

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

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ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

Performance analysis of 60 GHZ wireless communications for local area networks

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Advisor's Name Signature

Abstract

In this thesis coverage and capacity comparisons of WLAN 60 GHz frequency in LOS and NLOS scenarios are done with its counterpart 2.4 and 5 GHz frequencies. In addition, in capacity comparison different number of MIMO antenna systems are also compared for those three frequencies. For coverage comparison, cell coverage areas with acceptable performance are simulated and radiuses of the cells are compared. On the other hand, for capacity comparison the maximum Shannon capacity are simulated and the three standards are compared by the number of mega-bit/second capacities they accomplish. For both comparisons IEEE 802.11n, 802.11ac, 802.11ad path loss models are preferred for their respective frequencies because the equations are formulated by IEEE for Wi-Fi environments that this thesis studies.

The results indicate that 60 GHz in NLOS scenario has very poor coverage radius and in LOS this frequency coverage radius increased dramatically and covers well like lower frequencies. On the other hand, capacity of 60 GHz is the highest in every scenario compared to 2.4 and 5 GHz frequencies. Based on the MATLAB simulation outputs LOS scenario gives more capacity than NLOS ones on the same MIMO condition. Also as the number of antenna in MIMO systems increases, the capacity of all frequencies increases too. In addition, channel bonding for 60 GHz is also done like lower frequencies and as the number of channel bonded increases, the capacity increases proportionally.

Therefore, a 60 GHz 802.11ad WLAN standard in LOS scenario is preferred to be used than 2.4 and 5 GHz frequencies to meet high data rate demanding users keeping acceptable coverage radius. In addition, maximum number of MIMO antennas with channel bonding can be used for very high data rate intensive applications. To tackle the 60 GHz LOS blockage by humans or objects issue, more than one access points at different locations or relay nodes can be used.

Keywords: Coverage; Capacity; Path loss models; IEEE 802.11ad; 802.11n, 802.11ac; LOS; NLOS; MIMO; Channel bonding; and MATLAB.

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Lastly and most importantly, I wish to thank my wife for her loving support and also I wish to thank my parents, they raised me, supported me, taught me, and loved me. To them I am eternally grateful.

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List of symbols and abbreviations

Abbreviation &symbols	*Description*
5G	Fifth Generation
AAF	Amplify-And-Forward
AM	Amplitude Modulation
AMD	Advanced Micro Devices company
AP	Access point
AV	Audio/Visual
AWGN	Additive White Gaussian Noise
BER	Bit error rate
bps	bits per second
BW	bandwidth
CCK	Complementary Code Keying
CIR	Channel impulse response
CMOS	Complementary Metal-Oxide Semiconductor
CSMA	Carrier sense multiple access
DAF	Decode-And-Forward
dB	Decibel
dBm	Decibels of measured power referenced to one milliwatt
DBPSK	Differential Binary Phase Shift Key
DQPSK	Differential Quaternary Phase-Shift Keying
DSSS	Direct-sequence Spread Spectrum
Eb	Energy per bit
ECMA	European Computer Manufacturers Association
EIRP	Equivalent Isotropic Radiated Power
F	Noise figure

FCC	Federal Communications Commission
FHSS	Frequency hopping spread spectrum
FM	Frequency Modulation
Gb/s	Gigabit per second
GBSM	Geometry based stochastic model
GHz	Gigahertz
GPS	Global positioning service
Gr	Receiver antenna gain
Gt	Transmitter antenna gain
HD	High definition
HDMI	High-definition multimedia interface
HDTV	High definition television
HIS	High-Speed Interface
HRP	High-Rate PHY layer
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
IEEE-SA	IEEE Standards Association
IFE	In-flight entertainment
ISM	Industry, scientific, and medical
ITU	International Telecommunication Union
k	Boltzmann's constant
LOS	Line of sight
LRP	Low-Rate PHY layer
MAC	Medium Access Control
Mb/s	Megabit per second
MHz	Megahertz
MIMO	Multiple input multiple output
mm	millimeter
ms	Millisecond
N0	Noise power spectral density
NF	Noise floor

NIC	Network interface card
NLOS	Non line of sight
O2	Oxygen
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PAL	Protocol adaptation layer
PC	Personal computer
PCIe	peripheral component interconnect express
pdf	Probability density function
PHY	Physical layer
PL	Path loss
Pmin	The required minimum received power
Pr(D)	The received power at the edge of the cell
Pt	Transmit power
Q(x)	Q-function
QAM	Quadrature amplitude modulation
RF	Radio frequency
RMS	Root-mean-square
RX	receiver
SC	Single carrier
SCBT	Single Carrier Block Transmission
SDM	spatial division multiplexing
SF	Shadow fading
SISO	Single input and single-output
SNR	Signal to noise ratio
STA	Station
SV	Saleh and Valenzuela
T	Room temperature
T-R	Transmitter-receive
TV	Television
Tx	Transmitter

UEP-QPSK	Unequal Error Protection-Quadrature Phase Shift Keying
US	United states
USA	United states of America
USB	Universal Serial Bus
UWB	Ultra-wideband
W	System bandwidth
Wi-Fi	Wireless Fidelity
WiGig	Wireless Gigabit Alliance
WLAN	Wireless local area network
WPAN	Wireless personal area network
Xq	Additional attenuation due to specific obstruction
λ	Wavelength
σ	The standard variation of shadowing fading

Chapter 1. Introduction

Since the first wireless transatlantic radio wave transmission demonstration by Marconi from Cornwall, England, to Newfoundland, Canada, in 1901 (based on long wave), wireless communications have undergone tremendous growth. They were first used mainly by military and shipping companies and later quickly expanded into commercial use such as commercial broadcasting services (such as shortwave, AM and FM radio, terrestrial TV), cellular telephony, and global positioning service (GPS), wireless local area network (WLAN), and wireless personal area network (WPAN) technologies. Today, these wireless communications systems have become an integral part of daily life and continue to evolve in providing better quality and user experience [1]. This thesis focuses on studying the performance comparison of WLAN standards in the 2.4, 5, and 60 GHz unlicensed frequency bands to find a better WLAN standard to satisfy the present and future users' high data rate demands.

1.1. *Evolution of WLAN communications*

IEEE 802.11 is a series of standards that cover an implementation of WLAN in the 2.4, 3.7, 5, and 60 GHz frequency bands. These standards were created, and are maintained by, the IEEE 802.11 Local Area Network/ Metropolitan Area Network committee. The creation of this series of standards stemmed from a need in the late 1980′s for a standard WLAN solution capable of handling the expansion happening in the technology field at the time [2].

The implementation in its current form came by way of a 1985 US *Federal Communications Commission* FCC ruling which released a series of frequency bands for industry, scientific, and medical (ISM) purposes. The regulatory restrictions on these bands are such that they are for unlicensed use by Radio frequency (RF) devices. The intended goal of this was to allow for industrial (such as RF heating and microwaves) as well as medical imaging being able to operate without disrupting other forms of wireless transmission [2].

The standards of 802.11 are maintained, from a commercial standpoint, by the Wi-Fi Alliance, a trade association tasked with promoting the Wi-Fi brand as the WLAN solution, certifying products for compliance to the standards, and controlling the trademarks and logo's related to the

brand and its certified products. Wi-Fi is the defacto standard for WLAN computer communication and is ubiquitous throughout modern society as almost all portable, or cordless devices, make use of a version of Wi-Fi for connecting to a network and the Internet [2].

There have been 7 main variants of 802.11: 1997, b, a, g, n, ac, and ad. The first version of the Wi-Fi standard, 802.11-1997, was released in 1997 and uses the 2.4 GHz ISM band for communication. The 2.4 GHz band allows for better propagation due to its lower carrier frequency as compared to 5 GHz. The 802.11-1997 standards can achieve data rates of 1-2Mb/s and can cover an indoor operational radius of 20-30m. 802.11-1997 uses a frequency hopping spread spectrum (FHSS) modulation technique [2].

Following soon after 802.11-1997 was 802.11a which was released in September 1999. This standard was designed to utilize the 5 GHz ISM band, which increased the maximum possible data rate to 54Mb/s. This speed increase was possible due to the increased carrier frequency as well as a change in modulation to Orthogonal Frequency Division Multiplexing (OFDM). In addition, the 5 GHz band is relatively empty of electromagnetic interference, both natural and from other devices (microwave ovens, Bluetooth, cordless phones, baby monitors and others) and the effective range of 802.11a is similar to versions using 2.4 GHz [2].

The IEEE 802.11b standard returned to the original 2.4 GHz ISM band and is capable of up to 11Mb/s peak data rate. This limitation was due to interference issues in the 2.4 GHz band, the limitations of the lower frequency of the carrier band than in 802.11a, and the limitations of the use of the legacy CSMA modulation technique. 802.11b makes use of Direct-sequence Spread Spectrum (DSSS) modulation, and Complementary Code Keying (CCK) in its modulation. One can expect to achieve a range of about 35m [2].

Building on the foundation developed by 802.11b, the IEEE released the 802.11g standard in 2003. 802.11g use the 2.4 GHz band as well as the 14 channels from 802.11b. Through the use of OFDM, which was pulled from the 802.11a standard, 802.11g is able to achieve maximum raw data rates of 54Mb/s. 802.11g is fully backwards compatible with 802.11b. This increased speed and backwards compatibility was a win-win for everyone and resulted in an extremely fast adoption

rate among consumers and businesses. By mid-2003 most access points and NIC's were equipped for either dual band use on 802.11a, b, and g [2].

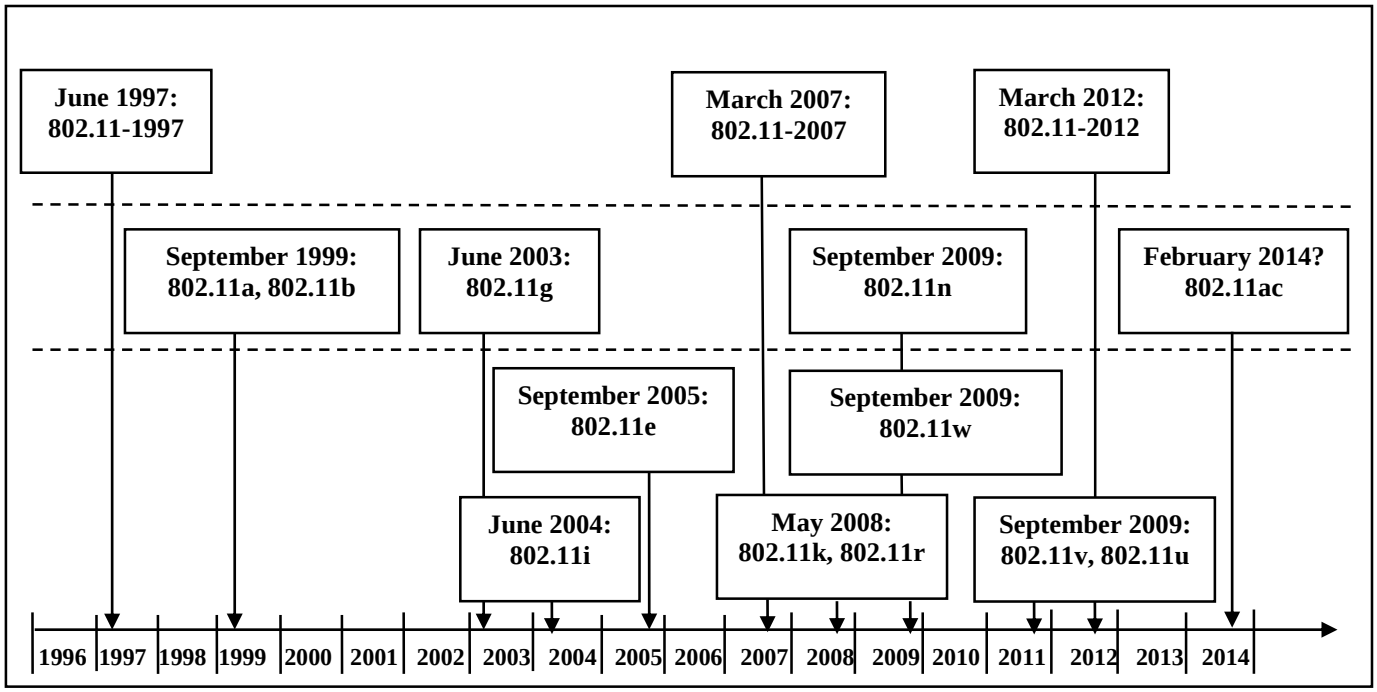


Figure 1: 802.11 timeline [3]

In 2009, 7 years after the release of 802.11g the next iteration of the Wi-Fi Standard was released in the form of 802.11n. This new standard stood to improve upon the shortcomings of both 802.11a and 11g by combining their strengths with improvements in modulation and antenna design while utilizing 2.4 and 5 GHz. 802.11n is capable of a raw data rate up to 600Mb/s by making use of 4 MIMO streams, each 40 MHz wide channels and 64 QAM constellation size. 802.11n uses a completely overhauled OFDM modulation technique with the inclusion of multiple-input multiple-output (MIMO) and a modernized frame aggregation approach [2]. It is backwards compatible with all the previous versions, 802.11a, b and g except in Greenfield mode of operation which have no backward compatibility. This mode of operation is not commonly used and is not supported by the 802.11ac standard [4].

As file sizes and Internet connections continue to increase in speed it is only natural that WLAN keeps pace with that trend. In late 2012 IEEE 802.11ac received approval of its 4.0 draft form. 802.11ac is the 6th iteration of the IEEE 802.11 standard and building on the designs of 11a and 11g. The modulation techniques used are similar to its predecessors in the use of MIMO and spatial

division multiplexing SDM and the uses of OFDM are keys to the increase in speed. It is backwards compatible with 802.11a and 11n [2]. Using up to 8 MIMO streams, each 160 MHz wide and 256 QAM constellation size, the 5 GHz band can achieve a theoretical maximum of 7 Gb/s data rates [5].

Advancements in technology are always happening, and Wi-Fi is no exception. The creation of the Wireless Gigabit Alliance (WiGig) was announced in May 2009, with the release of the first draft of IEEE 802.11ad happening in December 2009. WiGig will operate on the 2.4, 5, and 60 GHz bands (Tri band wireless networking). The intention is to maintain backwards compatibility with legacy versions [2]. The 60 GHz band can achieve 25 Gb/s data rates using 4 MIMO streams, each 2.16 GHz wide and 64 QAM constellation size. In addition, by channel bonding the four channels together, a maximum of 100 GB/s can be achieved [6]. The evolution of WLAN 802.11 standard explained above is summarized in the table 1 below.

IEEE standards	**802.11**	**802.11b**	**802.11a**	**802.11g**	**802.11n**	**802.11ac**	**802.11ad**
Spectrum	2.4 GHz	2.4 GHz	5 GHz	2.4 GHz	2.4 & 5 GHz	5 GHz	60 GHz
Time line	1997	1999	1999	2003	2009	2012	2013
Maximum physical rate	1-2 Mbps	11 Mbps	54 Mbps	54 Mbps	600 Mbps	7 Gbps	25 Gbps
Modulation technique	FHSS	DSSS/ CCK	OFDM	OFDM	OFDM/ MIMO	OFDM/ MIMO	SC,OFDM/ MIMO
Multi antenna scheme	Single antenna	Single antenna	Single antenna	Single antenna	Up to 4X4 MIMO	Up to 8X8 MIMO	Up to 4X4 MIMO
Channel Bandwidth	22 MHz	22 MHz	20 MHz	20 MHz	20 & 40 MHz	20,40,80& 160 MHz	2.160 GHz
Compatible with	None	802.11	None	802.11/ 802.11b	802.11a/b /g	802.11a/ 802.11n	Tri band

Table 1: Summarized comparison between IEEE 802.11 WLAN standards

1.2. *802.11 standards' frequency spectrum and their channelization*

The 802.11b standard uses the Industrial, Scientific, and Medical (ISM) band at 2.4 GHz. The available frequency spectrum (2.4–2.4835 GHz) is divided into 14 channels beginning at 2.412 GHz and incrementing by .005 GHz (or 5 MHz of bandwidth per channel). Out of those 14 channels only three non-overlapping channels are available for simultaneous operation: channels 1, 6, and 11 as shown on below figure [7].

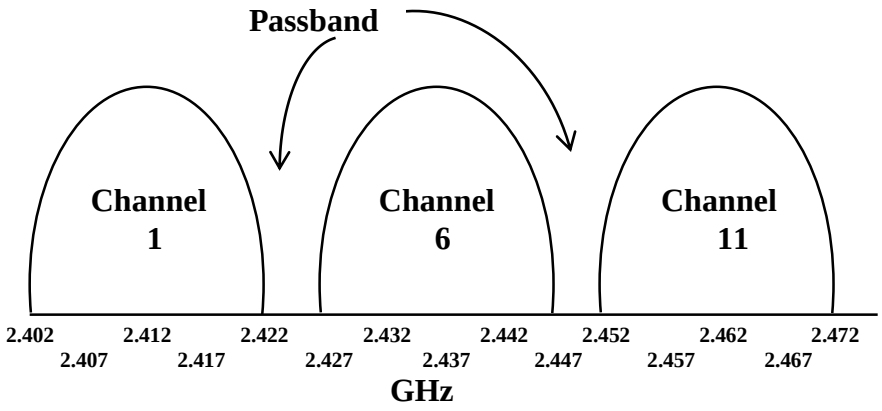


Figure 2: 802.11b channels [7]

The regulations of using the unlicensed 5 GHz frequency spectrum for 802.11a are different in different countries. In US, eight frequency channels can be used simultaneously in 5.15–5.35 GHz range as below figure. When using newer-model equipment that can also transmit in the extended band up to 23 simultaneous channels are available [7].

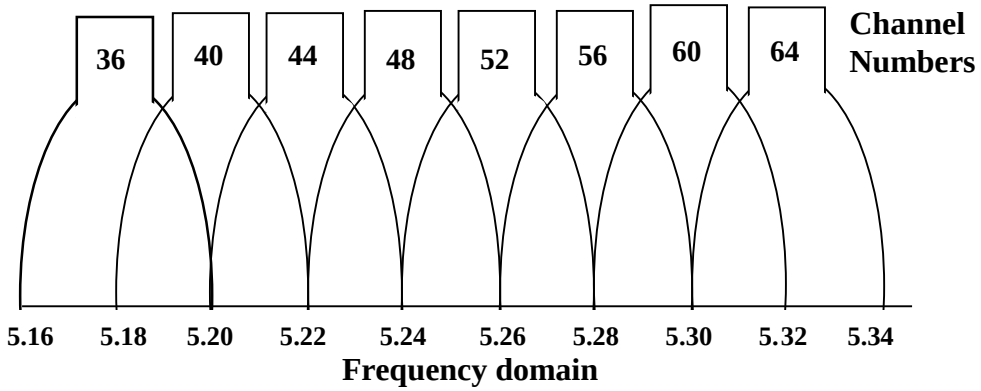


Figure 3: 802.11a channels [7]

The number of non-overlapping channels available for 802.11g is the same as the number of available channels for 802.11b. IEEE 802.11a and 802.11g each consume 20 MHz of bandwidth to transmit using OFDM; 802.11b uses about 22 MHz of bandwidth [7]. 802.11n which operates on both 2.4 and 5 GHz band provides 20 and 40 MHz channels, with 40 MHz comprised of two adjacent 20 MHz channels in either the 2.4 GHz or 5 GHz frequency band. In addition, there are no partially overlapped 20 MHz channels, and there are no partially overlapped 40 MHz channels [8].

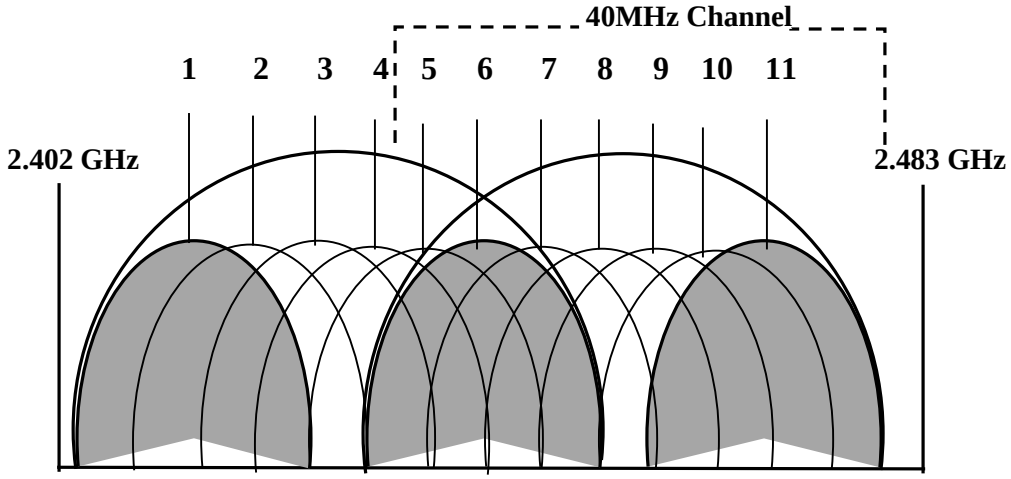


Figure 4: Channel bonding example at 2.4 GHz frequency in 802.11n [7]

802.11ac continues the 802.11n's design philosophy, i.e. only define 20, 40, 80 and 160 MHz non-overlapping channels. 80 MHz channels are comprised of adjacent 40 MHz channels, with no partially overlapped 80 MHz channels. And 160 MHz channels are comprised of adjacent 80 MHz channels, with no partially overlapped 160 MHz channels [8].

There are a maximum of six 80 MHz channels possible and when using adjacent channel bonding, there are only two 160 MHz channels, which is the primary reason for the inclusion of non-contiguous 160 MHz operation. Non-contiguous 160 MHz (80 + 80 MHz) channels are comprised of any two valid, non-adjacent 80 MHz channels. With non-contiguous operation many combinations of 80 + 80 MHz channelization is possible. Figure 5 illustrates the 802.11ac channelization [8].

