



PERFORMANCE COMPARISON OF 60GHZ WITH 2.4GHZ AND  
5GHZ FOR WLAN OVER RICIAN FADING CHANNEL

MASTERS OF SCIENCE IN COMMUNICATION ENGINEERING  
AND NETWORKING

SHIMELIS ABATE BELAY

HAWASSA UNIVERSITY

HAWASSA, ETHIOPIA

OCTOBER 2021

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5GHZ FOR WLAN OVER RICIAN FADING CHANNEL

SHIMELIS ABATE BELAY

A THESIS SUBMITTED TO THE  
DEPARTMENT OF COMMUNICATION ENGINEERING AND  
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## Declaration

I hereby declare that this M.Sc. this thesis is my original work and has not yet been submitted for a degree in Hawassa University and other institution, and all sources of materials used for the thesis have been duly acknowledged.

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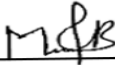
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## Abstract

Currently, number of wireless technologies deployed to connect daily activities of human being in different ways and systems. Among those technology Wireless Local Area Network (WLAN) the one which plays crucial role. Hence, it is delivered by use of 2.4GHz and 5GHz frequencies. Due to the number of users increase the two main problem became challenges which are spectrum scarcity and throughput. To solve the challenge there are several types of research are done and are going to be done related to 60GHz Millimeter Wave Frequency for WALN. In this thesis, coverage and capacity performance comparison of 60 GHz channel capacity over Rician fading channels with 2.4 GHz and 5 GHz for WLAN service to give a better selection for WLAN users in the future. By using with bit error rate (BER) and SNR for small-scale (fast) fading with higher M-ary QAM modulation scheme. As a result, the Rician Channel fading for 60GHz with comparisons of 2.4 and 5 GHz WLAN frequency has high throughputs, which is 60GHz channel capacity is 13.5 times of 5GHz channels, and 54 times channels of 2.4GHz. Therefore, it is more advantageous for high throughput user demands than 2.4 and 5GHz frequencies used for IEEE 802.11's Standards. 60 GHz distance coverage, relatively time less half coverage of than 2.4GHz frequency and less than by around 7-meter time less than 5GHz frequency coverage. Hence, the shorter the coverage of 60GHz give an advantage to best candidate for frequency re-use to solve spectrum scarcity.

**Key words:** Rician Fading, Coverage, Capacity



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## List of Abbreviation

- CBSM Correlation-based stochastic modeling
- CIR Channel Impulse Response
- dBm Decibel millimeter
- DMPC Dispersive multipath-channel model
- $E_b$  Signal energy per bit
- EIRP Effective Isotropic Radiation Power
- F Noise factor
- FSPL Free Space Path Loss
- GBSM Geometry based stochastic modeling
- $G_r$  Receiver Gain
- $G_t$  Transmitter Gain
- IEEE Institute of Electrical and Electronics Engineering
- K Kelvin
- A signal power of line of sight
- k k-factor
- LOS Line of Sight
- M-MIMO Massive MIMO
- MU-MIMO Multiple User Multiple Input Multiple Output
- $N_0$  Noise Power Spectral Density per bit (thermal noise)
- $\eta_B$  Spectral efficiency
- NF Noise Figure
- m Meter
- NLOS Non-Line-of-Sight
- $\eta_p$  Power efficiency
- PAM Pulse Amplitude Modulation



- Pdf            Probability Distribution Function
- PL            Path Loss
- PMs          Propagation Models
- Pn            Noise Power
- Pr            Received Power
- Ps            Power sensitive (Minimum Power of Rx)
- PSK          Phase Shift Key
- Pt            Transmitter Power
- QAM          Quadrature Amplitude Modulation
- WLAN        Wireless Local Area Network
- XL-MIMO    Extremely Large Regime
- $\lambda$             Lambda
- M            Modulation Index
- IEEE         Institute of Electrical and Electronics Engineering
- DSSS        Direct Sequence Spread Spectrum
- SISO         Single Input Single Output
- MIMO        Multiple Input Multiple Output
- OFDM        Orthogonal Frequency-Division Multiplexing



## CHAPTER 1

### 1. Introduction

#### 1.1. Background

A wireless communication is one of the fundamental technologies which affects our world day to day activity. In radio, communication there was a long history. The power-limited, space-varying, time-varying, frequency-varying wireless channel is one of nature's most difficult challenges. Engineers who can overcome these limits and transmit data over such challenging conditions will be rewarded handsomely. The explosive rise of personal communications services around the world in the 1990s is proof of the business prospects that come with dominating the wireless channel. The task of conquering the wireless channel is growing more challenging due to the emergence of newer wireless systems that require increasing amounts of bandwidth. This assignment necessitates a thorough understanding of wireless channel modeling. [1]. Current available Wireless Local Area Networking (WLAN) and Wireless Personal Area Networking (WPAN) frequency used like 2.4GHz and 5GHz even if they have a large wavelength which helps them to cover a wide area, they are not capable of solving current demands of high-capacity data rate and good performance service of wireless and wired technology. Even if the wire technology is reached 100 Gbps using optical fiber, still there are some challenges in wireless technology even if it is simple to implement it. There are two major advantages of adopting millimeter wave (mm-wave) frequency in future mobile networks, that is abundant spectral resources and short-wavelength [2]. Due to the short wavelength, the multi-path effects in wireless communications, e.g., diffraction and higher-order reflection are rather weak in mm-wave, and the penetration loss of mm-wave signals is significantly higher than the 2.4GHz and 5GHz. Hence, it is more desirable to fulfill mm-wave communications in line-of-sight (LOS) scenarios, since the link connectivity cannot be guaranteed in non-line-of-sight (NLOS). This particular propagation characteristic makes mm-wave links vulnerable to blockage caused by objects emerging between the transmitter and the receiver [2]. There are number of challenges in wireless technology which affect wireless system implementation as well as to use available license free frequency bands. Among number of challenges of wireless

channel is channel fading, for this challenge, number of research were done and are going to be done. This thesis also one of the types of research to provide a solution by performing a performance comparison of 60GHz frequency band with 2.4GHz and 5GHz for WLAN over Rician channel fading. There are several methods, which help to analyze and Models for 60GHz comparing with 2.4GHz and 5 GHz [3]. For license free 60GHz almost in America, Japan, Europe, and Korea except Australia have 7GHz bandwidth 2 to 3 Gbps wireless gigabit Ethernet could be achieved by using with simple Modulation Methods like PAM, PSK, and QAM in figure 1.1 below [4]. 60GHz regulation allows high transmission power to overcome the several signal attenuation problems while the maximum transmits the power in the unlicensed band is limited average power 40dBm with a maximum allowable antenna gain of 43dBm [5]. In addition to this FCC has opened a total of 10.85 GHz spectrum, 7GHz for Unlicensed and 3.85 GHz for Licensed uses [6].

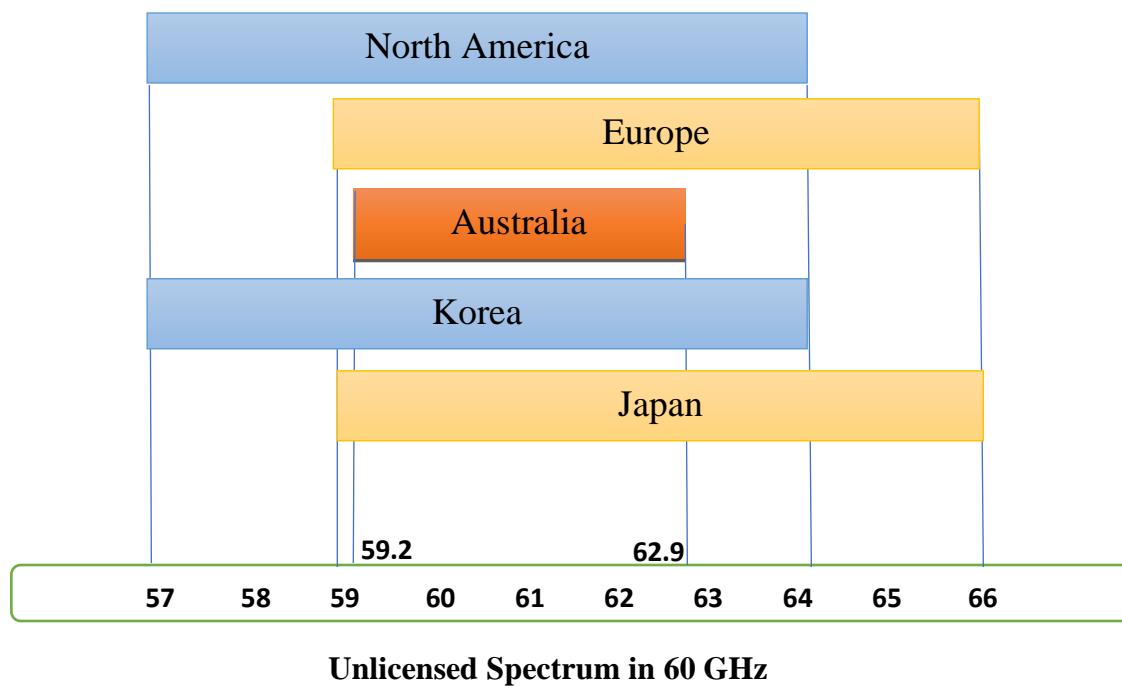


Figure 1. 1 International unlicensed Spectrum of 60GHz [6]

A communication system's main goal is to achieve one or more of the following objectives.



- The transmitted signal should take up the minimum amount of bandwidth in the allocated spectrum. This is evaluated in bandwidth efficiency, also known as spectral efficiency –  $\eta_B$ .
- The designed systems should be able to deliver information consistently at the lowest possible power level. This is expressed in respect of power efficiency –  $\eta_p$ .
- The ability to transport data at higher rates – R bits per second.
- By multipath effects and fading should not affect the planned systems.
- Other sources operating at the same frequency with a low Carrier to Co-channel signal Interference ratio should be prevented by the system (CCI).
- Adjacent channel interference from surrounding channels is minimal, as indicated by the Adjacent Channel Power Ratio (ACPR).
- Implementation is easier, and operational costs are lower [7].

This thesis, focus on some of the objectives listed above. A wireless communication system, have several wireless channel characteristics, which are help full to us. Understanding what are the main positive characteristics and challenging characteristics in wireless communication. In wireless communication, the transmitted signals arrive at the receiver end with high power loss due to different reasons. Which are *free-space path loss*, due to the dynamic nature of wireless channels, which experienced random fluctuations in time either the transmitter, receiver, or surrounding objects are moving due to changes reflections and attenuations as a result of *Large-Scale fading* and *Small-scale fading*, and due to *noise* created in the environments. Even though those loss cases available in this thesis mainly we focus on *small-scale fading* for WLAN system of wireless communication. As we have seen in the wireless communication system, there are different types of fading models like the following listed bellows.

Rayleigh When a non-line of sight (NLOS) path exists between the transmitter and the receiver, but only an indirect path exists, the resultant signal received at the receiver is the sum of all reflected and scattered waves.

When there is both a Line of Sight (LOS) and a Non-Line of Sight (NLOS) path between the transmitter and receiver, Rician fading occurs, and the received signal consists of both direct

and scattered multipath waves [8]. In this thesis, the work focuses on using *the Rician Fading channel method for channel capacity and coverage performance comparisons*.

As we see in Fig 1.2, the data rates range requirements for WLAN and WPAW. In the meantime, various standards for larger market manipulation must be distinguished. The Institute of Electrical and Electronics Engineering (IEEE) IEEE 802.15.3c is positioned to provide gigabit rates and longer operating ranges [9] [10].

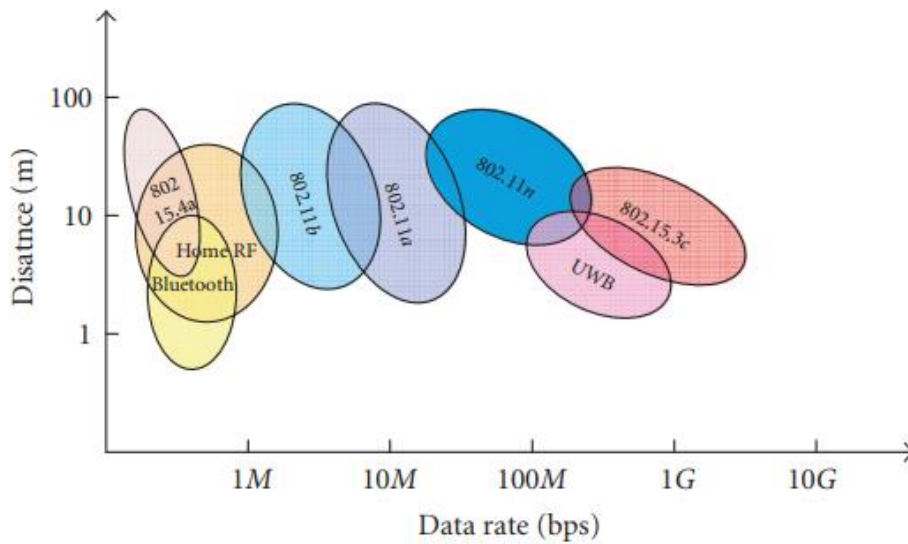


Figure 1. 2 WLAN and WPAN standards and applications have data rates and range requirements. IEEE 802.15.3c, or millimeter-wave technology, aims for very high data rates [9].



## 1.2. Statement of the Problem

The wireless technologies Currently used for in day today activity of human being. Which is used for WLAN with 2.4GHz and 5GHz frequency and different modulation methods. These are not able to satisfy or answer the challenge fully. Due to an increase of customer or user spectral and high throughput requests. Even though here are high demand of high data rate and good network coverage as well as good performance of the wireless system and frequency re-usage. As a result, this thesis will give a solution for high throughput data rate and good performance region or area, which close to real applicable point of view.



### 1.3. Objectives

#### General Objective

Comparing the performance of 60GHz its coverage and capacity with earlier WLAN frequency standards which are 2.4GHz and 5GHz. For the give solution for spectral scarcity and high bandwidth throughput challenges of wireless technologies.

#### Specific Objective

- Coverage evaluation of 60GHz, 5GHz and 2.4GHz frequency for Rician fading channel.
- Simulate path loss of 60GHz, 5GHz and 2.4GHz frequency for Rician fading channel.
- Capacity calculation of 60GHz, 5GHz and 2.4GHz frequency with LOS and NLOS for Rician fading channel higher M-QAM by using SNR and Bit Error Rate.
- Comparing Capacity 60GHz Millimeter Wave Radiofrequency with 2.4 and 5 GHz radiofrequency with M-QAM modulation Scheme at different level of SNR and BER.
- Comparing Coverage 60GHz Millimeter Wave Radiofrequency with 2.4 and 5 GHz radiofrequency.



## 1.4. Methodology

In this thesis, to answer among wireless challenges of spectral scarcity and high throughput demands due to an increase of wireless users. By performing the specific objectives, in the following chapters, see the characteristics of the 60GHz frequency band, the path loss model of the 60 GHz, 2.4 GHz, and 5 GHz for free space path loss. In addition, we take into consideration different parameter changes, which are transmitter distances, antenna gains of the transmitter and receiver in different environments, and path exponents, which help us to compare coverage as well as the probability of outage. Channel capacity of 60 GHz for Rician Channel fading with for M-ary QAM Modulation scheme for M which is 64 to 1024. With simulating software and Discussing on the result and finally concluding the discussions.

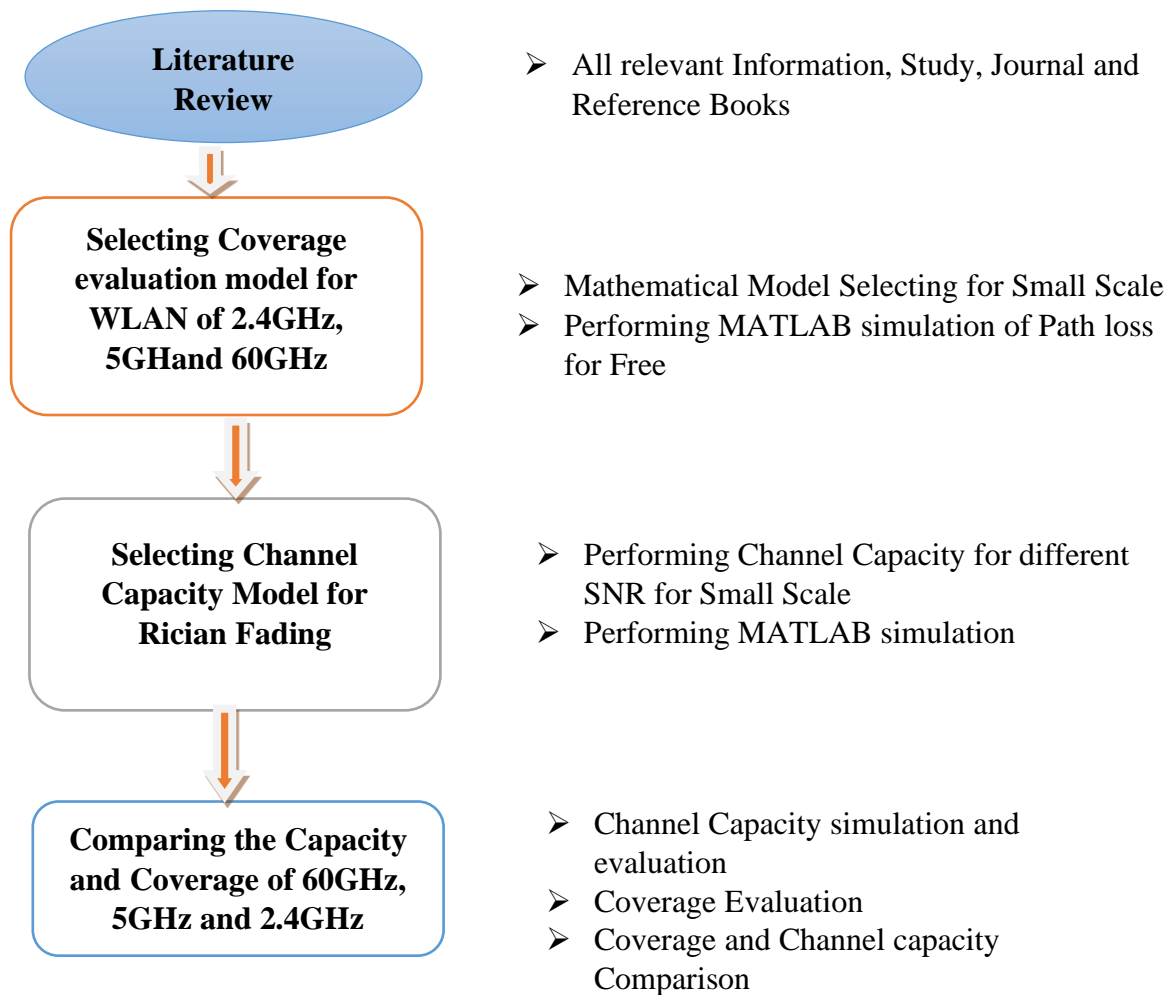


Figure 1. 3 Methodology for this Thesis.



