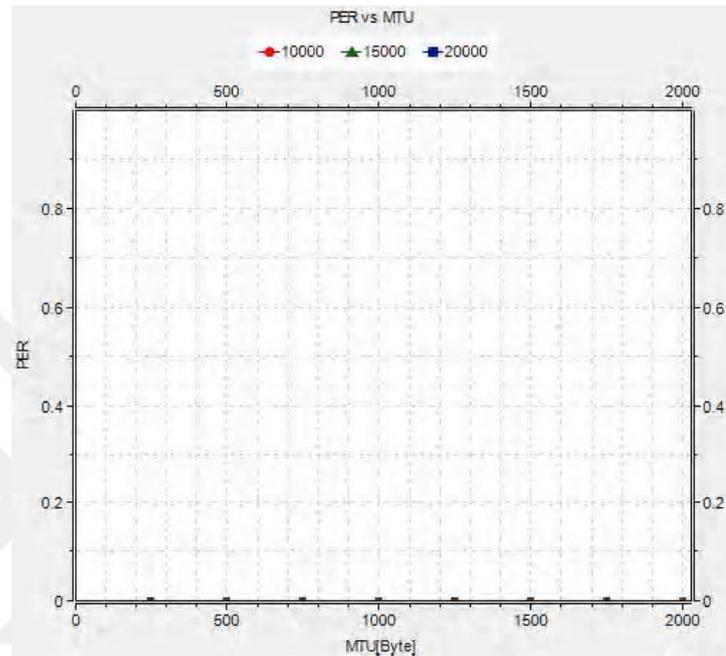
Figure 4.11: PER against MTU for different data payload size
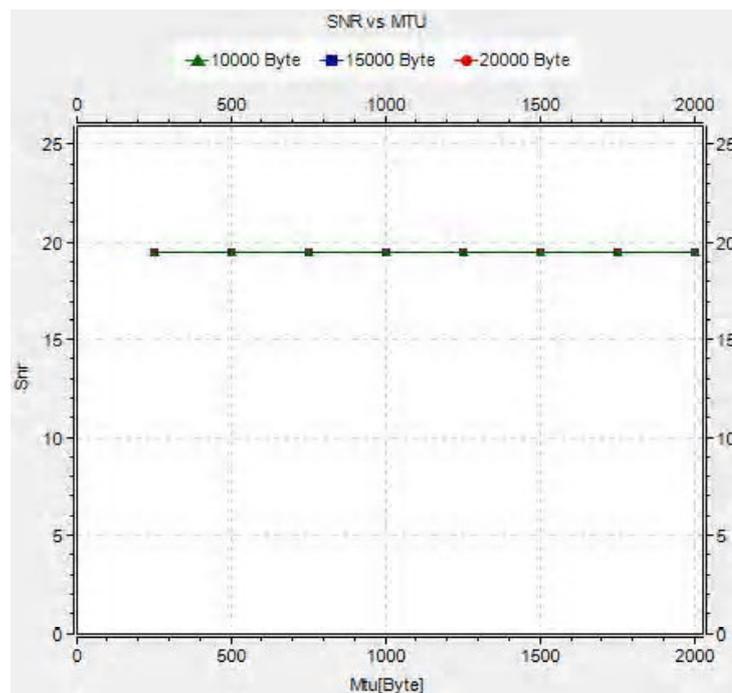
Figure 4.12: SNR against MTU for different data payload size

In this experiment, the transmitter and receiver host are 100 meters apart. The transmission power has strong enough to carry the frames to the receiver. Thereby, PER will not be observed in this experiment since the noise is low in the environment, as it is shown in Figure 4.11.

Since the received signal power (nearly -103 dBm) and the noise in the environment is the same for all combinations of MTU and data payload size, SNR is expected to be the same for all data payload sizes at different MTU sizes. Figure 4.12 indicates that the relationship between SNR and MTU for all data payload size. The SNR value is about 19 for all data payload sizes.

In all the curves in Figure 4.13, we observe that throughput increases exponentially as MTU increases in all cases except one. In transmission with the data payload size of 10000 bytes, it is seen that the throughput is the same for MTU sizes of 1750 and 2000 bytes. The throughput results obtained in this experiment are given in Appendix 25.
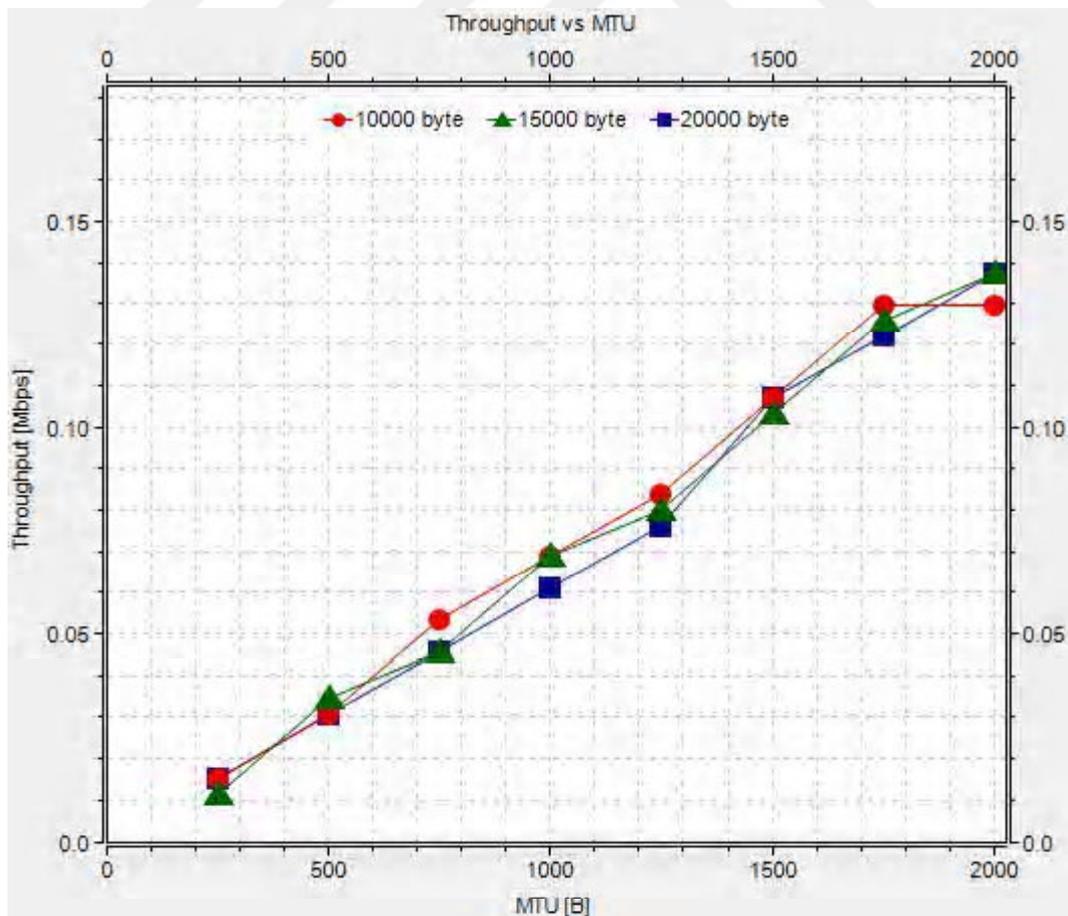
Figure 4.13: Throughput against MTU for different data payload size

5. CHAPTER

CONCLUSIONS

5.1. Conclusions, Suggestions and Future Work

This thesis aims to investigate how throughput, signal-to-noise ratio, packet error-rate values of a wireless communication vary according to various data-link layer parameters such as transmission power, distance, bit rate, and maximum transfer unit size. And, it intends to find out values or value ranges of these parameters in which IEEE 802.11g wireless standard works most efficiently.

The measurement results were obtained by using the Omnet++ 5.5.1 and the INET 4.2.0 platforms. The network contains two wireless hosts in the simulation environment where they can communicate with each other directly, so there is no centralized access point (Ad hoc mode). Transmitter host acts as a traffic source; on the other hand, receiver host acts as a traffic sink. The following assumptions were foreseen during the experiments.

- The IEEE 802.11g standard was the operation mode.

- The carrier frequency was 2.4 GHz.

- The background noise was -86 dBm

- The MAC layer did not use fragmentation.

- DCF was the primary access method.

- The Two Ray Ground Reflection was the path loss model.

- The receiver and transmitter antenna heights are 1.5 m.

- There is no antenna gain.

The experiments are divided into three main groups. We performed measurements

- by changing the values of distance and bit rate (in the section I),

- by changing the values of transmission power and distance (in the section II),

- by changing the values of the maximum transfer unit and data payload size (in the section III).