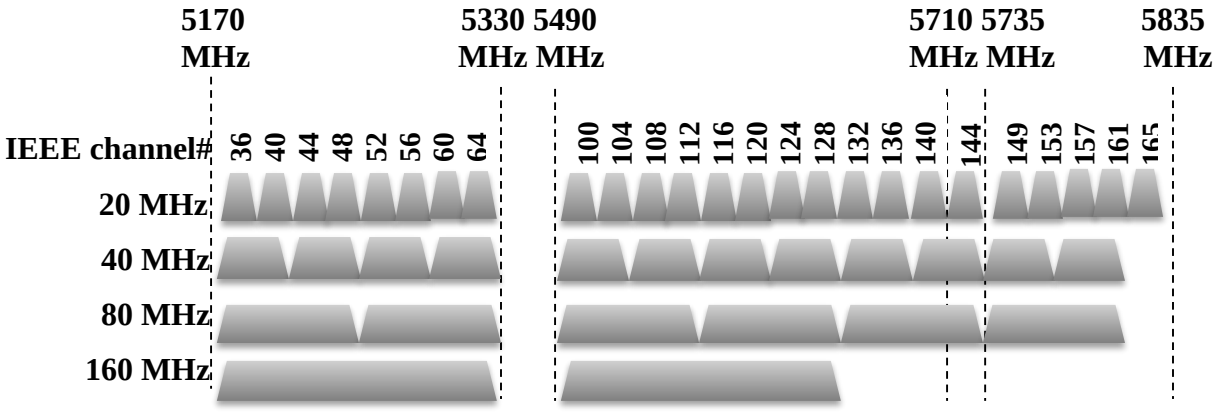


Figure 5: 802.11ac Channelization [8]

For 802.11ad, a single channel bandwidth is 2.16 GHz. The useful ISM band around 60 GHz (57 GHz to 66 GHz) is regulated differently in various regions of the world, illustrated in Figure 6. Four non overlapping channels are defined for this band, but they are not universally license free. Channel 2 is unlicensed band in all regions and is therefore used as the default channel [9].

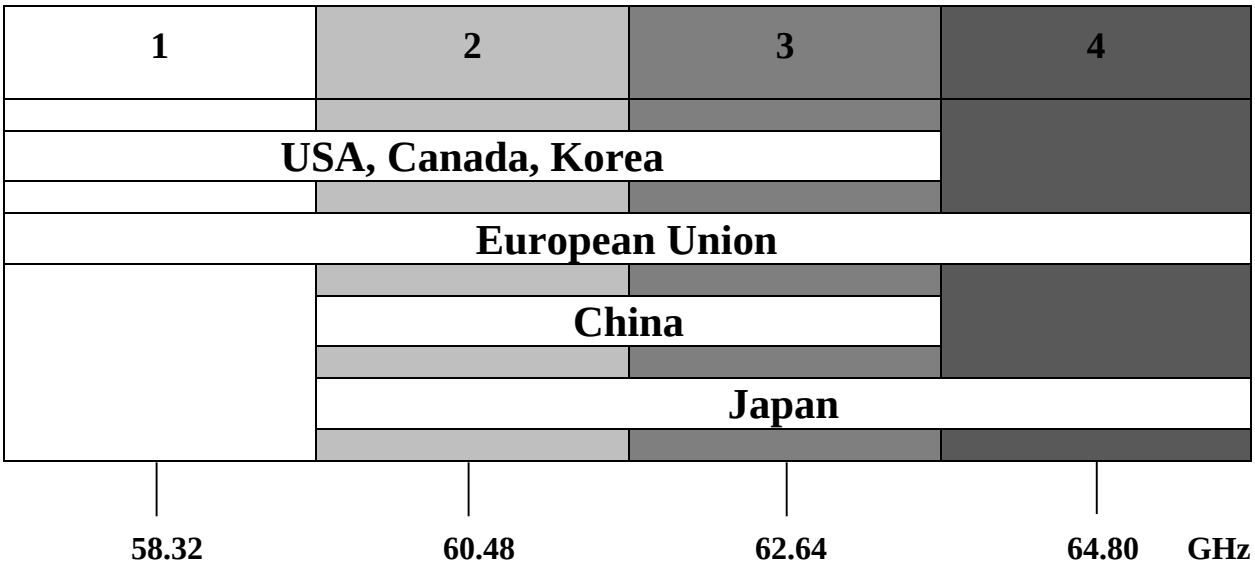


Figure 6: Channels in the 60 GHz band [9]

When we come to our country Ethiopia, our frequency usage regulations for WLAN networks and regulations on 60 GHz frequency is as follows [10]:

For the allocation of frequencies the world has been divided into three Regions. Our country is on region 1 of ITU frequency allocation regions as seen on the figure below.

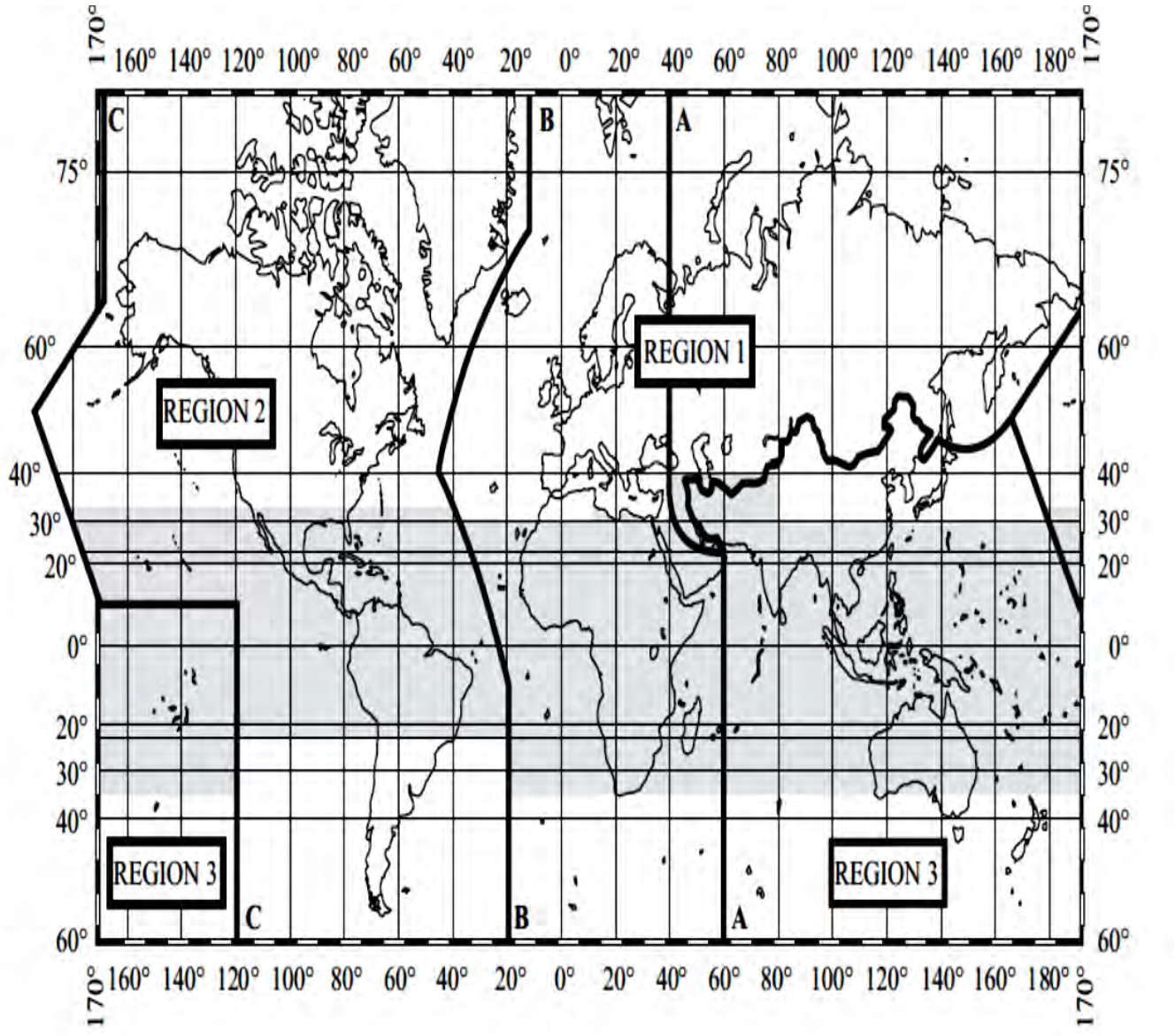


Figure 7: World map showing ITU different radio regulation regions [11]

Ethiopia follows European standards not Americans. Therefore, the frequency spectrum that our country uses on the 2.4 and 5 GHz are as follows [10]:

2.4 – 2.4835 GHz
5.1500-5.3500 GHz
5.4700 – 5.7250 GHz

The last bands, 5.725 – 5.825 that USA uses for WLAN are used for earth to space satellite communication in our country not for WLAN. In addition, the power limitation of both 2.4 GHz and 5 GHz for Wi-Fi usage in Ethiopia is set to 100mW or 20dBm [10].

On the other hand, for 60 GHz frequency, in our country there is no regulation set to whether to use it for WLAN or how much BW around this frequency being allocated for WLAN communication until now. Now the 60 GHz usages are only for inter-satellite communications and airborne radar services [10].

Recently at early 2016, there was a frequency regulation meeting worldwide by ITU-T to update changed regulations for all regions. But our country do not get this ITU-T radio regulations 2016 version up to now and also not freely available on the Internet as it needs special credentials. Therefore, in our country 60 GHz frequency is only in use for satellite and airborne radar communications and is not used and has no regulations for WLAN communications until now. As our region is the same as European region, all the four channels available around 60 GHz frequencies may become unlicensed and used in the future WLAN communications for high data rate demanding applications, i.e. 57 GHz to 66 GHz frequency bands [10].

Chapter 2. 60 GHz frequency for wireless communications

60 GHz frequency is a subset of millimeter wave band which refers to the frequency band of 30-300 GHz, where the wavelengths are in the range of 1-10 mm, hence the name mm-waves are given to this band [12]. This 60 GHz frequency has a great potential to enable wireless communication at Gbit/s rates with its 5 GHz block of globally overlapping bandwidth in the license-free spectrum [13].

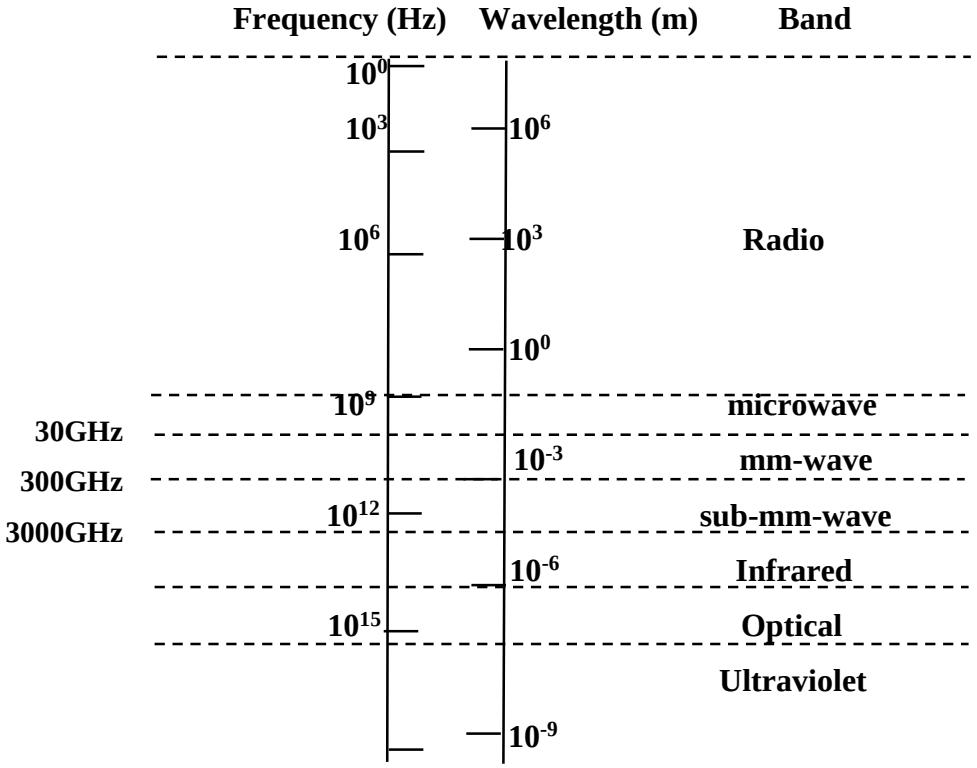


Figure 8: Electromagnetic spectrum allocations [1]

The earlier cost barrier in front of the millimeter-wave systems has now been breached with the recent advancement in Complementary Metal-Oxide Semiconductor (CMOS) technology. The possibility of producing low-cost 60 GHz chips attracted the attention of the industry to develop high data rate wireless applications, which is unlikely to be achieved with current wireless technologies at 2.4 and 5 GHz frequencies [13]. The existing WLAN communication technologies face serious difficulties in meeting the requirements of advanced applications. The limited bandwidth in the lower part of the electromagnetic spectrum makes it very challenging to achieve data rates beyond 1 Gbit/s with the IEEE 802.11 series. The shortage of available bandwidth in the

2.4 GHz and 5 GHz bands motivates the explorations of higher frequencies, specifically in the 60 GHz spectrum that offers one of the largest unlicensed bands globally allocated. The biggest advantage of 60 GHz over current wireless technologies is the huge 5 GHz bandwidth that is globally allocated in the unlicensed mm-wave bands [13].

The abundance of bandwidth also allows defining large channels which can simplify the system design. A typical 60 GHz system requires 0.5 bps/Hz spectral efficiency to achieve 1 Gb/s, which is 50 times lower than an IEEE 802.11n-like system. 60 GHz systems come with a power advantage as well. The regulations for the 60 GHz band allow 10 times higher transmit power – Equivalent Isotropic Radiated Power (EIRP) – than IEEE 802.11n systems. Additionally, radio signal transmissions at the higher frequencies inherently become more directional and require smaller antennas [13]. Considering the distance between antenna elements is half of the signal wavelength, at 60 GHz this would be roughly 2.5 mm. Therefore a 16 element array in a 4x4 configuration would only occupy a 1 cm x 1cm area [8]. Therefore it is possible to design multi-element 60 GHz antenna arrays in compact sizes. The use of multi-element antenna arrays with 60 GHz provides high gain and allows beamforming, which is the capability of focusing the antenna energy to a specific direction and minimizing the interference and interception possibility. Beamforming increases the potential of spatial frequency reuse in the millimeter wave band. This provides higher capacity by supporting more simultaneous communications [13]. Previously, point-to-point wireless systems operating at 60 GHz have been used for many years by the intelligence community for high security communications and by the military for satellite-to satellite communications [14].

The propagation characteristics are generally considered as the downside of the mm-wave technology. 60 GHz signals can hardly penetrate through building walls and human bodies due to heavy attenuation. On one hand, the limited transmission range prevents the use of 60 GHz as a complete WLAN solution throughout home. On the other hand, heavy attenuation means less interference and turns each room into a separate cell in which whole system capacity can be used to achieve higher throughput. The naturally isolated cells created by heavy attenuation also form a secure network environment [13].

2.1. *Propagation characteristics of 60 GHz frequency*

The Path loss (PL) at 60 GHz is much more severe than at lower frequencies since the free space PL at 60 GHz alone increases by approximately 22 dB and 28 dB compared to 5 GHz and 2.4 GHz band respectively. Furthermore, the PL at 60 GHz is subject to additional losses, unlike other WLAN frequencies, due to oxygen absorption and rain attenuation [1]. The propagation characteristics of this frequency are:

2.1.1. Oxygen absorption

Point-to-point wireless systems operating at 60 GHz have been used for many years by the intelligence community for high security communications and by the military for satellite-to satellite communications. Their interest in this frequency band stems from a phenomenon of nature: the oxygen molecule (O_2) absorbs electromagnetic energy at 60 GHz (see Figure 9). This absorption occurs to a much higher degree, 15dB/km, at 60 GHz than at lower frequencies typically used for wireless communications. This absorption weakens (attenuates) 60 GHz signals over distance, so that signals cannot travel far beyond their intended user. For this reason, 60 GHz is an excellent choice for covert satellite-to-satellite communications, because the earth's atmosphere acts like a shield preventing earth-based eavesdropping [14].

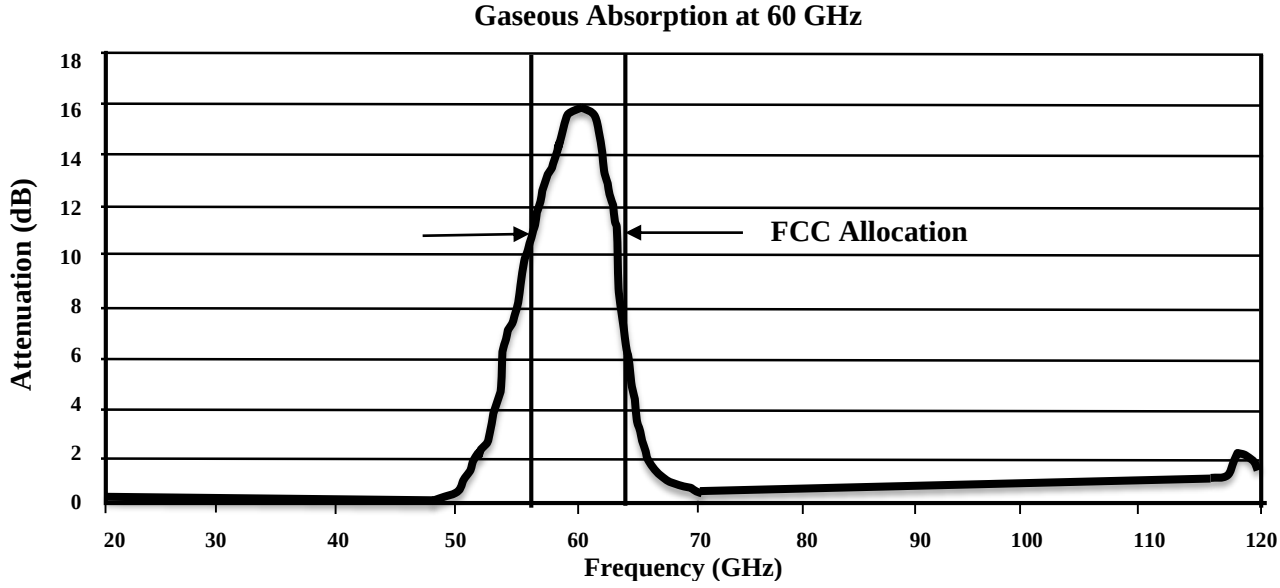


Figure 9: O_2 attenuation versus frequency [14]

Another consequence of O_2 absorption is that radiation from one particular 60 GHz radio link is quickly reduced to a level that will not interfere with other 60 GHz links operating in the same geographic vicinity. This reduction enables higher "frequency reuse". Consequently, more 60 GHz links can be used in the same area without worrying about interference. Also, the 60 GHz links are far more secure given their limited range [14].

2.1.2. Narrow beam width

Operating at higher frequencies inherently results in a more focused antenna. Therefore at 60 GHz, the beam width is far narrower than at the lower frequency unlicensed bands [14].

Frequency	**99.9% Beam width**
2.4 GHz	117 degrees
24 GHz	12 degrees
60 GHz	4.7 degrees

Table 2: Beam Width for Several Unlicensed Frequency Bands for 30cm diameter antennas [14]

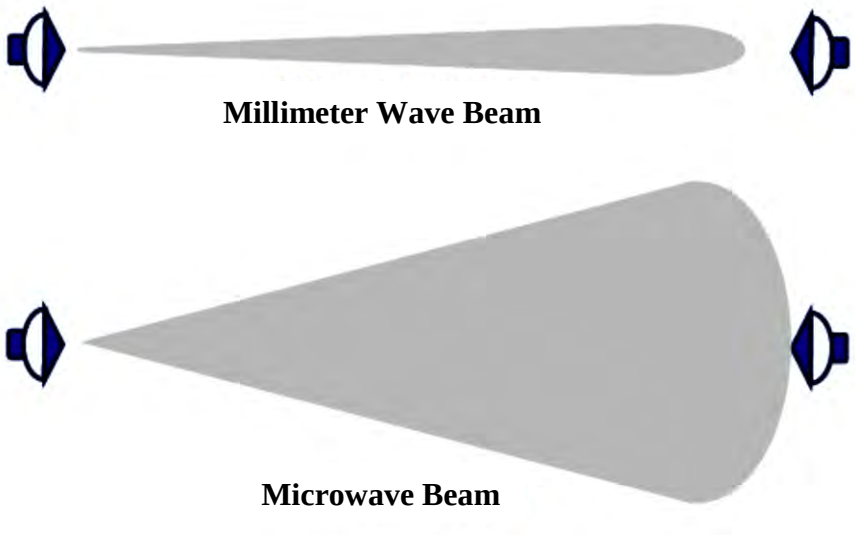


Figure 10: Millimeter wave Narrow Beams [15]

Highly focused antennas jointly minimize the possibility of interference and the risk that the transmission will be intercepted, whilst maximizing performance. Therefore, the combined effects of O_2 absorption and narrow beam spread result in high security, high frequency re-use, and low interference for 60 GHz links [14].

2.1.3. *Rain attenuation*

Coverage distances of millimeter-wave radios operating in the real world are limited primarily by rain. The maximum operating link distance is a function of level of availability desired (for example, 99.999% or 99.99%) and rainfall rates in the geographic area of intended use, i.e. as the rainfall rates increases the link distance decreases and link distance increases as level of availability and rainfall rates decrease. Figure 11 shows the attenuation due to rain (solid line) compared to O_2 absorption (dashed line) [14].