## 1.5. Literature review

Using 60GHz, the frequency for WLAN there are some researches indicates that it has the better performance as well as capacity than 2.4 and 5 GHz WLAN with the same modulation technique. According to Michael Melaku in [3] Performance analysis of 60 GHz wireless communications for local area networks 2.4 GHz has better coverage area than 5 GHz and 60 GHz. In the NLOS scenario, 2.4GHz as well as 5 GHz coverage area exceeds the 60 GHz with very much difference, more than 12 meters radius difference. On the other hand, Line of sight communications has a better coverage area than non-line of sight communications. As a result, 60 GHz has a very significant increase in coverage radius about 19 meters increase in radius securing those users can communicate to Access Point in 99.5% of the coverage area. In this thesis the work focuses on using AWGN as well as focused for large scale fading. This helps us to see the theoretical and maximum approximate of the 60GHz band wireless technology. Based on his comment of future work I stated working performance comparison over Rician channel fading for 60GHz WLAN.

A 60GHz wireless system is more suitable below 1 km communications distances, according to Jingjing Wang [4]. The channel capacity of M-ary PSK over Rayleigh fading channels was shown to be smaller than that of AWGN channels, especially in the 5 dB to 20 dB SNR regions. The capacity loss on Rayleigh fading channels becomes increasingly severe as the number of bits increases. In various SNR settings, the relationship between channel capacity and Rician parameters is demonstrated. According to their expectation the Rician parameter increases, the channel capacity increases proportionally. Their work only on PSK but this thesis works on higher M-ary QAM for higher Modulation which is 64 to 1024.



According to [11] works, with the 60GHz system being particularly important. They examine the impacts of large-scale propagation and small-scale multi-path fading in wireless communication and its mitigation with numerous antennas in Furthermore, the antenna array's gain allows for high-level modulation, which results in a high bit rate while maintaining a low bit error rate (BER). But this thesis differs by performing small scale fading in detail. As per an Overview of 60GHz technology presented in [9]. They showed that the feasibility study of with high allowable transmitted power they showed that with the small forms of factors and advanced circuit integration as well as the selection of modulation schemes. Which is differ from this thesis is this thesis only focus on small scale fading or flat fading with higher modulation schemes. As per 60GHz Photonic Millimeter-Wave for short medium range wireless transportations [11] in this work they showed that photonic for fair condition it gives up to 12.5gbps for shorter distance and it can be operatable up to 3000m and they compared its path loss with 77GHz and 120GHz the result shows that 60GHz has higher attenuation path loss after 100m accordingly. According to the [12] they show the 60GHz for OQPS/QPSK modulation as well as 16QAM but this thesis focuses of higher Modulation above 64QAM.

As per the IEEE802.11 has released different standards for starting in 1990s for various operating frequencies and ranges specifications. Some of them now outdated, and some are still active. And these standards are applied to WLAN network [13]. These standards also have used either 2.4G Hz or 5 GHz except IEEE 802.11 ad which used 60GHz frequency band.

IEEE 802.11 has different Wi-Fi Protocols, which are summarized with their frequencies, Channel widths, Access Methods, and theoretical Maximum data rates is presented in table 1.1.



Table 1.1 Summary of the IEEE 802.11 Wi-Fi Protocols [14]

Protocol	Frequency	Channel width	MIMO	Maximum Data Rate (theoretical)
802.11 ax	2.4 GHz and 5 GHz	20, 40, 80, 160 MHz	Multi-User (MU-MIMO)	2.4 Gbps*
802.11 ac wave 2	5GHz	20, 40, 80, 160 MHz	Multi-User (MU-MIMO)	1.73 Gbps**
802.11 ac wave 1	5 GHz	20, 40, 80 MHz	Single User (SU-MIMO)	866.7 Mbps**
802.11 n	2.4 GHz and 5 GHz	20, 40 MHz	Single User (SU-MIMO)	450 Mbps***
802.11 g	2.4 GHz	20 MHz	N/A	54 Mbps
802.11 a	5 GHz	20 MHz	N/A	54 Mbps
802.11 b	2.4 GHz	20 MHz	N/A	11 Mbps
Legacy 802.11	2.4 GHz	20 MHz	N/A	2 Mbps

\* 2 spatial streams modulated in 1024-QAM. \*\* 2 spatial streams modulated in 256-QAM. \*\*\* 3 spatial streams modulated in 64-QAM.

As we saw in the above table earlier, the IEEE802.11ac exhibits wide area coverage when compared to another standard. The IEEE802.11ac is using different antenna systems Multiple User MIMO and multi-spatial streams. As a result, it has higher data streaming rates. In addition, we see that in table 1.3 the maximum achievable PHY data rates for different channel bandwidth/spatial stream supported ranges in IEEE802.11ac. As well as channel bandwidth evolved over an IEEE 802.11n by added two channels 80MHz and 160MHz by adding non-overlapping (80MHz +80MHz) as well as newly added channel 144 as we see in fig 1.3 below.

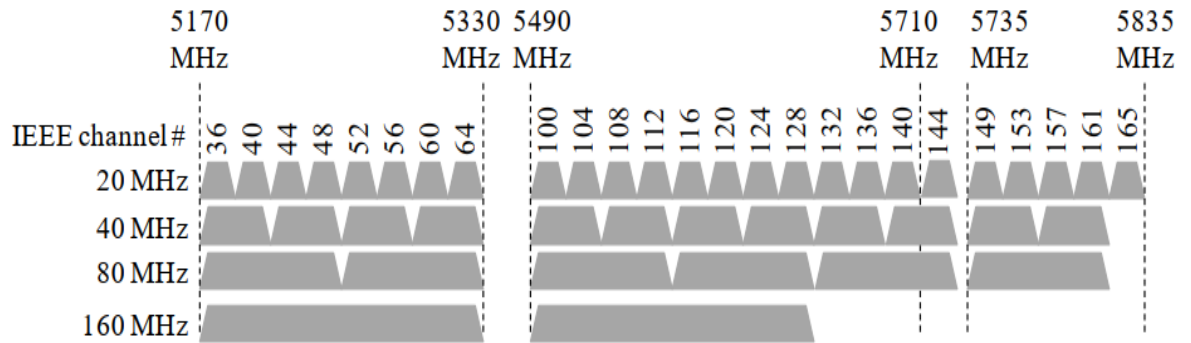


Figure 1. 4 IEEE 802.11ac Channelization has evolved an IEEE 802.11n [10]

Table 1.2 Maximum Achievable PHY Data Rates (Mbps) bandwidth/spatial streams IEEE802.11ac [15] [10] .

BW(MHz)/ Spatial Stream	20MHz	40MHz	80MHz	160MHz
1	86.7	200	433.3	866.7
2	173.3	400	866.7	1733
3	288.9	600	1300	2340
4	346.7	800	1733	3466
5	433.3	1000	2166	4333
6	577.8	1200	2340	5200
7	606.7	1400	3033	6066.7
8	693.3	1600	3466	6933

## CHAPTER 2

### 2. Characteristics of 60GHz frequency

This frequency is among license free frequency of Millimeter wave rages. It has the following main characteristics. Which is atmospheric absorption, transmitted energy is absorbed by atmospheric oxygen up to 98 percent as shown in below fig 1.4 [16].

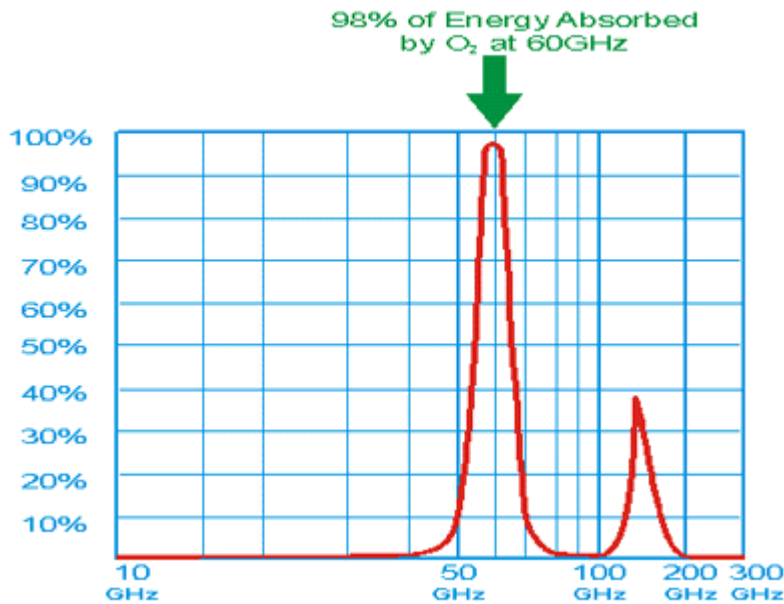


Figure 2.1 Atmospheric absorption of millimeter-wave frequency per kilometer

One of the benefits of 60GHz is frequency re-use. Which increases with distance increases because for the distance increase it has high path loss from the working area for the fixed wireless system as shown in fig 2.2 as show in [16].

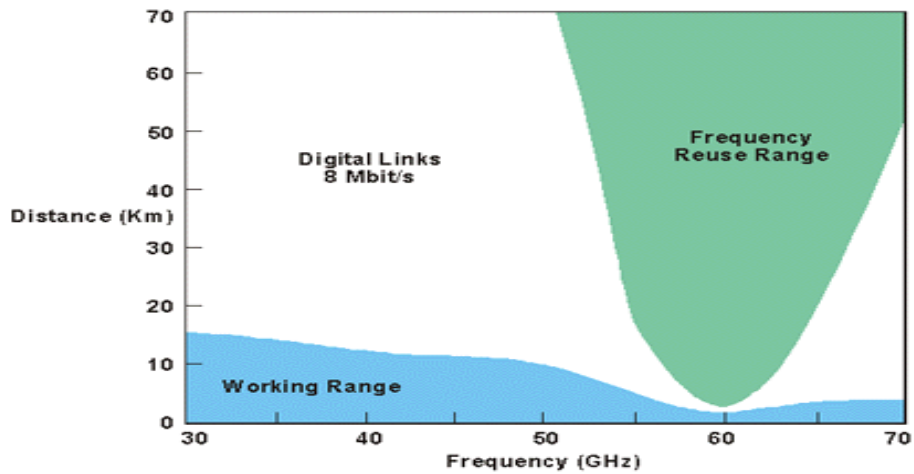


Figure 2.2 Frequency reuse of range of 60GHz compared the rest millimeter-wave versus distance

As the distance increase from 60GHz source the frequency, reuse rate increases highly as we see in the above figure 2.2 in addition to the above characteristic's we can see the summarized millimeter-wave propagation characteristics is shown in below fig 2.3.

### 2.1. Penetration Characteristics of 60GHz

The 60GHz millimeter wave frequency has different material penetration losses as listed in below table 2.1.

Table 2.1 60GHz Millimeter Wave with different material penetration attenuation Inside an office building

Environments	Material Under Test	Penetrations Loss	Reference
Inside an office building	Glassdoor	2 dB	[17]
Inside an office building	Plasterboard wall with metallic studs	9dB	
Inside an office building	Metal-backed, Blackboard	35.5dB	
	Mesh Glass	39.1	[18]
	Drywall	2.4	

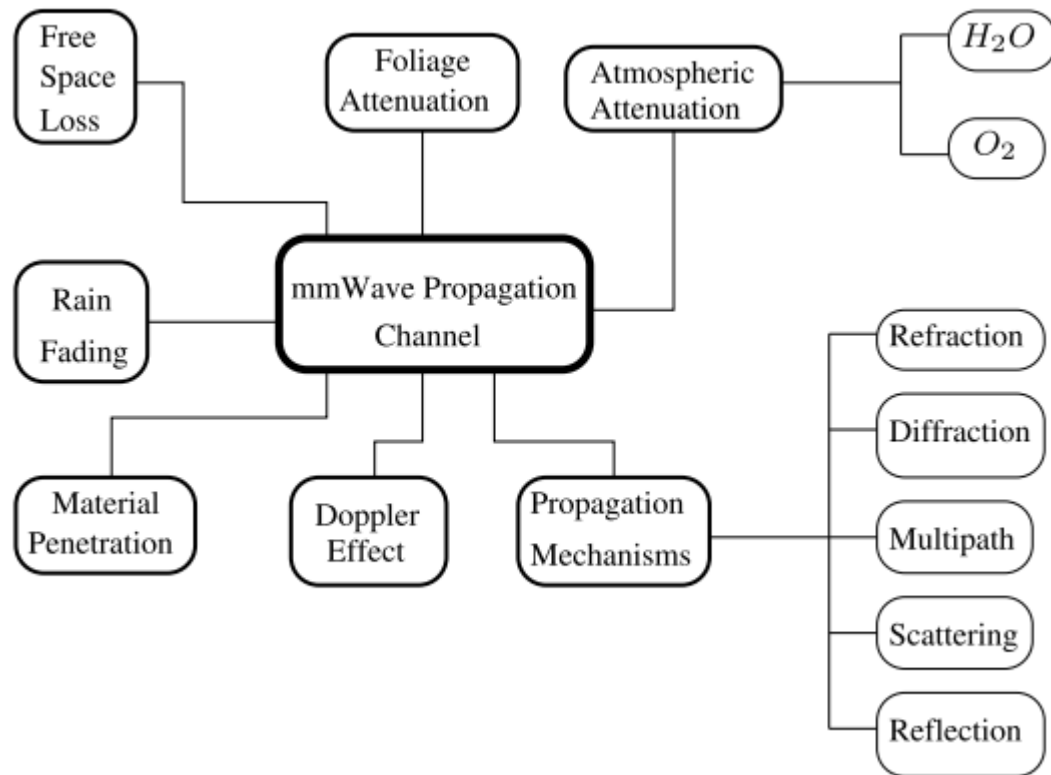


Figure 2.3 Millimeter-wave propagations characteristics [18]

According to [18] how the millimeter-wave propagation channel affected with different cases like Free space loss, Rain Fading, Material Penetration, Doppler Effect, Foliage Attenuation, Atmospheric Attenuation by water, and Oxygen. Penetration Loss of the millimeter-wave 60GHz in the indoor environment for glass door 2dB, the plastered wall with metallic stands 9dB, and metal-backed blackboard 35.5dB [17]. Due to different material properties, the penetrations loss varies. As a result, radio propagation is characterized using path loss, delay spread, shadow fading, and angle spread characteristics. These are primarily accomplished by studying free space path loss, an induced attenuation of rain, atmospheric and foliage, and material penetration loss, as well as data on radio-channel propagation mechanisms gathered from a number of channel measuring campaigns in a different environment.



## CHAPTER 3

### 3. Wireless Channel Modeling for WLAN

#### 3.1. Wireless Channel Characteristics

In a wireless network, the nodes use an omnidirectional antenna multiple access protocols to access the channel, as well as the transmitted energy, which reaches the nodes in the network. The wireless channels are exposed to a varieties of transmission obstacles for instance path losses, interferences, and blockages. These factors limit ranges of coverages, data rates, and reliabilities of the wireless transmission systems factors that affect the transmission depending upon the environmental conditions and the mobility of the transmitters and receivers. The transmitted signals reach to the receiver have two types of paths, such as: - Direct-path (LOS) and Multi-path (NLOS). The transmitted signal is called direct path when it reaches the receiver side directly, and the components of direct path signals are called direct path components. The sent signal is called multi-path when it arrives at the receiver side by different paths and experiences distinct phenomena, and the components of the received signals are called multi-path components. The transmitter signals are either reflected, diffracted, or scattered by the surroundings, and reach at the receiver shifted in amplitude, frequency, and phase for the direct path component.

The following are some of the most important properties of the wireless channel: –

- Path loss
- Fading
- Interference



➤ Doppler shift

In this thesis, we consider only two of the above characteristics which are path loss and fading. Path loss characteristics depends on environment where the transmitter and receiver exist. Path loss models were developed in channel-sounding studies utilizing a combination of numerical methods and empirical approximation of measured data [19]. For a link, path loss is defined as the ratio of transmitted power to received power. It is proportional to the propagation distance. Therefore, path loss estimation is critical for designing and implementing wireless communication networks. Path loss is influenced by a variety of factors, including the radio frequency employed and the environment in which the transmitter and receiver are located. The path loss model in which there is a direct-path signal between the transmitter and the receiver, with no extra attenuations or multipath components, is known as the free space propagation model. So, the pathloss model, the relationship between the transmitted power  $P_t$  and the received power  $P_r$  given as follows in equation 3.1.

$$PL[dB] = P_t - P_r = 10 * n * \log_{10}\left(\frac{4\pi d}{\lambda}\right) \quad (3.1)$$

Where  $d$  is distance between the transmitter and receiver,  $\lambda$  is the wavelength of the transmitted signal and  $n$  is the path loss exponent,  $n$  values vary according to the different cases of environments where the either the transmitter or receiver exists like indoor, outdoor, in a conference room, etc. In general, as the frequency and/or distance increase, propagation path loss increases. The receiver signal depends on the variation of the path loss  $PL$  [dB] and path exponent  $n$  for the constant transmitter power and transmitter and receiver gain.

$$P_r[dBm] = P_t[dBm] + G_t + G_r - PL[dB] \quad (3.2)$$



Where: -  $G_t$  - the transmitter antenna gain,  $G_r$  - the receiver antenna gains and  $P_t[\text{dBm}]$  – the transmission signal power.

The maximum EIRP Transmission output power and antenna gain for 60GHz millimeter Wave 35dBm and 25dBi respectively [3].

Fading is the strength variations of signal power at the receiver end received. The receiver cannot distinguish between different multipath components. It adds them either they give an interference which is constructive or destructive between them depending upon the phase of multipath components [20]. There are two types of fading mainly. –

- Fast fading and
- Slow fading

Slow Fading/Large-Scale fading itself indicates that the signal fades away slow. Slow fading occurs when an object partially absorbs the transmitted signal between the transmitter and receiver ends. Slow fading gets its name from the fact that the fade might last for several seconds or minutes. When the receiver end of a radio wave goes through the walls of a structure, or when the receiver is temporarily obscured from the transmitter by an object, slow fading occurs. The received end signal strengths vary randomly due to the obstructing or shielding objects. Slow fading objects has a tendency to vary the received signal powers at the receiver end, even though the distance between the transmitter and receiver ends remains constant. Slow fading is also known as shadow fading because the things that generate the fade, such as huge buildings or other structures, obstruct the direct transmission line between the transmitter and the receiver, Large-scale fading more relevant for cell site planning [21] [3] [22] [20] [23].