It has been concluded that the packet error-rate increases with the increase of distance for each data transfer rate. The recovery of corrupted data bits is successful within a certain distance range for each data transfer rate, so PER increases very slowly, even we can say it does not change. However, when the distance value comes out of that range, the increase in PER is accelerating because of the modulation techniques are weakened in the recovery of corrupted data bits. Furthermore, slower data transfer rates utilize simple modulation techniques like BPSK; on the other hand, faster data transfer rates utilize more complex modulation techniques. As a result, PER starts to increase at long distances for slower data rates; on the other side, it starts to increase at short distances for higher data transfer rates. When we compare the slow and fast data transfer rates, it has been noticed that while slower data transfer rates need lower transmission power, on the other hand, faster data transfer rates need higher transmission power to carry the same amount of data to the same distance. For example, when the distance is 50 m between the transmitter and receiver, the transmission power must be at least 0.2 mW for the data transfer rate of 6 Mbps. On the other hand, for the same distance, the transmission power must be at least 9.7 mW for the data transfer rate of 54 Mbps. In Table 5.1 and Table 5.2, the distance and minimum transmission power values or (ranges) are given for each data transfer rate in which the wireless communication operates at least 90% success. (See Appendix 26)

Table 5.1: The distance and minimum transmission power values or (ranges) for each data transfer rate in which the wireless communication operates at least 90% success.

Data Transfer Rate	Distance	Min Transmission Power
54 Mbps	10 m	≥ 0.4 mW
	20 m	≥ 1.6 mW
	30 m	≥ 3.5 mW
	40 m	≥ 6.2 mW
	50 m(Max)	≥ 9.7 mW
48 Mbps	10 m	≥ 0.3 mW
	20 m	≥ 1.2 mW
	30 m	≥ 2.7 mW
	40 m	≥ 4.7 mW
	50 m	≥ 7.3 mW
	60 m(Max)	≥ 10.6 mW
36 Mbps	30 m	≥ 0.9 mW
	50 m	≥ 2.5 mW
	70 m	≥ 4.8 mW
	90 m	≥ 7.9 mW
	100 m	≥ 9.8 mW
	110 m(Max)	≥ 12.0 mW
24 Mbps	30 m	≥ 0.5 mW
	50 m	≥ 1.2 mW
	70 m	≥ 2.4 mW
	100 m	≥ 4.8 mW
	120 m	≥ 6.9 mW
	150 m(Max)	≥ 10.8 mW
18 Mbps	50 m	≥ 0.6 mW
	100 m	≥ 2.1 mW
	150 m	≥ 4.7 mW
	200 m	≥ 6.0 mW
	200 m	≥ 8.4 mW
	230 m (Max)	≥ 11.3 mW
12 Mbps	50 m	≥ 0.3 mW
	100 m	≥ 1.1 mW
	150 m	≥ 2.5 mW
	200 m	≥ 4.4 mW
	250 m	≥ 8.2 mW
	270 m (Max)	≥ 11.1 mW
9 Mbps	50 m	≥ 0.3 mW
	100 m	≥ 1.1 mW
	150 m	≥ 2.4 mW
	200 m	≥ 4.2 mW
	250 m	≥ 7.9 mW
	270 m (Max)	≥ 10.7 mW

Table 5.2: The distance and minimum transmission power values or (ranges) for each data transfer rate in which the wireless communication operates at least 90% success. (Continued)

Data Transfer Rate	Distance	Min Transmission Power
6 Mbps	50 m	≥ 0.2 mW
	100 m	≥ 0.6 mW
	150 m	≥ 1.2 mW
	200 m	≥ 2.2 mW
	250 m	≥ 4.1 mW
	300 m	≥ 8.4 mW
	320 m(Max)	≥ 10.8 mW

As a result of the experiments, it has been noticed that higher MTU values enable the IEEE 802.11g to run faster. It works by dividing the bigger data from MTU value into a series of shorter pieces of data, thereby enhancing the chances of successful data transmission. A larger data frame has a higher probability of corruption than a smaller one. The error correction mechanism can correct some incorrect bits in a received frame, but as the bit error-rate increases, the probability of correcting bit errors is less likely.

On the other hand, it has been noticed that it has some downsides. The wrong or small MTU values can increase overhead, and thus causes lower throughput and medium utilization. Since more packets each containing a TCP/UDP and IP header will be sent and, it will bring an additional load to the network. Also, each frame transmission can be followed by a contention period and an ACK frame. Even, it increases delay, because the full package reaches the destination only when all its parts are received.

As a future study, it has been planned to obtain more intensive data with a more powerful machine to improve IEEE 802.11 performance by using machine learning and artificial intelligence methods.

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APPENDIX

APPENDIX 1: For 6 Mbps, SNR and PER values at different distances

Data Transfer Rate	Distance	SNR	PER
6	10	$\cong 3.90 \times 10^3$	$\cong 0$
6	20	$\cong 9.74 \times 10^2$	$\cong 0$
6	30	$\cong 4.33 \times 10^2$	$\cong 0$
6	40	$\cong 2.44 \times 10^2$	$\cong 0$
6	50	$\cong 1.56 \times 10^2$	$\cong 0$
6	60	$\cong 1.09 \times 10^2$	$\cong 0$
6	70	$\cong 7.95 \times 10^1$	$\cong 0$
6	80	$\cong 6.09 \times 10^1$	$\cong 0$
6	90	$\cong 4.81 \times 10^1$	$\cong 0$
6	100	$\cong 3.90 \times 10^1$	$\cong 0$
6	110	$\cong 3.22 \times 10^1$	$\cong 0$
6	120	$\cong 2.71 \times 10^1$	$\cong 0$
6	130	$\cong 2.31 \times 10^1$	$\cong 0$
6	140	$\cong 1.99 \times 10^1$	$\cong 0$
6	150	$\cong 1.74 \times 10^1$	$\cong 0$
6	160	$\cong 1.53 \times 10^1$	$\cong 0$
6	170	$\cong 1.35 \times 10^1$	$\cong 0$
6	180	$\cong 1.21 \times 10^1$	$\cong 0$
6	190	$\cong 1.08 \times 10^1$	$\cong 0$
6	200	$\cong 9.74 \times 10^0$	$\cong 0$
6	210	$\cong 8.84 \times 10^0$	$\cong 0$
6	220	$\cong 8.05 \times 10^0$	$\cong 0$
6	230	$\cong 7.21 \times 10^0$	$\cong 0$
6	240	$\cong 6.08 \times 10^0$	1.51×10^{-11}
6	250	$\cong 5.16 \times 10^0$	2.10×10^{-9}
6	260	$\cong 4.42 \times 10^0$	1.26×10^{-7}
6	270	$\cong 3.80 \times 10^0$	3.92×10^{-6}
6	280	$\cong 3.28 \times 10^0$	7.24×10^{-5}
6	290	$\cong 2.85 \times 10^0$	8.89×10^{-4}
6	300	$\cong 2.49 \times 10^0$	6.76×10^{-3}

APPENDIX 2: For 9 Mbps, SNR and PER values at different distances

Data Transfer Rate	Distance	SNR	PER
9	10	$\cong 3.90 \times 10^3$	$\cong 0$
9	20	$\cong 9.74 \times 10^2$	$\cong 0$
9	30	$\cong 4.33 \times 10^2$	$\cong 0$
9	40	$\cong 2.44 \times 10^2$	$\cong 0$
9	50	$\cong 1.56 \times 10^2$	$\cong 0$
9	60	$\cong 1.09 \times 10^2$	$\cong 0$
9	70	$\cong 7.95 \times 10^1$	$\cong 0$
9	80	$\cong 6.09 \times 10^1$	$\cong 0$
9	90	$\cong 4.81 \times 10^1$	$\cong 0$
9	100	$\cong 3.90 \times 10^1$	$\cong 0$
9	110	$\cong 3.22 \times 10^1$	$\cong 0$
9	120	$\cong 2.71 \times 10^1$	$\cong 0$
9	130	$\cong 2.31 \times 10^1$	$\cong 0$
9	140	$\cong 1.99 \times 10^1$	$\cong 0$
9	150	$\cong 1.74 \times 10^1$	$\cong 0$
9	160	$\cong 1.53 \times 10^1$	$\cong 0$
9	170	$\cong 1.35 \times 10^1$	6.94×10^{-13}
9	180	$\cong 1.21 \times 10^1$	3.07×10^{-11}
9	190	$\cong 1.08 \times 10^1$	7.63×10^{-10}
9	200	$\cong 9.74 \times 10^0$	1.20×10^{-8}
9	210	$\cong 8.84 \times 10^0$	1.31×10^{-7}
9	220	$\cong 8.05 \times 10^0$	1.06×10^{-6}
9	230	$\cong 7.21 \times 10^0$	1.02×10^{-5}
9	240	$\cong 6.08 \times 10^0$	2.26×10^{-4}
9	250	$\cong 5.16 \times 10^0$	$\cong 3.04 \times 10^{-3}$
9	260	$\cong 4.42 \times 10^0$	$\cong 3.04 \times 10^{-2}$
9	270	$\cong 3.80 \times 10^0$	$\cong 2.34 \times 10^{-1}$
9	280	$\cong 3.28 \times 10^0$	$\cong 8.56 \times 10^{-1}$
9	290	$\cong 2.85 \times 10^0$	$\cong 9.99 \times 10^{-1}$
9	300	$\cong 2.49 \times 10^0$	$\cong 1$