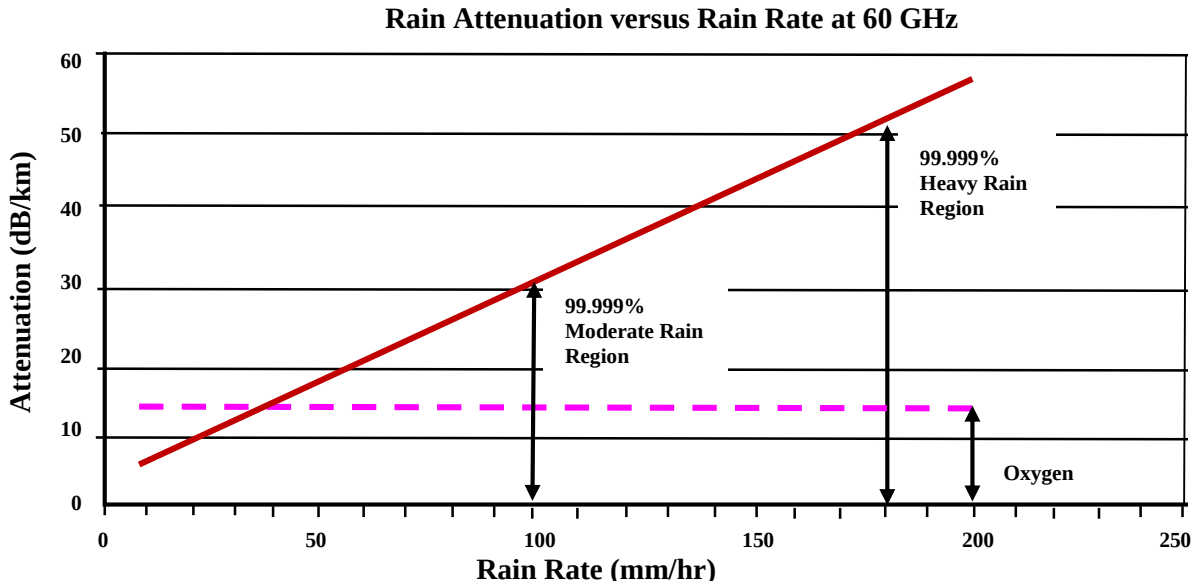


Figure 11: Attenuation versus Rain Rate [14]

In moderate rain regions, the rain attenuation is about twice the oxygen attenuation, and in heavy rain regions, the rain attenuation is more than three times the oxygen attenuation. Therefore, in designing a 60 GHz link to provide robust communication capability in the real world, rain attenuation is a larger factor than oxygen absorption. So, this combination of oxygen absorption and robust engineering enables 60 GHz links to provide the best of both worlds [14]. These attenuations and absorptions pose a severe challenge in delivering a gigabit wireless transmission with reliable link margin and make 60 GHz a promising candidate for indoor rather than outdoor applications [1].

2.1.4. *Human and Object shadowing*

Additional to the above propagation losses, millimeter wave experience significant attenuation losses from shadowing of human bodies, walls and common household objects. 60 GHz can hardly penetrate through building walls and human bodies due to heavy attenuation. For example, an average of 15 dB attenuation in the duration of 550 ms is reported when a human blocks the line-of-sight (LOS) path as seen in figure 12 [13]. Another example is: a signal attenuation of over 20 dB is observed for a painted board [1], brick wall attenuation 20 dB, a composite wall with studs in the path attenuation 35 dB, and path loss due to concrete as high as 70 dB [8], which means that signal penetration through walls would be difficult. It is thus expected that 60 GHz wireless communication for consumer electronics devices would be limited to in-room applications [1].

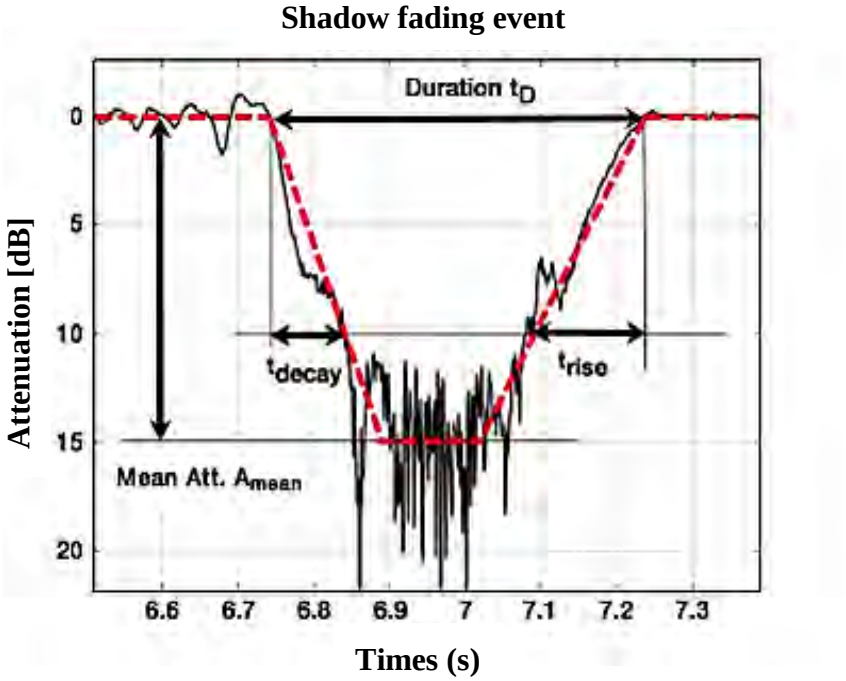


Figure 12: Human body attenuation in 60 GHz [13]

2.2. *Benefits of 60 GHz frequency band*

The biggest advantage of 60 GHz over current wireless technologies is the huge 5 GHz bandwidth that is globally allocated in this unlicensed mm-wave bands which can easily achieve more than 1 Gb/s data rates [13]. In addition to the high-data rates that can be easily accomplished in this

spectrum, energy propagation in the 60 GHz band has unique characteristics that make possible many other benefits. The 60 GHz band is offering the following key benefits:

- Unlicensed operation – no need to spend significant time and money in obtaining a license from a telecoms regulator [14]
- Highly secure operation – resulting from short transmission distances due to oxygen absorption and narrow antenna beam width [14, 16]
- Virtually interference-free operation – resulting from short transmission distances due to oxygen absorption, narrow antenna beam width, and limited use of 60 GHz spectrum [14]
- High level of frequency re-use enabled – communication needs of multiple customers within a small geographic region can be satisfied [14]
- In a dense deployment of networked nodes, 60 GHz networks offer wireless capacity more than 15 times greater than leading-edge Wi-Fi solutions in the legacy bands [4].
- The bandwidth is equally shared between users in 802.11n & ac but in 60 GHz each user gets a dedicated wireless gigabit link. As a result, system capacity scales up as the number of users increases [4].
- Due to the high frequency, 60 GHz antennas are only 1 mm^2–2 mm^2 in size, enabling design and implementation of antenna arrays of 16 or 32 antennas (in the same area of many fewer 2.4 GHz / 5 GHz antennas) [4].
- 60 GHz regulation allows much higher transmit power compared to other existing WLAN – help to overcome the higher path loss on this frequency [1].

2.3. *Mitigation techniques for 60 GHz frequency*

One of the critical factors that may influence the widespread adoption of the millimeter-wave technology in home networks will be the reliability of upcoming 60 GHz systems. Considering the high free-space path loss and heavy attenuation of signals in the 60 GHz band by the human body and objects, the millimeter wave systems should guarantee robust operation under the adverse effects of obstructions at home, which requires a thorough investigation prior to system design [13].

A 60 GHz system using only Omni-directional antennas cannot provide a satisfactory home networking performance in the presence of humans. To achieve 10^{-4} BER, a directional antenna with the minimum of 10 dB antenna gain should be used at least in the receiver side. In the denser environments which are open to more severe shadowing, the directional antennas should be used at both sides of the channel to minimize the required antenna gain [13].

One of the mitigating technique is selecting the position of access points. Distance and LOS availability are two key factors shaping the outage behavior of the access points. The center positions achieve lower outage rates than the edge positions at the same height since the average distance of the center positions to the receivers is shorter. On the other hand, the lower-height positions have the advantage of shorter distance to the receivers, which enables them to achieve lower outage rate. However, the blockage probability for their direct path is greater compared to the positions on the ceiling. Also we can see that the outage probability increases with the number of humans in the environment increases [13].

On the other hand, the obstruction from human of LOS link can cause the loss of communication since the biggest part of the signal energy is carried by the direct path. To mitigate the LOS link obstructions in 60 GHz networks:

1. Use of additional access points may be a solution. Such architectures require additional costs and have overhead in terms of complexity and interference. Other than increasing the number of deployed access points [13].
2. Using relay stations is another mitigation method. In this scheme, relay stations are used to relay packets when there is no LOS between source and destination units [13].
3. Another solution would be utilization of reflected rays in case of LOS path obstruction. A complex antenna system having adaptive beam steering capability may forward the signals over the reflective surfaces when the LOS path is blocked [13].

A 60 GHz network solely relying on utilizing reflections to overcome the LOS path obstruction may not provide robust connectivity. The quality and the robustness of the 60 GHz links can be improved by employing relay nodes in the network. In ad-hoc relaying, the source sends the data packets only to the relay and then the relay retransmits the data to the destination. In cooperative

relaying, the source sends the data packets to the relay and the destination, either simultaneously or sequentially, and then the destination combines both signals [13].

Two main strategies for the relay operation are Amplify-And-Forward (AAF) and Decode-And-Forward (DAF). In the AAF scheme, the relay simply amplifies the signal prior to retransmission. It is a very simple relay solution but it is not efficient for systems with critical link budgets since the noise is also amplified in this method. In the DAF scheme, the relay regenerates the signals by completely decoding and then re-encoding them before the transmission to the final destination. The regeneration of the signals in the DAF scheme can also help the system combat large propagation losses and improve the quality of the links despite its relatively higher complexity [13].

The relay node positions and the number of relays used gives different performances. I.e. the Best Node Relay scheme whose node can provide the best SNR performance for a particular link achieved the lowest outage rates among all the schemes. In the comparison of outage performance of the dedicated single relay deployments, the Relay Ceiling outperforms the Relay Middle scheme by using the advantage of its position which provides it with more robust LOS paths to the end nodes. In addition, the outage performance improves as the number of relays increases, the improvement becomes negligible when the number of relays is more than four [13].

2.4. *Potential Applications*

With the allocated bandwidth of 5 GHz in most countries, 60 GHz radio has become the technology enabler for many gigabit transmission applications that are technically constrained at lower frequency. A number of indoor applications are envisioned, such as:

(i) Cable replacement or uncompressed high definition (HD) video streaming that enables users to wirelessly display content to a remote screen with wired equivalent quality/experience [1]. This technology is the first of its kind and will eliminate the need for cable around personal computers, docking stations, and other consumer electronic devices. High-definition multimedia interface (HDMI), display port, USB 3.0, and peripheral component interconnect express (PCIe) 3.0 cables will all be eliminated [17].

(ii) 'Synch and go' file transfer that enables gigabytes of file transfer in a few seconds. [9] Fast downloads and uploads, wireless sync, and multi-gigabit-per-second WLANs will be possible over shorter distances [17].

(iii) Wireless docking stations that allow multiple peripherals (including an external monitor) to be connected without the need for frequent plugging and unplugging [1];

(iv) Wireless gigabit Ethernet that permits bidirectional multi-gigabit Ethernet traffic [1];

(v) Wireless gaming that ensures high-quality performance and low latency for exceptional user experience [1].

(vi) aircraft in-flight entertainment (IFE) and inside a car in-car entertainment [18]

Other future applications include the following:

(vii) High data rate inter-chip communications [12, 17]

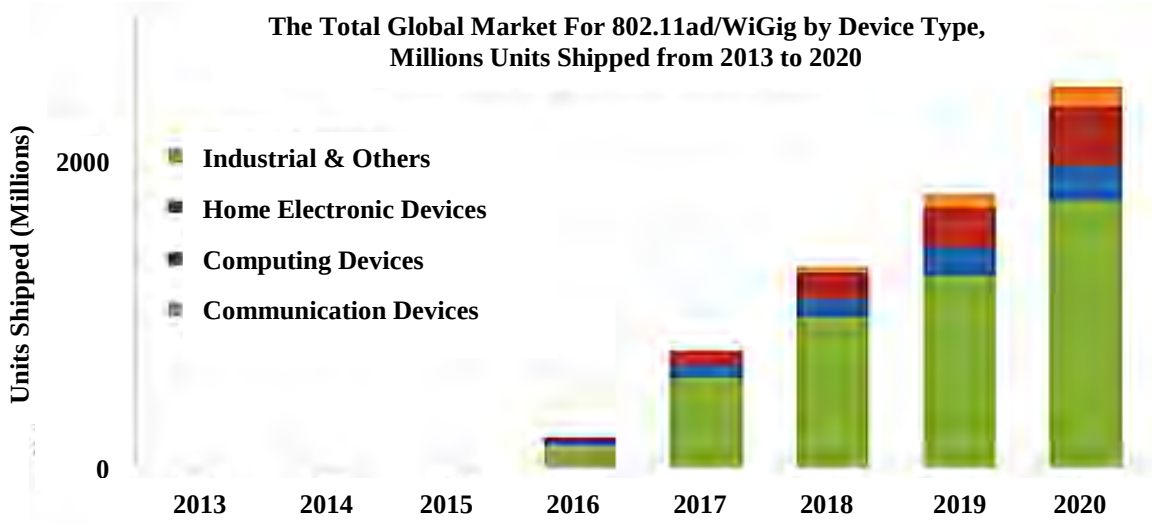
(viii) High data rate device-to-device communications [12]

(ix) Millimeter-wave for wireless backhaul connections [12]

(x) Millimeter wave communication for fifth generation (5G) broadband cellular communication [12, 19]

(xi) Information showers, massive data streaming while walking or driving [19]

When we come to the market trend of this 802.11ad/WiGig in 2009 users didn't need WiGig's (or 802.11ad) 7 Gbit/second maximum speeds and new chipsets that would lower cost and drive usage were slow to come to market. Now commercial use and product rollouts of WiGig/ 802.11ad are gathering pace including components from giants such as Qualcomm and Intel, and focused vendors such as SiBeam, now owned by Lattice Semiconductor, and Peraso Technologies [20].



Source: SAR Insight & Consulting, 'Wreless Gigabt IEEE 802.11ad The Technology and

Figure 13: Total Global market trend for 802.11ad/ WiGig [20]

Smart phones will account for most of the WiGig chip volumes. Chinese smart phone vendor LeTV launched the first WiGig-enabled smart phone in early 2016. This should give impetus to leading smart phone vendors such as Apple and Samsung to add WiGig in the next few years. Applications such as virtual reality headsets will drive WiGig in the longer term [20].

Among other uses, Dell, Intel, and Hewlett Packard rolled out WiGig docking stations in 2013, 2014, and 2015, respectively, making it possible to connect all peripheral devices via high-speed WiFi. Peraso Technologies chips enable wireless backhaul which is expected to grow rapidly with more vendors joining as we approach the 5G cellular era [20].

2.5. *Standards on 60 GHz*

The recent advances in mm-wave technology triggered the formation of various international standards groups and industry alliances. The leading standardization efforts are summarized as follows [13].

IEEE 802.15.3c: The process leading to development of IEEE 802.15.3c standard started in 2003 as an interest group under the 802.15 working group for wireless and personal area networks. It resulted in the approval by the IEEE Standards Association (IEEE-SA) Standards Board in 2009. The IEEE 802.15.3c standard is based on IEEE 802.15.3b and shares the same Medium Access Control (MAC) layer with modifications and extensions. The main application target of 802.15.3c is uncompressed video streaming at home, which requires data rates over 3.5 Gbit/s and pixel error rate below 10^{-9} at a maximum distance of 10 m. The standard defined four channels by allocating 2160 MHz band for each with 240 MHz upper and 140 MHz lower guard bands. IEEE 802.15.3c uses three PHY modes: Single-Carrier (SC) mode mainly for low-power low-cost data transfer applications, High-Speed Interface (HSI) mode with Orthogonal Frequency-Division Multiplexing (OFDM) modulation for low-latency bidirectional data transfer applications such as computer peripherals and Audio/Visual (AV) mode for uncompressed HD audio and video streaming [13].

IEEE 802.11ad: A task group was formed in 2009 to develop IEEE 802.11ad as an amendment to IEEE 802.11 to support gigabit wireless communications in the 60 GHz band. The initial efforts defined the necessary modifications and extensions to the IEEE 802.11 PHY and MAC layers to enable a throughput of at least 1 Gbit/s at top of the MAC. The IEEE 802.11ad standard includes a session transfer mechanism to support seamless handovers between Wi-Fi and 60 GHz bands. This feature will allow users to benefit from Gbit/s wireless speeds when 60 GHz is available and, when it is not, seamlessly transfer the connection to Wi-Fi for longer range. Compared to 802.15.3c, the Wi-Fi compatibility brings a great advantage to IEEE 802.11ad and makes it a more comprehensive solution for home networks rather than a single cable replacement [13]. The key advantage of IEEE 802.11ad over the other standardization activities in the 60 GHz arena is that it builds on the already existing strong market presence of Wi-Fi in the 2.4/5 GHz bands [8, 21].

It extends the successful WLAN system, and it supports fast session transfer among 2.4/5 GHz and 60 GHz. It also supports coexistence with other 60 GHz systems [21].

Wireless Gigabit Alliance (WiGig): the Wireless Gigabit Alliance (WiGig) was formed in May 2009 to establish a unified specification for 60 GHz wireless technology in order to create a truly global ecosystem of interoperable products for a diverse range of applications [1]. The specification is an organization formed by industrial members including Intel, AMD, Cisco, Microsoft and Samsung. They released the certification-ready version 1.0 specification in 2010. The purpose of the WiGig specification is to enable the gigabit wireless communications at data rates up to 7 Gbit/s while maintaining compatibility with existing Wi-Fi standards. The specification defines protocol adaptation layers to support common interfaces over 60 GHz such as data buses for PC peripherals and display interfaces for HDTVs, monitors, cameras and projectors. To support the backward compatibility with existing Wi-Fi devices, WiGig extends the MAC layer of IEEE 802.11 standards. In 2010, Wi-Fi alliance and WiGig alliance agreed on future cooperation to share the specifications. It is very likely that WiGig and IEEE 802.11ad will merge into a single standard in the near future. A single standard formed by WiGig and IEEE 802.11ad has a very high chance to be the leading mm-wave technology [13].

Ecma-387: The ECMA 387 standard was defined in 2008 and updated in 2010 by European Computer Manufacturers Association (ECMA) TC48 group to specify a PHY layer, a MAC sublayer, and an HDMI protocol adaptation layer (PAL) for 60 GHz wireless networks over indoor distances. Two types of devices are specified in the second version of ECMA 387 based on transceiver complexity and power requirements. Type A device supports data rates up to 6.350 Gbit/s without channel bonding over mandatory Single Carrier Block Transmission (SCBT) and up to 4.032 Gbit/s over optional OFDM. Type A devices also support sectoral or adaptive array antennas to achieve directional communication. Type B devices are rather simpler and support data rates up to 1.588 Gbit/s using Differential Binary Phase Shift Key (DBPSK) or up to 3.175 Gbit/s with optional Differential Quaternary Phase-Shift Keying (DQPSK) and Unequal Error Protection-Quadrature Phase Shift Keying (UEP-QPSK). Both types of devices can coexist and independently operate without requiring the other type of device. ECMA 387 also enables channel bonding to further increase the data rates by a factor of number of the bonded channels [13].

WirelessHD: The WirelessHD standard was finalized in 2008 by an industry consortium including SiBeam (later joined to SliconImage), Intel, Samsung and Philips. The aim of the specification was to enable wireless video area networks that can support uncompressed audio and video streaming at the data rate of 3.0 Gbit/s in 10 m with the application level BER of less than $4*10^{-11}$. The maximum theoretical data rate is as high as 28 Gbit/s to support common 3D formats. Similar to IEEE 802.15.3c, WirelessHD uses an OFDM based High-Rate PHY layer (HRP) and a Low-Rate PHY layer (LRP) with same frequency band plan and parameters. The WirelessHD standard supports smart antenna technology based on adaptive beam forming to operate in Non-Line-of-Sight (NLOS) conditions [13].

Chapter 3. Wireless channel models of WLAN frequencies

3.1. *Wireless Channel Modeling Approaches*

A reliable wireless system design and system performance evaluation requires a realistic channel model, which closely resembles real propagation environments. Accurate propagation channel modeling is the first major step to be carried out before any system design. A good radio channel model can provide detailed insight into the complex radio wave propagation mechanisms as well as allowing study of the achievable performance from both theoretical and simulation standpoints. Unfortunately, the mechanisms that govern radio propagation in a wireless communication channel are very complex and diverse. While it is important to keep the channel models as accurate as possible in order to sufficiently capture the key channel effects, the models developed must also be simple enough to be implemented. Hence, a good channel modeling approach involves a tradeoff between accuracy and simplicity of the system under investigation. Typically, the type of channel model that is desired depends critically on carrier frequency, bandwidth, the type of environment and system under consideration [1].

In the context of 60 GHz, for example, indoor environments with wideband systems are usually considered. In addition, due to the directional nature of 60 GHz communications systems, the channel models developed also include the effect of the antenna under study, referred to as the radio channel model, removing the effect of the antenna from the channel model results in a propagation channel, whereby the model is valid for any antenna types used in the channel model [1]. I.e. in the radio channel, the effects of the Tx and Rx antenna (antenna gain, polarization mismatch, etc.) are included in the channel, whereas the propagation channel is the channel that the radio system would experience when using isotropic Tx and Rx antenna elements [12].

3.2. *Classification of Channel Modeling Approach*

The complex phenomenon whereby a transmitted signal propagates through the wireless channel and arrives at the receiver, typically via many different paths, is known as multipath. During this process, the signal undergoes various propagation mechanisms such as reflection off the wall, scattering around furniture and/or diffraction around the corners of buildings. Therefore, many different types of simplifications and approximations can be used to model the wireless

communications channels, depending on their usage. In general, propagation channel models can be broadly divided into two main categories, namely deterministic and stochastic [1].