Fast fading the rapid variation of an amplitude, a phase, or multipath delays of the received signal, due to the interferences between multiple versions of the same transmitted signal arriving at the receiver at slightly different times. The delay spread is the time between receiving the first version of the signal and receiving the last echoed signal. Reflection, diffraction, and scattering are examples of multipath propagation of the transmitted signal that induce fast fading. At the receiver end, several signals from different paths can sometimes combine constructively or destructively, creating a change in the power level of the received signal. If there is no line-of-



sight path between the transmitter and the receiver, the received single envelope of a fast-fading signal is said to follow a Rayleigh distribution. The constructive and/or destructive interference of several signal paths between the transmitter and receiver causes small-scale fading. This occurs at the spatial scale of the order of the carrier wavelength and it is frequency-dependent [23]. Small-scale fading occurs when the amplitude and phase of a radio signal vary rapidly over a small period of time (a few wavelengths). When the receiver traverses a fraction of a wavelength in small-scale fading, the instantaneous received power signal can change by up to 30 to 40 decibels. Each path has its own Doppler shift, time delay, and path attenuation in mobile radio situations, As the mobile receiver travels around, multipath propagation produces a time-varying signal. This type of channel is linear, yet it changes over time small-scale fading, also called Rician fading. It happens when many versions of a sent signal arrive at slightly different times. The envelope of the received signal is statistically represented by a Rician distribution since there is a line-of-sight component. Rayleigh distribution describes the situation when there is no line-of-sight component. [24]

For channel characteristics, small-scale fading is influenced by the nature of the transmitted signal. Varied transmitted signals will undergo different fading depending on the relationship between signal parameters like bandwidth and symbol period, on one hand, and channel parameters like coherent time, Doppler spread coherence bandwidth, and delay spread, on the other. Frequency dispersion and time-selective fading occur as a result of Doppler spread. Time dispersion and frequency-selective fading are the results of delay spread.

Since all of the different layers of a wireless system must relate to the characteristics of the propagation channel at hand, accurate wireless channel models are essential for the development of reliable systems design. Before any detailed system design, accurate characterization and modeling of the propagation channel is required. A good wireless channel model may accurately mimic the wireless channel's good performance and provide insight into the most important radio propagation mechanisms. Small-scale multipath fading is more relevant to the design of reliable and efficient communication systems. Channel models are often implemented as channel emulators and/or simulators so that the performance aspects of many different parts of the wireless system of interest can be assessed and optimized. [21] [3] [23].

## Rician Fading

The Rician fading model is similar to Rayleigh fading, with the exception that Rician fading has a strong dominant component of the signal amplitude that is Line-of-Sight. The Refined Rician models further take into account the following:

- The dominant wave can be a phasor sum of two or more dominant signals, such as line-of-sight plus ground reflection, and these combined signals are handled as a deterministic process.
- Shadow attenuation can also affect the dominant wave. This is a common assumption in satellite channel modeling. [25]

## Rice distribution

A Rice or Rician distribution is a way to model the paths of scattered signals power take to a receiver end. Specifically, this distribution models line-of-sight scatter transmissions path between two stations that have no an obstruction. Line-of-sight as well as scatter may include FM radio waves, microwaves, MRI images in the presence of noise, and satellite transmissions. The distribution also models Rician fading, which is a way to show how signal cancellations affect radio propagation. In [26, 5] the presence of a line of site the transmitted signal written as follows;

$$S(t) = \sum_{i=0}^{N-1} r_i \cos(\omega_c t + \omega_{id} t + \varphi_i) + A \cos(\omega_c t + \omega_d t) \quad (3.3a)$$

Where  $r_i$  indirect path signal power of for N multipath,  $\omega_d$  Doppler shift for direct path,  $\omega_{id}$  Doppler shift for indirect path, A direct path signal power, and  $\varphi_i$  angle of arrival to the receiver, to use the above equation we need real time simulation but, in this thesis, not considered.

For their line-of-sight propagation path the small-scale fading envelop distribution is Rician distribution, which has a probability density function, given by: [27]

$$P(r) = \frac{r}{\sigma^2} e^{-\left(\frac{r^2 + A^2}{2\sigma^2}\right)} I_0\left(\frac{Ar}{\sigma^2}\right) \quad \text{For } A \geq 0, r \geq 0 \quad (3.3b)$$

Where:  $A$  peak amplitude of the dominant LOS signal,  $I_0$  Modified Bessel function of the first kind and zero-order,  $r$  the mean power of the scatter non-line of site and  $\sigma$  standard deviation of the local power.

In this model, the channel response to any input depends only on the channel impulse response (CIR) function of the channel plus channel noise which expressed as follows [28]

$$r = h * S + n \tag{3.3 c}$$

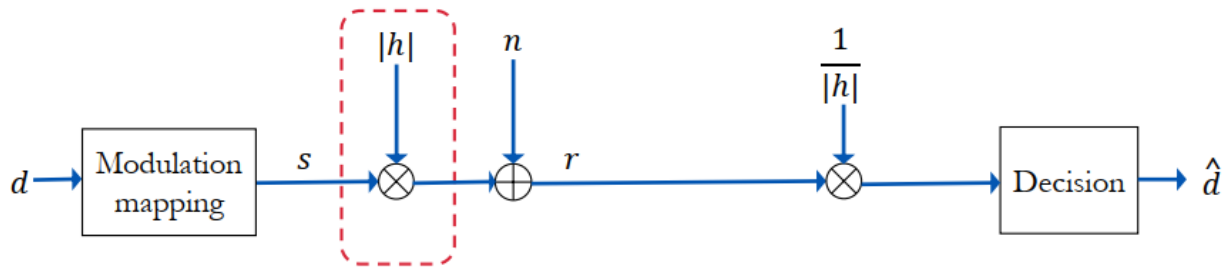


Figure 3.1 System Simulation Model for Modulation and detection over flat fading channel of small scale. [28]

To simulate flat fading, the values for the fading variable  $h$  are drawn from complex normal distribution for figure 3.1 model

$$h = |X + jY| \tag{3.3 d}$$

where  $X$  and  $Y \sim N(\mu, \sigma^2)$  are Gaussian random variables with non-zero mean  $\mu$  and standard deviation  $\sigma^2$  as given [28]. And the value of mean and Standard deviation evaluated as follows

$$\mu = \sqrt{\frac{k}{2(k+1)}} \quad \text{and} \quad \sigma = \sqrt{\frac{1}{2(k+1)}}$$

In the above figure 3.1 if the expectation of  $h$  square is different from zero  $E[h] \neq 0$ ; then the  $|h|$  is Rician distributed resulting in a Rician flat fading channel with the factor  $k = \frac{[E[h]]^2}{\sigma^2}$ .

### Rice factors

The Rician  $k$  factor it is the ratio of LOS signal power component over the scattered, reflected powers, and it is essential for understanding the behavior of a short-range wireless channel. It



determines the distributions of the received signals amplitude. Rician k-factor is useful in determining the bits error rates (BER) of a channel among other useful methods. K factor is difficult to precisely quantify by physically isolating the direct wave from the scattered components. The k-factor, on the other hand, was calculated using a variety of channel samples. For instance, at various frequencies the Rician k factor is calculated using the approach of matching first and second moments. For both the received signal amplitude and the sample mean, this method equals the theoretical mean. The theoretical mean of a Rician distributed random variable is shown in equation (3.4 b). Rician factor k is written as [25] [29]

$$k = \frac{A^2}{2\sigma^2} \tag{3.4 b}$$

Where  $A$  signal power is a dominant component and  $\sigma$  local mean scattered powers.

$$k \text{ factor in dB, } K[dBm] = 10\log_{10}\left(\frac{A^2}{2\sigma^2}\right) \tag{3.5}$$

The total mean power is the sum of the power in line-of-site and the local mean scattered power.

$$\bar{P} = A^2 + 2\sigma^2 \tag{3.6}$$

Where  $\bar{P}$  total mean power

k factors show the quality of LOS power as it increases probability of distribution for Rician channel fading.

$$A^2 = 2\sigma^2 k$$

$$\bar{P} = 2\sigma^2 k + 2\sigma^2$$

$2\sigma^2 = \frac{\bar{P}}{k+1}$  and substituting it to

$$A^2 = \frac{\bar{P}}{k+1} k$$

For the value of  $k = 0$  it the channel transformed into Rayleigh fading and when  $k$  became infinite there is no channel fading which means when there is no NLOS signal approach to the receiver.

The pdf in terms of  $k$  factor expressed as follows

$$P(r) = \frac{r}{\sigma^2} e^{-\left(\frac{r^2(k+1)}{\bar{P}}+k\right)} I_0\left(2r \sqrt{\frac{(1+K)k}{\bar{P}}}\right)$$

From above expression the probability distribution of  $k$ -factor is  $\bar{P} = 1dB$  and the random variable  $r=0-5$  as well as different  $k$ -factor values resulting from MATLAB.

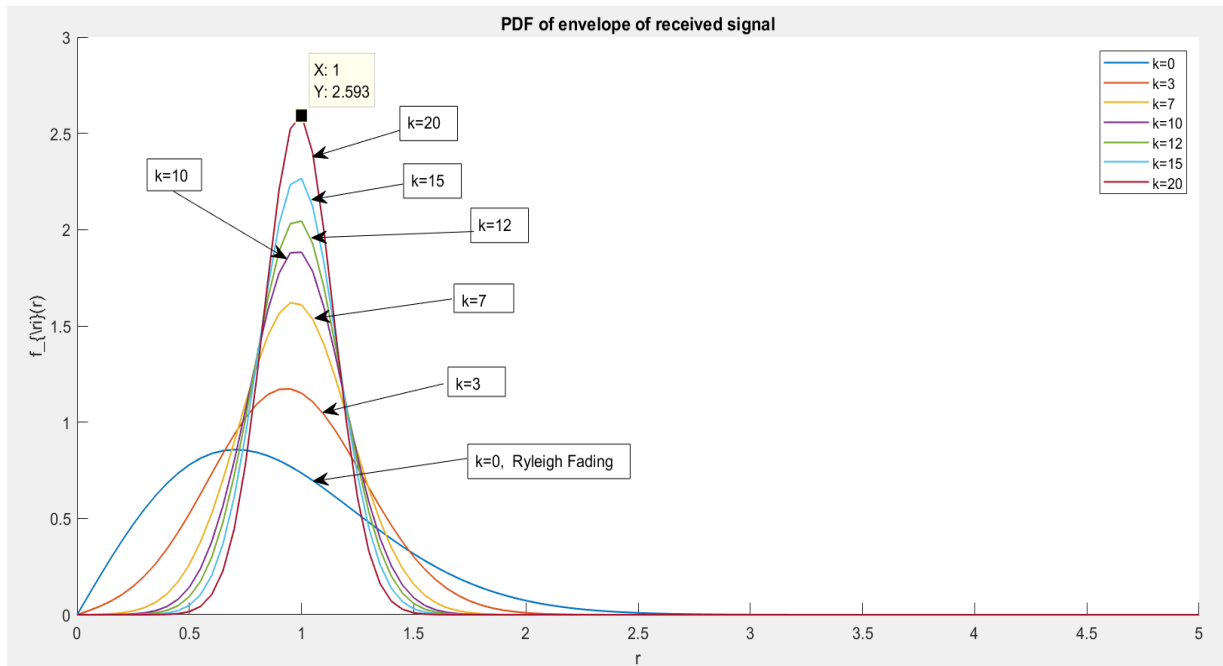


Figure 3.2 The Rician  $k$ -factor probability distribution

The function which shows that an increase pdf caused by the line-of-sight signal increases which influence  $k$ -factor value as equation (3.4b).

### Power margin

It is the difference of the received power  $P_r$  and minimum working power (sensitive Power)  $P_s$



$$P_m = P_r - P_s \tag{3.7 a}$$

Where  $P_m$  is Power Margin, and  $P_r$  is the received power and  $P_s$  the minimum power the receiver end operates or work which is called Receiver Sensitivity.

### Signal to Noise Ratio

SNR is the ratio of signal power to the noise power at the receiver Rx as given by

$$SNR[dBm] = P_r [dBm] - P_n[dBm] \tag{3.7 b}$$

$$SNR[dBm] = P_t[dBm] + G_t[dBm] + G_r[dBm] - PL(d)[dBm] - (10 \log_{10}(KT) [dBm] + 10 \log_{10}(B)[dBm] + NF)[dBm] \tag{3.7 c}$$

Where:-  $P_r$  receiver power,  $P_n$  noise power,  $G_t$  transmitter gain, and  $G_r$  receiver gain,  $P_t$  transmitter power,  $PL(d)$  Path loss at distance  $d$ ,  $K$  Boltzmann's constant,  $T$  room temperature (290°K)  $B$  Bandwidth  $NF$  Noise figure and this noise figure for this work set to 0 [9] [19] The power margin helps us to gate channel capacity of for the given millimeter wave.

### Receiver Sensitivity

The most important question during performance evaluation of wireless link:

- The maximum transmit power allowable by different standards
- The signal and channel bandwidth required
- The desired range and environment to be performed and
- The SNR required for the link with good performance

To answer the question above first we have to estimate or determine the receiver sensitivity and link budget of the system. The sensitivity of the system depends on the system noise figure, the required SNR, Channel bandwidth, and system temperature [19].

The SNR expressed in terms of  $\frac{E_b}{N_o}$  as follows



$$SNR[dB] = 10 \log_{10} \left( \frac{E_b}{N_0} \frac{R_b}{B} \right) = \frac{E_b}{N_0[dB]} + 10 \log_{10} \left( \frac{R_b}{B} \right) \quad (3.8a)$$

Where  $R_b$  Data rate and  $B$  is Bandwidth  $\frac{E_b}{N_0[dB]}$  is the signal energy of bit per thermal noise

Based on equation (3.8a)  $SNR_{dB}$  we can find that

$$\frac{E_b}{N_0[dB]} = SNR[dB] - 10 \log_{10} \left( \frac{R_b}{B} \right) \quad (3.8b)$$

According to Nyquist theorem the maximum bit rate is given as the bit rate is equals to bandwidth times the logarithmic base 2 of Modulation  $M$  in [30]:

$$R_b = 2B \log_2 M \quad (*)$$

where  $M = 2^q$  (\*\*)

Then substituting equation the value of  $M$  for \*\* to bitrate of \* we found that bit rate as follows

$$R_b = 2B \log_2(2^q) = 2Bq \quad (***)$$

Finally substituting bitrate of equation (\*\*\*) in equation (3.8b) we get

$$SNR[dB] = \frac{E_b}{N_0[dB]} + 10 \log_{10}(2q) \quad (3.8c)$$

The sensitivity defined for the system is as follows according to [19] [31] as follows:

$$PS_{[dBm]} \leq Pr[dBm] = Pt[dBm] - Pl[dBm]$$

$$PS_{[dBm]} \leq Pt[dBm] - Pl[dBm] \quad (3.9a)$$

where  $PS_{[dBm]}$  is Sensitivity

K - Boltzmann's constants  $k=1.381 * 10^{-23}$  joules/kelvin

T- Room Temperature T= 290 Kelvin

$NF_{dB}$  – Noise Figure

The input, noise power density  $P_n$  is the noise originating on the source resistance feeding the receiver.

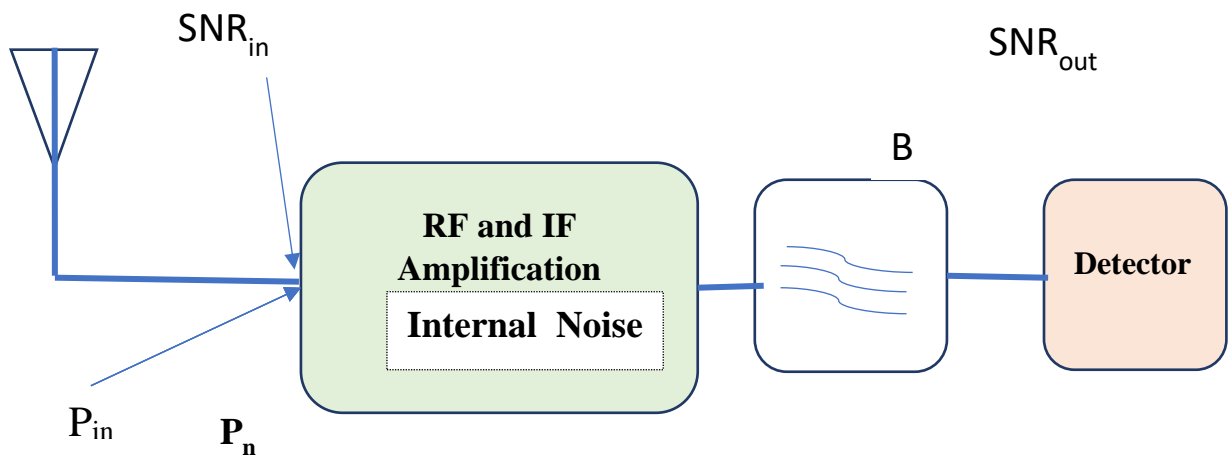


Figure 3.3 The receiver circuit of the system for a wireless system [31].

$$\text{Thermal Noise power } P_n \text{ [dB]} = 10 \log_{10}(kT) \text{ dBm/Hz}$$

$$\text{Thermal Noise power } P_n \text{ [dB]} = -174 \text{ dBm/Hz}$$

$$\text{Thermal Noise floor } P_n \text{ [dB]} = -174 \frac{\text{dBm}}{\text{Hz}} + 10 \log_{10}(B) \tag{3.9 b}$$

The noise floor of 60GHz for channel band width of 2.16GHz the for equation above 3.9 b

$$\text{Noise floor } P_n \text{ [dB]} = -174 \frac{\text{dBm}}{\text{Hz}} + 93.344 \text{ dBm} = -80.655 \text{ dBm} \quad (****)$$

The noise floor of 5GHz for channel bandwidth 160 MHz

$$\text{Noise floor } P_n \text{ [dB]} = -174 \frac{\text{dBm}}{\text{Hz}} + 10 \log_{10}(B) = -91.96 \text{ dBm}$$

The noise floor for 2.4 GHz for channel 40MHz



$$\text{Noise floor } PN_{[dB]} = -174 \frac{dBm}{Hz} + 10 \log_{10}(B) = -97.97 \text{ dBm}$$

Therefore, above results of Noise floor  $PN_{[dB]}$  the for 2.16GHz, 160MHz and 40MHz for the three frequencies substituting them to the equation (3.8 c) substituting into equation (3.9a) we find Sensitivity of the 60GHz, 5GHz and 2.4GHz frequency as follows:

For 60GHz 2.16GHz bandwidth receiver sensitivity

$$PS_{dBm} = -80.655 \text{ dBm} + NF_{dB} + \frac{E_b}{N_0}_{[dB]} + 10 \log_{10}(q) \quad (3.10a)$$

For 5GHz 0.16GHz bandwidth receiver sensitivity

$$PS_{dBm} = -91.97 \text{ dBm} + NF_{dB} + \frac{E_b}{N_0}_{[dB]} + 10 \log_{10}(q) \quad (3.10b)$$

For 5GHz 0.04GHz bandwidth receiver sensitivity

$$PS_{dBm} = -97.97 \text{ dBm} + NF_{dB} + \frac{E_b}{N_0}_{[dB]} + 10 \log_{10}(q) \quad (3.10c)$$

For noise factor  $NF_{dB}$  equals to 0 and for sensitivity power the SNR or  $E_b/N_0$  will depends up on channel Bandwidth for the same modulation schemes. Whereas, SNR also depends the distance between the transmitter and receiver. As a result, SNR of 60GHz is 120.65- Pl, for 5GHz is 121.96-Pl and for 2.4GHz is 127.97-Pl. to set the sensitivity, first we should have to get the probability outage of acceptable bit error rate  $E_b/N_0$  of each Modulation.