APPENDIX 3: For 12 Mbps, SNR and PER values at different distances

Data Transfer Rate	Distance	SNR	PER
12	10	$\cong 3.90 \times 10^3$	$\cong 0$
12	20	$\cong 9.74 \times 10^2$	$\cong 0$
12	30	$\cong 4.33 \times 10^2$	$\cong 0$
12	40	$\cong 2.44 \times 10^2$	$\cong 0$
12	50	$\cong 1.56 \times 10^2$	$\cong 0$
12	60	$\cong 1.09 \times 10^2$	$\cong 0$
12	70	$\cong 7.95 \times 10^1$	$\cong 0$
12	80	$\cong 6.09 \times 10^1$	$\cong 0$
12	90	$\cong 4.81 \times 10^1$	$\cong 0$
12	100	$\cong 3.90 \times 10^1$	$\cong 0$
12	110	$\cong 3.22 \times 10^1$	$\cong 0$
12	120	$\cong 2.71 \times 10^1$	$\cong 0$
12	130	$\cong 2.31 \times 10^1$	$\cong 0$
12	140	$\cong 1.99 \times 10^1$	$\cong 0$
12	150	$\cong 1.74 \times 10^1$	$\cong 0$
12	160	$\cong 1.53 \times 10^1$	$\cong 0$
12	170	$\cong 1.35 \times 10^1$	4.03×10^{-13}
12	180	$\cong 1.21 \times 10^1$	2.12×10^{-11}
12	190	$\cong 1.08 \times 10^1$	5.87×10^{-10}
12	200	$\cong 9.74 \times 10^0$	1.02×10^{-8}
12	210	$\cong 8.84 \times 10^0$	1.22×10^{-7}
12	220	$\cong 8.05 \times 10^0$	1.08×10^{-6}
12	230	$\cong 7.21 \times 10^0$	1.15×10^{-5}
12	240	$\cong 6.08 \times 10^0$	2.93×10^{-4}
12	250	$\cong 5.16 \times 10^0$	$\cong 4.53 \times 10^{-3}$
12	260	$\cong 4.42 \times 10^0$	$\cong 4.90 \times 10^{-2}$
12	270	$\cong 3.80 \times 10^0$	$\cong 3.90 \times 10^{-1}$
12	280	$\cong 3.28 \times 10^0$	$\cong 9.80 \times 10^{-1}$
12	290	$\cong 2.85 \times 10^0$	$\cong 1$
12	300	$\cong 2.49 \times 10^0$	$\cong 1$

APPENDIX 4: For 18 Mbps, SNR and PER values at different distances

Data Transfer Rate	Distance	SNR	PER
18	10	$\cong 3.90 \times 10^3$	$\cong 0$
18	20	$\cong 9.74 \times 10^2$	$\cong 0$
18	30	$\cong 4.33 \times 10^2$	$\cong 0$
18	40	$\cong 2.44 \times 10^2$	$\cong 0$
18	50	$\cong 1.56 \times 10^2$	$\cong 0$
18	60	$\cong 1.09 \times 10^2$	$\cong 0$
18	70	$\cong 7.95 \times 10^1$	$\cong 0$
18	80	$\cong 6.09 \times 10^1$	$\cong 0$
18	90	$\cong 4.81 \times 10^1$	$\cong 0$
18	100	$\cong 3.90 \times 10^1$	$\cong 0$
18	110	$\cong 3.22 \times 10^1$	$\cong 0$
18	120	$\cong 2.71 \times 10^1$	5.97×10^{-13}
18	130	$\cong 2.31 \times 10^1$	1.13×10^{-10}
18	140	$\cong 1.99 \times 10^1$	7.16×10^{-9}
18	150	$\cong 1.74 \times 10^1$	2.10×10^{-7}
18	160	$\cong 1.53 \times 10^1$	3.44×10^{-6}
18	170	$\cong 1.35 \times 10^1$	3.62×10^{-5}
18	180	$\cong 1.21 \times 10^1$	2.71×10^{-4}
18	190	$\cong 1.08 \times 10^1$	$\cong 1.56 \times 10^{-3}$
18	200	$\cong 9.74 \times 10^0$	$\cong 7.35 \times 10^{-3}$
18	210	$\cong 8.84 \times 10^0$	$\cong 3.00 \times 10^{-2}$
18	220	$\cong 8.05 \times 10^0$	$\cong 1.09 \times 10^{-1}$
18	230	$\cong 7.21 \times 10^0$	$\cong 4.32 \times 10^{-1}$
18	240	$\cong 6.08 \times 10^0$	$\cong 9.99 \times 10^{-1}$
18	250	$\cong 5.16 \times 10^0$	$\cong 1$
18	260	$\cong 4.42 \times 10^0$	$\cong 1$
18	270	$\cong 3.80 \times 10^0$	$\cong 1$
18	280	$\cong 3.28 \times 10^0$	$\cong 1$
18	290	$\cong 2.85 \times 10^0$	$\cong 1$
18	300	$\cong 2.49 \times 10^0$	$\cong 1$

APPENDIX 5: For 24 Mbps, SNR and PER values at different distances

Data Transfer Rate	Distance	SNR	PER
24	10	$\cong 3.90 \times 10^3$	$\cong 0$
24	20	$\cong 9.74 \times 10^2$	$\cong 0$
24	30	$\cong 4.33 \times 10^2$	$\cong 0$
24	40	$\cong 2.44 \times 10^2$	$\cong 0$
24	50	$\cong 1.56 \times 10^2$	$\cong 0$
24	60	$\cong 1.09 \times 10^2$	$\cong 0$
24	70	$\cong 7.95 \times 10^1$	$\cong 0$
24	80	$\cong 6.09 \times 10^1$	3.49×10^{-12}
24	90	$\cong 4.81 \times 10^1$	3.52×10^{-9}
24	100	$\cong 3.90 \times 10^1$	5.41×10^{-7}
24	110	$\cong 3.22 \times 10^1$	2.46×10^{-5}
24	120	$\cong 2.71 \times 10^1$	4.93×10^{-4}
24	130	$\cong 2.31 \times 10^1$	$\cong 5.61 \times 10^{-3}$
24	140	$\cong 1.99 \times 10^1$	$\cong 4.33 \times 10^{-2}$
24	150	$\cong 1.74 \times 10^1$	$\cong 2.47 \times 10^{-1}$
24	160	$\cong 1.53 \times 10^1$	$\cong 7.61 \times 10^{-1}$
24	170	$\cong 1.35 \times 10^1$	$\cong 9.99 \times 10^{-1}$
24	180	$\cong 1.21 \times 10^1$	$\cong 1$
24	190	$\cong 1.08 \times 10^1$	$\cong 1$
24	200	$\cong 9.74 \times 10^0$	$\cong 1$
24	210	$\cong 8.84 \times 10^0$	$\cong 1$
24	220	$\cong 8.05 \times 10^0$	$\cong 1$
24	230	$\cong 7.21 \times 10^0$	$\cong 1$
24	240	$\cong 6.08 \times 10^0$	$\cong 1$
24	250	$\cong 5.16 \times 10^0$	$\cong 1$
24	260	$\cong 4.42 \times 10^0$	$\cong 1$
24	270	$\cong 3.80 \times 10^0$	$\cong 1$
24	280	$\cong 3.28 \times 10^0$	$\cong 1$
24	290	$\cong 2.85 \times 10^0$	$\cong 1$
24	300	$\cong 2.49 \times 10^0$	$\cong 1$

APPENDIX 6: For 36 Mbps, SNR and PER values at different distances

Data Transfer Rate	Distance	SNR	PER
36	10	$\cong 3.90 \times 10^3$	$\cong 0$
36	20	$\cong 9.74 \times 10^2$	$\cong 0$
36	30	$\cong 4.33 \times 10^2$	$\cong 0$
36	40	$\cong 2.44 \times 10^2$	$\cong 0$
36	50	$\cong 1.56 \times 10^2$	$\cong 0$
36	60	$\cong 1.09 \times 10^2$	3.47×10^{-10}
36	70	$\cong 7.95 \times 10^1$	6.71×10^{-7}
36	80	$\cong 6.09 \times 10^1$	1.05×10^{-4}
36	90	$\cong 4.81 \times 10^1$	$\cong 4.02 \times 10^{-3}$
36	100	$\cong 3.90 \times 10^1$	$\cong 6.92 \times 10^{-2}$
36	110	$\cong 3.22 \times 10^1$	$\cong 6.24 \times 10^{-1}$
36	120	$\cong 2.71 \times 10^1$	$\cong 9.99 \times 10^{-1}$
36	130	$\cong 2.31 \times 10^1$	$\cong 1$
36	140	$\cong 1.99 \times 10^1$	$\cong 1$
36	150	$\cong 1.74 \times 10^1$	$\cong 1$
36	160	$\cong 1.53 \times 10^1$	$\cong 1$
36	170	$\cong 1.35 \times 10^1$	$\cong 1$
36	180	$\cong 1.21 \times 10^1$	$\cong 1$
36	190	$\cong 1.08 \times 10^1$	$\cong 1$
36	200	$\cong 9.74 \times 10^0$	$\cong 1$
36	210	$\cong 8.84 \times 10^0$	$\cong 1$
36	220	$\cong 8.05 \times 10^0$	$\cong 1$
36	230	$\cong 7.21 \times 10^0$	$\cong 1$
36	240	$\cong 6.08 \times 10^0$	$\cong 1$
36	250	$\cong 5.16 \times 10^0$	$\cong 1$
36	260	$\cong 4.42 \times 10^0$	$\cong 1$
36	270	$\cong 3.80 \times 10^0$	$\cong 1$
36	280	$\cong 3.28 \times 10^0$	$\cong 1$
36	290	$\cong 2.85 \times 10^0$	$\cong 1$
36	300	$\cong 2.49 \times 10^0$	$\cong 1$