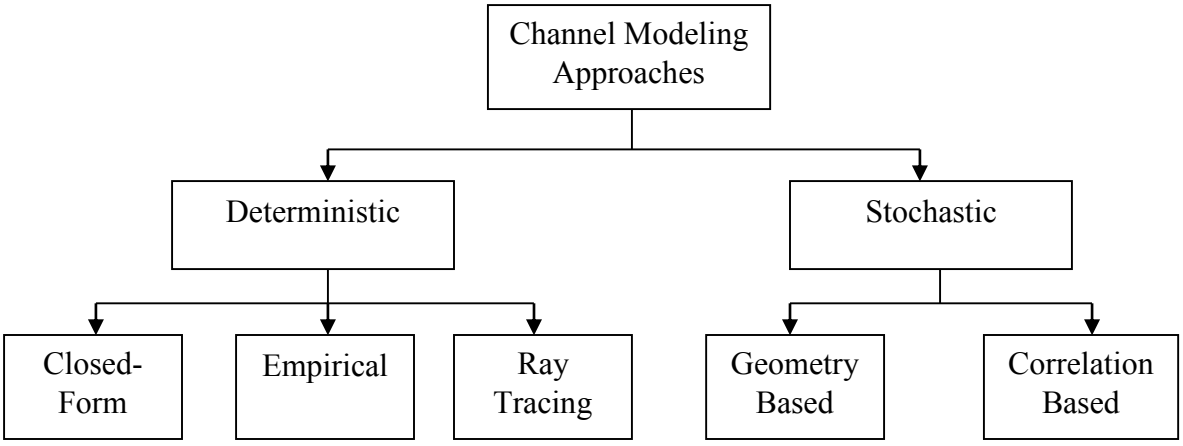


Figure 14: Classification of channel modeling approaches [1]

3.2.1. Deterministic Modeling

Deterministic model approaches can be further divided into three subgroups: the closed-form approach, empirical (based on measurement) approach and ray tracing approach. A good example of the closed-form approach is the two-path signal model, a very simple model that allows theoretical and analytical analysis for different transmission schemes. However, this approach is too conservative to represent the realistic scenario of the environment under study. On the other hand, the empirical approach extracts channel parameters from the data collected in channel measurements conducted in a specific environment under study. Hence, the empirical approach is very accurate, despite its mathematical simplicity. But such accuracy comes at the expense of high complexity due to the large amount of measurement data needed. In the ray tracing approach, advanced electromagnetic theory and simulation tools (such as the uniform theory of diffraction and finite difference time domain) are used in developing the desired channel model. Ray tracing is highly environment-specific and its accuracy is heavily dependent on the availability of the materials and topographical database to be utilized in the modeling [1].

3.2.2. Stochastic Modeling

Stochastic models are derived based on the measurement data collected in a large array of locations within the environment under study in order to provide a good statistical representation of the channel. This subsequently enables derivation of the probability density function (pdf) of the channel and thus the key channel parameters. The pdf and its associated channel parameters will be used to generate the channel impulse response (CIR) needed for simulation purposes [1].

The stochastic approach can also be divided into two subgroups: the geometry based stochastic model (GBSM) and the correlation based model. The GBSM is sometimes referred to as the ray-based model. In GBSM, scatterers are distributed in a specific manner on a certain predefined geometrical shape such as an ellipse or circle between the transmitter (TX) and receiver (RX) in order to imitate the effect of wave propagation. Typically, a single bounce is assumed for simplicity. On the other hand, the correlation-based modeling approach, which has been widely used to model multiple antenna systems, employs the channel second-order statistics. In this approach, the transfer functions of each TX and RX antenna element pair, as well as their signal correlations, are characterized [1].

Chapter 4. Theoretical performance comparison of the three frequencies

For all the modeling approaches discussed above, two important channel properties can be characterized, namely large-scale and small-scale channel characterizations. Large-scale channel characterization consists of path loss (PL) and shadowing effects [1]. Large scale channel characterization is used to estimate the coverage area of a wireless communication system. Path loss refers to the attenuation of transmitted signal strength over the communication distance. It is defined as the ratio of the transmitted signal strength to the received signal strength. Shadowing is a result of the variation of the propagation path. Log-normal shadowing is the most common model for shadowing [22].

Generally, the path loss (PL) as a function of distance, d, is thus given by

$$PL(d)[dB] = PL_{ave}(d)[dB] + X_{\sigma}[dB] \quad (1)$$

where $PL_{ave}(d)$ is the average path loss and X_{σ} is the shadowing fading.

$$PL_{ave}(d)[dB] = PL(d_0)[dB] + 10n\log_{10}\left(\frac{d}{d_0}\right) + \sum_{q=1}^{Q} X_q \, , for \; d \geq d_0 \quad (2)$$

where d_0 and n denote the reference distance and PL exponent respectively and the term X_q accounts for the additional attenuation due to specific obstruction by objects or shadowing. Typically *PL* (d_0) values are referred to d_0 = 1m [1].

4.1. Coverage comparison

The received signal strength in wireless communications is primarily determined by the path loss and shadowing. Therefore, the communication range of a wireless system is designed upon the path loss and shadowing models. The conventional simplified models can be used to capture the large-scale propagation and analyze the valid communication range or cell coverage [22].

The communication range or cell coverage, as in (3) [22], is the expected percentage of the area within a cell where the received signal strength is above a given minimum:

$$C = Q(\alpha) + e^{\left(\frac{2-2\alpha}{\beta 2}\right)} * Q\left(\frac{2-\alpha\beta}{\beta}\right) \quad (3)$$

$$\alpha = \frac{p_{min} - P_r(D)}{\sigma}, \quad \beta = 10nlog_{10}\left(\frac{e}{\sigma}\right), \quad \Pr(D) = P_t - PL(D)$$

where P_{min} is the required minimum received power; σ is the standard variation of shadowing fading; and Q(x) is the probability that a Gaussian random variable X, with the mean of 0 and the variance of 1, is greater than x. $P_r(D)$ is the received power at the edge of the cell [22].

The size of the cell should be so determined that the minimal received SNR is guaranteed to maintain the quality of service. In designing the range of a wireless communication system, we must keep the cellular coverage above a specific level in order to maintain the acceptable performance in most areas of the cell [22]. In the following, we analyze the cell size of 60 GHz WLAN communication and compare it to that of 2.4 and 5 GHz WLAN technology.

In the analysis, the transmitted signal strengths take the suggested values from the regulations: 35 dBm for 60 GHz and 25 dBm for 2.4 and 5 GHz that operate near the US Federal Communications Commission (FCC) regulatory limit [1, 22]. It can be seen from Table 3 that the EIRP of the 60 GHz system is approximately 10 times larger than 2.4/5 GHz.

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

Table 3: Comparison of the typical implementation of 60 GHz, UWB and 802.11n systems in terms of their output power, antenna gain and EIRP output [1]

The receiver minimum input sensitivity P_{min} is assumed the typical value of -60 dBm [22]. On the other hand, the 802.11n, 802.11ac and 802.11ad path loss models will be used for 2.4, 5 and 60

GHz WLAN communication channel modeling respectively to find PL(D). First let us see the path loss models of each IEEE 802.11 standards.

4.1.1. 802.11ad path loss model

The IEEE802.11ad channel model constitutes a mix of measurement based stochastic parameters, ray tracing, empirical distributions and theoretical models. Ray tracing is used to determine the cluster delays and angles, empirical distributions are used for the amplitude and intra-cluster angular distribution of reflected rays and theoretical models for the polarization properties. Blockage models for human body shadowing are included on top of the modeling framework [12]. As IEEE 802.11ad proposed path loss model for 60 GHz WLAN networks, The following IEEE 802.11ad formula in [23] will be used on this thesis.

$$PL[dB] = A + 20\log_{10} f + 10n log_{10} R \quad (4)$$

where A and n are parameters specific for the scenario and antenna system, f is the carrier frequency in GHz, R is the distance between TX and RX in m [23].

To generate instantaneous path loss realizations, the normal in dB shadow fading (SF) model should be used together with the average path loss model. SF standard deviation σ is specific for the scenario and antenna system parameters. The path loss model parameters for the conference room, enterprise cubicle, and living room scenario are shown in Table 4 [23].

Scenario	*A*, dB	*n*	SF std. dev., dB
Conference room STA-STA LOS	32.5	2.0	0
Conference room STA-STA NLOS	51.5	0.6	3.3
Conference room STA-AP LOS	32.5	2.0	0
Conference room STA-AP NLOS	45.5	1.4	3.0
Living room LOS	32.5	2.0	0
Living room NLOS	44.7	1.5	3.4
Cubicle environment Near/Far laptop location, LOS	32.5	2.0	0
Cubicle environment Far laptop location, NLOS	44.2	1.8	1.5

Table 4: Summary of path loss model parameters [23]

4.1.2. 802.11n and 802.11ac path loss model

These models are based on the cluster model developed by Saleh and Valenzuela (SV) channel model which is geometry-based stochastic channel model. The 802.11n path loss model can be used for both 2.4 GHz and 5 GHz frequency bands, since the experimental data and published results for both bands were used in developing the model [24, 25]. IEEE 802.11ac large scale propagation is also characterized by this path loss model [25, 26]. IEEE 802.11n proposes six delay profile models for different environments (Models A-F):

- Model A (optional, should not be used for system performance comparisons), flat fading model with 0 ns rms delay spread (one tap at 0 ns delay model). This model can be used for stressing system performance, occurs small percentage of time (locations).
- Model B with 15 ns rms delay spread.
- Model C with 30 ns rms delay spread.
- Model D with 50 ns rms delay spread.
- Model E with 100 ns rms delay spread.
- Model F with 150 ns rms delay spread.

The path loss model for indoor propagation that IEEE 802.11n proposes consists of the free space loss PL_{FS} (slope of 2) up to a breakpoint distance and slope of 3.5 after the breakpoint distance [24]. Because the path loss differs at close range (around 5 to 10 meters) compared to larger distances. These short breaking point distances are considered free space (i.e., open space with no path reflections). For larger distances after breaking point, path reflections from the environment (especially reflections from surrounding walls) generally result in a steeper overall drop in signal strength at the receiver [27]. The breakpoint distances for the channel models are given in table 5. Also included in the path loss model is the shadow fading loss due to large scale obstructions [24, 25]. The path loss model is given as follows:

$$PL(d) = PL_{FS}(d) + SF \qquad d \le d_{dB}$$
$$PL(d) = PL_{FS}(d_{dB}) + 35\log_{10}\left(\frac{d}{d_{dB}}\right) + SF \qquad d > dBP \tag{5}$$

where d is the separation distance between the transmitter and receiver in meters, PL_{FS} is the free space path loss in dB, d_{BP} is the breakpoint distance in meters, and SF is the shadow fading loss in

dB. The shadow fading loss is modeled by log-normal distribution (Gaussian in dB) with zero mean, as follows:

$$p(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{\left(-\frac{x^2}{2\sigma^2}\right)} \quad (6)$$

where σ is the standard deviation of the shadow fading [24, 25]

The breakpoint distance is also the transition for the shadow fading standard deviation. Table 5 gives the shadow fading standard deviation before and after the breakpoint. For all channel models, LOS conditions are used before the breakpoint and NLOS after the breakpoint [25].

The expression for free space path loss, $PL_{FS}(d)$ is

$$PL_{FS}(d) = -10 \log_{10} \left(\frac{G_t G_r \lambda^2}{(4\pi d)^2}\right) \quad (7)$$

where *Gt* , *Gr* are the transmitter and receiver antenna gains, respectively, *d* is the distance between them, in meters (known as T-R separation), and λ is the wavelength of the transmitted carrier frequency [27]. Assuming unity antenna gains (*Gt* = *Gr* = 1), (7) can be written as:

$$PL_{FS}(d) = 10 \log_{10} \left(\frac{(4\pi d)^2}{\lambda^2}\right) = 20 \log_{10} \left(\frac{4\pi}{\lambda}\right) + 20 \log_{10} d \quad (8)$$

For 5 GHz,

$$PL_{FS}(d) = 46.4dB + 20 \log_{10} d \quad (9)$$

For 2.4 GHz,

$$PL_{FS}(d) = 40dB + 20 \log_{10} d \quad (10)$$

New Model	d_{BP} (m)	Slope before d_{BP}	Slope after d_{BP}	Shadow fading std. dev. (dB) before d_{BP} (LOS)	Shadow fading std. dev. (dB) after d_{BP} (NLOS)
A (optional)	5	2	3.5	3	4
B	5	2	3.5	3	4
C	5	2	3.5	3	5
D	10	2	3.5	3	5
E	20	2	3.5	3	6
F	30	2	3.5	3	6

Table 5: Path loss model parameters [24]

Model mapping to a particular environment is presented in the below table [25].

RMS delay			
Model	**Spread (ns)**	**Environment**	**Example**
A	0	N/A	N/A
B	15	Residential	Intra-room, room-to-room
C	30	Residential/small office	Conference room, classroom
D	50	Typical office	Sea of cubes, large conference room
E	100	Large office	Multi-story office, campus small hotspot
F	150	Large space (indoors/outdoors)	Large hotspot, industrial, city square

Table 6: Channel models environments [25]

Channel model A is flat fading Rayleigh, no delay spread and no multipath, and is not applicable to a wideband system like 802.11. This channel model was only included for its utility in analytical modeling. The most commonly used channel models are B, D, and E [25].

4.1.3. Coverage comparison key parameters

IEEE path loss models for the three frequencies on three standards will be used to compare the coverage distance of the three WLAN frequencies. Living room environment scenario is chosen for this comparison. Let us first compare in NLOS case. Therefore, In IEEE 802.11n and ac for 2.4 and 5 GHz, the breakpoint d_{BP} for living room or residential environment is 5 meters and the standard deviation of the shadowing for NLOS after d_{BP} is 4 dB and before d_{BP} is 3 dB. On the other hand, for 60 GHz NLOS communication, the path loss parameters for living room environment A and n are 44.7 and 1.5 respectively. The standard deviation of the shadowing is 3.4 dB. For living room LOS case, the path loss parameters for 60 GHz A and n are 32.5 and 2.0 respectively and the standard deviation of shadowing is assumed to be 0.00000000001 dB as 0dB is undefined when some number divided by it on MATLAB. Also for 2.4 and 5 GHz, IEEE 802.11n/ac path loss defines LOS below d_{BP} NLOS above d_{BP}. Based on that d_{BP} is 5 meters and the standard deviation of the shadowing for LOS below d_{BP} is 3 dB but above d_{BP} the communication is in NLOS scenario as there are reflected multipath signals in addition to LOS path. So 60 GHz LOS communications will be compared to 2.4 and 5 GHz frequency NLOS scenario with 4dB shadow fading after d_{BP} and 3 dB LOS before the breaking point distance d_{BP}.

4.2. Capacity comparison

The maximum channel capacity over a single input and single-output (SISO) antenna system links can be calculated according to the Shannon capacity for AWGN channel with continuous-valued inputs and outputs is given by [28]:

$$C = W \log_2(1 + SNR) \qquad (11)$$

where W is the system bandwidth, SNR is the receive signal to noise ratio, defined as Eb/N0, where Eb is the energy per bit and N0 is the noise power spectral density [28].

It can be concluded from (11) that a high data rate can be achieved with a low bandwidth if the SNR is high. However, a high SNR requires either a short distance between transmitter and receiver, or a high transmit power, or high gain antennas. In addition, Increasing bandwidth seem like an obvious way to improve the channel capacity, but it also increases the noise in the channel

and therefore reduces the signal-to-noise ratio at a fixed signal level. Therefore, increasing bandwidth makes sense only if the SNR is sufficiently high [16]. To formulate SNR for this capacity comparison, first the received signal power at a distance d is given by [28]:

$$P_r[dB] = P_t + G_t + G_r - PL \quad (12)$$

where Pt is the transmit power, PL is the path loss, Gt and Gr are antenna gain for transmit and receive antennas respectively, both assumed to be 0 dB for simplicity. All expressions are in decibels (dB) [28].

According to FCC ruling the maximum allowable transmit power on 60 GHz frequency is 40dBm, Pt ≤ 40dBm [28]. Also the EIRP transmit limit for 2.4/5 GHz is typically confined to 30 dBm due to the crowded Industrial, Scientific and Medical band [1]. The path loss models to find PL that we use for this comparison are also the one that we use for coverage comparison, i.e. IEEE 802.11 proposed path loss models for respective frequencies that are stated above for both LOS and NLOS channels. For 60 GHz 802.11ad model, for both 2.4 GHz and 5 GHz frequency 802.11n/ac path loss models are used.

Secondly, if thermal noise as the primary source of interference, the required sensitivity at the receiver can be calculated as

$$S_r = NF + F + SNR \quad (13)$$

where NF is the noise floor calculated by thermal noise

$$N = kTWF \quad (14)$$

F is the noise figure (optimistically) assumed to be 0 dB, SNR is the signal to noise ratio at the receiver, k is Boltzmann's constant, 1.38×10^{-23} J/K (W.S/K), and T is the room temperature (typically 290K) [28].

$$N = kTW \qquad as\ F = 0dB \quad (15)$$

As we know Watt to dBm conversion formula is [29]:

$$N[dBm] = 10 * \log_{10} N(w) + 30 \quad (16)$$

Using formula 15 and 16, for the 60 GHz system with 2.16 GHz BW, the noise floor is calculated as -80.6 dBm. For 2.4 and 5 GHz, the noise floor is calculated as -97.9 dBm for 40 MHz in 802.11n and -91.96 dBm for 160 MHz in 802.11ac respectively.

To ensure adequate performance at the receiver, the minimum received power should be greater than or equal to the required sensitivity [28].

$$P_r \geq S_r$$

$$P_t - PL(d) \geq NF + SNR$$

$$SNR \leq P_t - NF - PL(d) \quad (17)$$

Therefore, the received SNR versus communication distance for 60 GHz wireless system over LOS and NLOS channels, when maximum allowable transmit power, 40 dBm, is used, can be derived as:

$$SNR \leq 120.6 - PL(d) \quad (18)$$

As a result, the relationship between the maximum capacity and communication distance is then given by

$$C \leq \log_2(1 + 10^{120.6 - PL(d)})$$

$$C_{max} = \log_2(1 + 10^{120.6 - PL(d)}) \quad (19)$$

For 60 GHz bandwidth 2.16 GHz or 2160 MHz, the Shannon capacity in Mbps becomes:

$$C_{max} = 2160 * \log_2(1 + 10^{120.6 - PL(d)}) \quad (20)$$

Similarly, For 2.4 and 5 GHz the SNR and Shannon capacity vs communication distance, when maximum allowable transmit power, 30 dBm, is used, are as follows:

For 2.4 GHz,

$$SNR \leq 127.9 - PL(d)$$

$$C \leq \log_2(1 + 10^{127.9 - PL(d)})$$

$$C_{max} = \log_2(1 + 10^{127.9 - PL(d)}) \quad (21)$$

i.e. for 40 MHz bandwidth, the capacity becomes:

$$C_{max} = 40 * \log_2(1 + 10^{127.9 - PL(d)}) \quad (22)$$

For 5 GHz,

$$SNR \leq 121.96 - PL(d)$$

$$C \leq \log_2(1 + 10^{121.96 - PL(d)})$$

$$C_{max} = \log_2\left(1 + 10^{121.96 - PL(d)}\right) \quad (23)$$

i.e. for 40 MHz bandwidth, the capacity becomes:

$$C_{max} = 40 * \log_2(1 + 10^{121.96 - PL(d)}) \quad (24)$$

i.e. for 160 MHz bandwidth, the capacity becomes:

$$C_{max} = 160 * \log_2(1 + 10^{121.96 - PL(d)}) \quad (25)$$

For MIMO systems, in general ideal case the Shannon capacity will grow proportional with the smallest number of antennas min(N; M) where M and N are number of transmitter and receiver antennas [30, 31].

$$C_{MIMO} \approx \min(M, N) * W * \log_{10}(1 + SNR) \quad (26)$$

when M=N, $C_{MIMO} \approx M * W * \log_{10}(1 + SNR) \approx N * W * \log_{10}(1 + SNR)$

For 3X3 MIMO case, for each frequencies the results of Shannon capacity is as follows:

For 802.11n 2.4 GHz – 40 MHz channel,

$$C_{max} = 3 * 40 * \log_2(1 + 10^{127.9 - PL(d)}) \quad (27)$$

For 802.11n 5 GHz – 40 MHz channel,

$$C_{max} = 3 * 40 * \log_2(1 + 10^{121.96 - PL(d)}) \quad (28)$$

For 802.11ac 5 GHz – 160 MHz channel,

$$C_{max} = 3 * 160 * \log_2(1 + 10^{121.96 - PL(d)}) \quad (29)$$

For 802.11ad 60 GHz – 2160 MHz channel,

$$C_{max} = 3 * 2160 * \log_2(1 + 10^{120.6 - PL(d)}) \quad (30)$$

For maximum MIMO scenario case, for each frequency the result of Shannon capacity is as follows:

For 802.11n 2.4 GHz – 40 MHz channel, the maximum MIMO is 4X4

$$C_{max} = 4 * 40 * \log_2(1 + 10^{127.9 - PL(d)}) \quad (31)$$

For 802.11n 5 GHz – 40 MHz channel, the maximum MIMO is 4X4

$$C_{max} = 4 * 40 * \log_2(1 + 10^{121.96 - PL(d)}) \quad (32)$$

For 802.11ac 5 GHz – 160 MHz channel, the maximum MIMO is 8X8

$$C_{max} = 8 * 160 * \log_2(1 + 10^{121.96 - PL(d)}) \quad (33)$$

For 802.11ac 5 GHz – 160 MHz channel, MIMO 6X6 to compare to 8X8 MIMO

$$C_{max} = 6 * 160 * \log_2(1 + 10^{121.96 - PL(d)}) \quad (34)$$

For 802.11ad 60 GHz – 2160 MHz channel, the maximum MIMO is 4X4

$$C_{max} = 4 * 2160 * \log_2(1 + 10^{120.6 - PL(d)}) \quad (35)$$

In addition, 802.11n and 802.11ac use channel bonding to increase the base channel 20 MHz to bigger channel bandwidth. On the other hand, 60 GHz frequency uses only a single channel to achieve highest capacity than the other frequencies. If we use channel bonding for 60 GHz frequency, the capacity increases proportionally as the number of channels bonded together. The maximum data rate achieved using four channels are four times than a single channel data rate [6]. So channel bonding the four channels of 60 GHz is four times maximum capacity of a single channel. Therefore the Shannon capacity of 60 GHz bonding the channels can be calculated as:

$$C_{max} = N * 4 * 2160 * \log_2(1 + 10^{120.6 - PL(d)}) \quad (36)$$

where N is the number channels bonded.