### Noise Figure $NF_{dB}$

The noise factor of a device is the amount of noise power that added to the desired signal, because of degrading quality. The noise factor F is defined as the ratio of noise power delivered by the noise component over the noise power delivered by the noiseless component whose input power is  $N_0 = kT_0B$ . Noise Factor F is the ratio of input signal power to noise ratio to the output signal power to noise ratio [32].

$$F = \frac{SNR_{in}}{SNR_{out}} \quad (3.11)$$

The Noise Figure in dB is the difference of the input  $SNR_{in}$  and the output  $SNR_{out}$  at room temperature and expressed as follows [32]

$$NF_{dB} = 10 \log_{10}(F) = SNR_{in} - SNR_{out} \quad (3.12)$$

Here in this thesis, we consider  $NF_{dB}$  zero for the simplicity of this work.

### 3.2. Channel Capacity

The performance of any wireless communications links are measured in terms of Channel Capacity, which are defined as the maximum rate at which the information's can transmit over a channel with arbitrarily the small number of errors. The Shannon-Hartley channel capacity theorem is typically used at the start of any waveform and link budget evaluation to offer the communication analyst an upper bound on the data rate for a given bandwidth B and signal to noise ratios (SNR) [19] that is shown in below figure 3.2. Achievable data rate, however, greatly depends on other parameters; we will see it in the next chapters. In Shannon-Hartley, consider a bandlimited Gaussian channel operating in the presence of additive Gaussian noise:

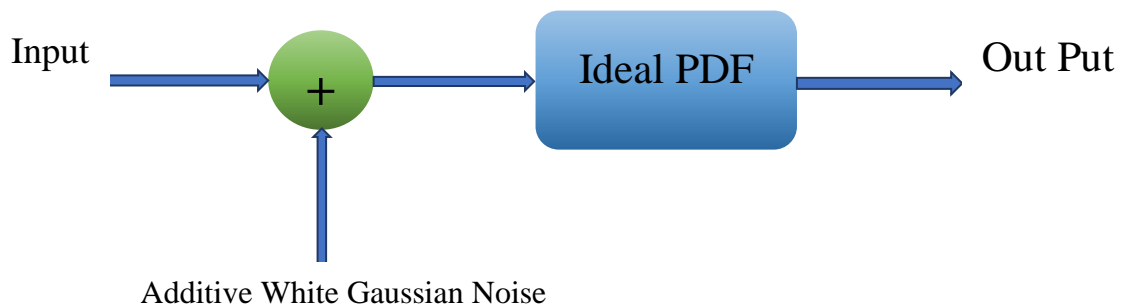


Figure 3.4 Shannon-Hartley Channel Capacity System Model [20]



The Shannon-Hartley theorem states that the channel capacity given by

$$C = B \log_2 \left( 1 + \frac{S}{N} \right) \quad (3.13)$$

Where C the channel capacity in bits per second, B is the bandwidth of the channel in Hertz and S/N is the signal-to-noise ratio [33] [4]

An objective in the communication system design is the ability to sending reliable information at the lowest practical power level. At the lowest available power level, the system should be able to provide acceptable bit-error-rate (BER) performance. Often, this performance is monitored in terms of BER versus  $E_b/N_0$ . The quantity  $E_b/N_0$  is called power efficiency, denoted as  $\eta_p$ . The ratio of signal energy per bit ( $E_b$ ) to noise power spectral density per bit ( $N_0$ ) necessary at the receiver input to achieve a specific BER is known as power efficiency [34]. Bit energy per thermal noise is defined as the below equation.

$$\eta_p = \frac{E_b}{N_0} \quad (3.14)$$

Where: -  $E_b$  signal energy per bit,  $N_0$  is Noise Power Spectral density per bit

### 3.3. Channel Modeling

Channel Model is a mathematical representation of the effect of a communication channel through which wireless signals propagate in space from the transmitter to the receiver in a form of electro magnetic radio frequency signal. Which attenuated due to the nature of the medium it passes. The channel models represent the power losses gained by signals as they pass through wireless mediums. Generally, Channel Modeling is categorized into two methods, which are the Analytical Channel Model and Physical channel model.



## Physical channel models

A physical channel model characterizes the radio path that connects the transmitter and receiver ends to define an environment. Physical Channel Model mostly model wave's propagation parameters such as Direction of Departure (DOD), Direction of Arrival (DOA), complex amplitude, and delay. Stochastic and deterministic models are the two classified parts of physical Channel Model. The deterministic modeling method as per the theory of electromagnetic wave propagation. Therefore, environmental-specific parameters are used to model the propagation channel [3] [17]. This method was subdivided into the three methods below. Closed-Form method, Empirical method and Ray-tracing-based deterministic modeling. Closed-Form method which is particularly; The two-path signal model is a simple closed-form modeling method that can be used to investigate several communication designs theoretically and analytically. However, in defining the realistic channel model environment under consideration, this strategy is conservative as well. An Empirical method, which is the empirical-based deterministic modeling method, channel parameters take out from environmental specifics measurement campaign data collected under study. This method provides more accurate channel propagation characteristics, but with increased data complexity. Several empirical models for the millimeter-wave spectrum, mostly in the 60 GHz band. The third one is Ray-tracing-based deterministic modeling, it is Ray-based solvers employ the identical theory of diffraction and finite-difference time-domain to create ray-tracing-based deterministic models, which are used to predict the accurate behaviors of electromagnetic waves Simulate power loss and shadowing effects along the ray paths. Proposed millimeter-wave the parameters of the radio channel, such as delay spread, angle spread, shadowing fading changes, and path loss exponents, can be resolute using 3D ray-tracing simulations. Some of the ray-



tracing based millimeter wave channels simulators are WinProp software, which offers simulations for frequencies up to 75 GHz, and Radio Access Network Plan Professional, which supports simulations in the frequency ranges of 100 MHz to 70 GHz [17].

### Analytical Channel Models

This channel model is divided into two main groups, that is, *correlation-based stochastic modeling and propagation models*.

#### Correlation-based stochastic modeling (CBSM)

The CBSMs are employed primarily for evaluating the theoretical performance of massive MIMO and XL-MIMO channels [35]. CBSM is less computationally complex than the Geometry Based Stochastic Model [36], but it is also more basic, making it ineffective for modeling accurate massive MIMO channels with spherical wave fronts. The non-dispersive independent identically distributed Rayleigh fading model, non-dispersive correlated channel models, and dispersive multipath-channel model are the three forms of CBSMs.

- A. Non-dispersive independent identical distributed Rayleigh fading model. All of the channel links are assumed to be uncorrelated in this model [17]. As a result, the components of the fast-fading channel matrix are distributed Gaussian variables that are independent and identical.
- B. Non-dispersive Correlated channel models. Because of its simplicity, it has been broadly used to quantify the Doppler-induced received signal correlation for massive MIMO channels. However, employing this basic model has resulted in unrealistic results related channel capacity. The Weichsel Berger model [37] and the Kronecker based stochastic



model [38] are two examples of this concept. For capacity evaluation of both low and high SNR systems, a Kronecker-based stochastic model was used;

- C. Dispersive multipath-channel model (DMPC). Multiple azimuth angles of arrival (AOA) (i.e., multiple independent paths) arriving from different user equipment can be supported by the dispersive MPC model of massive MIMO channel (UE) [17]. Path attenuation times the steering vector of an AOA is primarily used to characterize each individual path. As a result, UEs at various angular positions can be differentiated primarily based on their AOAs, allowing for analysis of inter-user interference (IUI) or inter-cell interference (ICI) performance.

### Propagation Models (PMs)

PMs use propagation parameters such the virtual channel representation model, maximum entropy model, and finite scattered model to characterize the MIMO channel matrix [19]. In general, the scattering geometry can be used to construct channel impulse responses (CIRs) using analytical channel models. Obtaining values for probability distribution parameters and testing models through channel measurement campaigns, however, remains important.

For Wireless channel to any model will have simplified and generally with transmitted signal  $S(t)$  and the received signal  $R(t)$  always there exist additive white Gaussian  $N(t)$ , and expressed as follows model as follows: [36] [27]

$$R(t) = S(t) + N(t) \quad (3. 15)$$

### Probability of bit error rate ( $P_{BER}$ )

Any wireless communication has limitation of link existence between the two or multiple ends connection. Therefore, to meet this requirement we should have to set the max bit error rate that

affect link. These probabilities of error parameter use for us to evaluate the performance the link with Rician fading. The BER for M-ary QAM modulation scheme is defined as [37]:

$$P_{BER} = \frac{4}{\log_2(M)} * \left(1 - \frac{1}{\sqrt{M}}\right) * Q\left(\sqrt{\frac{3\log_2(M)}{M-1} * \frac{E_b}{N_0}}\right) \quad \text{for } M > 1, N_0 \neq 0$$

3.16

Where  $P_{BER}$  Probability of bit error rate, M is modulation index,  $E_b/N_0$  signal to noise ratio and  $Q(x)$  is error function. This equation helps as to evaluate the relation of  $E_b/N_0$  versus Probability of BER. Which means for given or maximum BER set  $1*10^{-5}$  [38]

For above equation Q-function  $Q(x)$  is expressed as follows [39]

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt \quad (3.17)$$

Equation (3.21) by complementary error function  $erfc(x)$  [39] the integral part will be change as follows:

$$Q(x) = \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right) \quad (3.18)$$

Therefore, by substituting Q-function equation (3.18) in to equation (3.16)

$$P_{BER} = \frac{4}{\log_2(M)} \left(1 - \frac{1}{\sqrt{M}}\right) * \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right)$$

$$P_{BER} = \frac{2}{\log_2(M)} \left(1 - \frac{1}{\sqrt{M}}\right) * erfc\left(\frac{x}{\sqrt{2}}\right) \quad (3.19)$$

for  $M \geq 2$

Where  $x = \sqrt{\frac{3\log_2(M)}{M-1} * \frac{E_b}{N_0}}$

Using the equation (3.23) and by setting the value of  $E_b/N_0$  from 0 dBm to 30 dBm for Modulation  $M = [64 \ 128 \ 256 \ 512 \ 1024]$  of quadrature amplitude modulation scheme of BER probability of error for 2.4GHz, 5GHz and 60GHz frequency for evaluation of minimum value of  $E_b/N_0$  for data transmission guaranty or acceptable BER is less than or equal to  $1*10^{-5}$  [38].

Base on the maximum BER value  $1 \cdot 10^{-5}$  [38]. The minimum  $E_b/N_0$  and SRN as well as for given standard deviation of different environment, the minimum required A and k-factor values can be determined for each Modulation Scheme. And this gives get minimum channel capacity of the channel for each modulation scheme of the three frequency bands.

From equation (3.16) to (3.19) for the given Modulation scheme and BER the required  $E_b/N_0$  found either from probability of bit error rate MATLAB plot of using the invers Q-function.

For 64QAM modulation scheme  $BER=10^{-5}$ :

$$M = 64, \sqrt{M} = 8, \log_2(M) = 6$$

By substituting each value in equation (3.16)

$$P_{BER} = \frac{4}{\log_2(M)} * \left(1 - \frac{1}{\sqrt{M}}\right) * Q\left(\sqrt{\frac{3 \log_2(M)}{M-1}} * \frac{E_b}{N_0}\right)$$

$$10^{-5} = \frac{4}{6} * \left(1 - \frac{1}{8}\right) * Q\left(\sqrt{\frac{3*6}{64-1}} * \frac{E_b}{N_0}\right)$$

$$10^{-5} = \frac{7}{12} Q\left(\sqrt{\frac{18}{63}} * \frac{E_b}{N_0}\right)$$

For inverse  $Q(x)$  the approximate value is taken from inverse Q-function table.

$$Q^{-1}\left(\frac{P_{BER}}{\left(\frac{4}{\log_2(M)} * \left(1 - \frac{1}{\sqrt{M}}\right)\right)}\right) = \sqrt{\frac{3 \log_2(M)}{M-1}} * \frac{E_b}{N_0} \quad (3.20)$$

Using equation (3.20)  $E_b/N_0$  value evaluated as follows

$$Q\left(\sqrt{\frac{18}{63}} * \frac{E_b}{N_0}\right) = \frac{12}{7} * 10^{-5} = 1.71 * 10^{-5}$$

$$Q^{-1}\left(\sqrt{\frac{18}{63}} * \frac{E_b}{N_0}\right) = Q^{-1}(1.71 * 10^{-5}) = 3.04$$

Therefore,

$$\sqrt{\frac{18}{63} * \frac{E_b}{N_0}} = 4.1430$$



$$\frac{E_b}{N_o} = (4.1430)^2 * \frac{63}{18} = 60.075$$

$E_b/N_o$  dBm=10log ( $E_b/N_o$ )

$$\frac{E_b}{N_o} [dBm] = 10 * \log(60.07556) = 17.78dB$$

In the same way for 128QAM, 256QAM, 512QAM and 1024QAM

The minimum value of  $E_b/N_o$  became as follows:

For 128QAM:

$$\frac{E_b}{N_o} [dB] = 10 * \log(94.5587) = 19.76dB$$

For 256QAM:

$$\frac{E_b}{N_o} [dB] = 10 * \log(177.953) = 22.5dB$$

For 512QAM:

$$\frac{E_b}{N_o} [dB] = 10 * \log(313.383) = 24.96dB$$

For 1024QAM:

$$\frac{E_b}{N_o} [dB] = 10 * \log(558.8282) = 27.47dB$$

Using this  $E_b/N_o$  value of each modulation scheme the coverage distance, SNR and receiver sensitivity be evaluated in the next section.

## CHAPTER 4

### 4. System Model

Based on equation 3.13 for wireless channel when there is fading with strong dominant signal in addition to the multipath signals the mathematical model will be changed as follows for the transmitted signal  $S(t)$  and the receiver  $R(t)$

$$R(t) = H(t) \times S(t) + N(t) \quad (4.1)$$

Where  $H(t)$  the fading coefficient or slop of the transmitted signal. This coefficient  $H(t)$  varies for the existence of Line-of-sight dominant signal and  $N(t)$  Gaussian noise. When there is strong dominant LOS signal component exist, the fading channel became Rician, the Rician fading distribution, pdf of such function given by:

$$f_{(ric)} = \frac{r}{\sigma^2} e^{-\left(\frac{r^2+A^2}{2\sigma^2}\right)} I_0\left(\frac{Ar}{\sigma^2}\right), \quad r \geq 0, A \geq 0 \quad (4.2)$$

Where  $r$  is a random variable related to dominant amplitude,  $\sigma$  Variance of in-phase and quadrature components and  $A$  is Amplitude,  $I_0(x)$  is modified Bessel function of the zero-order [27].

#### Coverage model for WLAN

In coverage model the received power equation helps for the wireless system to determine the minimum receiving power and the maximum distance covered by the wireless system of communication which is given as follows in [7]:

$$Pr = Pt \frac{GtGr\lambda^n}{(4\pi d)^n}$$

$$Pr_{[dBm]} = Pt_{[dBm]} + Gt + Gr - Pl_{[dBm]} \quad (4.3)$$

Where  $Pr$  is Received power,  $Pt$  is Transmitted Power  $Gt$  Transmitter Gain,  $Gr$  Receiver Gain and  $Pl$  is path loss. The most common path loss model assumes a linear dependence (through

the path loss exponent  $n$ ) between the path loss, PL, in dB, and the logarithms of the distances as below equation (4.4) [40].

$$PL(d)[dB] = PL(d_0)[dB] + 10 * n * \log_{10} \left( \frac{d}{d_0} \right) \quad (4.4)$$

where  $PL(d_0)$  is the path loss at reference distance  $d_0$  in most cases the reference distance  $d_0 = 1m$  for 60GHz millimeter-wave [41]. In addition, the more generalized free space path loss includes the frequencies of the transmitted signal dependence as driven in the below equation (4.5).

$$PL(d)[dB] = PL(d_0)[dB] + 10 * n * \log_{10} \left( \frac{d}{d_0} \right) + 10 * n * \log_{10} \left( \frac{f}{f_0} \right) \quad (4.5) [40]$$

Base on the equations 3.1 and 4.5 for free-space path loss exponent  $n = 2$ . Free Space path loss [FSPL] [18] [17] the distance in meter and the carrier frequency in Hz looks below equation 4.6.

In other way  $Pr$  is equal to the product of received bit energy  $E_b$  and bit rate  $R_b$

$$Pr = \frac{E_b}{N_o} * R_b * N_o \quad (4.6a)$$

Then substitute (\*) into equation (4.6a)

$$Pr = \frac{E_b}{N_o} * N_o * 2 \log_2(M) \quad (4.6b)$$

From equation (4.3c) for each modulation scheme and to its specific  $E_b/N_o$  obtained by equation (3.20) in the previous chapter 3 now received power is found.

For 64QAM:

$M=64$ ,  $E_b/N_o = 17.78dB$ , and  $N_o = -174dBm$  or  $-204dB$ . therefore,

$$Pr[dB] = \frac{E_b}{N_o} + N_o + 10 \log_{10}(2 * \log_2(M))$$

$$Pr = 17.78 - 204 + 10 \log_{10}(2 * \log_2(M64))$$

$$Pr = 17.78 - 204 + 10 \log_{10}(12)$$



$$Pr = 17.78 - 204 + 10.79 \text{ dB}$$

$$Pr = -175\text{dBw or } -145\text{dBmwatt}$$

To get the distance it requires transmission power Pt. This Pt is different for different frequency it is varies according to the gain applied to the system. Therefore, first getting Pr for all modulation is better.

For 128QAM:

M=128, Eb/No=19.76dB and No =-174dBm or -204dB

$$Pr = 19.76 - 204 + 10\log_{10}(14)$$

$$Pr = 19.76 - 204 + 10\log_{10}(14)$$

$$Pr = -172.78 \text{ dBw or } -142.78\text{dBmw}$$

Pr evaluated for reaming modulation scheme as done two previous done.