APPENDIX 7: For 48 Mbps, SNR and PER values at different distances

Data Transfer Rate	Distance	SNR	PER
48	10	$\cong 3.90 \times 10^3$	$\cong 0$
48	20	$\cong 9.74 \times 10^2$	$\cong 0$
48	30	$\cong 4.33 \times 10^2$	2.25×10^{-13}
48	40	$\cong 2.44 \times 10^2$	6.08×10^{-7}
48	50	$\cong 1.56 \times 10^2$	$\cong 1.36 \times 10^{-3}$
48	60	$\cong 1.09 \times 10^2$	$\cong 1.85 \times 10^{-1}$
48	70	$\cong 7.95 \times 10^1$	$\cong 9.99 \times 10^{-1}$
48	80	$\cong 6.09 \times 10^1$	$\cong 1$
48	90	$\cong 4.81 \times 10^1$	$\cong 1$
48	100	$\cong 3.90 \times 10^1$	$\cong 1$
48	110	$\cong 3.22 \times 10^1$	$\cong 1$
48	120	$\cong 2.71 \times 10^1$	$\cong 1$
48	130	$\cong 2.31 \times 10^1$	$\cong 1$
48	140	$\cong 1.99 \times 10^1$	$\cong 1$
48	150	$\cong 1.74 \times 10^1$	$\cong 1$
48	160	$\cong 1.53 \times 10^1$	$\cong 1$
48	170	$\cong 1.35 \times 10^1$	$\cong 1$
48	180	$\cong 1.21 \times 10^1$	$\cong 1$
48	190	$\cong 1.08 \times 10^1$	$\cong 1$
48	200	$\cong 9.74 \times 10^0$	$\cong 1$
48	210	$\cong 8.84 \times 10^0$	$\cong 1$
48	220	$\cong 8.05 \times 10^0$	$\cong 1$
48	230	$\cong 7.21 \times 10^0$	$\cong 1$
48	240	$\cong 6.08 \times 10^0$	$\cong 1$
48	250	$\cong 5.16 \times 10^0$	$\cong 1$
48	260	$\cong 4.42 \times 10^0$	$\cong 1$
48	270	$\cong 3.80 \times 10^0$	$\cong 1$
48	280	$\cong 3.28 \times 10^0$	$\cong 1$
48	290	$\cong 2.85 \times 10^0$	$\cong 1$
48	300	$\cong 2.49 \times 10^0$	$\cong 1$

APPENDIX 8: For 54 Mbps, SNR and PER values at different distances

Data Transfer Rate	Distance	SNR	PER
54	10	$\cong 3.90 \times 10^3$	$\cong 0$
54	20	$\cong 9.74 \times 10^2$	$\cong 0$
54	30	$\cong 4.33 \times 10^2$	7.57×10^{-10}
54	40	$\cong 2.44 \times 10^2$	1.31×10^{-4}
54	50	$\cong 1.56 \times 10^2$	$\cong 6.42 \times 10^{-2}$
54	60	$\cong 1.09 \times 10^2$	$\cong 9.99 \times 10^{-1}$
54	70	$\cong 7.95 \times 10^1$	$\cong 1$
54	80	$\cong 6.09 \times 10^1$	$\cong 1$
54	90	$\cong 4.81 \times 10^1$	$\cong 1$
54	100	$\cong 3.90 \times 10^1$	$\cong 1$
54	110	$\cong 3.22 \times 10^1$	$\cong 1$
54	120	$\cong 2.71 \times 10^1$	$\cong 1$
54	130	$\cong 2.31 \times 10^1$	$\cong 1$
54	140	$\cong 1.99 \times 10^1$	$\cong 1$
54	150	$\cong 1.74 \times 10^1$	$\cong 1$
54	160	$\cong 1.53 \times 10^1$	$\cong 1$
54	170	$\cong 1.35 \times 10^1$	$\cong 1$
54	180	$\cong 1.21 \times 10^1$	$\cong 1$
54	190	$\cong 1.08 \times 10^1$	$\cong 1$
54	200	$\cong 9.74 \times 10^0$	$\cong 1$
54	210	$\cong 8.84 \times 10^0$	$\cong 1$
54	220	$\cong 8.05 \times 10^0$	$\cong 1$
54	230	$\cong 7.21 \times 10^0$	$\cong 1$
54	240	$\cong 6.08 \times 10^0$	$\cong 1$
54	250	$\cong 5.16 \times 10^0$	$\cong 1$
54	260	$\cong 4.42 \times 10^0$	$\cong 1$
54	270	$\cong 3.80 \times 10^0$	$\cong 1$
54	280	$\cong 3.28 \times 10^0$	$\cong 1$
54	290	$\cong 2.85 \times 10^0$	$\cong 1$
54	300	$\cong 2.49 \times 10^0$	$\cong 1$

APPENDIX 9: Transmitter and receiver power values at different distances

(Data Rate = 6 Mbps)

Trans. Power (mW)	Distance(m)	Trans. Power (dBm)	Rec. Power (dBm)
0.5	50	≅-3.02	≅-94.08
0.5	100	≅-3.02	≅-113.11
0.5	150	≅-3.02	≅-116.63
0.5	200	≅-3.02	≅-119.13
0.5	250	≅-3.02	≅-121.89
0.5	300	≅-3.02	≅-125.06
1.0	50	0.0	≅-94.08
1.0	100	0.0	≅-100.10
1.0	150	0.0	≅-113.62
1.0	200	0.0	≅-116.12
1.0	250	0.0	≅-118.88
1.0	300	0.0	≅-122.05
1.5	50	≅1.77	≅-94.08
1.5	100	≅1.77	≅-100.10
1.5	150	≅1.77	≅-103.62
1.5	200	≅1.77	≅-114.36
1.5	250	≅1.77	≅-117.12
1.5	300	≅1.77	≅-120.29
2.0	50	≅3.02	≅-94.08
2.0	100	≅3.02	≅-100.10
2.0	150	≅3.02	≅-103.62
2.0	200	≅3.02	≅-113.11
2.0	250	≅3.02	≅-115.87
2.0	300	≅3.02	≅-119.04
2.5	50	≅3.98	≅-94.08
2.5	100	≅3.98	≅-100.10
2.5	150	≅3.98	≅-103.62
2.5	200	≅3.98	≅-112.14
2.5	250	≅3.98	≅-114.90
2.5	300	≅3.98	≅-118.07
3.0	50	≅4.78	≅-94.08
3.0	100	≅4.78	≅-100.10
3.0	150	≅4.78	≅-103.62
3.0	200	≅4.78	≅-106.12
3.0	250	≅4.78	≅-114.11
3.0	300	≅4.78	≅-117.27
3.5	50	≅5.45	≅-94.08

APPENDIX 10: Transmitter and receiver power values at different distances (Continued)

(Data Rate = 6 Mbps)

Trans. Power (mW)	Distance(m)	Trans. Power (dBm)	Rec. Power (dBm)
3.5	100	≅5.45	≅-100.10
3.5	150	≅5.45	≅-103.62
3.5	200	≅5.45	≅-106.12
3.5	250	≅5.45	≅-113.44
3.5	300	≅5.45	≅-116.61
4.0	50	≅6.03	≅-94.08
4.0	100	≅6.03	≅-100.10
4.0	150	≅6.03	≅-103.62
4.0	200	≅6.03	≅-106.12
4.0	250	≅6.03	≅-112.86
4.0	300	≅6.03	≅-116.03
4.5	50	≅6.54	≅-94.08
4.5	100	≅6.54	≅-100.10
4.5	150	≅6.54	≅-103.62
4.5	200	≅6.54	≅-106.12
4.5	250	≅6.54	≅-112.35
4.5	300	≅6.54	≅-115.51
5.0	50	≅6.99	≅-94.08
5.0	100	≅6.99	≅-100.10
5.0	150	≅6.99	≅-103.62
5.0	200	≅6.99	≅-106.12
5.0	250	≅6.99	≅-108.88
5.0	300	≅6.99	≅-115.06
5.5	50	≅7.41	≅-94.08
5.5	100	≅7.41	≅-100.10
5.5	150	≅7.41	≅-103.62
5.5	200	≅7.41	≅-106.12
5.5	250	≅7.41	≅-108.88
5.5	300	≅7.41	≅-114.64
6.0	50	≅7.79	≅-94.08
6.0	100	≅7.79	≅-100.10
6.0	150	≅7.79	≅-103.62
6.0	200	≅7.79	≅-106.12
6.0	250	≅7.79	≅-108.88
6.0	300	≅7.79	≅-114.26
6.5	50	≅8.13	≅-94.08