When the maximum number of channels, four channels, is bonded together for one communication the maximum Shannon capacity is:

$$C_{max} = 4 * 4 * 2160 * \log_2(1 + 10^{120.6 - PL(d)}) \quad (37)$$

Chapter 5. Results of the simulations

In this chapter we simulate based on the previous chapter theoretical comparison formulas and interpret the simulation results using the MATLAB codes in the Appendix A for both coverage comparison and capacity comparison. On the coverage comparison, the line of sight (LOS) and non-line of sight (NLOS) scenarios for the three frequencies are compared as stated theoretically on the previous chapter. On the other hand, for capacity comparisons in addition to LOS and NLOS scenarios stated on previous chapter above for the three 802.11 standards, different MIMO antenna systems are also compared.

5.1. Coverage simulations

Based on theoretical cell coverage area and path loss model formulas in chapter 4, figure 15 depicts the NLOS percentage coverage area variation on the y-axis upon the communication distance on the x-axis. Also on the MATLAB code, at which distance 99.5 % coverage area is accomplished is calculated and give the below results. So to provide 99.5% coverage of a cell in NLOS scenario, the 60 GHz communication can only support a cell of 3.2 meters in radius due to its fast path loss upon distance, while the 2.4 GHz and 5 GHz communication can support up to about 23.2 and 15.3 meter radius respectively.

5.1.1. NLOS 99.5% coverage area MATLAB result

- Coverage radius for 2.4 GHz is about – 23.2 meters
- Coverage radius for 5 GHz is about – 15.3 meters
- Coverage radius for 60 GHz is about – 3.2 meters

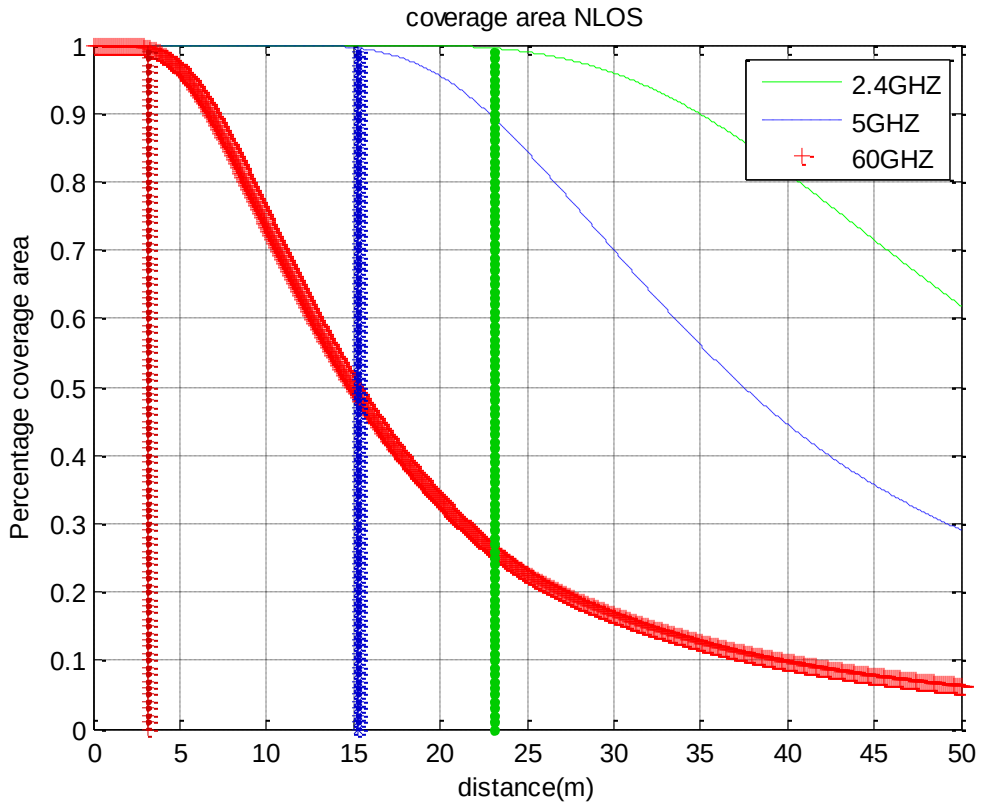


Figure 15: NLOS Percentage Coverage Area

5.1.2. LOS 99.5% coverage area MATLAB result

For LOS scenario stated in the previous chapter, 802.11n/ac 2.4 GHz and 5 GHz frequency LOS below d_{BP} and NLOS after d_{BP} scenario is compared with 802.11ad LOS scenario. Figure 16 shows the percentage coverage areas of those three frequencies with respect to communication distance according to their respective 802.11 path loss models. Also using MATLAB, 99.5% coverage radius is resulted as follows:

- Coverage radius for 2.4 GHz is about – 23.2 meters
- Coverage radius for 5 GHz is about – 15.3 meters
- Coverage radius for 60 GHz is about – 22.3 meters

Therefore to provide 99.5% coverage in LOS system, the 60 GHz communication distance is significantly increased and can further support a cell of about 22.3 meters in radius. The 2.4 GHz and 5 GHz communication below d_{BP} is LOS, above d_{BP} is NLOS as IEEE path loss model states no multipath up to d_{BP}, so 60 GHz LOS scenario is compared to 2.4 and 5 GHz LOS below d_{BP} and NLOS above d_{BP}.

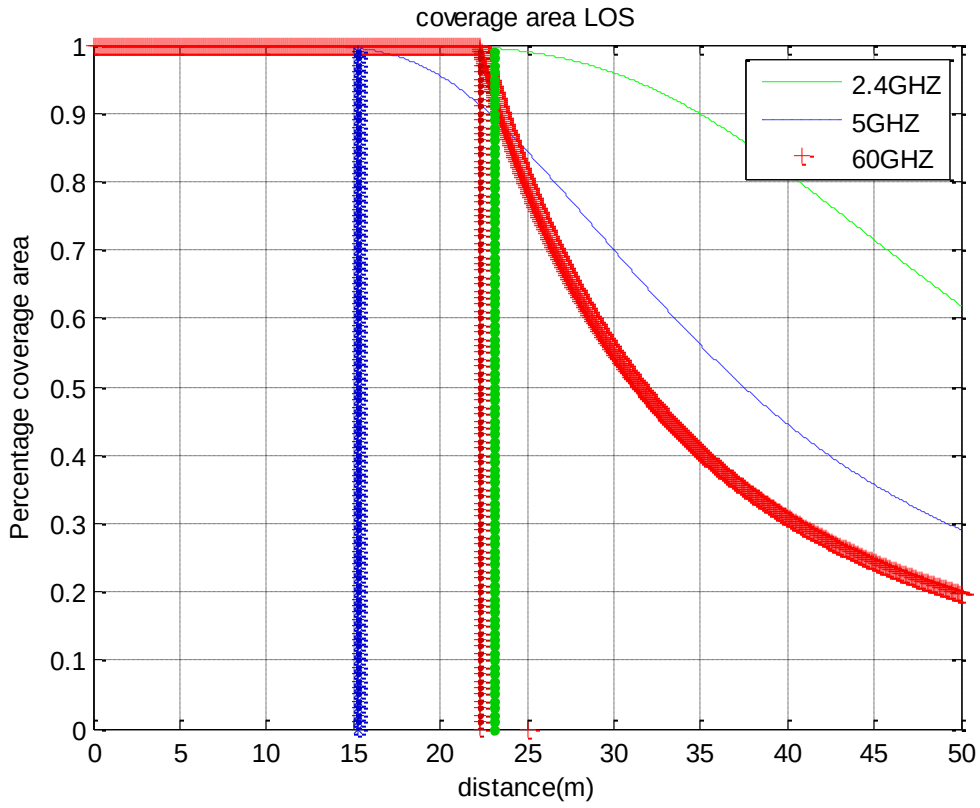


Figure 16: LOS Percentage Coverage Area

The comparison between LOS and NLOS scenarios coverage radius for 99.5% area coverage for specifically 60 GHz frequency simulation graph result is as follows:

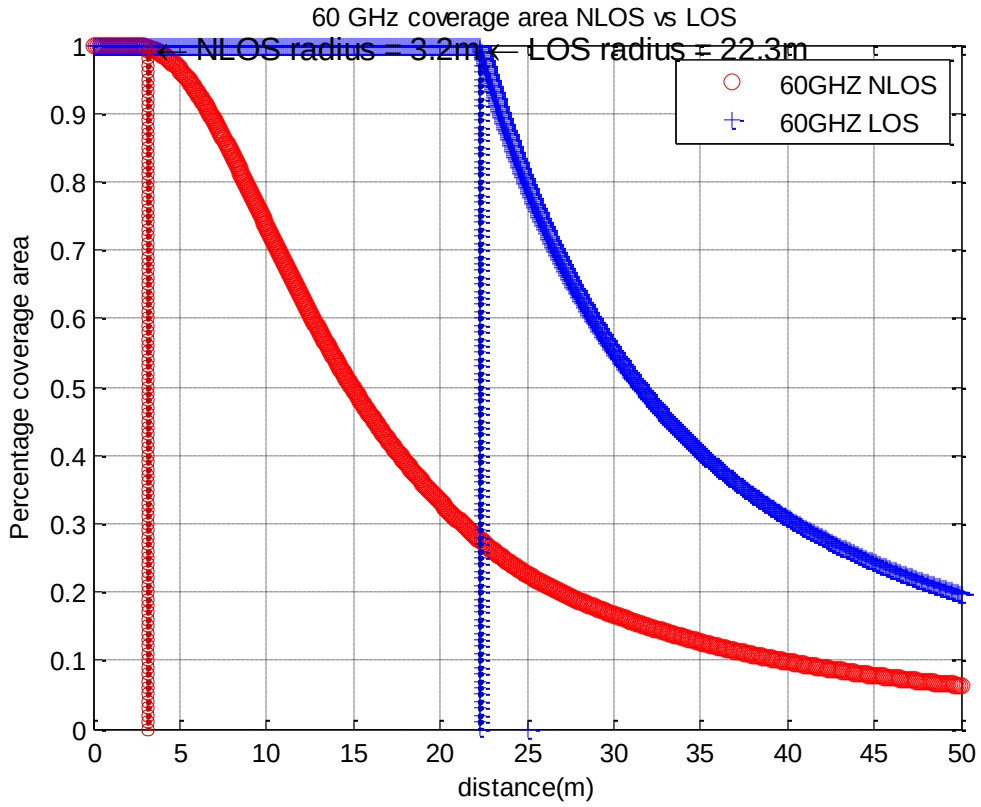


Figure 17: NLOS vs. LOS Percentage Coverage Area comparison

Based on the above MATLAB graphs and results, 60 GHz coverage in LOS scenario is almost the same as 2.4 GHz coverage but in NLOS 60 GHz have very poor communication distances than 2.4 and 5 GHz frequencies. Therefore, 60 GHz communications should be in line of sight and use mitigation technique like relays and more than one APs (access points) to avoid LOS path blockages by humans or objects as 60 GHz cannot penetrate through objects unlike 2.4 and 5 GHz. For Living room environment the coverage area of 60 GHz in NLOS scenario is not enough but in LOS is more than enough for one room as the communication does not pass to other rooms that avoids interference from neighboring Wi-Fis and gives secure communications. For room to room communication we can use other APs jointly working together.

5.2. Capacity simulations

The simulation results of the previous chapter theoretical capacity comparison of the three 802.11 standards, namely 802.11n, 802.11ac and 802.11ad, are given below. The comparison is done on different scenarios. First LOS and NLOS cases with single input single output (SISO) antenna system are compared then capacity at respective maximum possible multiple input multiple output (MIMO) antenna numbers for those standards are evaluated. Finally up to now no channel bonding used for 60 GHz communication. This frequency only uses one channel unlike 2.4 GHz and 5 GHz communications. When channel bonding is used for 802.11ad 60 GHz communication the same as 802.11n and 802.11ac is simulated to get its capacity both in NLOS and LOS scenarios.

5.2.1. SISO antenna systems capacity comparison

In this SISO scenario the antennas at both transmitters and receivers are only one antenna. First NLOS then LOS cases are seen for those three 802.11 standards as below. The maximum capacity accomplished at close proximity to APs and the far end minimum capacity at 99.5% coverage radius, which is obtained on coverage comparison, from the AP for each of the frequencies are also obtained and indicated on all MATLAB capacity comparison simulation results. As seen on the coverage comparison, the coverage radius of 2.4 GHz and 5 GHz are given as 23.2 and 15.3 meter radius respectively. On the other hand, for 60 GHz the coverage radius, which gives 99.5 % percentage coverage area, for NLOS and LOS scenarios are given as 3.2 and 22.3 meters respectively.

Based on 802.11 respective path loss models from IEEE, 802.11n/ac has LOS path only below d_{BP} and NLOS paths above d_{BP} but for 802.11ad states NLOS and LOS scenarios without breaking points. So 60 GHz frequency both NLOS and LOS scenarios will be compared the same as coverage comparison with 2.4 GHz and 5 GHz LOS below d_{BP} and NLOS above d_{BP} scenario as stated on IEEE 802.11n/ac path loss models.

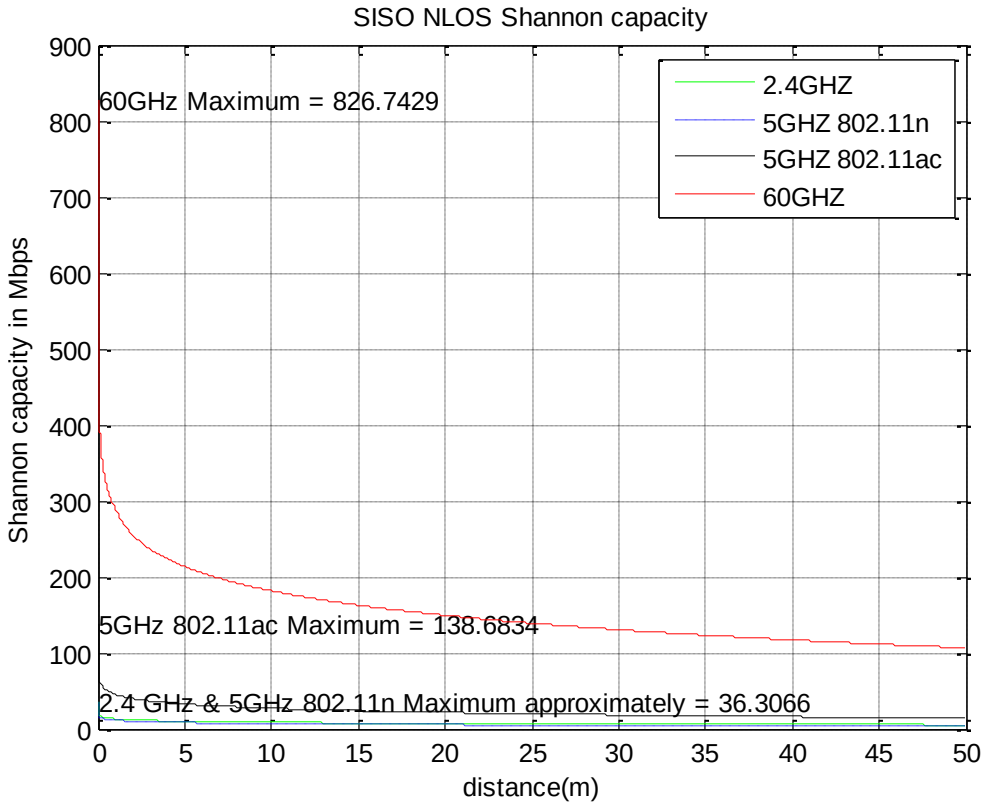


Figure 18: NLOS SISO system Shannon capacity

As seen on the figure 18, 802.11ad has highest capacity, secondly 802.11ac and the least one is 802.11n. This shows that even in NLOS scenario the capacity of 60 GHz communication has the highest communication speeds but as seen on coverage comparison above the coverage of this frequency is the least one and is very small for WLAN communications.

On LOS system the transmitter and receiver antennas are in line of sight with each other. Almost all of the transmit power is in the line of sight path. There is a significant increase when compared to NLOS case for 60 GHz, about 200Mbps increase as seen on figure 20. So 60 GHz communication should be in LOS because this frequency has increased in both coverage and capacity values than NLOS.

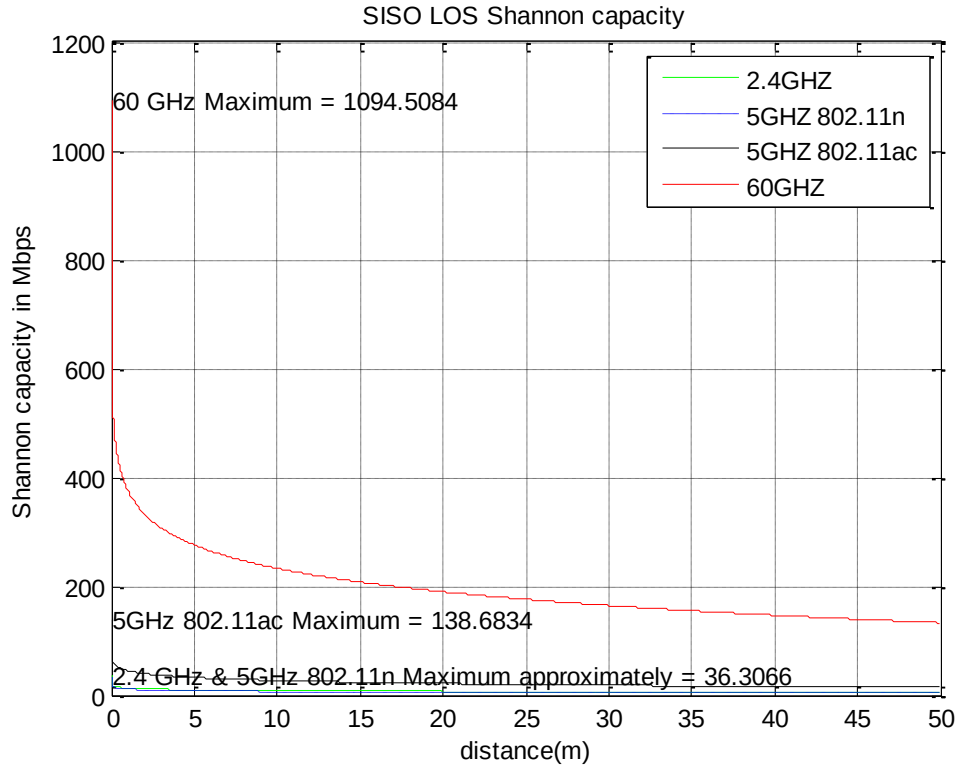


Figure 19: LOS SISO system Shannon capacity

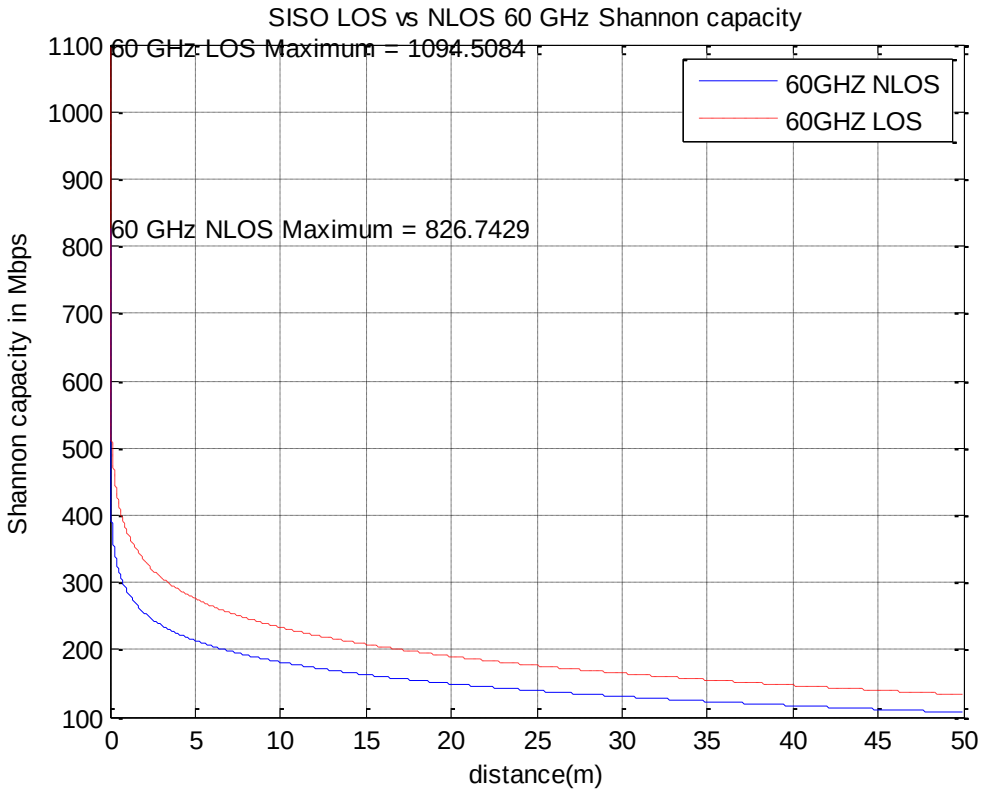


Figure 20: LOS vs. NLOS SISO system comparison

5.2.2. Maximum MIMO systems for each 802.11 standards

The maximum possible MIMO systems for each 802.11 standards are given in chapter 4 as 802.11n can have up to 4X4 MIMO antenna systems, 802.11ac can have up to 8X8 MIMO antenna systems and 802.11ad can have up to 4X4 MIMO antenna systems.