For 256MAM:

Pr= -169.46dBw or -139.46dBmw

For 512QAM:

Pr=-166.49dBw or -136.49dBmw

For 1024QAM:

Pr=-163.52dBw or -133.52dBmw

The free space path loss

$$FSPL_{[dBm]} = 20\log_{10}\left(\frac{4\pi}{c}\right) + 20\log_{10}(f_{(Hz)}) + 20\log_{10}(d_{(m)}) \tag{4.7}$$

From the above equation, we can drive free space path loss for each carrier frequency which we compare in this thesis and we change the frequency in Hz to GHz and we will get the below equation (4.7b)

$$FSPL_{[dBm]} = 20\log_{10}\left(\frac{4\pi}{c}\right) + 20\log_{10}10^9 + 20\log_{10}(f_{(GHz)}) + 20\log_{10}(d_{(m)}) \quad (4.7b)$$

$$FSPL_{[dBm]} = 32.44 + 20\log_{10}(f_{(GHz)}) + 20\log_{10}(d_{(m)}) \quad (4.8)$$

➤ For 60 GHz free space became as follows

$$FSPL_{[dBm]} = 32.44 + 20\log_{10}(60_{(GHz)}) + 20\log_{10}(d_{(m)})$$

$$FSPL_{[dBm]} = 68.00 + 20\log_{10}(d_{(m)}) \quad (4.7)$$

➤ For 5 GHz free Space

$$FSPL_{[dBm]} = 32.44 + 20\log_{10}(5_{(GHz)}) + 20\log_{10}(d_{(m)})$$

$$FSPL_{[dBm]} = 46.42 + 20\log_{10}(d_{(m)}) \quad (4.8)$$

➤ For 2.4 GHz free Space

$$FSPL_{[dBm]} = 32.44 + 20\log_{10}(2.4_{(GHz)}) + 20\log_{10}(d_{(m)})$$

$$FSPL_{[dBm]} = 40.04 + 20\log_{10}(d_{(m)}) \quad (4.9)$$

But for different scenarios equation 4.4 will be changed as follows due to different radio propagation characteristics', since its value or result depends on the distance exist between the transmitter and the receiver for given 60GHz. In [18] the path loss with variable the path loss exponent for large scale (for long normal).

$$PL = PL_0 + 10n\log\left(\frac{d}{d_0}\right) + S \quad (4.10)$$

Where  $d_0$  (m) is the free-space reference distance and  $S$  denotes log-normal shadowing associated with a standard deviation of  $\sigma$ . Furthermore,  $PL_0$  indicates the reference free-space loss at distance  $d_0$  and  $n$  is the path-loss exponent. Regardless of the shadowing parameter  $S$ , (4.7) describes the power attenuation of the transmitted signal at distances  $d$  and  $d_0$ . The path-loss equation of (4.7) has many extensions. The shadowing  $S$ , on the other hand, describes the power fluctuations caused by large obstructing objects, like as buildings, around the basic linear depiction of the PL. The path loss exponent specifies the slope of the path-loss as a fraction of the distance, and it varies depending on the scenario in concern, such as LOS and NLOS. In the



absence of multipath reflections, a LOS link has a smaller path loss, resulting in lower path loss exponent values between the transmitter and receiver. In an NLOS scenario, however, the path-loss is substantially greater than in a LOS scenario, because the LOS channel between the communicating nodes is blocked, and the received signals are mostly produced by reflected or scattered multipath components. In Table 4.1 lists the values of n, which were derived empirically from measurements in these frequency bands.

To get specific received level for given BER and  $E_b/N_0$  found from equation (3.20) and applying

Table 4.1 Parameter for SNR versus distance of 60GHz, 5GHz and 2.4GH for higher MQAM's

No	Parameters	Frequency								
		60GHz			5GHz			2.4GHz		
1	Transmission power in dBm [5] [42]	40	37	34	29	29	26	36	30	27
2	gain in dBm [5] [42]	0	6	9	0	6	9	0	6	9
3	Bandwidth	2.16GHz			160MHz			40MHz		
4	Modulation	M = [64 128 256 512 1024]			M = [64 128 256 512 1024]			M = [64 128 256 512 1024]		
5	Distance in meter	0 to 100m								
6	Thermal noise	-174dBm or -204dB								
Required Parameter										
1	SNR relative to									
2	Relative distance									

Finally, to determine the distance between each frequency with different  $P_t$  and the same antenna gain for BER limit settled by using the parameter table 4.1.

For 60GHz frequency for initial step transmitter as well as receiver having unit gain which means 0dB and its  $P_t=40dBm$  first we find at  $d_0=1m$  for  $n=2$  as per equation (4.1) and (4.4)



$$Pr = Pt \frac{GtGr\lambda^n}{(4\pi d)^n}$$

$$Pr = Pt[dBm] + Gt + Gr + 20 \log(\lambda) - 20 \log(4\pi(do))$$

$$Pr [do] = Pt[dBm] + Gt + Gr + 20 \log(\lambda) - 20 \log(4\pi(do))$$

$$Pr [1m] = 40dBm + 0 + 0 + 20 \log(0.005) - 20 \log(4\pi(1m))$$

$$Pr [1m] = 40dBm - 46.02 - 21.98$$

$$Pr[1m] = -28dBmw \text{ or } -58dBw$$

For Pt=37dBm at do=1m and Gt=Gr=6dBm

$$Pr[1m] = -19dBmw \text{ or } -49dBw$$

For Pt=34dBm at do=1m and Gt=Gr=9dBm

$$Pr[1m] = -16dBmw \text{ or } -46dBw$$

This result is for 60GHz and for 5GHz as well as 2.4GHz do found in the same way of the above.

For 5GHz: Pt =29dBm, Gt=Gr=0dB, n=2

$$Pr [do] = Pt[dBm] + Gt + Gr + 20 \log(\lambda) - 20 \log(4\pi(do))$$

$$Pr [1m] = 29dBm + 20 \log(0.06) - 20 \log(4\pi(1m))$$

$$Pr[1m] = -17.42dBmw \text{ or } 47.42dBw$$

For 5GHz: Pt = 29dBm, Gt=Gr=6dB, n=2

$$Pr[1m] = -5.42dBmw \text{ or } -45.42dBw$$

For 5GHz: Pt = 26dBm, Gt=Gr=9dB, n=2

$$Pr[1m] = -2.42dBmw \text{ or } -32.42dBw$$

For 2.4GHz: Pt =36dBm, Gt=Gr=0dB, n=2

$$Pr [do] = Pt[dBm] + Gt + Gr + 20 \log(\lambda) - 20 \log(4\pi(do))$$



$$Pr [1m] = 36dBm + 20 \log(0.125) - 20\log (4\pi(1m))$$

$$Pr[1m] = 8dBmw \text{ or } -22dBw$$

For 2.4GHz: Pt 30dBm, Gt=Gr=6dB, n=2

$$Pr[1m] = 2dBmw \text{ or } -28dBw$$

For 2.4GHz: Pt 27dBm, Gt=Gr=9dB, n=2

$$Pr[1m] = -13dBmw \text{ or } -43dBw$$

Noise Power -

Noise power in the receiver is usually denoted by thermal noise generated in the frontend receiver amplifier. The noise power can be determined as follows:

$$P_n = FkT_0B \tag{4.11}$$

Where: F is received noise figure, T<sub>0</sub> is reference receiver temperature in degree Kelvin (290) , k is, Boltzmann’s constant which is 1.38\*10<sup>-23</sup> Joules/Kelvin and B is the receiver bandwidth

### Channel Capacity Model for WLAN

Based on Shannon Capacity Theorem the channel Capacity of the system is the product of Bandwidth with logarithm to base 2 of one plus the signal to noise ratio [4].

$$C = B \log_2(1 + SNR) \tag{4.12a}$$

Where C is channel Capacity in bit per second, B is the bandwidth of the channel in hertz; S/N is Signal to Noise. In this case, for higher SNR the channel capacity increases, or if Noise increases highly the channel capacity decrease. In addition to this as the bandwidth increase,



the channel capacity also increases in contrary while bandwidth decrease channel capacity decrease. In other form the SNR expressed in terms of received power Pr and noise power Pn.

$$SNR = Pr - Pn [dBm] \tag{4.13}$$

$$SNR = \frac{Eb}{N0} * 2 * \log_2(M)$$

For this thesis to get channel capacity for each frequency with the higher modulations MQAM's using equation (3.8a) and (\*) performed as follows.

First the SNR value in the form of Eb/No and modulation level or scheme.

$$C = B \log_2(1 + SNR)$$

$$C = B \log_2(1 + (\frac{Eb}{N0} * \frac{Rb}{B}))$$

$$C = B \log_2(1 + (\frac{Eb}{N0} * 2 * \log_2(M))) \tag{4.14}$$

Second the SNR value in the form of Rician k-factor and standard deviation as per equation)

To evaluate channel capacity for each frequency using the following parameters in the table below table 4.2.

Table 4.2 Parameter used to get channel capacity of for Rician channel fading over different frequency bands for higher modulation MQAM's.

Given Parameters		
1	Modulation MQAM	M= [64 128 256 512 1024]
2	Bit per symbol	q = [6 7 8 9 10]
3	frequency	60GHz, 5GHz and 2.4GHz
4	Bandwidth	2.16GHz, 0.16GHz and 0.04GHz
5	Eb/No	0 to 25dBm
7	No	-174dBm of or $3.981 * 10^{-18}$
Required parameters		



1	Eb/No Correspond to BER $1 \cdot 10^{-5}$ [38] for each modulation scheme	
2	Minimum SNR	

The maximum signal power of the three frequency bands, which we will compare in this thesis 2.4GHz, 5GHz, and 60GHz according to different regulatory bodies we can see with different environments indoor cases and outdoor cases in the below tables.

FCC Rules and regulation of 2.4GHz for Point to Multipoint transmission the Maximum transmission is 36dBm = 4 watt for wireless equipment such as wireless access point, router, or bridge. This thesis the work focusses on the point-to-Multipoint transmission of frequency band regulation since we are considering at least there exists a movement either the transmitter or the receiver of the WLAN system that will be exposed to different fading effects.

Table 4.3 FCC 2.4GHz Band maximum Transmission power regulation for point to multi point [42]

Maximum Power from International Radiator	Maximum Antenna gain (dBi)	EIRP [dBm]	EIRP [watt]
30dBm or 1watt	6	36dBm	4watt
27dBm or 500mW	9	36dBm	4watt
24dBm or 250mW	12	36dBm	4watt
21dBm or 125mW	15	36dBm	4watt
18dBm or 63mW	18	36dBm	4watt
15dBm or 32mW	21	36dBm	4watt
12dBm or 16mW	24	36dBm	4watt



According to FCC rules and regulations for 2.4GHz point-to-point transmission, the maximum transmission for every 1dBi of international radiator wireless devices, such as a wireless access point, router, or bridge, is reduced below the initial 30dBm, while the antenna gains increase from 6dBi to 30dBi.

Table 4.4 FCC 2.4GHz Band rules maximum Transmission power regulation for point to point [42]

Maximum Power from International Radiator	Maximum Antenna gain (dBi)	EIRP [dBm]	EIRP [watt]
30dBm or 1watt	6	36dBm	4watt
29dBm or 800mW	9	38dBm	6.3watt
28dBm or 630mW	12	40dBm	10watt
27dBm or 500mW	15	42dBm	16watt
26dBm or 400mW	18	44dBm	25watt
25dBm or 316mW	21	46dBm	39.8watt
24dBm or 250mW	24	48dBm	63watt
23dBm or 200mW	27	50dBm	100watt
22dBm or 160mW	30	52dBm	158watt

Table 4.5 FCC 5GHz Band and rules for point to point and point to multipoint transmission power for indoor and outdoor cases [42]

Band	Frequency (GHz)	Channels	Permitted use location	Point to Point maximum international radiator power	Point to point-max EIRP	Point to multipoint maximum international radiator power	Point to multipoint max EIRP



UNII (low)	5.15 – 5.25	36, 40, 44, 48	Indoor only	16dBm 40mW	22dBm 160mW	16dBm 40mW	22dBm 160m
UNII-2 (middle)	5.25 – 5.35	52, 56, 60, 64	Indoor or outdoor	23dBm 200mW	29dBm 800mW	23dBm 200mW	29dBm 800m
UNII-2 Extended	5.470 – 5.725	100, 104, 108, 112, 116, 120, 124, 128, 132, 136, 140	Indoor or outdoor	23dBm 200mW	29dBm 800mW	23dBm 200mW	29dBm 800m
UNII-3 (upper)	5.725 – 5.825	149, 161	Typical outdoor	Antenna to 23dBi	200watt	29dBm 800mW	35dBm 3200mW

Fixed point-to-point in the UNII3 band can use directional antennas with a gain of up to 23dBi without reducing the RF output power of the Intentional Radiator, as shown in table 4.4. For every 1dBm increase in antenna gain above 23dBi, a 1dB reduction is required.

Thermal Noise power

$$N_0 = kT \tag{4.20}$$

Where  $N_0$  Noise Power Spectral density, where  $k$  Boltzmann Constant which is  $1.38 \times 10^{-23} \text{J/K}$  and  $T$  environmental temperature which is 290 Kelvin. Moreover, the  $P_n$  noise power is

$$P_n = N_0 B$$

$$N_{[\text{dBm}]} = -174 \text{dBm} + 10 \log_{10} (B) \text{ dBm}$$

Where  $P_n$  Noise power  $B$  bandwidth  $N_0$  Thermal Noise Power



Where  $N_{0[dBm]} = 10\log_{10}(kT*1000) = -174dBm$

### 4.1 60 GHz Channelization

According to different IEEE 802.15.3C and IEEE 802.11 ad [43] [44] we see that the channel bandwidth 2160MHz with four non-overlapping channels 57.24 – 59.4, 59.4 – 61.56, 61.56 – 63.72, and 63.72 – 65.88 GHz. Having three different Modulation and Coding Schemes (MCS)  
 1. Single Carrier MCS 2. OFDM MSC and 3. Control MCS. A common forward error correction is used for all MCS's. In the below table we can see the summarized Modulation Schemes, Code rate, and physical rate.

Table 4.6 The three Modulation Code Schemes and their Modulation, Code rate and Physical rate of IEEE 802.11 ad

MCS	Modulation	Code rate	Physical rate
SC MCS	$\pi/2$ BPSK	$\frac{1}{2}$	385 Mbps to 4620 Mbps
	$\pi/2$ QPSK	$\frac{5}{8}$	
	$\pi/2$ 16QAM	$\frac{3}{4}$ $\frac{13}{16}$	
OFDM MCS	Spread QPSK	$\frac{1}{2}$ $\frac{5}{8}$ $\frac{3}{4}$ $\frac{13}{16}$	693 Mbps to 6756.75 Mbps
	QPSK		
	16QAM		
	64QAM		
Control MCS	$\pi/2$ DBPSK	$\frac{1}{2}$ (Spreading factor of 32)	27.5 Mbps



## CHAPTER 5

### 5. Result and Discussion

Based on the objectives what will be done in this thesis are result evaluation and discussion. In 5.1. Coverage evaluation of 60GHz, 5GHz and 2.4GHz frequency over Rician fading channels. In 5.2. Simulate the path loss of 60GHz millimeter-wave frequency with the Rician fading channel model. In 5.3. Capacity calculation of 60GHz millimeter-wave frequency for the Rician fading channel model for M-ary QAM. In 5.4 comparing the channel capacity of 60GHz with 2.4GHz and 5GHz radio frequencies by using models described in the methodology in section 5.3

#### 5.1. Coverage evaluation of 60GHz, 5GHz and 2.4GHz frequency over Rician fading channels

For the 60GHz millimeter wave will be done using equations (4.6) and (4.7). First, by considering the different regulatory bodies of the Transmission power or signal for all three frequencies we can evaluate not only the 60GHz millimeter-wave frequency but also 2.4GHz and 5GHz band frequencies with path loss exponent  $n=2$  conditions as well as without Rician fading using table 4.4 and 4.6. And using the MATLAB code in the appendix A code 1. And the result is shown in figure 5.1.

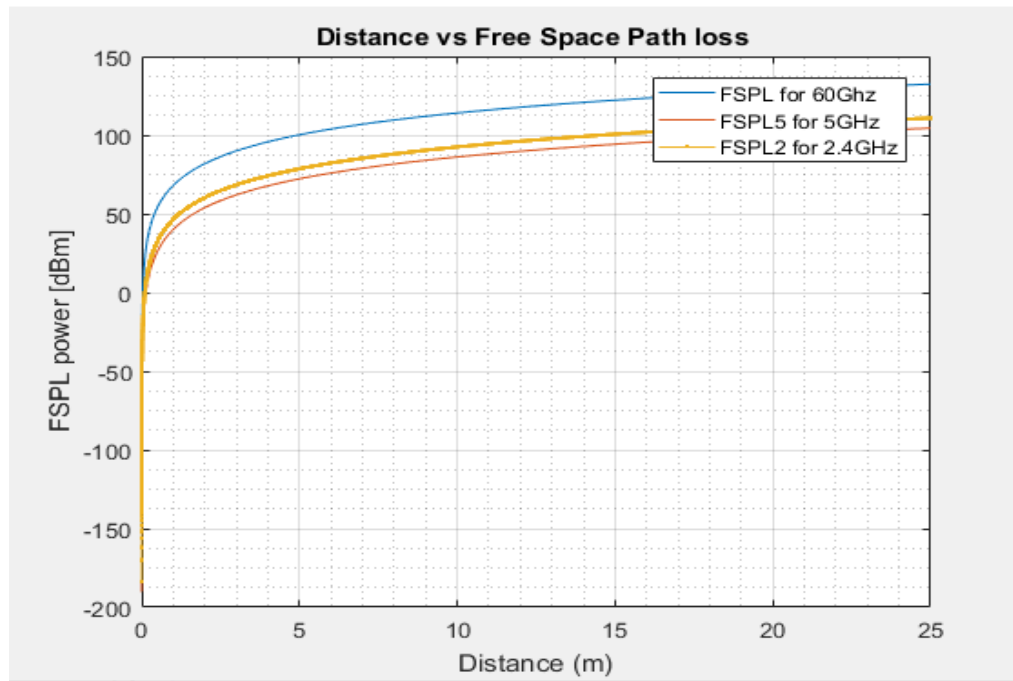
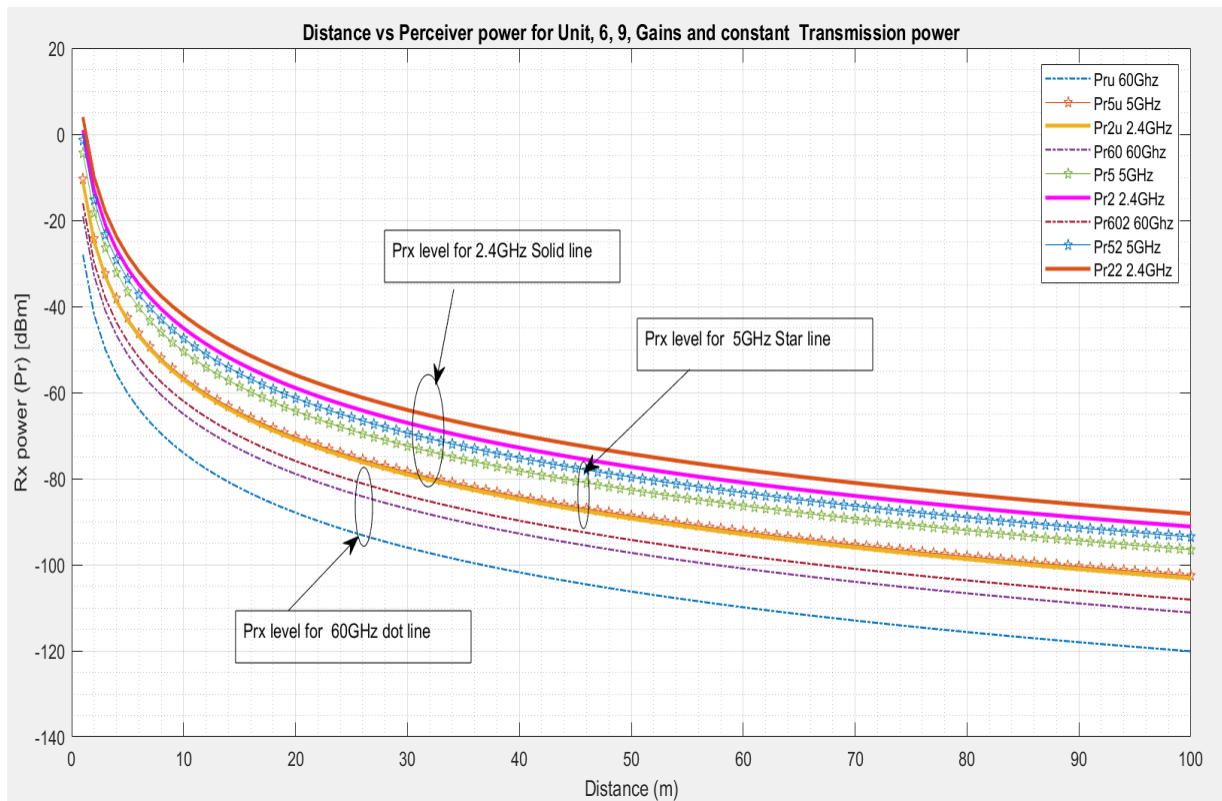


Figure 5.1 Free Space Path Loss of 2.4GHz, 5GHz, and 60GHz frequency bands

In figure 5.1 when a distance increases the higher frequency has higher free Space path loss than the lowers frequency. Therefore, to overcome this loss using antenna gain is a solution. The next result shows how this loss reduced by using the parameter given in table 4.1, equation (4.3) and MATLAB in appendix A code 3. Whose result is shown in figure 5.2.