APPENDIX 11: Transmitter and receiver power values at different distances (Continued)

(Data Rate = 6 Mbps)

Trans. Power (mW)	Distance(m)	Trans. Power (dBm)	Rec. Power (dBm)
6.5	100	$\cong$8.13	$\cong$-100.10
6.5	150	$\cong$8.13	$\cong$-103.62
6.5	200	$\cong$8.13	$\cong$-106.12
6.5	250	$\cong$8.13	$\cong$-108.88
6.5	300	$\cong$8.13	$\cong$-113.92
7.0	50	$\cong$8.46	$\cong$-94.08
7.0	100	$\cong$8.46	$\cong$-100.10
7.0	150	$\cong$8.46	$\cong$-103.62
7.0	200	$\cong$8.46	$\cong$-106.12
7.0	250	$\cong$8.46	$\cong$-108.88
7.0	300	$\cong$8.46	$\cong$-113.60
7.5	50	$\cong$8.76	$\cong$-94.08
7.5	100	$\cong$8.76	$\cong$-100.10
7.5	150	$\cong$8.76	$\cong$-103.62
7.5	200	$\cong$8.76	$\cong$-106.12
7.5	250	$\cong$8.76	$\cong$-108.88
7.5	300	$\cong$8.76	$\cong$-113.30
8.0	50	$\cong$9.04	$\cong$-94.08
8.0	100	$\cong$9.04	$\cong$-100.10
8.0	150	$\cong$9.04	$\cong$-103.62
8.0	200	$\cong$9.04	$\cong$-106.12
8.0	250	$\cong$9.04	$\cong$-108.88
8.0	300	$\cong$9.04	$\cong$-113.02
8.5	50	$\cong$9.30	$\cong$-94.08
8.5	100	$\cong$9.30	$\cong$-100.10
8.5	150	$\cong$9.30	$\cong$-103.62
8.5	200	$\cong$9.30	$\cong$-106.12
8.5	250	$\cong$9.30	$\cong$-108.88
8.5	300	$\cong$9.30	$\cong$-112.75
9.0	50	$\cong$9.55	$\cong$-94.08
9.0	100	$\cong$9.55	$\cong$-100.10
9.0	150	$\cong$9.55	$\cong$-103.62
9.0	200	$\cong$9.55	$\cong$-106.12
9.0	250	$\cong$9.55	$\cong$-108.88
9.0	300	$\cong$9.55	$\cong$-112.50
9.5	50	$\cong$9.78	$\cong$-94.08

APPENDIX 12: Transmitter and receiver power values at different distances (Continued)

(Data Rate = 6 Mbps)

Trans. Power (mW)	Distance(m)	Trans. Power (dBm)	Rec. Power (dBm)
9.5	100	$\cong$9.78	$\cong$-100.10
9.5	150	$\cong$9.78	$\cong$-103.62
9.5	200	$\cong$9.78	$\cong$-106.12
9.5	250	$\cong$9.78	$\cong$-108.88
9.5	300	$\cong$9.78	$\cong$-112.27
10.0	50	10.0	$\cong$-94.08
10.0	100	10.0	$\cong$-100.10
10.0	150	10.0	$\cong$-103.62
10.0	200	10.0	$\cong$-106.12
10.0	250	10.0	$\cong$-108.88
10.0	300	10.0	$\cong$-112.05

APPENDIX 13: Transmitter power and SNR values at different distances

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	SNR
0.5	50	≅7.79
0.5	100	≅1.95
0.5	150	-
0.5	200	-
0.5	250	-
0.5	300	-
1	50	≅15.58
1	100	≅3.90
1	150	≅1.74
1	200	-
1	250	-
1	300	-
1.5	50	≅23.37
1.5	100	≅5.85
1.5	150	≅2.60
1.5	200	≅1.47
1.5	250	-
1.5	300	-
2	50	≅31.16
2	100	≅7.79
2	150	≅3.47
2	200	≅1.95
2	250	-
2	300	-
2.5	50	≅38.95
2.5	100	≅9.74
2.5	150	≅4.33
2.5	200	≅2.44
2.5	250	≅1.29
2.5	300	-
3	50	≅46.74
3	100	≅11.69
3	150	≅5.20
3	200	≅2.93
3	250	≅1.55
3	300	-
3.5	50	≅54.53

APPENDIX 14: Transmitter power and SNR values at different distances (Continued)

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	SNR
3.5	100	≅13.64
3.5	150	≅6.06
3.5	200	≅3.41
3.5	250	≅1.81
3.5	300	-
4	50	≅62.32
4	100	≅15.58
4	150	≅6.93
4	200	≅3.90
4	250	≅2.07
4	300	-
4.5	50	≅70.11
4.5	100	≅17.53
4.5	150	≅7.79
4.5	200	≅4.39
4.5	250	≅2.33
4.5	300	-
5	50	≅77.90
5	100	≅19.48
5	150	≅8.66
5	200	≅4.87
5	250	≅2.58
5	300	-
5.5	50	≅85.69
5.5	100	≅21.43
5.5	150	≅9.53
5.5	200	≅5.36
5.5	250	≅2.84
5.5	300	≅1.37
6	50	≅93.48
6	100	≅23.37
6	150	≅10.39
6	200	≅5.85
6	250	≅3.10
6	300	≅1.50
6.5	50	≅101.27

APPENDIX 15: Transmitter power and SNR values at different distances (Continued)

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	SNR
6.5	100	≅25.32
6.5	150	≅11.26
6.5	200	≅6.33
6.5	250	≅3.36
6.5	300	≅1.62
7	50	≅109.05
7	100	≅27.27
7	150	≅12.12
7	200	≅6.82
7	250	≅3.62
7	300	≅1.75
7.5	50	≅116.84
7.5	100	≅29.21
7.5	150	≅12.99
7.5	200	≅7.31
7.5	250	≅3.87
7.5	300	≅1.87
8	50	≅124.63
8	100	≅31.16
8	150	≅13.85
8	200	≅7.79
8	250	≅4.13
8	300	≅2.00
8.5	50	≅132.42
8.5	100	≅33.11
8.5	150	≅14.72
8.5	200	≅8.28
8.5	250	≅4.39
8.5	300	≅2.12
9	50	≅140.21
9	100	≅35.06
9	150	≅15.58
9	200	≅8.77
9	250	≅4.65
9	300	≅2.24
9.5	50	≅148.00

APPENDIX 16: Transmitter power and SNR values at different distances (Continued)

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	SNR
9.5	100	≅37.00
9.5	150	≅16.45
9.5	200	≅9.25
9.5	250	≅4.91
9.5	300	≅2.37
10	50	≅155.79
10	100	≅38.95
10	150	≅17.31
10	200	≅9.74
10	250	≅5.16
10	300	≅2.49

APPENDIX 17: Transmitter power and PER values at different distances

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	PER
0.5	50	$\cong 0.00$
0.5	100	$\cong 2.36 \times 10^{-1}$
0.5	150	-
0.5	200	-
0.5	250	-
0.5	300	-
1	50	$\cong 0.00$
1	100	$\cong 2.21 \times 10^{-6}$
1	150	$\cong 8.05 \times 10^{-1}$
1	200	-
1	250	-
1	300	-
1.5	50	$\cong 0.00$
1.5	100	$\cong 5.26 \times 10^{-11}$
1.5	150	$\cong 4.10 \times 10^{-3}$
1.5	200	$\cong 1.00$
1.5	250	-
1.5	300	-
2	50	$\cong 0.00$
2	100	$\cong 0.00$
2	150	$\cong 2.55 \times 10^{-5}$
2	200	$\cong 2.37 \times 10^{-1}$
2	250	-
2	300	-
2.5	50	$\cong 0.00$
2.5	100	$\cong 0.00$
2.5	150	$\cong 2.00 \times 10^{-7}$
2.5	200	$\cong 9.50 \times 10^{-3}$
2.5	250	$\cong 1.00$
2.5	300	-
3	50	$\cong 0.00$
3	100	$\cong 0.00$
3	150	$\cong 1.76 \times 10^{-9}$
3	200	$\cong 5.83 \times 10^{-4}$
3	250	$\cong 9.99 \times 10^{-1}$
3	300	-
3.5	50	$\cong 0.00$

APPENDIX 18: Transmitter power and PER values at different distances (Continued)