From the simulation result figures below it can be concluded that using MIMO antenna systems enhance the capacity of all frequencies. Possible number of antennas should be used as increasing the number of antenna, increases the capacity proportionally. To see this for 802.11n 3X3, 802.11ac 6X6, and 802.11ad 3X3 MIMO antenna systems are simulated to compare to their maximum MIMO antenna systems respectively in both NLOS and LOS cases.

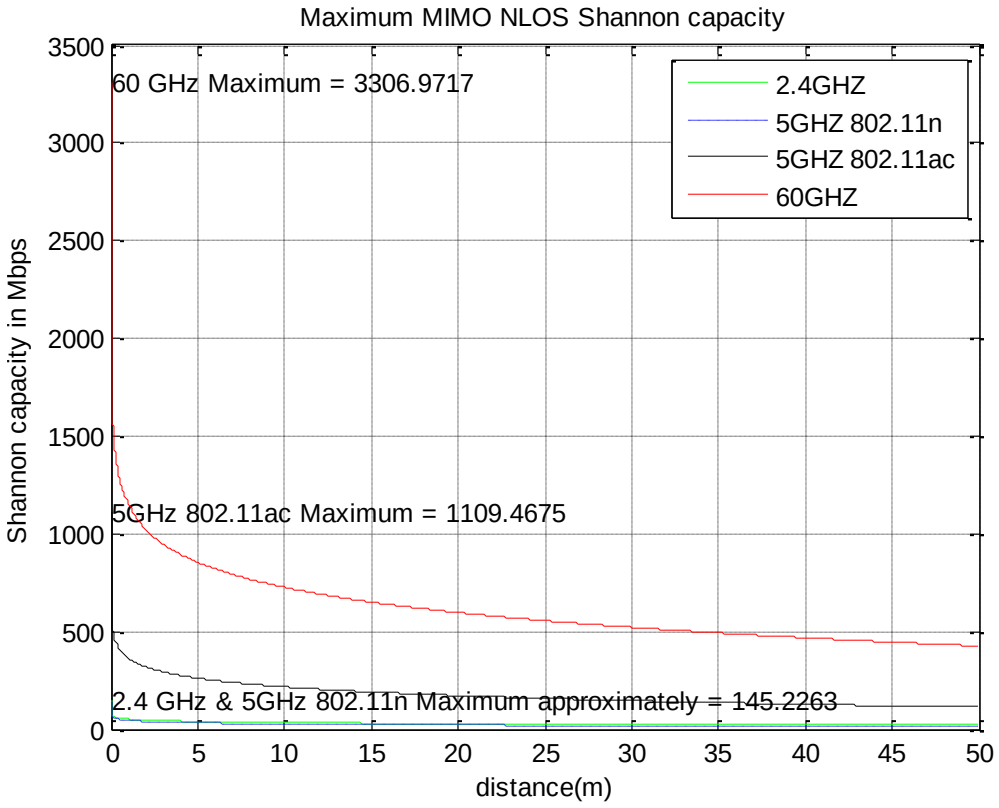


Figure 21: Maximum MIMO NLOS system

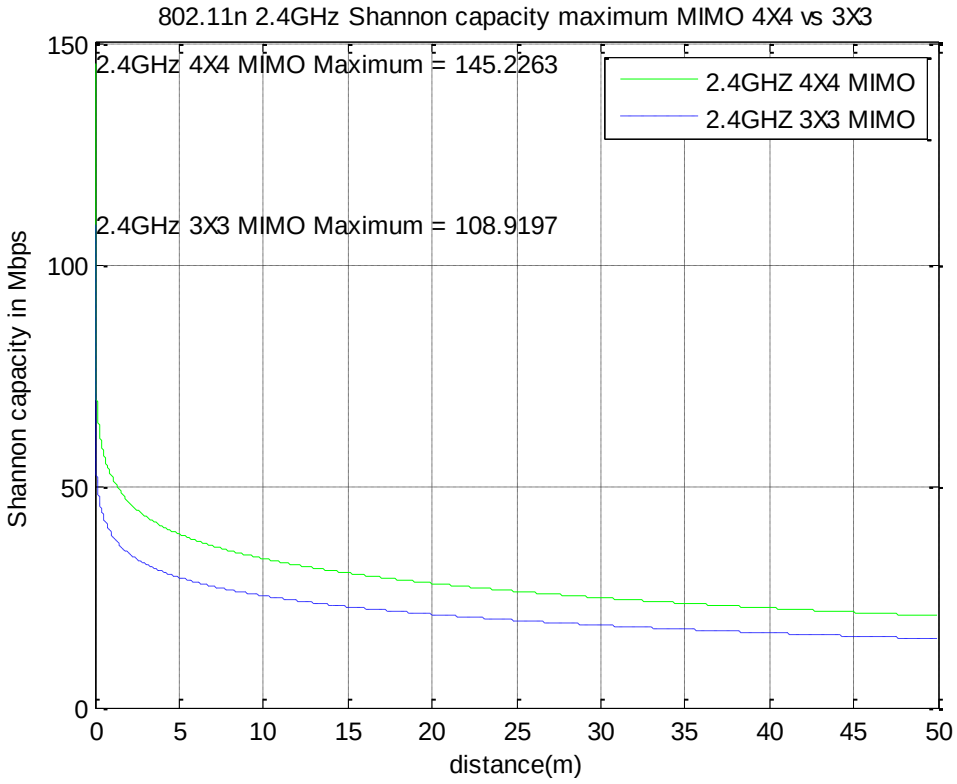


Figure 22: 802.11n 2.4GHz Shannon capacity maximum 4X4 vs. 3X3 MIMO

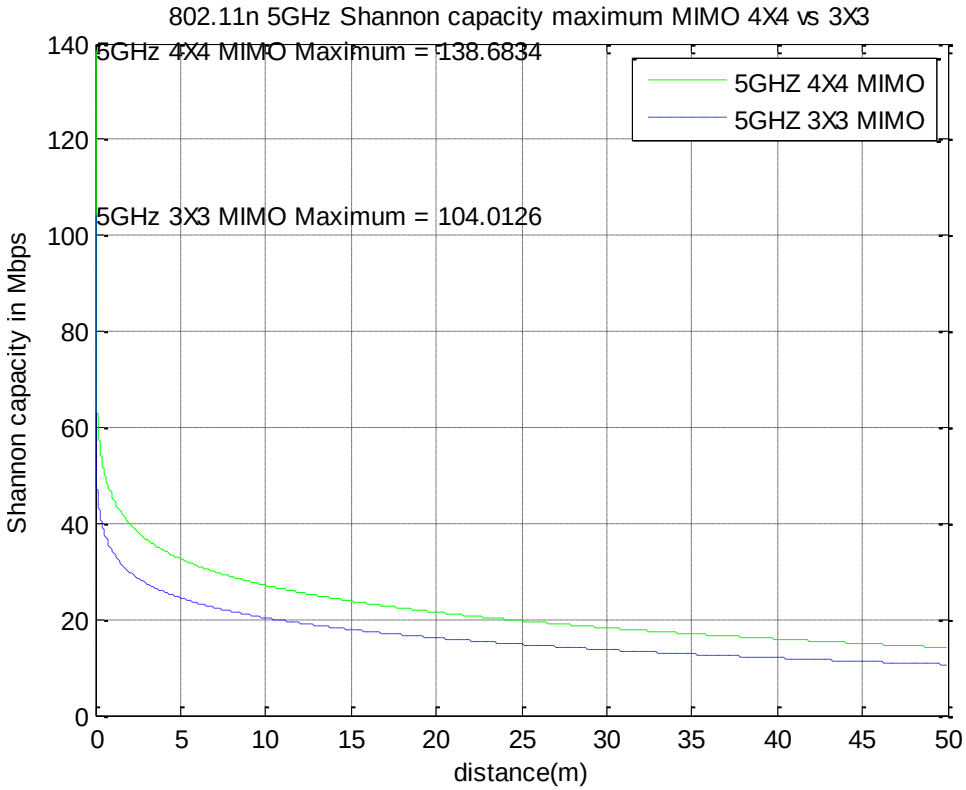


Figure 23: 802.11n 5GHz Shannon capacity maximum 4X4 vs. 3X3 MIMO

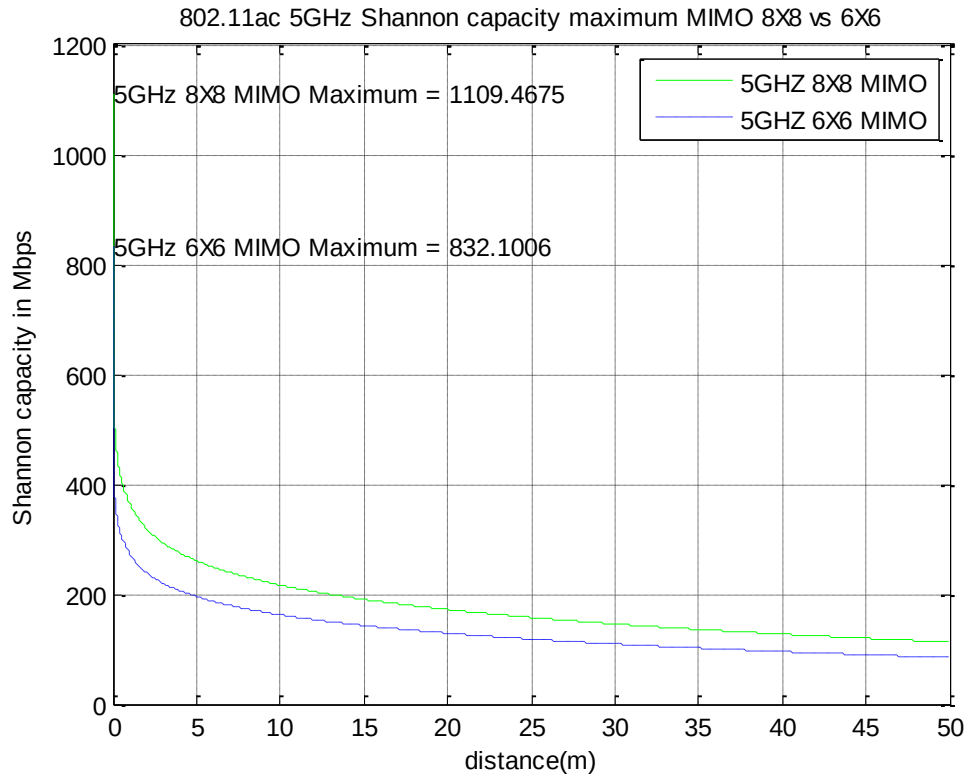


Figure 24: 802.11ac 5GHz Shannon capacity maximum 8X8 vs. 6X6 MIMO

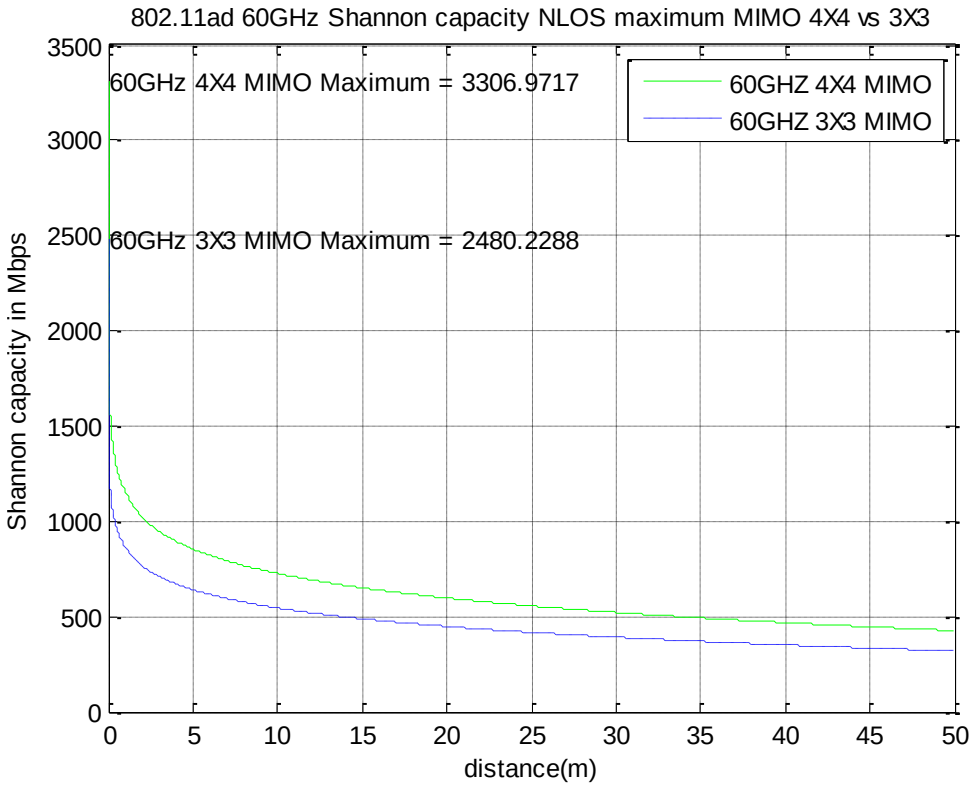


Figure 25: 802.11ad 60GHz Shannon capacity NLOS maximum 4X4 vs. 3X3 MIMO

The same is true for LOS case, 60 GHz has the highest capacity of all the three frequencies in this scenario and also as MIMO number of antennas increases, the data rate of this LOS communication is increased proportionally the same as NLOS communication. In addition, based on the output in figure 28, LOS communication has better capacity than NLOS communications, i.e. about 1000 Mbps (or 1Gbps) increase seen than NLOS scenario.

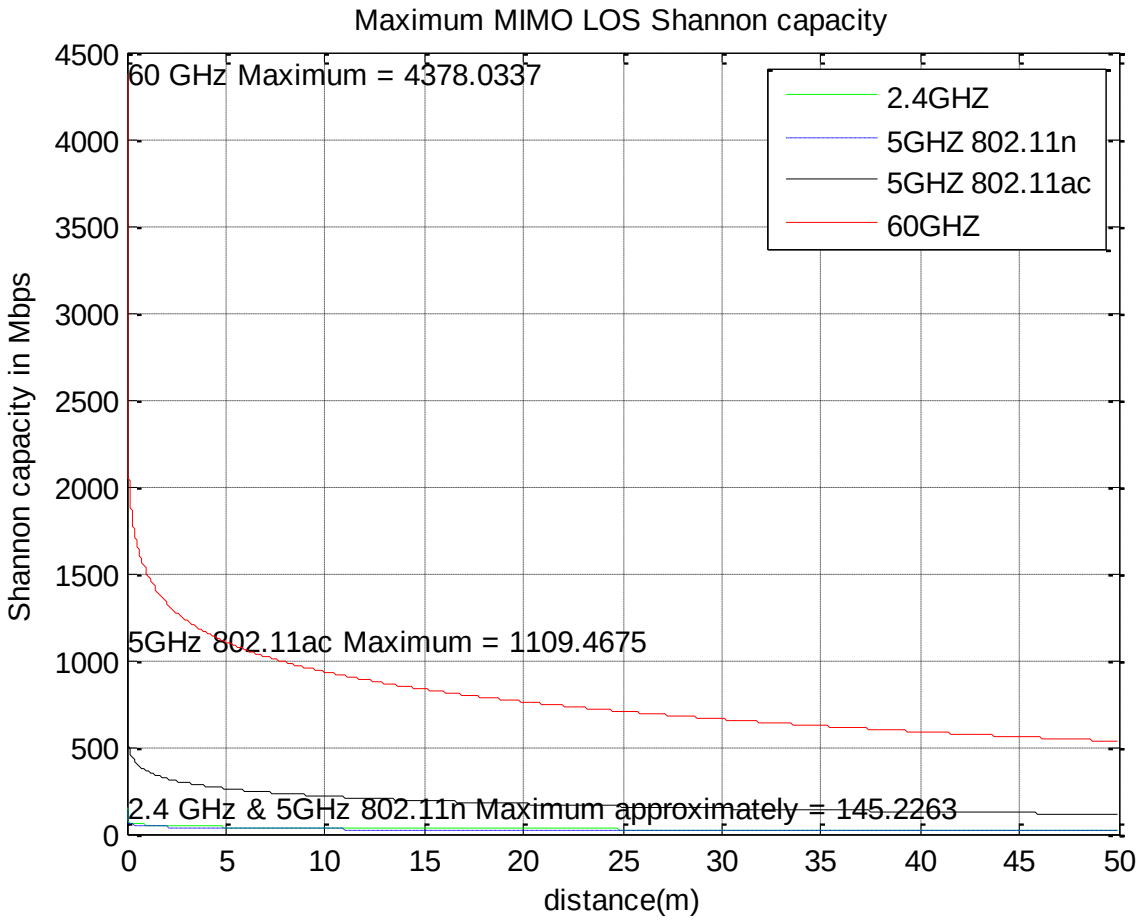


Figure 26: Maximum MIMO LOS system

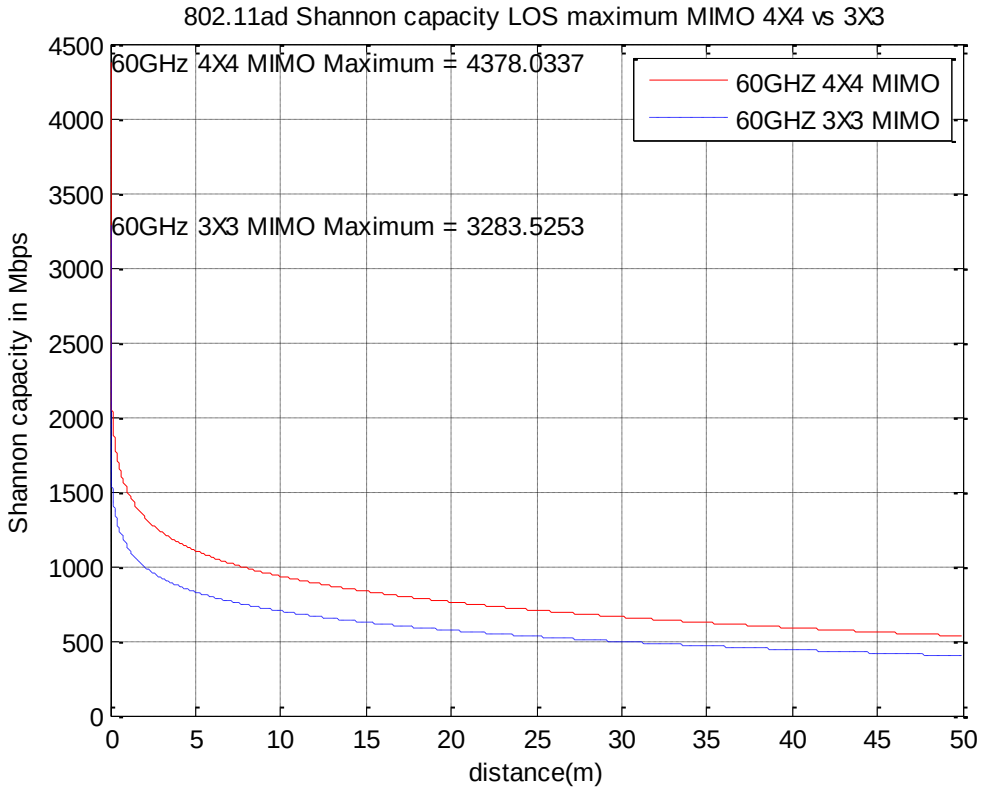


Figure 27: 802.11ad 60GHz Shannon capacity LOS maximum 4X4 vs. 3X3 MIMO

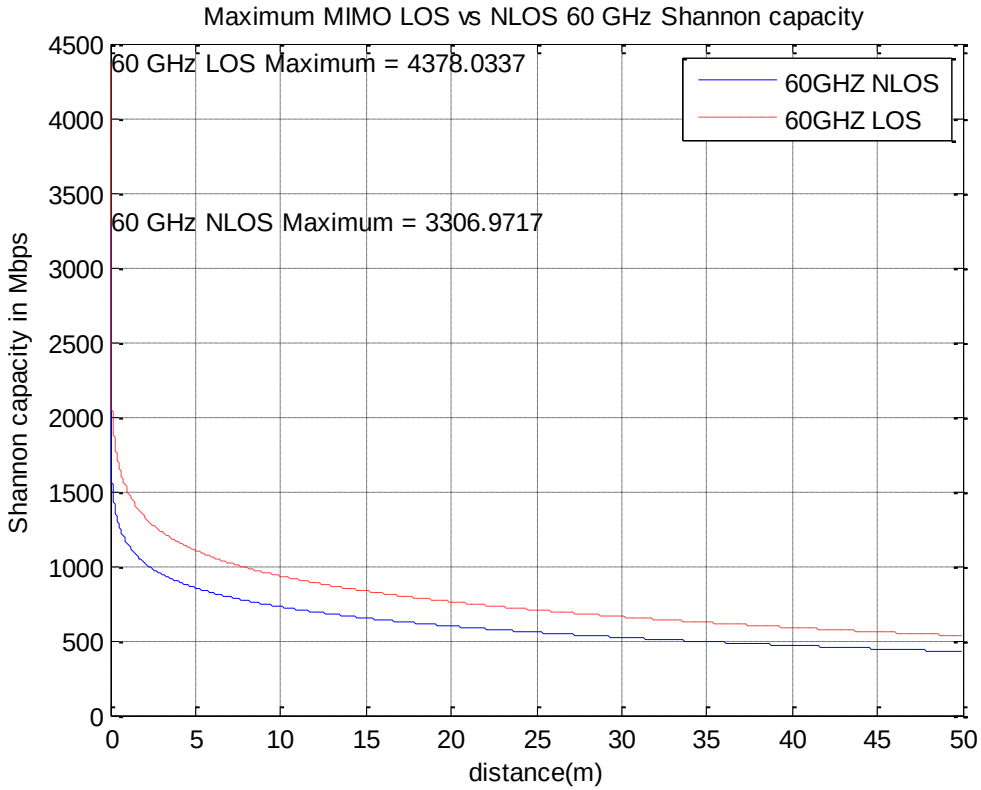


Figure 28: Maximum MIMO LOS vs. NLOS comparison

5.2.3. 60 GHz capacity increase with channel bonding

2.4 GHz and 5 GHz communications use channel bonding to get higher capacity starting from 802.11n which bonds two basic 20 MHz channels and get 40 MHz channel for its communication. Similarly 802.11ac bonds eight 20 MHz or four 802.11n 40 MHz to get 160 MHz channel as one to give faster data rate than 802.11n. On the contrary 60 GHz 802.11ad do not use channel bonding when giving the fastest data rate when compared to these above standards. Using chapter 4 section 4.2 theories on channel bonding capacity comparison, if we use channel bonding in 60 GHz communications the data rate, we get increased more and more. In this simulation 60 GHz all four channels are bonded and the simulation results are as below in both NLOS and LOS scenarios. As seen on the results there are a significant increase when bonding the channels, i.e. four times increase when bonding four channels. In addition, LOS is compared with NLOS scenario for channel bonding case in figure 31.