## 5.2 Distance versus Received power for different frequency and different antenna gains

In the above figure 5.2 result shows Rx power level of 60GHz, 5GHz, and 2.4GHz frequencies without antenna gain and with different antenna gains. The result shows three selected frequencies for their recommended Maximum EIRP Transmitter powers and transmitter and receiver gains of 0dB, 6dB, and 9dB. There are higher losses in all frequency for 0dB gain. When the gain increases by 6dB on both transmitter and receiver side received level shows change for all frequency. From the plot at 20 meters. For 60GHz the change shows that 9 dB and 12dB from 0dB to 6dB gains change, and 0dB to 9dB gains change respectively. For 5GHz the level shows 6.65dB and 9.48dB for 0dB to 6dB gains change, and from 0dB to 9dB gains change respectively. For 2.4GHz is 12dB and 15dB from 0dB to 6dB gain change and 0dB to 9dB gain changes respectively. When we change the transmitter and receiver gain by reducing the transmitted power our receiving level increases. This condition is varying according with different environment where the transmitter and receiver exist. Due to this, the path loss

exponent varies according to the table 4.1. As the path loss exponent varies the path loss of the selected frequency are varies when the value of path loss increases the path loss and when the path loss exponent decreases the path loss decrease. For the existence of LOS between the transmitter and receiver, there should be one dominant signal rather than a multipath component of the signal that arrives at the receiver. As we have seen in section 4 of this work k-factor or the slop of the signal used to determine the existing dominant component impacts on the received signal.

### 5.2 BER versus Eb/No analysis for wireless system of over Rician channel fading

For BER evaluation based on chapter 3 of probability of BER equation (3.23), the parameter table 4.2 and MATLAB code in appendix A code 2. The maximum BER value which is guarantee for wireless communication between devices BER  $1 \times 10^{-5}$  [38]. And the corresponding minimum value of Eb/No for different modulation scheme of MQAM is shown in MATLAB simulation result of figure 5.3 below.

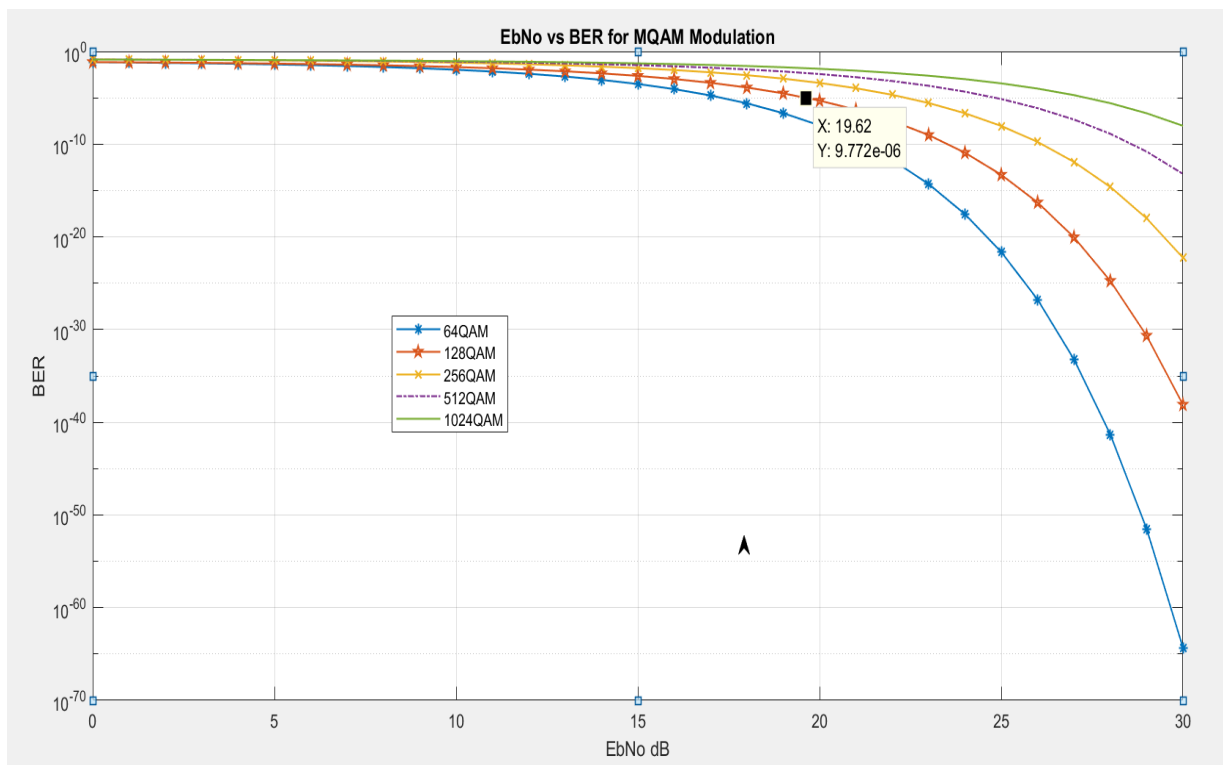


Figure 5.3 BER versus Eb/No for MQAM for Rician Fading channel



As we see in figure 5.3 for Rician MQAM modulation the BER decrease as  $E_b/N_0$  increase. For wireless system operation less than BER  $10^{-5}$ . The required  $E_b/N_0$  will be 6.55dBm for 64QAM, 8.16dBm for 128QAM, 10.34dBm for 256QAM, 12.26dBm for 512QAM and 14.33dBm for 1024QAM. As modulation level increases the receiver level increase. To use this Rician channel fading with higher modulation schemes the communication system should have to use above the minimum  $E_b/N_0$ . Using equation (3.8a) the minimum SNR for each modulation evaluated from MATLAB result above figure 5.3. In addition to this the using equation (3.10a to 3.10c) the sensitivity of each frequency evaluated. Table 5.1 shows  $E_b/N_0$ , SNR and sensitivity of for each Modulation.

Table 5.1 MATLAB result for minimum  $E_b/N_0$ , minimum SNR and receiver sensitivity for BER  $1 \times 10^{-5}$  for higher modulation scheme

Modulation (M)	BER	$E_b/N_0$ dBm	SNR dBm	Sensitivity dBm for 60GHz	Sensitivity dBm for 5GHz	Sensitivity dBm for 2.4GHz
64	$1 \times 10^{-5}$	17.78	28.57	-52.08	-63.39	-69.39
128	$1 \times 10^{-5}$	19.76	31.22	-49.43	-60.75	-66.75
256	$1 \times 10^{-5}$	22.5	34.54	-46.11	-57.42	-63.42
512	$1 \times 10^{-5}$	24.96	37.51	-43.14	-54.46	-60.46
1024	$1 \times 10^{-5}$	27.47	40.48	-40.17	-51.49	-57.49

In table 5.1 seen that minimum  $E_b/N_0$  or minimum SNR require to provide WLAN service for different modulations schemes increases and modulation scheme increase. In addition, sensitivity increases as modulation increases. As a result, the coverage distance became small. To increase the coverage and as well as the throughput capacity it needs higher SNR or  $E_b/N_0$  for all modulation scheme types. As we have seen figure resulting SNR below the point in the table the communication of data became down because of either the distance between the



transmitter and receiver or transmitted power and/or either transmitter/ receiver gains. Therefore, here we see the SNR and distance relation for three frequencies by using the following equations (3.7b, 3.7c, and 4.20).

Which is

$$SNR[dBm] = Pt[dBm] + Gt[dBm] + Gr[dBm] - PL(d)[dBm] - (10 \log_{10}(KT) [dBm] + 10 \log_{10}(B)[dBm] + NF[dBm])$$

Where the thermal noise  $N_0 = -174$ dBm. And using parameters in table 4.1 the minimum SNR versus distance for each frequency bands and respective modulation scheme relating to MATLAB result table 5.1.

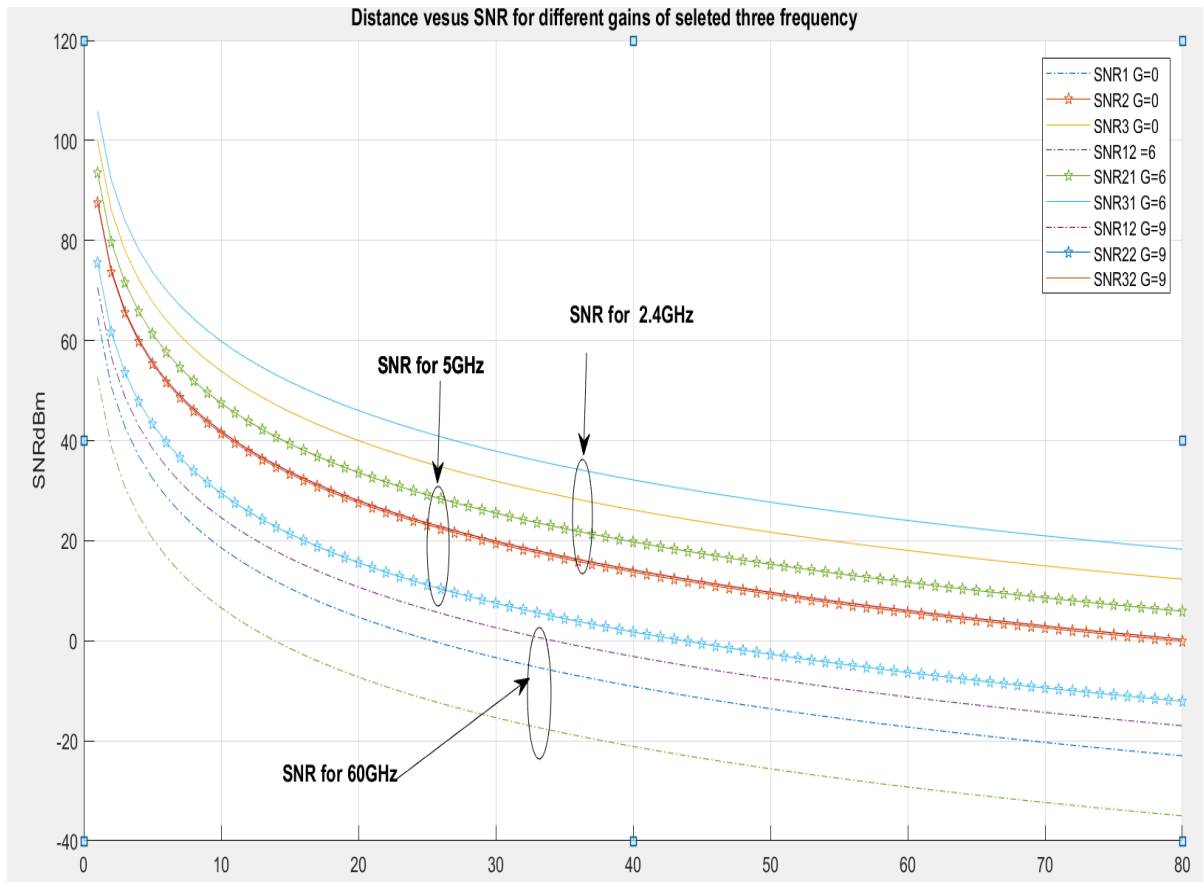


Figure 5.4 SNR versus distance for 60GHz, 5GHz and 2.4GHz

From figure 3.4 as seen the relation between SNR and distance shows as distance increase the SNR decreases and with different antenna gains SNR decreasing rate decreased all frequencies. For more detail table 5.2 shows all relations.

Table 5.2 the maximum limit of distance for minimum SNR value of each modulation with different antenna gains

	Modulation for 60GHz					Antenna Gain
	64QAM	128QAM	256QAM	512QAM	1024QAM	
SNR	17.33	19.63	22.37	24.82	27.34	0dBm
Distance 1	5.86m	5.23m	4.5m	4.02m	3.58m	6dBm
Distance 2	10.67m	9.5m	8.33m	7.35	6.45m	



Distance 3	14.4m	13.1m	11.2m	9.9m	8.73	9dBm
	Modulation for 5GHz					Gain
	64QAM	128QAM	256QAM	512QAM	1024QAM	
SNR	17.33	19.63	22.37	24.82	27.34	0dBm
Distance 1	18.4m	16.35m	14.33m	12.6m	11.14m	
Distance 2	33.5m	30.25m	26m	23m	20.3m	6dBm
Distance 3	45.2m	40.1m	35m	31m	27.4m	9dBm
	Modulation for 2.4GHz					Gain
	64QAM	128QAM	256QAM	512QAM	1024QAM	
SNR	17.33	19.63	22.37	24.82	27.34	0dBm
Distance 1	34.43m	33.5m	26.6m	23.5m	20.8m	
Distance 2	62.1m	56.4m	48.4m	43m	27.3m	6dBm
Distance 3	84.1m	74.85m	65.5m	57.7m	50.09m	9dBm

In the above simulation result figure 5.4 and table 5.4 of SNR versus distance it shows while gain increase from 0dB to 9dB the coverage distance increases proportionally whereas distance increase the SNR decreases inversely for each modulation system even if they have differences. For example, for highest M = 1024 of 60GHz during the first where gain is 0dB and transmission power  $P_t=40\text{dBm}$  as taken from parameter table 4.1 the distance to reach the minimum SNR for 27.34dBm table 5.2 results gained for BER is 3.58m. While the gain increase by 6dB on both side of transmitter and receiver the distance became 11.14m which shows that the distance increased by 7.56m. When gain increased by 9dBm and the transmission power reduced to 34dBm to keep the maximum EIRP regulation allowed by regulatory body the distance became 20.8m. The distance difference is 17.22m. This shows that stile increasing gain for 60GHz

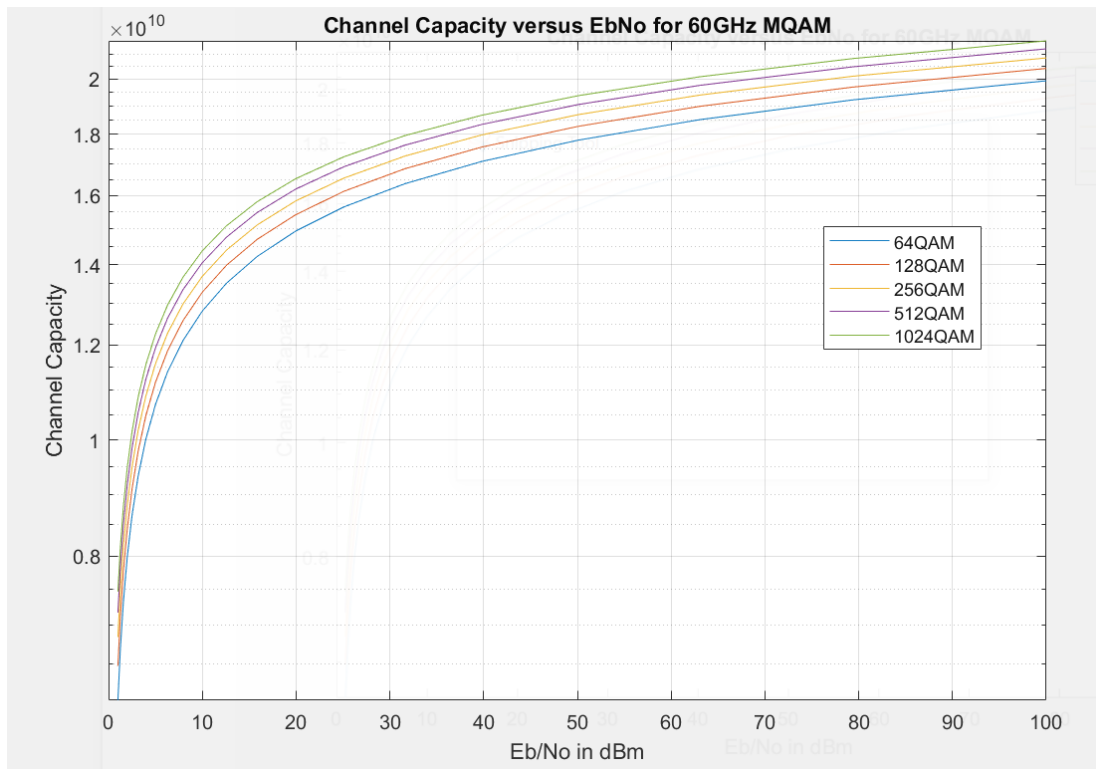


allows the system to cover more area. In the same way for 5GHz increasing antenna gain of the wireless system of its high modulation shows the distance increases from 6.45m to 20.3 for 6dB gain and from 6.45m to 27.3m for 9dB gain from this the differences are 13.85m and 20.83m respectively. For 2.4GHz the distance increases from 8.73m to 27.4m for 6 dB gain and from 8.73 to 50.09m. The difference of distance due to gain variation is 18.67m and 42.17m. when it seen 2.4GHz has high variation in distance with an increase of gain.