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	PER
3.5	100	$\cong 0.00$
3.5	150	$\cong 1.64 \times 10^{-11}$
3.5	200	$\cong 3.46 \times 10^{-5}$
3.5	250	$\cong 5.71 \times 10^{-1}$
3.5	300	-
4	50	$\cong 0.00$
4	100	$\cong 0.00$
4	150	$\cong 2.02 \times 10^{-13}$
4	200	$\cong 2.22 \times 10^{-6}$
4	250	$\cong 1.08 \times 10^{-1}$
4	300	-
4.5	50	$\cong 0.00$
4.5	100	$\cong 0.00$
4.5	150	$\cong 0.00$
4.5	200	$\cong 1.49 \times 10^{-7}$
4.5	250	$\cong 1.95 \times 10^{-2}$
4.5	300	-
5	50	$\cong 0.00$
5	100	$\cong 0.00$
5	150	$\cong 0.00$
5	200	$\cong 1.03 \times 10^{-8}$
5	250	$\cong 4.55 \times 10^{-3}$
5	300	-
5.5	50	$\cong 0.00$
5.5	100	$\cong 0.00$
5.5	150	$\cong 0.00$
5.5	200	$\cong 7.27 \times 10^{-10}$
5.5	250	$\cong 9.55 \times 10^{-4}$
5.5	300	$\cong 1.00$
6	50	$\cong 0.00$
6	100	$\cong 0.00$
6	150	$\cong 0.00$
6	200	$\cong 5.26 \times 10^{-11}$
6	250	$\cong 2.09 \times 10^{-4}$
6	300	$\cong 9.99 \times 10^{-1}$
6.5	50	$\cong 0.00$

APPENDIX 19: Transmitter power and PER values at different distances (Continued)

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	PER
6.5	100	$\cong 0.00$
6.5	150	$\cong 0.00$
6.5	200	$\cong 3.84 \times 10^{-12}$
6.5	250	$\cong 4.72 \times 10^{-5}$
6.5	300	$\cong 9.93 \times 10^{-1}$
7	50	$\cong 0.00$
7	100	$\cong 0.00$
7	150	$\cong 0.00$
7	200	$\cong 0.00$
7	250	$\cong 1.09 \times 10^{-1}$
7	300	$\cong 7.73 \times 10^{-1}$
7.5	50	$\cong 0.00$
7.5	100	$\cong 0.00$
7.5	150	$\cong 0.00$
7.5	200	$\cong 0.00$
7.5	250	$\cong 2.55 \times 10^{-6}$
7.5	300	$\cong 4.01 \times 10^{-1}$
8	50	$\cong 0.00$
8	100	$\cong 0.00$
8	150	$\cong 0.00$
8	200	$\cong 0.00$
8	250	$\cong 6.04 \times 10^{-7}$
8	300	$\cong 1.77 \times 10^{-1}$
8.5	50	$\cong 0.00$
8.5	100	$\cong 0.00$
8.5	150	$\cong 0.00$
8.5	200	$\cong 0.00$
8.5	250	$\cong 1.45 \times 10^{-7}$
8.5	300	$\cong 7.61 \times 10^{-2}$
9	50	$\cong 0.00$
9	100	$\cong 0.00$
9	150	$\cong 0.00$
9	200	$\cong 0.00$
9	250	$\cong 3.51 \times 10^{-8}$
9	300	$\cong 3.33 \times 10^{-2}$

APPENDIX 20: Transmitter power and PER values at different distances (Continued)

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	PER
9.5	50	$\cong 0.00$
9.5	100	$\cong 0.00$
9.5	150	$\cong 0.00$
9.5	200	$\cong 0.00$
9.5	250	$\cong 8.56 \times 10^{-9}$
9.5	300	$\cong 1.49 \times 10^{-2}$
10	50	$\cong 0.00$
10	100	$\cong 0.00$
10	150	$\cong 0.00$
10	200	$\cong 0.00$
10	250	$\cong 2.10 \times 10^{-9}$
10	300	$\cong 6.77 \times 10^{-3}$

APPENDIX 21: Transmitter power and Throughput values at different distance

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	Throughput (Mbps)
0.5	50	$\cong 3.85 \times 10^{-4}$
0.5	100	$\cong 0$
0.5	150	$\cong 0$
0.5	200	$\cong 0$
0.5	250	$\cong 0$
0.5	300	$\cong 0$
1	50	$\cong 3.85 \times 10^{-4}$
1	100	$\cong 3.85 \times 10^{-4}$
1	150	$\cong 0$
1	200	$\cong 0$
1	250	$\cong 0$
1	300	$\cong 0$
1.5	50	$\cong 3.85 \times 10^{-4}$
1.5	100	$\cong 3.85 \times 10^{-4}$
1.5	150	$\cong 3.85 \times 10^{-4}$
1.5	200	$\cong 0$
1.5	250	$\cong 0$
1.5	300	$\cong 0$
2	50	$\cong 3.85 \times 10^{-4}$
2	100	$\cong 3.85 \times 10^{-4}$
2	150	$\cong 3.85 \times 10^{-4}$
2	200	$\cong 0$
2	250	$\cong 0$
2	300	$\cong 0$
2.5	50	$\cong 3.85 \times 10^{-4}$
2.5	100	$\cong 3.85 \times 10^{-4}$
2.5	150	$\cong 3.85 \times 10^{-4}$
2.5	200	$\cong 0$
2.5	250	$\cong 0$
2.5	300	$\cong 0$
3	50	$\cong 3.85 \times 10^{-4}$
3	100	$\cong 3.85 \times 10^{-4}$
3	150	$\cong 3.85 \times 10^{-4}$
3	200	$\cong 3.85 \times 10^{-4}$
3	250	$\cong 0$
3	300	$\cong 0$

APPENDIX 22: Transmitter power and Throughput values at different distance (Continued)

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	Throughput (Mbps)
3.5	50	$\cong 3.85\times10^{-4}$
3.5	100	$\cong 3.85\times10^{-4}$
3.5	150	$\cong 3.85\times10^{-4}$
3.5	200	$\cong 3.85\times10^{-4}$
3.5	250	$\cong 0$
3.5	300	$\cong 0$
4	50	$\cong 3.85\times10^{-4}$
4	100	$\cong 3.85\times10^{-4}$
4	150	$\cong 3.85\times10^{-4}$
4	200	$\cong 3.85\times10^{-4}$
4	250	$\cong 0$
4	300	$\cong 0$
4.5	50	$\cong 3.85\times10^{-4}$
4.5	100	$\cong 3.85\times10^{-4}$
4.5	150	$\cong 3.85\times10^{-4}$
4.5	200	$\cong 3.85\times10^{-4}$
4.5	250	$\cong 0$
4.5	300	$\cong 0$
5	50	$\cong 3.85\times10^{-4}$
5	100	$\cong 3.85\times10^{-4}$
5	150	$\cong 3.85\times10^{-4}$
5	200	$\cong 3.85\times10^{-4}$
5	250	$\cong 3.85\times10^{-4}$
5	300	$\cong 0$
5.5	50	$\cong 3.85\times10^{-4}$
5.5	100	$\cong 3.85\times10^{-4}$
5.5	150	$\cong 3.85\times10^{-4}$
5.5	200	$\cong 3.85\times10^{-4}$
5.5	250	$\cong 3.85\times10^{-4}$
5.5	300	$\cong 0$
6	50	$\cong 3.85\times10^{-4}$
6	100	$\cong 3.85\times10^{-4}$
6	150	$\cong 3.85\times10^{-4}$
6	200	$\cong 3.85\times10^{-4}$
6	250	$\cong 3.85\times10^{-4}$
6	300	$\cong 0$

APPENDIX 23: Transmitter power and Throughput values at different distance (Continued)

(Data Rate = 6 Mbps)

Transmitter Power (mW)	Distance(m)	Throughput (Mbps)
6.5	50	$\cong 3.85 \times 10^{-4}$
6.5	100	$\cong 3.85 \times 10^{-4}$
6.5	150	$\cong 3.85 \times 10^{-4}$
6.5	200	$\cong 3.85 \times 10^{-4}$
6.5	250	$\cong 3.85 \times 10^{-4}$
6.5	300	$\cong 0$
7	50	$\cong 3.85 \times 10^{-4}$
7	100	$\cong 3.85 \times 10^{-4}$
7	150	$\cong 3.85 \times 10^{-4}$
7	200	$\cong 3.85 \times 10^{-4}$
7	250	$\cong 3.85 \times 10^{-4}$
7	300	$\cong 0$
7.5	50	$\cong 3.85 \times 10^{-4}$
7.5	100	$\cong 3.85 \times 10^{-4}$
7.5	150	$\cong 3.85 \times 10^{-4}$
7.5	200	$\cong 3.85 \times 10^{-4}$
7.5	250	$\cong 3.85 \times 10^{-4}$
7.5	300	$\cong 0$
8	50	$\cong 3.85 \times 10^{-4}$
8	100	$\cong 3.85 \times 10^{-4}$
8	150	$\cong 3.85 \times 10^{-4}$
8	200	$\cong 3.85 \times 10^{-4}$
8	250	$\cong 3.85 \times 10^{-4}$
8	300	$\cong 0$
8.5	50	$\cong 3.85 \times 10^{-4}$
8.5	100	$\cong 3.85 \times 10^{-4}$
8.5	150	$\cong 3.85 \times 10^{-4}$
8.5	200	$\cong 3.85 \times 10^{-4}$
8.5	250	$\cong 3.85 \times 10^{-4}$
8.5	300	$\cong 0$
9	50	$\cong 3.85 \times 10^{-4}$
9	100	$\cong 3.85 \times 10^{-4}$
9	150	$\cong 3.85 \times 10^{-4}$
9	200	$\cong 3.85 \times 10^{-4}$
9	250	$\cong 3.85 \times 10^{-4}$
9	300	$\cong 0$