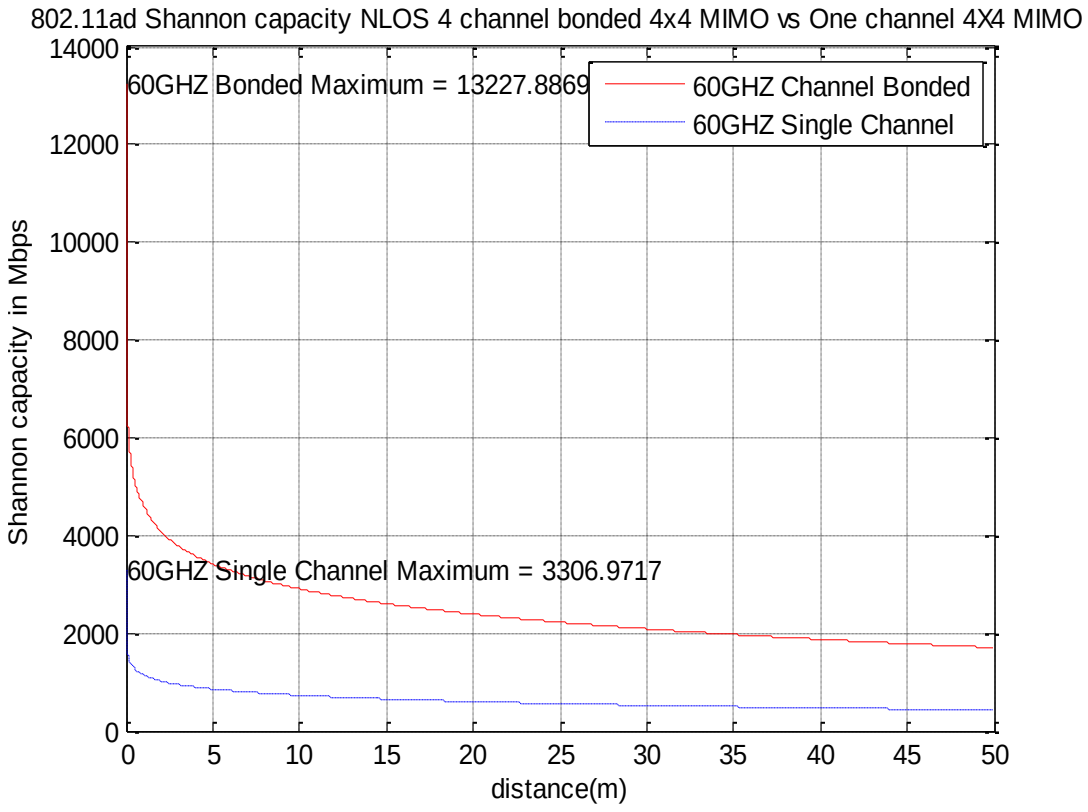


Figure 29: 802.11ad capacity increase using channel bonding NLOS 4X4 MIMO system

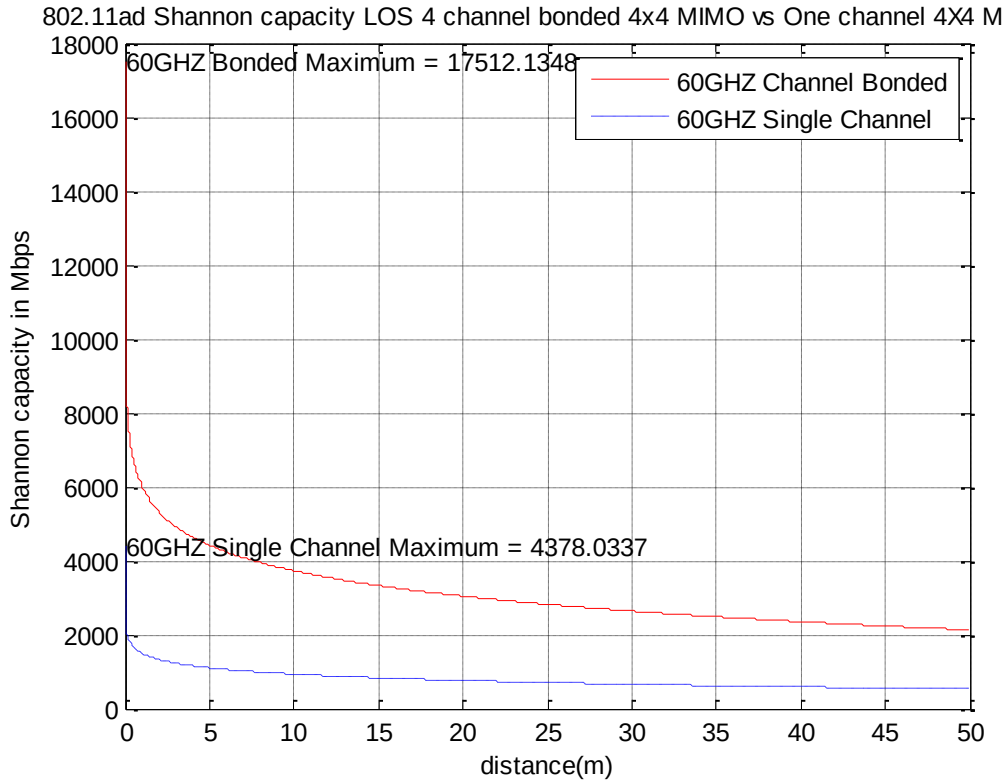


Figure 30: 802.11ad capacity increase using channel bonding LOS 4X4 MIMO system

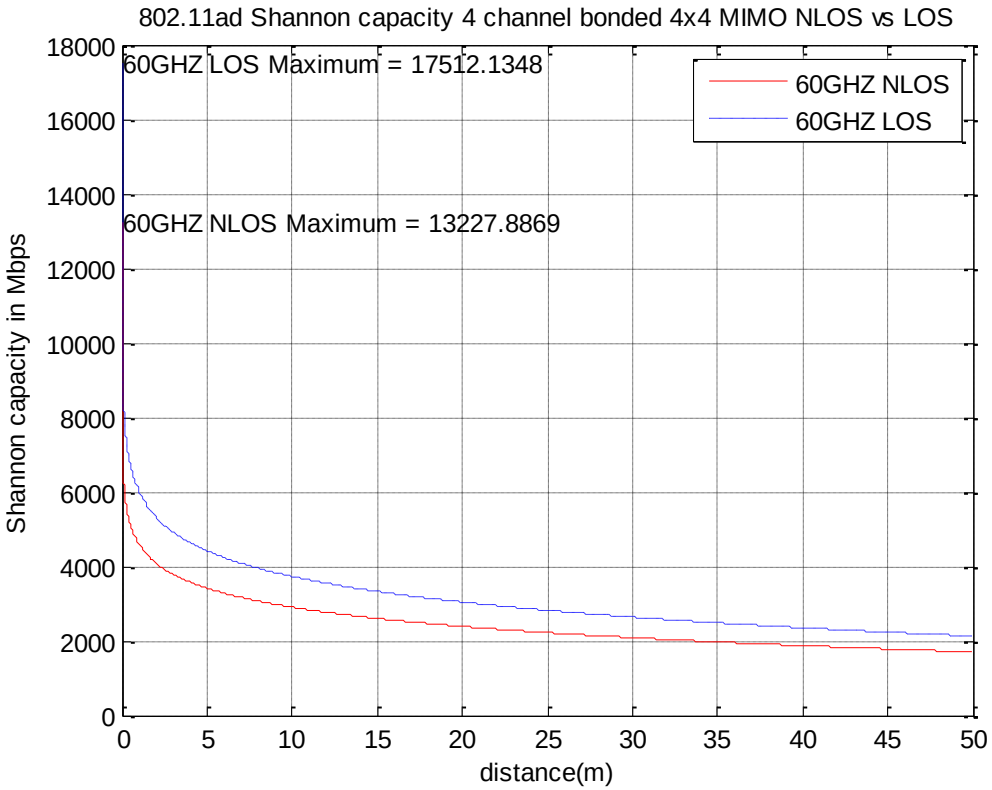


Figure 31: 802.11ad capacity channel bonding 4X4 MIMO LOS vs. NLOS comparison

Chapter 6. Conclusions and Recommendations

In conclusion, generally 2.4 GHz has better coverage area than 5 and 60 GHz. In NLOS scenario 2.4 and 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 have better coverage area than non-line of sight communications. As a result, 60 GHz has very significant increase in coverage radius about 19 meters increase in radius securing that users can communicate to AP in 99.5% of the coverage area.

Because 802.11ad standard coverage in NLOS is very small as the path loss is very high and this frequency attenuates very quickly than its counterparts. Therefore, LOS scenario should be used to focus all the powers to the LOS path and achieve a better coverage. To mitigate the 60 GHz human and objects LOS path blocking problem, either a number of APs at different positions or DAF relay nodes at different positions can be used to retransmit through those other APs and relay nodes.

In general LOS capacity is higher than NLOS capacities at the same MIMO antenna conditions. In addition, 60 GHz 802.11ad standard has the highest capacity of all those three compared frequency standards on both LOS and NLOS scenarios at the same MIMO conditions. In addition, increasing the number of antennas in MIMO systems increases the capacity proportionally for all frequencies. So using as much as possible MIMO antennas is best to get the best performance in data rate for users.

Although 60 GHz antenna size favors it to integrate a lot of antennas in a small area as compared to others lower frequencies, a maximum of 4 antennas can be used until now unlike 802.11ac maximum 8 antennas. But from the simulation results capacities of 802.11ac 8X8 MIMO is much lower than capacities of 60 GHz 802.11ad 4X4 MIMO. On the other hand, as we see the trend on all simulated capacity comparisons on all scenarios, the capacity for all three standards decreases exponentially as the users go farther and farther from AP. So at close proximity the data rate of all communications are higher than the far end.

802.11n and 802.11ac use channel bonding to get to this higher capacity than the previous 802.11 legacy standards that use the basic 20 or 22 MHz channels. When 802.11ad uses channel bonding, there is a capacity increase proportional to the number of channels bonded together. Thus bonding all four channels in 60 GHz frequency increases the data rate about four times than a single channel. So channel bonding can be used for highly bandwidth intensive applications to meet the present and future user demands.

As 60 GHz also have very narrow beam width than the other two WLAN frequencies, i.e. dedicated channel can be given to every user at the same location with close proximity unlike 2.4 GHz and 5 GHz that share one channel with the closely located users. This makes 60 GHz overall system capacity increases as the number of users increased and every user get its dedicated Gbps communication speed.

If we use 60 GHz 802.11ad standard in living homes that this thesis based up on, we can get very good security and interference free communications on all homes as other homes signals do not pass through their walls and reach neighboring homes. However, if we use 2.4 GHz and 5 GHz frequencies, the possibility of security breach by intercepting the user signals is very high and interference between neighboring homes and also interference from other devices using these frequencies disrupts the communications. This will not allow us to give better quality and consistent fast communication speed experiences.

Therefore, 60 GHz 802.11ad standards have better performance in capacity and accomplish the present and future Gbps data rate demanding applications. In addition, the coverage area of the two low frequencies are greater than 60 GHz frequency in NLOS but in LOS the 60 GHz frequency coverage is significantly enhanced and comparable to WLAN low frequencies. So 60 GHz in LOS scenario with either more than one APs or relay nodes at different locations should be used to exploit its highest capacity and tackle the coverage or blockage issues. In addition, as much as possible number of MIMO antennas and channel bonding can be used to increase the data rate even more for very high data rate intensive applications.

6.1.1. Recommendations for Future research works

There is a very high potential on 60 GHz frequency for future usages as the communication trend take us to high data rate applications. A lot of researches have been done on 60 GHz frequency recently but not all issues are assessed. Some of the recommended future research areas are as follows:

- ✓ Designing a 60 GHz WLAN network on different room scenario including access points and relay node positions.
- ✓ Coverage and capacity performance comparisons of WLAN frequencies using other path loss models.
- ✓ Coverage and capacity performance comparison of 60 GHz channel capacity over Rayleigh and Ricean fading channels with 2.4/5 GHz.
- ✓ Study on Pico cellular networks using millimeter wave frequencies for faster throughputs on mobile networks.
- ✓ Study millimeter waves' usage on fifth generation (5G) Mobile networks and their performance analysis.
- ✓ Frequency reuse, bit error rate, Overall system capacity comparisons of 60 GHz with 2.4/5 GHz lower frequencies.
- ✓ Study Tri-band Wi-Fi solution using all frequencies advantages.

Appendix A MATLAB codes

1. Coverage NLOS systems simulation code

```
pmin = -60;
ptx1 = 25;
ptx2 = 25;
ptx3 = 35;
d = 0:0.001:50;
x = [-25:.001:25];
sigmaLOS1 = 3;
sigmaLOS2 = 3;
sigmaNLOS1 = 4;
sigmaNLOS2 = 4;
sigmaNLOS3 = 3.4;
SFLOS1 = normpdf(x,0,sigmaLOS1);
SFLOS2 = normpdf(x,0,sigmaLOS2);
SFNLOS1 = normpdf(x,0,sigmaNLOS1);
SFNLOS2 = normpdf(x,0,sigmaNLOS2);
SFNLOS3 = normpdf(x,0,sigmaNLOS3);
if d <= 5
 PL1NLOS = 54.03 + 35.*log10(d./5) + SFLOS1;
 PL2NLOS = 60.4 + 35.*log10(d./5) + SFLOS2;
 PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d) + SFNLOS3;
else
 PL1NLOS = 54.03 + 35.*log10(d./5) + SFNLOS1;
 PL2NLOS = 60.4 + 35.*log10(d./5) + SFNLOS2;
 PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d) + SFNLOS3;
end
pr1NLOS = ptx1 - PL1NLOS;
pr2NLOS = ptx2 - PL2NLOS;
pr3NLOS = ptx3 - PL3NLOS;
```

```
if d <= 5
 alpha1NLOS = (pmin - pr1NLOS)./sigmaLOS1;
 alpha2NLOS = (pmin - pr2NLOS)./sigmaLOS2;
 alpha3NLOS = (pmin - pr3NLOS)./sigmaNLOS3;
else
 alpha1NLOS = (pmin - pr1NLOS)./sigmaNLOS1;
 alpha2NLOS = (pmin - pr2NLOS)./sigmaNLOS2;
 alpha3NLOS = (pmin - pr3NLOS)./sigmaNLOS3;
end
e = exp(1);
if d <= 5
 beta1NLOS = 10*3.5*log10(e)./sigmaLOS1;
 beta2NLOS = 10*3.5*log10(e)./sigmaLOS2;
 beta3NLOS = 10*1.5*log10(e)./sigmaNLOS3;
else
 beta1NLOS = 10*3.5*log10(e)./sigmaNLOS1;
 beta2NLOS = 10*3.5*log10(e)./sigmaNLOS2;
 beta3NLOS = 10*1.5*log10(e)./sigmaNLOS3;
end
Cov1NLOS = qfunc(alpha1NLOS) + exp((2-
2.*alpha1NLOS*beta1NLOS)./(beta1NLOS*beta1NLOS)).*qfunc((2-
alpha1NLOS*beta1NLOS)./beta1NLOS);
Cov2NLOS = qfunc(alpha2NLOS) + exp((2-
2.*alpha2NLOS*beta2NLOS)./(beta2NLOS*beta2NLOS)).*qfunc((2-
alpha2NLOS*beta2NLOS)./beta2NLOS);
Cov3NLOS = qfunc(alpha3NLOS) + exp((2-
2.*alpha3NLOS*beta3NLOS)./(beta3NLOS*beta3NLOS)).*qfunc((2-
alpha3NLOS*beta3NLOS)./beta3NLOS);
figure(1);
plot(d,Cov1NLOS,'-g');
hold on;
```

```
grid on;
plot(d,Cov2NLOS,'--');
hold on;
plot(d,Cov3NLOS,'+r');
title('coverage area NLOS');
xlabel('distance(m)');
ylabel('Percentage coverage area');
legend('2.4GHZ','5GHZ','60GHZ');
hold on;
Cov1NLOSrd = round(Cov1NLOS.*10000);
idx1 = find(Cov1NLOSrd == 9950);
didx1 = d(idx1);
dapx1 = didx1(1)
x1 = [dapx1:dapx1];
y1 = [0:0.01:0.995];
line(x1,y1,'Color',[0,0.8,0],'Marker','.','MarkerSize',5)
Cov2NLOSrd = round(Cov2NLOS.*10000);
idx2 = find(Cov2NLOSrd == 9950);
didx2 = d(idx2);
dapx2 = didx2(1)
x2 = [dapx2:dapx2];
y2 = [0:0.01:0.995];
line(x2,y2,'Color',[0,0,0.8],'Marker','*','MarkerSize',5)
Cov3NLOSrd = round(Cov3NLOS.*10000);
idx3 = find(Cov3NLOSrd == 9950);
didxNLOS3 = d(idx3);
dapx3 = didxNLOS3(1)
x3 = [dapx3:dapx3];
y3 = [0:0.01:0.995];
line(x3,y3,'Color',[0.8,0,0],'Marker','+','MarkerSize',5)
```

2. Coverage LOS systems simulation code

```
pmin = -60;
ptx1 = 25;
ptx2 = 25;
ptx3 = 35;
d = 0:0.001:50;
x = [-25:.001:25];
sigmaLOS1 = 3;
sigmaLOS2 = 3;
sigmaNLOS1 = 4;
sigmaNLOS2 = 4;
sigmaLOS3 = 0.00000000001;
SFLOS1 = normpdf(x,0,sigmaLOS1);
SFLOS2 = normpdf(x,0,sigmaLOS2);
SFLOS3 = normpdf(x,0,sigmaLOS3);
SFNLOS1 = normpdf(x,0,sigmaNLOS1);
SFNLOS2 = normpdf(x,0,sigmaNLOS2);
if d <= 5
  PL1LOS = 54.03 + 35.*log10(d./5) + SFLOS1;
  PL2LOS = 60.4 + 35.*log10(d./5) + SFLOS2;
  PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d) + SFLOS3;
else
  PL1LOS = 54.03 + 35.*log10(d./5) + SFNLOS1;
  PL2LOS = 60.4 + 35.*log10(d./5) + SFNLOS2;
  PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d) + SFLOS3;
end
pr1 = ptx1 - PL1LOS;
pr2 = ptx2 - PL2LOS;
pr3 = ptx3 - PL3LOS;
if d <= 5
```

```
  alpha1LOS = (pmin - pr1)./sigmaLOS1;
  alpha2LOS = (pmin - pr2)./sigmaLOS2;
  alpha3LOS = (pmin - pr3)./sigmaLOS3;
else
  alpha1LOS = (pmin - pr1)./sigmaNLOS1;
  alpha2LOS = (pmin - pr2)./sigmaNLOS2;
  alpha3LOS = (pmin - pr3)./sigmaLOS3;
end
e = exp(1);
if d <= 5
  beta1LOS = 10*3.5*log10(e)./sigmaLOS1;
  beta2LOS = 10*3.5*log10(e)./sigmaLOS2;
  beta3LOS = 10*2*log10(e)./sigmaLOS3;
else
  beta1LOS = 10*3.5*log10(e)./sigmaNLOS1;
  beta2LOS = 10*3.5*log10(e)./sigmaNLOS2;
  beta3LOS = 10*2*log10(e)./sigmaLOS3;
end
Cov1LOS = qfunc(alpha1LOS) + exp((2-
2.*alpha1LOS*beta1LOS)./(beta1LOS*beta1LOS)).*qfunc((2-
alpha1LOS*beta1LOS)./beta1LOS);
Cov2LOS = qfunc(alpha2LOS) + exp((2-
2.*alpha2LOS*beta2LOS)./(beta2LOS*beta2LOS)).*qfunc((2-
alpha2LOS*beta2LOS)./beta2LOS);
Cov3LOS = qfunc(alpha3LOS) + exp((2-
2.*alpha3LOS*beta3LOS)./(beta3LOS*beta3LOS)).*qfunc((2-
alpha3LOS*beta3LOS)./beta3LOS);
figure(2);
plot(d,Cov1LOS,'-g');
hold on;
grid on;
```

```
plot(d,Cov2LOS,'--');
hold on;
plot(d,Cov3LOS,'+r');
title('coverage area LOS');
xlabel('distance(m)');
ylabel('Percentage coverage area');
legend('2.4GHZ','5GHZ','60GHZ');
hold on;
Cov1LOSrd = round(Cov1LOS.*10000);
idx1 = find(Cov1LOSrd == 9950);
didx1 = d(idx1);
dapx1 = didx1(1)
x1 = [dapx1:dapx1];
y1 = [0:0.01:0.995];
line(x1,y1,'Color',[0,0.8,0],'Marker','.','MarkerSize',5)
Cov2LOSrd = round(Cov2LOS.*10000);
idx2 = find(Cov2LOSrd == 9950);
didx2 = d(idx2);
dapx2 = didx2(1)
x2 = [dapx2:dapx2];
y2 = [0:0.01:0.995];
line(x2,y2,'Color',[0,0,0.8],'Marker','*','MarkerSize',5)
Cov3LOSrd = round(Cov3LOS.*10000);
idx3 = find(Cov3LOSrd == 9950);
didxLOS3 = d(idx3);
dapx3 = didxLOS3(1)
x3 = [dapx3:dapx3];
y3 = [0:0.01:0.995];
line(x3,y3,'Color',[.8,0,0],'Marker','+','MarkerSize',5)
```