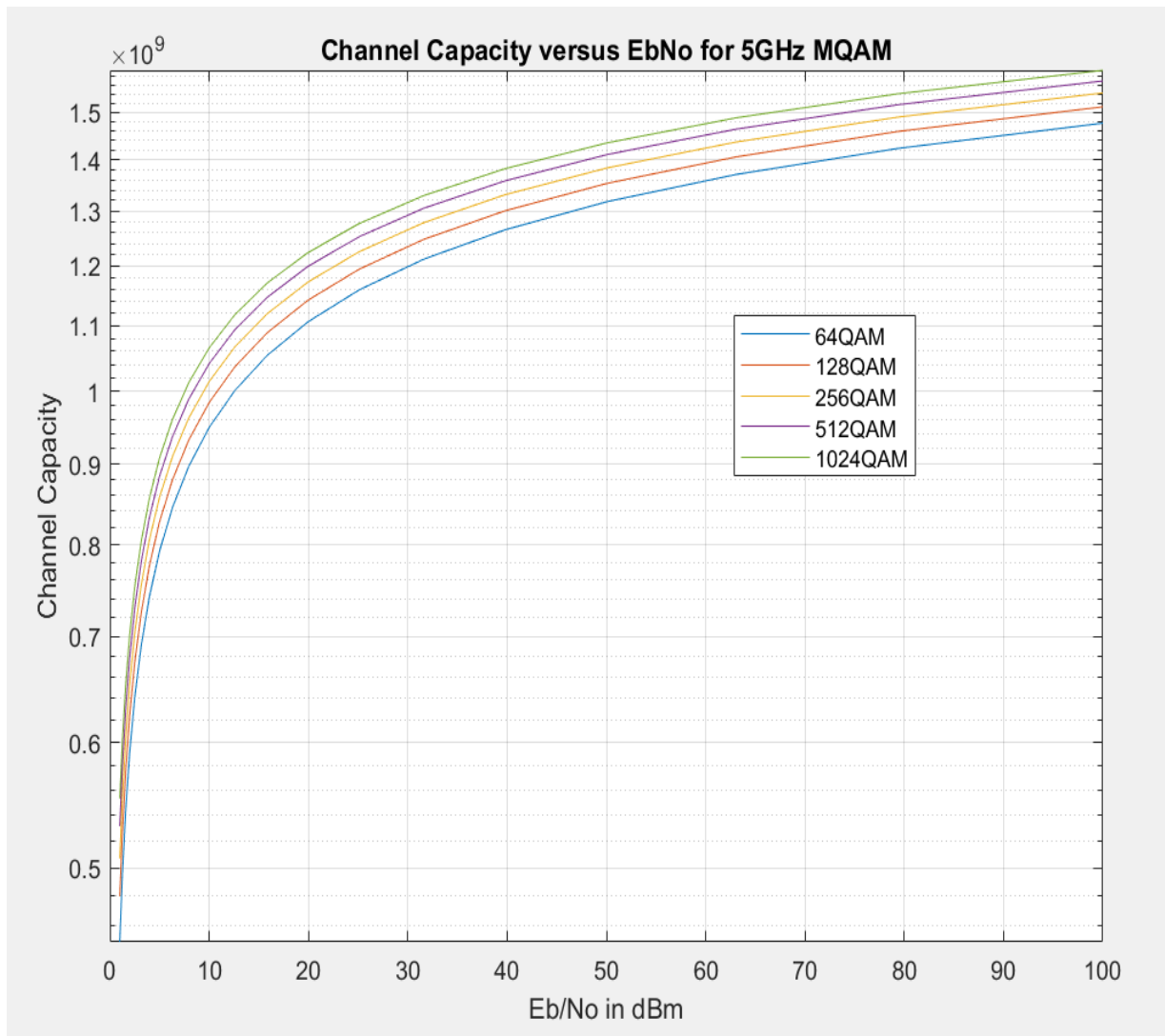
### 5.3. Capacity evaluation of 60GHz, 5GHz, and 2.4GHz over Rician fading channel for different modulation schemes of MQAM

As per Shannon Hartley channel capacity theory described in chapter 3 and 4, here evaluated using equation (3.13) and the receiver sensitivity equation of (3.11). And converting SNR in the form of  $E_b/N_0$  and modulation schemes as per equation (4.14). As well as using parameter table 4.3.

Based on the parameter table 4.3 and equation (4.14) the following MATLAB results shows how the capacity of the three frequencies with their respective bandwidth and the higher modulation schemes.



5.5 Channel capacity versus  $E_b/N_0$  for 60 GHz different modulation scheme of QAM



5.6 Channel capacity versus  $E_b/N_0$  for 5 GHz different modulation scheme of QAM

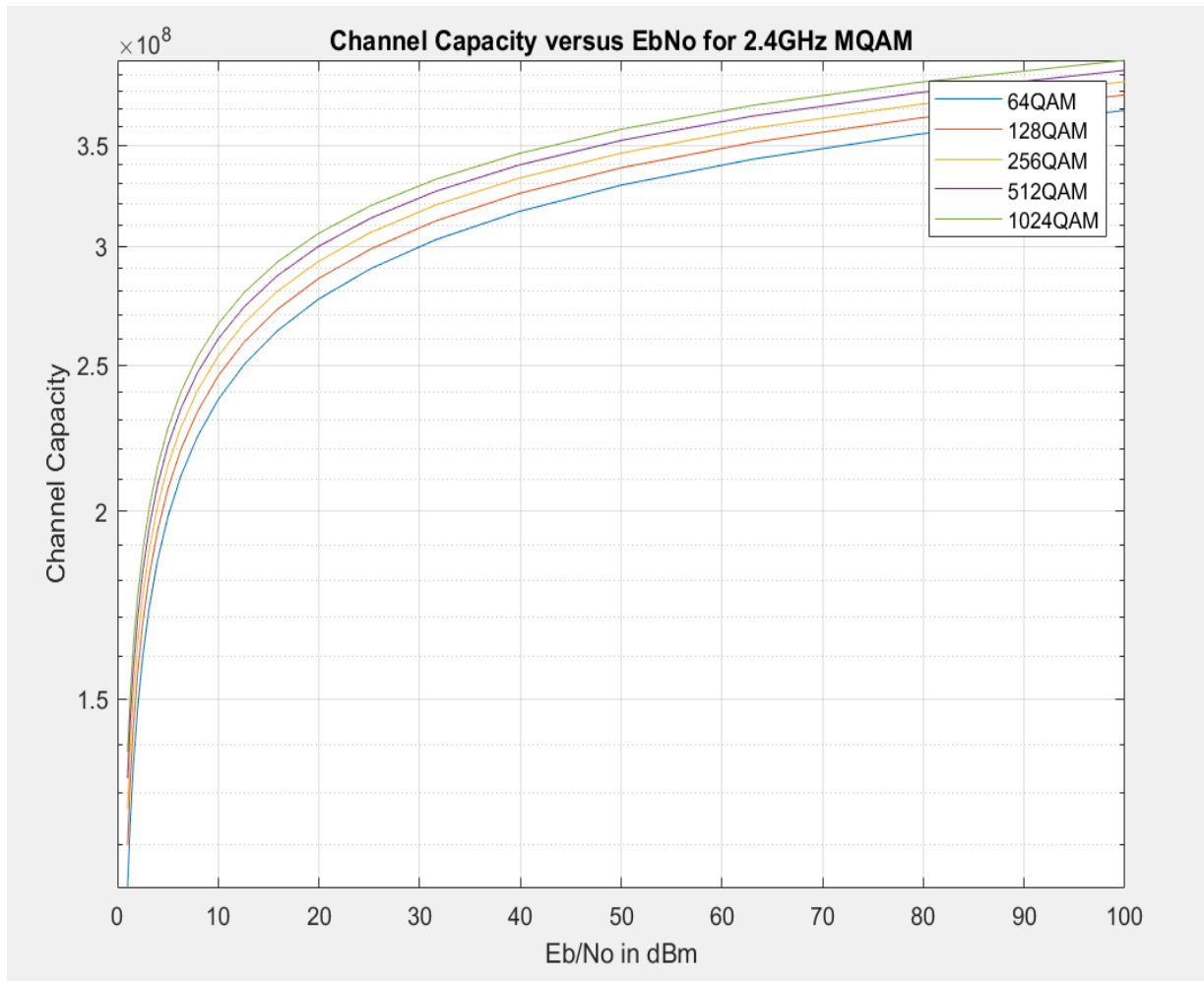
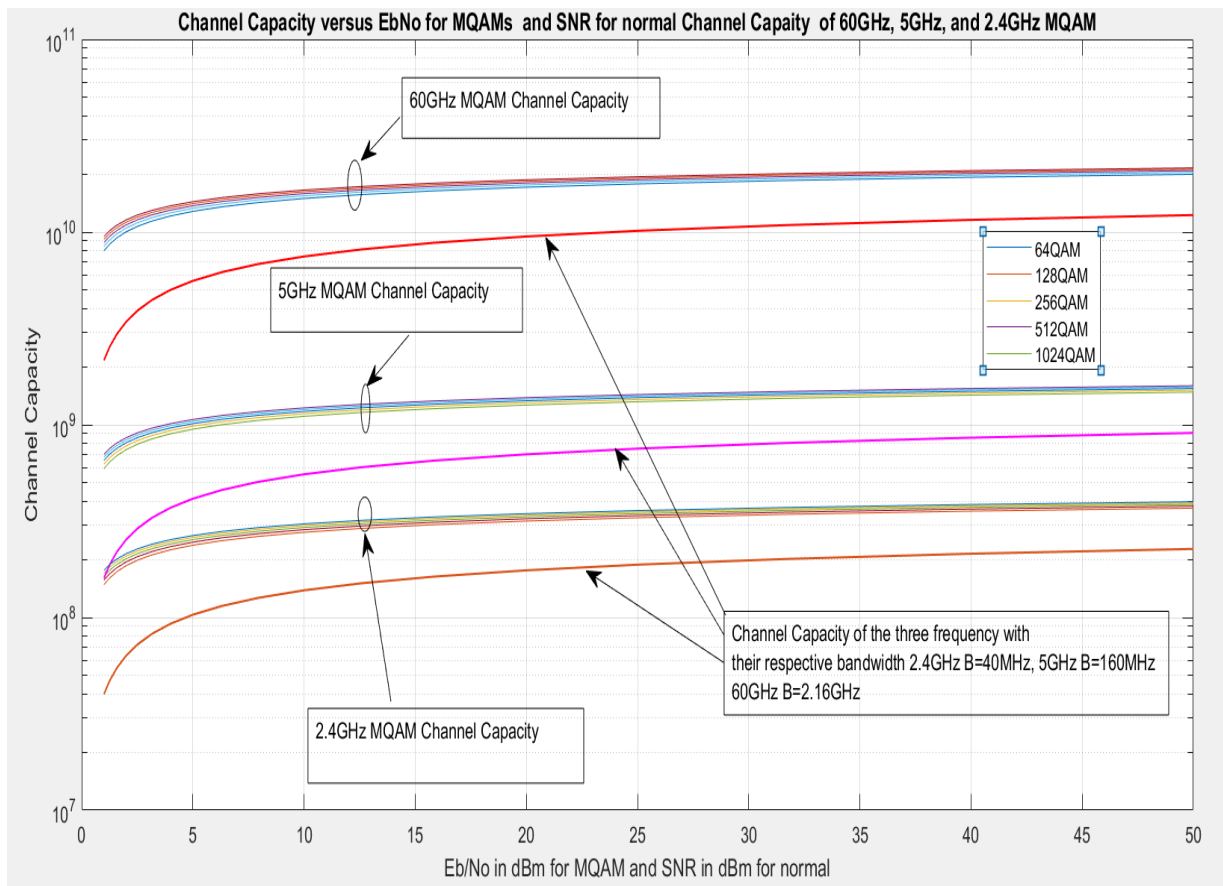


Figure 5.7 Channel capacity versus Eb/No for 2.4 GHz different modulation scheme of QAM



### 5.8 Channel capacity versus Eb/No for 60GHz, 5GHz, and 2.4 GHz different modulation scheme of QAM

Based on the MATLAB plot results in figure 5.5, 5.6, 5.7 and 5.8 the channel capacity of 2.4GHz, 5GHz and 60GHz based on BER set, the simulation result listed in table 5.4. Based on the result observed the channel capacity is from 252Mb up to 326 Mb for 2.4GHz and its modulation scheme 64QAM -1024QAM. The channel capacity for 5GHz from 1.009Gb up to 1.34Gb for modulation scheme 64QAM – 1024QAM. And the channel capacity for 60GHz from 13.62Gb up to 17.65Gb for the modulation scheme of 64QAM – 1024QAM. The single lines in MATLAB result figure 5.8 shows that direct Shannon Hartly channel capacity which less than Rician fading channel capacity. Eb/No increase by either of the following cases: By transmitter power or by antenna gain of transmitter and receiver for fixed distance. As a result, the channel



capacity increases proportionally. If Eb/No increasing rate is greater than the distance increasing rate increases the channel capacity for all modulation schemes.

Table 5.3 Channel capacity of 2.4GHz, 5GHz and 60GHz for different MQAM with respect to BER 10<sup>-5</sup>.

No	Modulation		Channel Capacity		
			2.4GHz B= 40MHz	5GHz B=160GHz	60GHz B=2.160GHz
1	64QAM	Eb/No = 6.51dBm	2.52*10 <sup>8</sup>	1.009*10 <sup>9</sup>	1.362*10 <sup>10</sup>
2	128QAM	Eb/No = 8.16dBm	2.737*10 <sup>8</sup>	1.095*10 <sup>9</sup>	1.431*10 <sup>10</sup>
3	256QAM	Eb/No =10.33dBm	2.948*10 <sup>8</sup>	1.18*10 <sup>9</sup>	1.593*10 <sup>10</sup>
4	512QAM	Eb/No=12.26dBm	3.11*10 <sup>8</sup>	1.246*10 <sup>9</sup>	1.682*10 <sup>10</sup>
5	1024QAM	Eb/No=14.33dBm	3.26*10 <sup>8</sup>	1.34*10 <sup>9</sup>	1.765*10 <sup>10</sup>

### 5.3. Comparing Capacity 60GHz Millimeter Wave Radiofrequency with 2.4 and 5 GHz radiofrequency

Base on the above results, for the 60GHz in section 5.2 figures 5.3 to 5.8. When we comparisons 60GHz frequency band with 2.4 GH and 5GHz frequency bands base on previous work results show in table 1.2 for both frequency bands and with a different standard. Which is up to higher modulation. As well as higher bandwidth and their result shows that the maximum capacity for both 2.4 and 5GHz is 2.4Gbps for IEEE 802.11 ax. However, in this thesis result of for higher modulation with minimum Eb/No it gives higher capacity. And here as we see in section 5.2 for highest modulations of MQAM when we compare it, it shows that there a big difference between the lower frequency channel capacities it is 13.5 times greater than that of 5GHz, and 54.2 GHz greater than that of 2.4GHz frequency bands for different modulation scheme simulated above section 5.2 for channel capacity versus Eb/No for M=64 to M=1024. As a result, the channel capacity comparisons are shown in table 5.5.



Table 5.4 Channel Capacity difference of 60GHz, 5GHz and 2.4 GHz for Eb/No at 25dBm

At min Eb/No dBm for all modulation scheme sensitivity	Difference with 60GHz	Difference with 5GHz	Difference with 2.4GHz
60GHz	1	1/13.2	1/54.04
5GHz	13.2	1	1/4.11
2.4GHz	54.04	4.11	1

### 5.4. Comparing Coverage 60GHz Millimeter Wave Radiofrequency with 2.4 and 5 GHz radiofrequency

For the coverage comparisons as we see in section 5.1 of figure 5.1 and 5.2 results the lower frequency bands has lower attenuation loss than 60GHz frequency band. As the distance between the source and the receiver increases, the frequency loss attenuation increases. To overcome the higher loss attenuation of 60 GHz frequency we need higher transmitter gain value. When 60GHz compared to 5GHz and 2.4GHz receiver sensitivity for WLAN, the 60GHz receiver sensitivity is excessively high, as we have observed in the previous discussions. Additionally, as the modulation scheme is increase, the receiver sensitivity increases, which is proportional to the distance between transmitter and receiver. Because we will be using an omnidirectional antenna. As per the section 5.1 of figure 5.4 and table 5.1 the operational range for M=64 and above which is 10.78 SNR and above, for all three-frequency range the distance will be covered is for 60GHz below 9 meter, for 5GHz is below 27 meter and for 2.4GHz is

below 50 meter. Based on this for higher modulation 5GHz is 3times of 60GHz, and 2.4GHz is 5 times coverage above 60GHz. This shows that 60GHz has less coverage range and use full or selective for frequency re-use.

Table 5.5 The distance covered for SNR > 27.34 for gain 9dB of 1024 QAM modulation scheme of each frequency.

SNR=27.34dB	Distance	Difference with 60GHz
60GHz	<20.8m	0
5GH	< 27.3m	6.5m
2.4GHz	<50.09m	30.1m

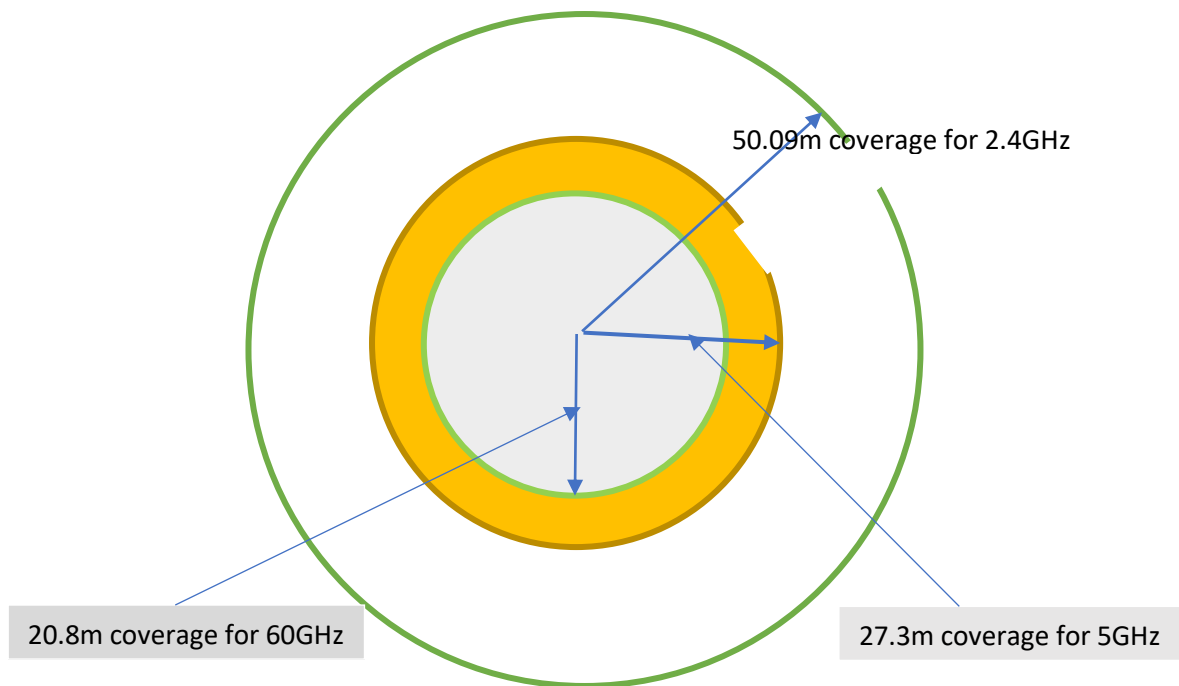


Figure 5.9 Distance covered by 60GHz, 5GH and 2.4GHz for Rician channel fading.