APPENDIX 24: Transmitter power and Throughput values at different distance (Continued)

(Data Rate = 6 Mbps)

| Transmitter Power (mW)	Distance(m)	Throughput (Mbps)
9.5	50	$\cong 3.85 \times 10^{-4}$
9.5	100	$\cong 3.85 \times 10^{-4}$
9.5	150	$\cong 3.85 \times 10^{-4}$
9.5	200	$\cong 3.85 \times 10^{-4}$
9.5	250	$\cong 3.85 \times 10^{-4}$
9.5	300	$\cong 0$
10	50	$\cong 3.85 \times 10^{-4}$
10	100	$\cong 3.85 \times 10^{-4}$
10	150	$\cong 3.85 \times 10^{-4}$
10	200	$\cong 3.85 \times 10^{-4}$
10	250	$\cong 3.85 \times 10^{-4}$
10	300	$\cong 0$

APPENDIX 25: MTU and Throughput at different data payload size

(Data Rate = 6 Mbps)

MTU	Payload Size	Throughput
250	$\cong 10000$	$\cong 1.53 \times 10^{-2}$
250	15000	$\cong 1.15 \times 10^{-2}$
250	20000	$\cong 1.53 \times 10^{-2}$
500	10000	$\cong 3.05 \times 10^{-2}$
500	15000	$\cong 3.44 \times 10^{-2}$
500	20000	$\cong 3.05 \times 10^{-2}$
750	10000	$\cong 5.35 \times 10^{-2}$
750	15000	$\cong 4.58 \times 10^{-2}$
750	20000	$\cong 4.58 \times 10^{-2}$
1000	10000	$\cong 6.87 \times 10^{-2}$
1000	15000	$\cong 6.87 \times 10^{-2}$
1000	20000	$\cong 6.11 \times 10^{-2}$
1250	10000	$\cong 8.40 \times 10^{-2}$
1250	15000	$\cong 8.02 \times 10^{-2}$
1250	20000	$\cong 7.63 \times 10^{-2}$
1500	10000	$\cong 1.07 \times 10^{-1}$
1500	15000	$\cong 1.03 \times 10^{-1}$
1500	20000	$\cong 1.07 \times 10^{-1}$
1750	10000	$\cong 1.30 \times 10^{-1}$
1750	15000	$\cong 1.26 \times 10^{-1}$
1750	20000	$\cong 1.23 \times 10^{-1}$
2000	10000	$\cong 1.30 \times 10^{-1}$
2000	15000	$\cong 1.38 \times 10^{-1}$
2000	20000	$\cong 1.38 \times 10^{-1}$

APPENDIX 26: Minimum required transmission power against distance for each data transfer rate in which wireless communication operates at least 90% success.