## CHAPTER 6

### Conclusions

Based on the results and discussions section 5 and the objective of this thesis, have seen that the comparison of 60GHz WLAN with other 2.4GHz and 5GHz WLAN. As a distance increase the 60GHz has high attenuation loss of signal which indicates that for different modulation scheme it requires different SNR to start carrying data with lower bit-error-rate for example if we see the MATLAB results as the modulation scheme increase it requires higher  $E_b/N_0$ . Which means it need higher SNR to get high capacity for MQAM Rician fading channels and to overcome above the receiver sensitivity level. The Rician Channel fading for 60GHz with comparisons of 2.4 and 5 GHz WLAN frequency has high data throughputs, which is 60GHz channel capacity is 13.5 times of 5GHz channels, and 54 times channels of 2.4GHz. Therefore, it is more advantageous for high through put user demands than 2.4 and 5GHz frequencies used for IEEE 802.11's Standards. 60 GHz distance coverage, relatively 6.5 meter less than 5GHz frequency and 30m less than 2.4GHz frequency. Hence, it is selective for frequency re-use which means reduce spectrum request issue as well interference, because it serves for short distance. For the shorter, the distance the throughput of the higher frequency 60GHz is higher than 2.4GHz and 5GHz even it requires high  $E_b/N_0$  or SNR to get high capacity through put in contrast the lowers frequency operate at lower  $E_b/N_0$ . Since using 60GHz has lower coverage for WLAN it is use full for frequency re-usage and it satisfies high data through put user demands.



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## APPENDIX A

### Code 1: Free Space Path loss

% Free Space Path loss of three selected frequency comparison for their recommended Transmitter powers and transmitter and receiver gain.

```
d= [0.0:0.00001:25]; % Distance between Transmitter and Receiver
```

```
FSPL=68.00 + 20*log(d); % Free Space Path loss for carrier frequency 60GHz
```

```
FSPL5=46.42 + 20*log(d); % Free Space Path loss for carrier frequency 5GHz
```

```
FSPL2=40.04 + 20*log(d); % Free Space Path loss for carrier frequency 2.4GHz
```

```
plot(d,FSPL,d,FSPL2,d,FSPL5,'-'),legend('FSPL for 60Ghz','FSPL5 for 5GHz', 'FSPL2 for 2.4GHz')
```

```
grid on, grid minor
```

```
xlabel('Distance (m)')
```

```
ylabel('FSPL power [dBm]')
```

```
title('Distance vs Free Space Path loss ')
```

### Code 2. EbNo vs BER of for performance evaluation of modulation

% EbNo vs BER for performance evaluation of modulation MQAM Modulation Scheme

```
EbNodBm=0:1:20; %Eb/No bit SNRb in dBm
```

```
M1=64; %Modulation for 64QAM
```

```
M2=128; %Modulation for 128QAM
```

```
M3=256; %Modulation for 256QAM
```

```
M4=512; %Modulation for 512QAM
```

```
M5=1024; %Modulation for 1024QAM
```



```

EbNo=10.^(EbNodBm/10);
%inside the Q-function
x1=sqrt(3*log2(M1)./(M1-1)*(EbNo)*2*log2(M1)); % Q-function Q(x)'s x value of first
Modulation
x2=sqrt(3*log2(M2)./(M2-1)*(EbNo)*2*log2(M2)); % Q-function Q(x)'s x value of second
Modulation
x3=sqrt(3*log2(M3)./(M3-1)*(EbNo)*2*log2(M3)); % Q-function Q(x)'s x value of third
Modulation
x4=sqrt(3*log2(M4)./(M4-1)*(EbNo)*2*log2(M4)); % Q-function Q(x)'s x value of fourth
Modulation
x5=sqrt(3*log2(M5)./(M5-1)*(EbNo)*2*log2(M5)); % Q-function Q(x)'s x value of fifth
Modulation
%Probability of BER for each Modulation Schem of MQAM's
P_BER1=2/log2(M1)*(1-(1/sqrt(M1)))*(1/(sqrt(2*pi))*erfc(x1./sqrt(2)));
P_BER2=2/log2(M2)*(1-(1/sqrt(M2)))*(1/(sqrt(2*pi))*erfc(x2./sqrt(2)));
P_BER3=4/log2(M3)*(1-(1/sqrt(M3)))*(1/(sqrt(2*pi))*erfc(x3./sqrt(2)));
P_BER4=4/log2(M4)*(1-(1/sqrt(M4)))*(1/(sqrt(2*pi))*erfc(x4./sqrt(2)));
P_BER5=4/log2(M5)*(1-(1/sqrt(M5)))*(1/(sqrt(2*pi))*erfc(x5./sqrt(2)));
semilogy(EbNodBm,P_BER1,'*-',EbNodBm,P_BER2,'p-',EbNodBm,P_BER3,'x-
','EbNodBm,P_BER4,'-','EbNodBm,P_BER5)
grid on
legend ('64QAM', '128QAM', '256QAM', '512QAM', '1024QAM')
title ('EbNo vs BER for MQAM Modulation')
xlabel ('EbNo dB')
ylabel('BER')

```

Code 3: Receiving level for required acceptable BER for unit gain and maximum transmission power or maximum EIRP

% Receiving level of the three selected frequency comparison for their recommended Transmitter powers and transmitter and receiver gain.



```
d=[0:1:200]; % Distance between Transmitter and Receiver
Pt=40; % the maximum Transmitting Power Pt in dBm for indoor of 60GHz
Pt2=30; % the maximum Transmitting Power Pt in dBm for indoor environment of 2.4GHz
Pt5=30; % the maximum Transmitting Power Pt in dBm for indoor environment of 5GHz
G=0; % Transmitter and Receiver unit gain gain of 60, 5, and 2.4 GHz
Gt60=6; % Transmitter gain of 60GHz
Gt2=6; % Receiver gain of 2.4GHz
Gt5=6; % Receiver gain of 5GHz
Gr60=6; % Receiver gain of 60GHz
Gr2=6; % Receiver gain of 2.4GHz
Gr5=6; % Receiver gain of 5GHz
Gt602=9; % Transmitter gain of 60GHz
Gt22=9; % Receiver gain of 2.4GHz
Gt52=9; % Receiver gain of 5GHz
Gr602=9; % Receiver gain of 60GHz
Gr22=9; % Receiver gain of 2.4GHz
Gr52=9; % Receiver gain of 5GHz
Pru=Pt + 2*G - 68.00 - 20*log(d);
Pr5u=Pt5 + 2*G - 46.42 - 20*log(d);
Pr2u=Pt2 + 2*G - 40.04 - 20*log(d);
Pr60=Pt + Gt60 + Gr60 - 68.00 - 20*log(d);
Pr5=Pt5 + Gt5 + Gr5 - 46.42 - 20*log(d);
Pr2=Pt2 + Gt2 + Gr2 - 40.04 - 20*log(d);
Pr602=Pt + Gt602 +Gr602 - 68.00 - 20*log(d);
Pr52=Pt5 + Gt52 + Gr52 - 46.42 - 20*log(d);
Pr22=Pt2 + Gt22 + Gr22 - 40.04 - 20*log(d);
plot(d,Pru,d,Pr5u,d,Pr2u,d,Pr60,d,Pr5,d,Pr2,d,Pr602,d,Pr52,d,Pr22,'.-'),legend('Pru
60Ghz','Pr5u 5GHz', 'Pr2u 2.4GHz','Pr60 60Ghz','Pr5 5GHz', 'Pr2 2.4GHz','Pr602
60Ghz','Pr52 5GHz', 'Pr22 2.4GHz')
grid on, grid minor
```



```

xlabel('Distance (m)')
ylabel('Rx power (Pr) [dBm]')
title('Distance vs Perceiver power for Unit, 6, 10, Gains and constant Transmission power ')

```

Code 4. MATLAB Codes of Rician Channel fading

% Channel capacity of WLAN frequency with their Channel Bandwidth

```

SNRdB=[0:0.01:25];
B=2160;% Channel Bandwidth 2.160GHz
B2=160;% Channel Bandwidth 160MHz
B3=40;% Channel Bandwidth 40MHz
SNR=10.^(SNRdB/10);
C=B.*(log(1+SNR)/log(2)); % in MHz
C2=B2.*(log(1+SNR)/log(2)); %in MHz
C3=B3.*(log(1+SNR)/log(2)); % in MHz
semilogy(SNRdB,C,SNRdB,C2,SNRdB,C3 )
legend(' 60GHz ','5GHz','2.4GHz')
xlabel('SNRdB in dB')
ylabel('Capacity in Mbps')
title('Channel Capacity Shannon channel for different SNR without Fading ')

```

Code 5. Distance versus SNR for different gains of selected three frequency

```

d=0:1:80; %distace between tx and rx im Meter
%::::::::::for Gain=0dBm::::::::::
Pt1=40; % Transmitter power in dBm of 60GHz
Pt2=30; % Transmitter power in dBm of 5GHz
Pt3=30; % Transmitter power in dBm of 60GHz
Gt=0; % unit gain or 0dBm
Gr=0; % unit gain or 0dBm
%::::::::::for Gain=6dBm ::::::::::::

```



Pt11=40; % Transmitter power in dBm of 60GHz

Pt21=30; % Transmitter power in dBm of 5GHz

Pt31=30; % Transmitter power in dBm of 60GHz

Gt1=6; % gain in dBm

Gr1=6; % gain in dBm

%:::::::::: for gain 9dBm::::::::::

Pt12=40; % Transmitter power in dBm of 60GHz

Pt22=30; % Transmitter power in dBm of 5GHz

Pt32=30; % Transmitter power in dBm of 60GHz

Gt2=9; % gain in dBm

Gr2=9; % gain in dBm

Pn1 =-80.655; %Noise power for 60Ghz channel Bandwidth of 2.16GHz

Pn2 =-91.959; %Noise power for 5Ghz channel Bandwidth of 160MHz

Pn3 =-97.979; %Noise power for 2.4Ghz channel Bandwidth of 40MHz

Pr1=Pt1+Gt+Gr- 68.00 - 20\*log(d); %receiver power for first carrier frequency

Pr2=Pt2+Gt+Gr- 46.42 - 20\*log(d); %receiver power for second carrier frequency

Pr3=Pt3+Gt+Gr-40.04 - 20\*log(d); %receiver power for third carrier frequency

Pr11=Pt11+Gt1+Gr1- 68.00 - 20\*log(d); %receiver power for first carrier frequency

Pr21=Pt21+Gt1+Gr1- 46.42 - 20\*log(d); %receiver power for second carrier frequency

Pr31=Pt31+Gt1+Gr1-40.04 - 20\*log(d); %receiver power for third carrier frequency

Pr12=Pt12+Gt2+Gr2- 68.00 - 20\*log(d); %receiver power for first carrier frequency

Pr22=Pt22+Gt2+Gr2- 46.42 - 20\*log(d); %receiver power for second carrier frequency

Pr32=Pt32+Gt2+Gr2-40.04 - 20\*log(d); %receiver power for third carrier frequency

SNR1=Pr1-Pn1; % Signal to noise ratio for 60GHz



SNR2=Pr2-Pn2; % Signal to noise ratio for 5GHz

SNR3=Pr3-Pn3; % Signal to noise ratio for 2.4GHz

SNR11=Pr11-Pn1; % Signal to noise ratio for 60GHz

SNR21=Pr21-Pn2; % Signal to noise ratio for 5GHz

SNR31=Pr31-Pn3; % Signal to noise ratio for 2.4GHz

SNR12=Pr12-Pn1; % Signal to noise ratio for 60GHz

SNR22=Pr22-Pn2; % Signal to noise ratio for 5GHz

SNR32=Pr32-Pn3; % Signal to noise ratio for 2.4GHz

hold on

semilogy(d,SNR1,'-.',d,SNR2,'-p',d,SNR3,d,SNR11,'-.',d,SNR21,'-p',d,SNR31,d,SNR12,'-.',d,SNR22,'-p',d,SNR32)

grid on

legend ('SNR1 G=0','SNR2 G=0','SNR3 G=0','SNR12 =6','SNR21 G=6','SNR31 G=6','SNR12 G=9','SNR22 G=9','SNR32 G=9')

title ('Distance versus SNR for different gains of selected three frequency')

xlabel ('distance in meter')

ylabel ('SNRdBm')

Code 6. Eb/No versus channel capacity for combined three frequencies with their respective channel bandwidth, and MQAMs. As well as the normal channel capacity versus SNR.

M\_Modulation=[64 128 256 512 1024]

index = 1;

for M = M\_Modulation

EbNodBm=0:1:20;

EbNo= 10.^(EbNodBm/10);



```
% ::::::::::: 5GHz channel capacity of MQAM :::::::::::
B1=2.16*10^9;% Bandwidth of 60GHz
SNR=EbNo*2*log2(M);% SNR in terms of k_factor
C1=B1*log2(1+SNR);% Channel Capacity
SNRdBm=0:1:20;
SNRn=10.^(SNRdBm/10);
C=B1*log2(1+SNRn);
semilogx( EbNo,C1,SNRn,C)% plot of Eb/No versus Channel Capacity
semilogy( EbNo,C1,SNRn,C)
hold on
```

```
% ::::::::::: 5GHz channel capacity of MQAM :::::::::::
B2=160*10^6;% Bandwidth of 5GHz
C2=B2*log2(1+SNR);% Channel Capacity
SNRdBm=0:1:20;
SNRn=10.^(SNRdBm/10);
C=B2*log2(1+SNRn);
semilogx( EbNo,C2, SNRn,C)% plot of Eb/No versus Channel Capacity
semilogy( EbNo,C2, SNRn,C)
hold on
```

```
% ::::::::::: 2.4GHz channel Capacity of MQAM :::::::::::
B3=40*10^6;% Channel Bandwidth of 2.4GHz
C3=B3*log2(1+SNR);% Channel Capacity for
SNRdBm=0:1:20;
SNRn=10.^(SNRdBm/10);
C=B3*log2(1+SNRn);
semilogx(EbNo,C3, SNRn,C)% plot of Eb/No versus Channel Capacity
semilogy(EbNo,C3, SNRn,C)
hold on
```



```

legend ('64QAM','128QAM','256QAM','512QAM','1024QAM')
xlabel('Eb/No in dBm for MQAM and SNR in dBm for normal')
ylabel('Channel Capacity')
title('Channel Capacity versus EbNo for MQAMs and SNR for normal Channel Capaity of
60GHz, 5GHz, and 2.4GHz MQAM')
grid on
indext = index + 1;
end

```

Code 7 Channel capacity for MQAM of 60GHz and bandwidth 2.16GHz

```

M_Modulation=[64 128 256 512 1024]
index = 1;
for M = M_Modulation

EbNodBm=0:1:20;
EbNo= 10.^(EbNodBm/10);
% ::::::::::: 60GHz channel Capaicy of MQAM :::::::::::
B1=2.16*10^9;%Bandwidth of 60GHz
SNR=EbNo*2*log2(M);% SNR in terms of k_factor
C1=B1*log2(1+SNR);% Channel Capacity
SNRndBm=0:1:20;
SNRn=10.^(SNRndBm/10);
C=B1*log2(1+SNRn);
semilogy( EbNo,C1,SNRn,C)% plot of Eb/No versus Channel Capacity

```

```

hold on

legend ('64QAM','128QAM','256QAM','512QAM','1024QAM')
xlabel('Eb/No in dBm')
ylabel('Channel Capacity')
title('Channel Capacity versus EbNo for 60GHz MQAM')
grid on
indext = index + 1;
end

```

Code 8 Channel capacity for MQAM of 5GHz and bandwidth 0.16GHz

```

M_Modulation=[64 128 256 512 1024]
index = 1;

```



```
for M = M_Modulation
```

```
EbNodBm=0:1:20;  
EbNo= 10.^(EbNodBm/10);  
SNR=EbNo*2*log2(M);% SNR in terms of k_factor  
% ::::::::::: 5GHz channel Capacity of MQAM :::::::::::  
B2=160*10^6;% Bandwidth of 5GHz  
C2=B2*log2(1+SNR);% Channel Capacity  
SNRndBm=0:1:20;  
SNRn=10.^(SNRndBm/10);  
C=B2*log2(1+SNRn);  
semilogy( EbNo,C2,SNRn,C)% plot of Eb/No versus Channel Capacity  
hold on  
  
legend ('64QAM','128QAM','256QAM','512QAM','1024QAM')  
xlabel('Eb/No in dBm')  
ylabel('Channel Capacity')  
title('Channel Capacity versus EbNo for 5GHz MQAM')  
grid on  
indext = index + 1;  
end
```

Code 9 Channel capacity for MQAM of 2.4GHz and bandwidth 0.04GHz

```
M_Modulation=[64 128 256 512 1024]  
index = 1;  
for M = M_Modulation  
  
EbNodBm=0:1:20;  
EbNo= 10.^(EbNodBm/10);  
SNR=EbNo*2*log2(M);% SNR in terms of k_factor
```



```
% ::::::::::: 2.4GHz channel Capacity of MQAM :::::::::::
B3=40*10^6;%Channel Bandwidth of 2.4GHz
C3=B3*log2(1+SNR);% Channel Capacity for
SNRdBm=0:1:20;
SNRn=10.^(SNRdBm/10);
C=B3*log2(1+SNRn);
semilogy(EbNo,C3,SNRn,C)% plot of Eb/No versus Channel Capacity
hold on
legend ('64QAM','128QAM','256QAM','512QAM','1024QAM')
xlabel('Eb/No in dBm')
ylabel('Channel Capacity')
title('Channel Capacity versus EbNo for 60GHz, 5GHz, and 2.4GHz MQAM')
grid on
indext = index + 1;
end
```