Distance = [110-150]m

Distance = [160-200]m

Distance = [210-250]m

Distance = [260-320]m
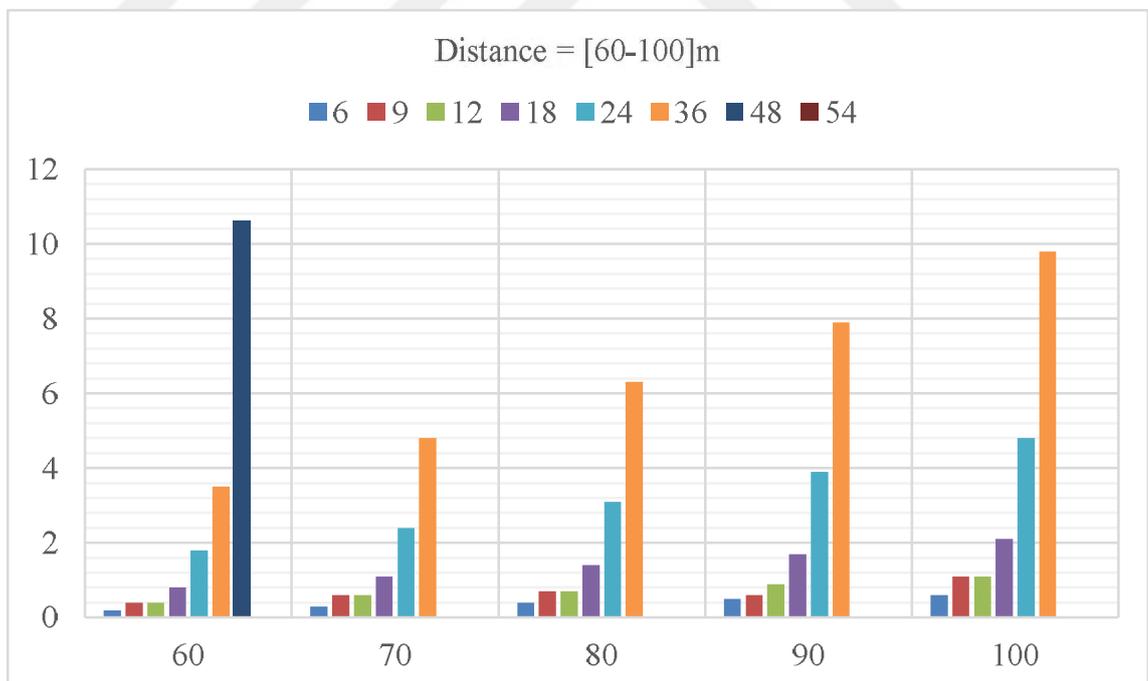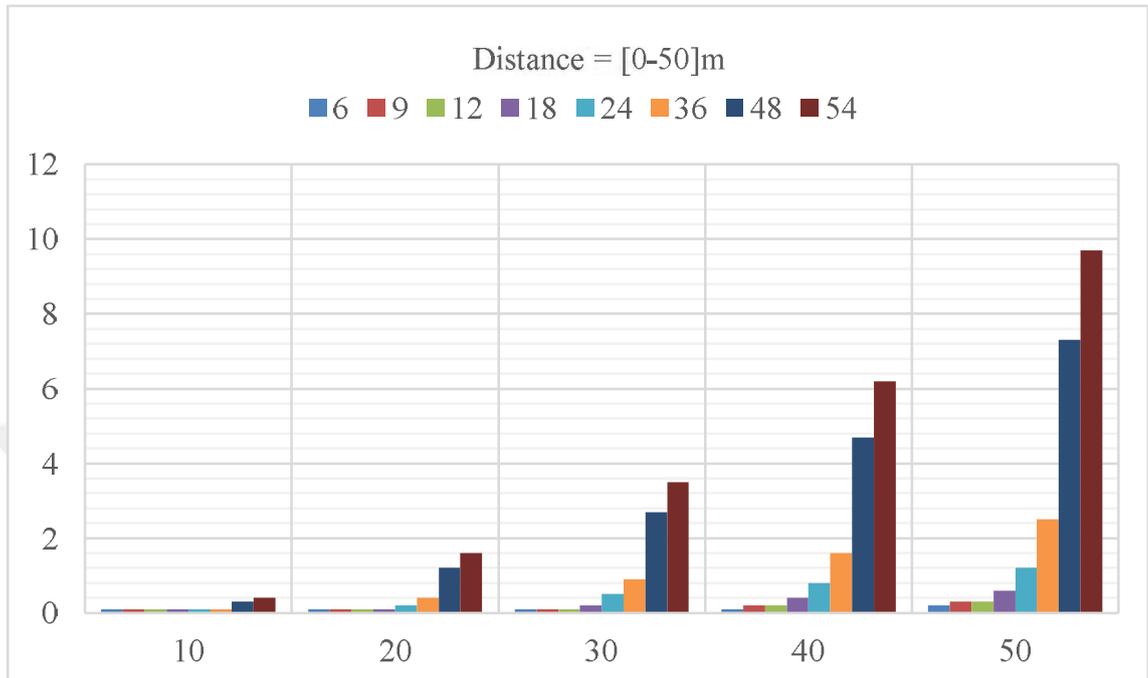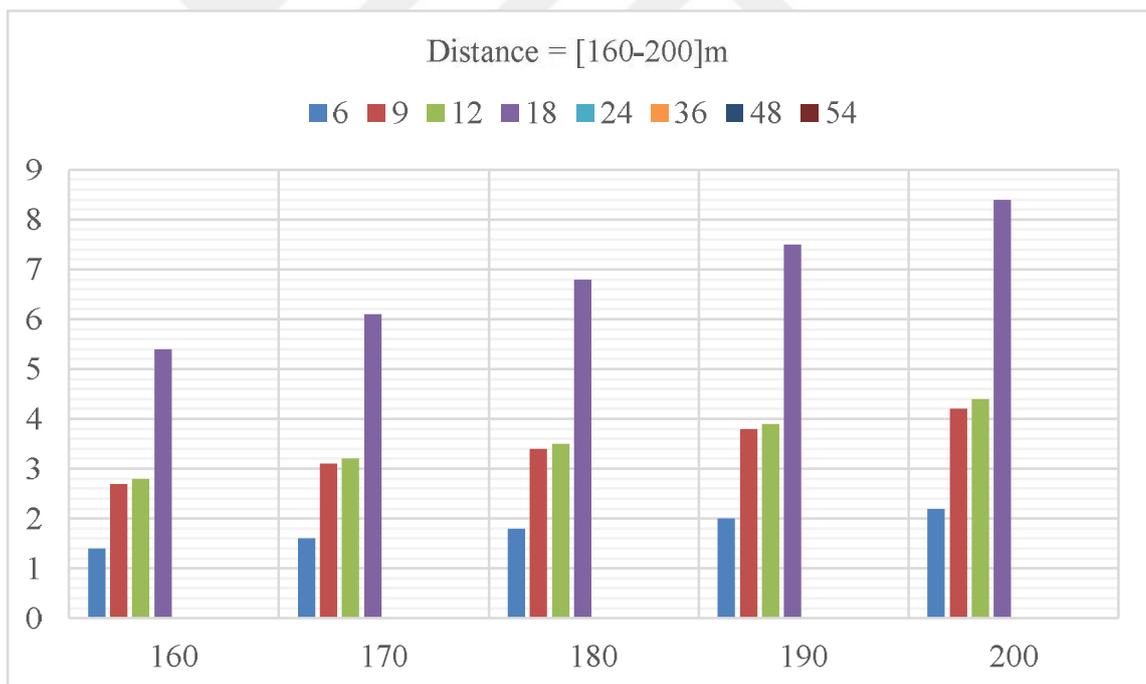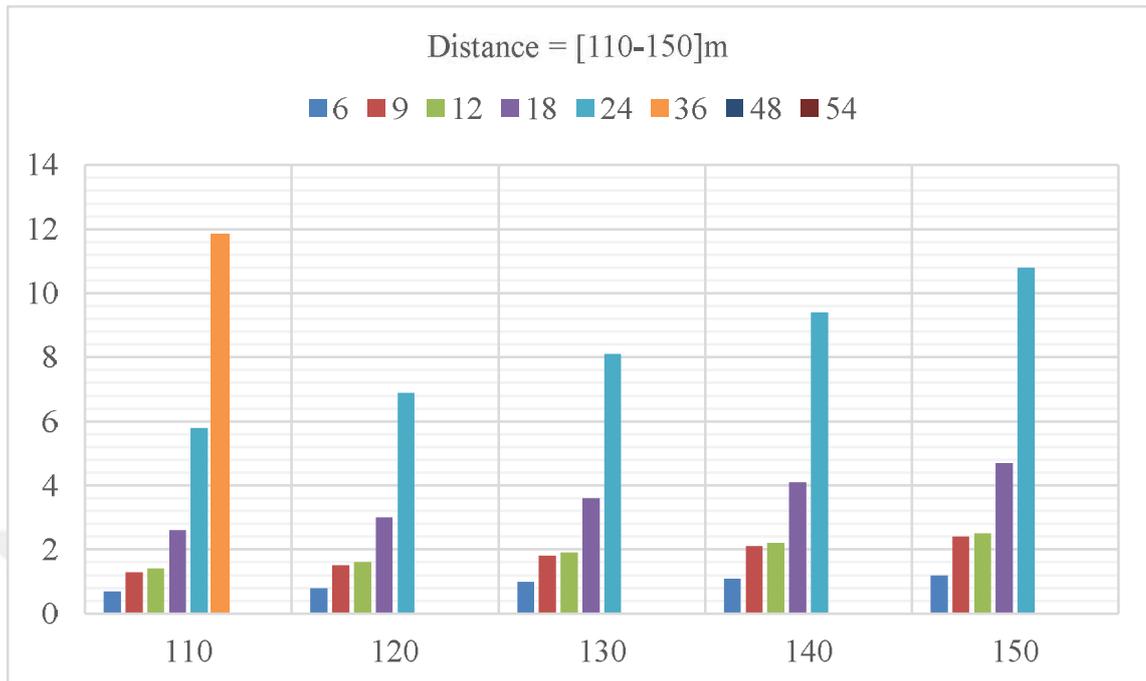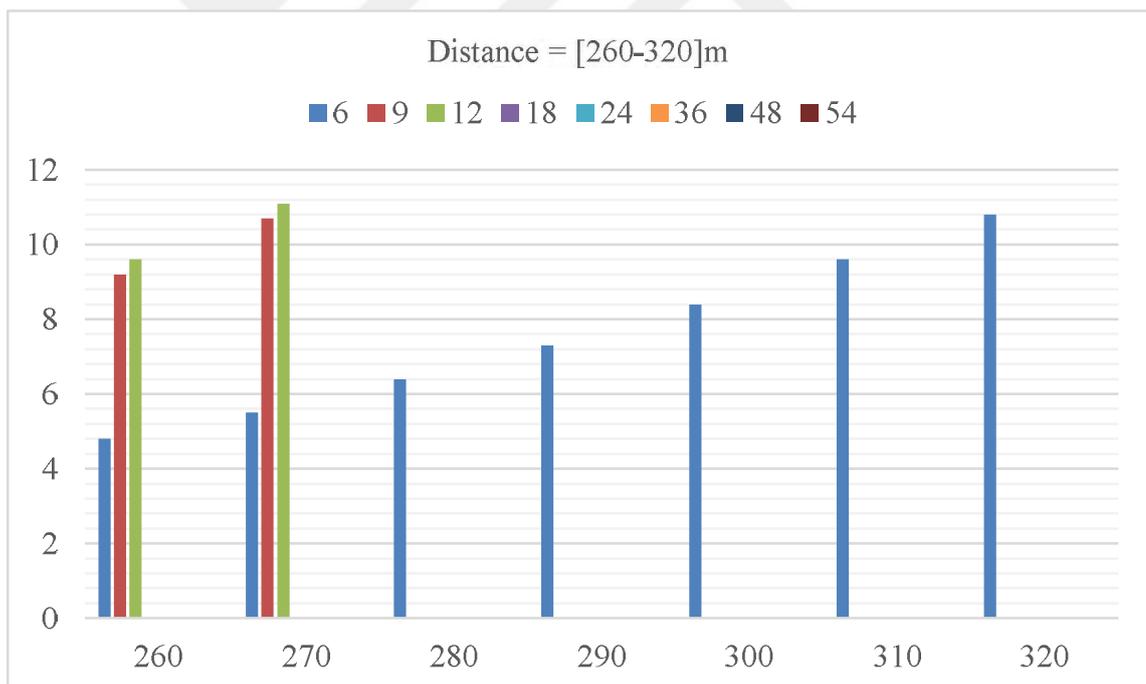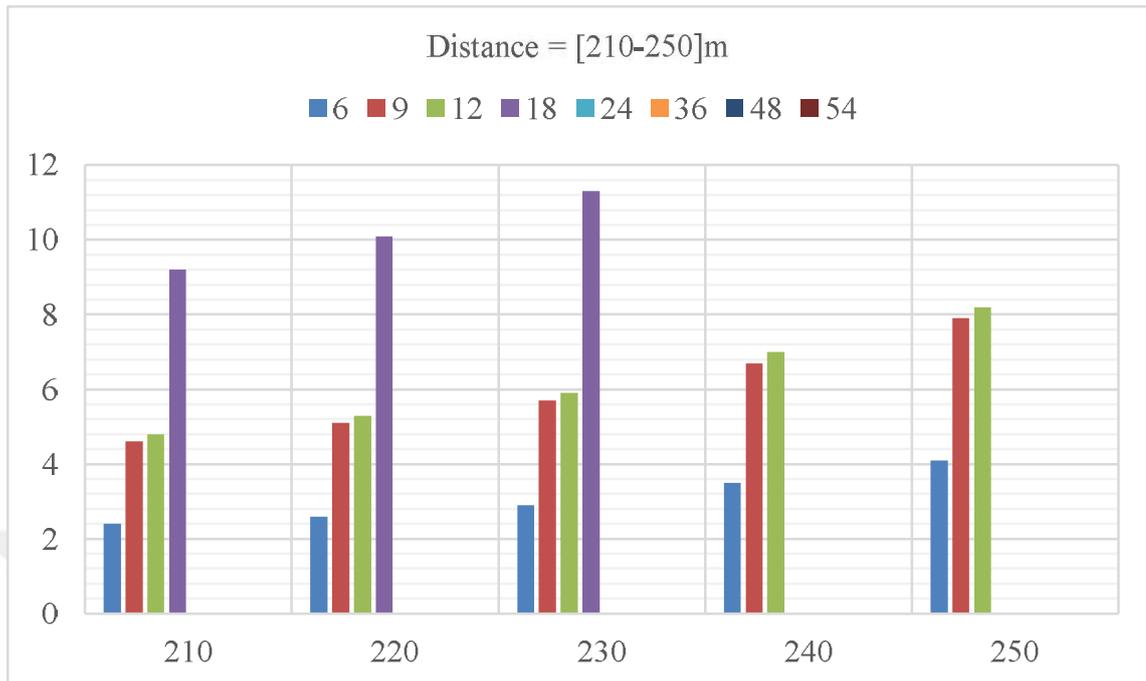
CURRICULUM VITAE

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Master's Degree	Erciyes University	2020
License	Eastern Mediterranean University, Computer Engineering, Northern Cyprus	2006
High School	Kongre High School, Sivas	1999

WORK EXPERIENCE

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