3. Coverage comparison LOS vs NLOS systems code

```
pmin = -60;
ptx3 = 35;
d = 0:0.001:50;
x = [-25:.001:25];
sigmaNLOS3 = 3.4;
sigmaLOS3 = 0.00000000001;
SFNLOS3 = normpdf(x,0,sigmaNLOS3);
SFLOS3 = normpdf(x,0,sigmaLOS3);
PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d) + SFNLOS3;
PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d) + SFLOS3;
pr3NLOS = ptx3 - PL3NLOS;
prLOS3 = ptx3 - PL3LOS;
alpha3NLOS = (pmin - pr3NLOS)./sigmaNLOS3;
alpha3LOS = (pmin - prLOS3)./sigmaLOS3;
e = exp(1);
beta3NLOS = 10*1.5*log10(e)./sigmaNLOS3;
beta3LOS = 10*2*log10(e)./sigmaLOS3;
Cov3NLOS = qfunc(alpha3NLOS) + exp((2-
2.*alpha3NLOS*beta3NLOS)./(beta3NLOS*beta3NLOS)).*qfunc((2-
alpha3NLOS*beta3NLOS)./beta3NLOS);
Cov3LOS = qfunc(alpha3LOS) + exp((2-
2.*alpha3LOS*beta3LOS)./(beta3LOS.*beta3LOS)).*qfunc((2-
alpha3LOS.*beta3LOS)./beta3LOS);
figure(13);
plot(d,Cov3NLOS,'or');
hold on;
grid on;
plot(d,Cov3LOS,'+b');
title('60 GHz coverage area NLOS vs LOS');
```

```
xlabel('distance(m)');
ylabel('Percentage coverage area');
legend('60GHZ NLOS','60GHZ LOS');
Cov3NLOSrd = round(Cov3NLOS.*10000);
idx3N = find(Cov3NLOSrd == 9950);
didxNLOS3 = d(idx3N);
dapx3N = didxNLOS3(1);
x3N = [dapx3N:dapx3N];
y3N = [0:0.01:0.995];
line(x3N,y3N,'Color',[.8,0,0],'Marker','o','MarkerSize',5)
text(x3N,.995,' \leftarrow NLOS radius = 3.2m','FontSize',12);
Cov3LOSrd = round(Cov3LOS.*10000);
idx3 = find(Cov3LOSrd == 9950);
didxLOS3 = d(idx3);
dapx3 = didxLOS3(1);
x3 = [dapx3:dapx3];
y3 = [0:0.01:0.995];
line(x3,y3,'Color',[0,0,0.8],'Marker','+','MarkerSize',5)
text(x3,.995,' \leftarrow LOS radius = 22.3m','FontSize',12);
```

4. Capacity of NLOS SISO systems code

```
d1 = 0.00001:0.001:50;
d2 = 0.00001:0.001:50;
d3 = 0.00001:0.001:50;
sigmaLOS1 = 3;
sigmaLOS2 = 3;
sigmaNLOS1 = 4;
sigmaNLOS2 = 4;
sigmaNLOS3 = 3.4;
```

```
x1 = (0.00001:0.001:50);
x2 = (0.00001:0.001:50);
x3 = (0.00001:0.001:50);
SFLOS1 = normpdf(x1,0,sigmaLOS1);
SFLOS2 = normpdf(x2,0,sigmaLOS2);
SFNLOS1 = normpdf(x1,0,sigmaNLOS1);
SFNLOS2 = normpdf(x2,0,sigmaNLOS2);
SFNLOS3 = normpdf(x3,0,sigmaNLOS3);
if d1 <= 5
  PL1 = 54.03 + 35.*log10(d1./5) + SFLOS1;
else
  PL1 = 54.03 + 35.*log10(d1./5) + SFNLOS1;
end
if d2 <= 5
  PL2 = 60.4 + 35.*log10(d2./5) + SFLOS2;
else
  PL2 = 60.4 + 35.*log10(d2./5) + SFNLOS2;
end
PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d3) + SFNLOS3;
Capacity1 = 0.040.*log2(1 + 10.^(127.9-PL1));
Capacity2 = 0.040.*log2(1 + 10.^(121.96-PL2));
Capacity3 = 0.160.*log2(1 + 10.^(121.96-PL2));
CapacityNLOS4 = 2.160.*log2(1 + 10.^(120.6-PL3NLOS));
figure(4);
plot(d1,Capacity1,'-g');
title('SISO NLOS Shannon capacity');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
grid on;
indexmax = find(max(Capacity1) == Capacity1);
xmax = d1(indexmax);
```

```
ymax = Capacity1(indexmax);
strmax = ['2.4 GHz & 5GHz 802.11n Maximum approximately = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d2,Capacity2,'--');
hold on;
plot(d2,Capacity3,'-k');
indexmax = find(max(Capacity3) == Capacity3);
xmax = d2(indexmax);
ymax = Capacity3(indexmax);
strmax = ['5GHz 802.11ac Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d3,CapacityNLOS4,'-r');
legend('2.4GHZ','5GHZ 802.11n','5GHZ 802.11ac','60GHZ');
indexmax = find(max(CapacityNLOS4) == CapacityNLOS4);
xmax = d3(indexmax);
ymax = CapacityNLOS4(indexmax);
strmax = ['60GHz Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

5. Capacity of LOS SISO systems code

```
d1 = 0.00001:0.001:50;
d2 = 0.00001:0.001:50;
d3 = 0.00001:0.001:50;
sigmaLOS1 = 3;
sigmaLOS2 = 3;
sigmaNLOS1 = 4;
sigmaNLOS2 = 4;
```

```
sigmaNLOS3 = 3.4;
sigmaLOS3 = 0.00000000001;
x1 = (0.00001:0.001:50);
x2 = (0.00001:0.001:50);
x3 = (0.00001:0.001:50);
SFLOS1 = normpdf(x1,0,sigmaLOS1);
SFLOS2 = normpdf(x2,0,sigmaLOS2);
SFNLOS1 = normpdf(x1,0,sigmaNLOS1);
SFNLOS2 = normpdf(x2,0,sigmaNLOS2);
SFNLOS3 = normpdf(x3,0,sigmaNLOS3);
SFLOS3 = normpdf(x3,0,sigmaLOS3);
if d1 <= 5
  PL1 = 54.03 + 35.*log10(d1./5) + SFLOS1;
else
  PL1 = 54.03 + 35.*log10(d1./5) + SFNLOS1;
end
if d2 <= 5
  PL2 = 60.4 + 35.*log10(d2./5) + SFLOS2;
else
  PL2 = 60.4 + 35.*log10(d2./5) + SFNLOS2;
end
PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d3) + SFLOS3;
Capacity1 = 0.040.*log2(1 + 10.^(127.9-PL1));
Capacity2 = 0.040.*log2(1 + 10.^(121.96-PL2));
Capacity3 = 0.160.*log2(1 + 10.^(121.96-PL2));
CapacityLOS4 = 2.160.*log2(1 + 10.^(120.6-PL3LOS));
figure(5);
plot(d1,Capacity1,'-g');
title('SISO LOS Shannon capacity');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
```

```
grid on;
indexmax = find(max(Capacity1) == Capacity1);
xmax = d1(indexmax);
ymax = Capacity1(indexmax);
strmax = ['2.4 GHz & 5GHz 802.11n Maximum approximately = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d2,Capacity2,'--');
hold on;
plot(d2,Capacity3,'-k');
indexmax = find(max(Capacity3) == Capacity3);
xmax = d2(indexmax);
ymax = Capacity3(indexmax);
strmax = ['5GHz 802.11ac Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d3,CapacityLOS4,'-r');
legend('2.4GHZ','5GHZ 802.11n','5GHZ 802.11ac','60GHZ');
indexmax = find(max(CapacityLOS4) == CapacityLOS4);
xmax = d3(indexmax);
ymax = CapacityLOS4(indexmax);
strmax = ['60 GHz Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

6. Capacity SISO NLOS vs. LOS comparison code

```
d3 = 0.00001:0.001:50;
sigmaNLOS3 = 3.4;
sigmaLOS3 = 0.00000000001;
x3 = (0.00001:0.001:50);
```

```
SFNLOS3 = normpdf(x3,0,sigmaNLOS3);
SFLOS3 = normpdf(x3,0,sigmaLOS3);
PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d3) + SFNLOS3;
PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d3) + SFLOS3;
CapacityNLOS4 = 2.160.*log2(1 + 10.^(120.6-PL3NLOS));
CapacityLOS4 = 2.160.*log2(1 + 10.^(120.6-PL3LOS));
figure(3);
plot(d3,CapacityNLOS4,'-b');
indexmax = find(max(CapacityNLOS4) == CapacityNLOS4);
xmax = d3(indexmax);
ymax = CapacityNLOS4(indexmax);
strmax = ['60 GHz NLOS Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
title('SISO LOS vs NLOS 60 GHz Shannon capacity');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
grid on;
hold on;
plot(d3,CapacityLOS4,'--r');
legend('60GHZ NLOS','60GHZ LOS');
indexmax = find(max(CapacityLOS4) == CapacityLOS4);
xmax = d3(indexmax);
ymax = CapacityLOS4(indexmax);
strmax = ['60 GHz LOS Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

7. Capacity of maximum MIMO NLOS systems code

```
d1 = 0.00001:0.001:50;
d2 = 0.00001:0.001:50;
d3 = 0.00001:0.001:50;
sigmaLOS1 = 3;
sigmaLOS2 = 3;
sigmaNLOS1 = 4;
sigmaNLOS2 = 4;
sigmaNLOS3 = 3.4;
x1 = (0.00001:0.001:50);
x2 = (0.00001:0.001:50);
x3 = (0.00001:0.001:50);
SFLOS1 = normpdf(x1,0,sigmaLOS1);
SFLOS2 = normpdf(x2,0,sigmaLOS2);
SFNLOS1 = normpdf(x1,0,sigmaNLOS1);
SFNLOS2 = normpdf(x2,0,sigmaNLOS2);
SFNLOS3 = normpdf(x3,0,sigmaNLOS3);
if d1 <= 5
  PL1 = 54.03 + 35.*log10(d1./5) + SFLOS1;
else
  PL1 = 54.03 + 35.*log10(d1./5) + SFNLOS1;
end
if d2 <= 5
  PL2 = 60.4 + 35.*log10(d2./5) + SFLOS2;
else
  PL2 = 60.4 + 35.*log10(d2./5) + SFNLOS2;
end
PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d3) + SFNLOS3;
Capacity1 = 4.*0.04.*log2(1 + 10.^(127.9-PL1));
Capacity2 = 4.*0.04.*log2(1 + 10.^(121.96-PL2));
```

```
Capacity3 = 8.*0.16.*log2(1 + 10.^(121.96-PL2));
CapacityNLOS4 = 4.*2.160.*log2(1 + 10.^(120.6-PL3NLOS));
figure(4);
plot(d1,Capacity1,'-g');
grid on;
title('Maximum MIMO NLOS Shannon capacity');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
indexmax = find(max(Capacity1) == Capacity1);
xmax = d1(indexmax);
ymax = Capacity1(indexmax);
strmax = ['2.4 GHz & 5GHz 802.11n Maximum approximately = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d2,Capacity2,'--');
hold on;
plot(d2,Capacity3,'-k');
indexmax = find(max(Capacity3) == Capacity3);
xmax = d2(indexmax);
ymax = Capacity3(indexmax);
strmax = ['5GHz 802.11ac Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d3,CapacityNLOS4,'-r');
legend('2.4GHZ','5GHZ 802.11n','5GHZ 802.11ac','60GHZ');
indexmax = find(max(CapacityNLOS4) == CapacityNLOS4);
xmax = d3(indexmax);
ymax = CapacityNLOS4(indexmax);
strmax = ['60 GHz Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

8. Capacity of NLOS maximum MIMO vs. other MIMO code

```
d1 = 0.00001:0.001:50;
d2 = 0.00001:0.001:50;
d3 = 0.00001:0.001:50;
sigmaLOS1 = 3;
sigmaLOS2 = 3;
sigmaNLOS1 = 4;
sigmaNLOS2 = 4;
sigmaNLOS3 = 3.4;
x1 = (0.00001:0.001:50);
x2 = (0.00001:0.001:50);
x3 = (0.00001:0.001:50);
SFLOS1 = normpdf(x1,0,sigmaLOS1);
SFLOS2 = normpdf(x2,0,sigmaLOS2);
SFNLOS1 = normpdf(x1,0,sigmaNLOS1);
SFNLOS2 = normpdf(x2,0,sigmaNLOS2);
SFNLOS3 = normpdf(x3,0,sigmaNLOS3);
if d1 <= 5
  PL1 = 54.03 + 35.*log10(d1./5) + SFLOS1;
else
  PL1 = 54.03 + 35.*log10(d1./5) + SFNLOS1;
end
if d2 <= 5
  PL2 = 60.4 + 35.*log10(d2./5) + SFLOS2;
else
  PL2 = 60.4 + 35.*log10(d2./5) + SFNLOS2;
end
PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d3) + SFNLOS3;
Capacity1m = 4.*0.04.*log2(1 + 10.^(127.9-PL1));
Capacity2m = 4.*0.04.*log2(1 + 10.^(121.96-PL2));
```

```
Capacity3m = 8.*0.16.*log2(1 + 10.^(121.96-PL2));
CapacityNLOS4m = 4.*2.160.*log2(1 + 10.^(120.6-PL3NLOS));
Capacity1 = 3.*0.04.*log2(1 + 10.^(127.9-PL1));
Capacity2 = 3.*0.04.*log2(1 + 10.^(121.96-PL2));
Capacity3 = 6.*0.16.*log2(1 + 10.^(121.96-PL2));
CapacityNLOS4 = 3.*2.160.*log2(1 + 10.^(120.6-PL3NLOS));
figure(7);
plot(d1,Capacity1m,'-g');
grid on;
title('802.11n 2.4GHz Shannon capacity maximum MIMO 4X4 vs 3X3');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
indexmax = find(max(Capacity1m) == Capacity1m);
xmax = d1(indexmax);
ymax = Capacity1m(indexmax);
strmax = ['2.4GHz 4X4 MIMO Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d2,Capacity1,'--');
legend('2.4GHZ 4X4 MIMO','2.4GHZ 3X3 MIMO');
indexmax = find(max(Capacity1) == Capacity1);
xmax = d2(indexmax);
ymax = Capacity1(indexmax);
strmax = ['2.4GHz 3X3 MIMO Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
figure(8);
plot(d1,Capacity2m,'-g');
grid on;
title('802.11n 5GHz Shannon capacity maximum MIMO 4X4 vs 3X3');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
```

```
indexmax = find(max(Capacity2m) == Capacity2m);
xmax = d1(indexmax);
ymax = Capacity2m(indexmax);
strmax = ['5GHz 4X4 MIMO Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d2,Capacity2,'--');
legend('5GHZ 4X4 MIMO','5GHZ 3X3 MIMO');
indexmax = find(max(Capacity2) == Capacity2);
xmax = d2(indexmax);
ymax = Capacity2(indexmax);
strmax = ['5GHz 3X3 MIMO Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
figure(9);
plot(d1,Capacity3m,'-g');
grid on;
title('802.11ac 5GHz Shannon capacity maximum MIMO 8X8 vs 6X6');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
indexmax = find(max(Capacity3m) == Capacity3m);
xmax = d1(indexmax);
ymax = Capacity3m(indexmax);
strmax = ['5GHz 8X8 MIMO Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d2,Capacity3,'--');
legend('5GHZ 8X8 MIMO','5GHZ 6X6 MIMO');
indexmax = find(max(Capacity3) == Capacity3);
xmax = d2(indexmax);
ymax = Capacity3(indexmax);
strmax = ['5GHz 6X6 MIMO Maximum = ',num2str(ymax)];
```

```
text(xmax,ymax,strmax,'HorizontalAlignment','left');
figure(10);
plot(d1,CapacityNLOS4m,'-g');
grid on;
title('802.11ad 60GHz Shannon capacity NLOS maximum MIMO 4X4 vs 3X3');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
indexmax = find(max(CapacityNLOS4m) == CapacityNLOS4m);
xmax = d1(indexmax);
ymax = CapacityNLOS4m(indexmax);
strmax = ['60GHz 4X4 MIMO Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d2,CapacityNLOS4,'--');
legend('60GHZ 4X4 MIMO','60GHZ 3X3 MIMO');
indexmax = find(max(CapacityNLOS4) == CapacityNLOS4);
xmax = d2(indexmax);
ymax = CapacityNLOS4(indexmax);
strmax = ['60GHz 3X3 MIMO Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

9. Capacity of maximum MIMO LOS systems code

```
d1 = 0.00001:0.001:50;
d2 = 0.00001:0.001:50;
d3 = 0.00001:0.001:50;
sigmaLOS1 = 3;
sigmaLOS2 = 3;
sigmaNLOS1 = 4;
sigmaNLOS2 = 4;
sigmaNLOS3 = 3.4;
sigmaLOS3 = 0.00000000001;
x1 = (0.00001:0.001:50);
x2 = (0.00001:0.001:50);
x3 = (0.00001:0.001:50);
SFLOS1 = normpdf(x1,0,sigmaLOS1);
SFLOS2 = normpdf(x2,0,sigmaLOS2);
SFNLOS1 = normpdf(x1,0,sigmaNLOS1);
SFNLOS2 = normpdf(x2,0,sigmaNLOS2);
SFNLOS3 = normpdf(x3,0,sigmaNLOS3);
SFLOS3 = normpdf(x3,0,sigmaLOS3);
if d1 <= 5
  PL1 = 54.03 + 35.*log10(d1./5) + SFLOS1;
else
  PL1 = 54.03 + 35.*log10(d1./5) + SFNLOS1;
end
if d2 <= 5
  PL2 = 60.4 + 35.*log10(d2./5) + SFLOS2;
else
  PL2 = 60.4 + 35.*log10(d2./5) + SFNLOS2;
end
PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d3) + SFLOS3;
Capacity1 = 4.*0.04.*log2(1 + 10.^(127.9-PL1));
```

```
Capacity2 = 4.*0.04.*log2(1 + 10.^(121.96-PL2));
Capacity3 = 8.*0.16.*log2(1 + 10.^(121.96-PL2));
CapacityLOS4 = 4.*2.16.*log2(1 + 10.^(120.6-PL3LOS));
figure(5);
plot(d1,Capacity1,'-g');
grid on;
title('Maximum MIMO LOS Shannon capacity');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
indexmax = find(max(Capacity1) == Capacity1);
xmax = d1(indexmax);
ymax = Capacity1(indexmax);
strmax = ['2.4 GHz & 5GHz 802.11n Maximum approximately = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d2,Capacity2,'--');
hold on;
plot(d2,Capacity3,'-k');
indexmax = find(max(Capacity3) == Capacity3);
xmax = d2(indexmax);
ymax = Capacity3(indexmax);
strmax = ['5GHz 802.11ac Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d3,CapacityLOS4,'-r');
legend('2.4GHZ','5GHZ 802.11n','5GHZ 802.11ac','60GHZ');
indexmax = find(max(CapacityLOS4) == CapacityLOS4);
xmax = d3(indexmax);
ymax = CapacityLOS4(indexmax);
strmax = ['60 GHz Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

10.Capacity of LOS maximum MIMO vs. other MIMO code

```
d1 = 0.00001:0.001:50;
sigmaLOS3 = 0.00000000001;
x3 = (0.00001:0.001:50);
SFLOS3 = normpdf(x3,0,sigmaLOS3);
PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d3) + SFLOS3;
CapacityLOS4m = 4.*2.16.*log2(1 + 10.^(120.6-PL3LOS));
CapacityLOS4 = 3.*2.16.*log2(1 + 10.^(120.6-PL3LOS));
figure(11);
plot(d3,CapacityLOS4m,'-r');
grid on;
title('802.11ad Shannon capacity LOS maximum MIMO 4X4 vs 3X3');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
indexmax = find(max(CapacityLOS4m) == CapacityLOS4m);
xmax = d1(indexmax);
ymax = CapacityLOS4m(indexmax);
strmax = ['60GHz 4X4 MIMO Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d1,CapacityLOS4,'--');
legend('60GHZ 4X4 MIMO','60GHZ 3X3 MIMO');
indexmax = find(max(CapacityLOS4) == CapacityLOS4);
xmax = d1(indexmax);
ymax = CapacityLOS4(indexmax);
strmax = ['60GHz 3X3 MIMO Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

11.Capacity of Maximum MIMO NLOS vs. LOS comparison code

```
d3 = 0.00001:0.001:50;
sigmaNLOS3 = 3.4;
sigmaLOS3 = 0.00000000001;
x3 = (0.00001:0.001:50);
SFNLOS3 = normpdf(x3,0,sigmaNLOS3);
SFLOS3 = normpdf(x3,0,sigmaLOS3);
PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d3) + SFNLOS3;
PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d3) + SFLOS3;
CapacityNLOS4 = 4.*2.160.*log2(1 + 10.^(120.6-PL3NLOS));
CapacityLOS4 = 4.*2.160.*log2(1 + 10.^(120.6-PL3LOS));
figure(6);
plot(d3,CapacityNLOS4,'-b');
indexmax = find(max(CapacityNLOS4) == CapacityNLOS4);
xmax = d3(indexmax);
ymax = CapacityNLOS4(indexmax);
strmax = ['60 GHz NLOS Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
title('Maximum MIMO LOS vs NLOS 60 GHz Shannon capacity');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
grid on;
hold on;
plot(d3,CapacityLOS4,'--r');
legend('60GHZ NLOS','60GHZ LOS');
indexmax = find(max(CapacityLOS4) == CapacityLOS4);
xmax = d3(indexmax);
ymax = CapacityLOS4(indexmax);
strmax = ['60 GHz LOS Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

12.NLOS Capacity 60GHz 4 channel bonded vs. single channel code

```
d3 = 0.00001:0.001:50;
sigmaNLOS3 = 3.4;
x3 = (0.00001:0.001:50);
SFNLOS3 = normpdf(x3,0,sigmaNLOS3);
PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d3) + SFNLOS3;
Capacity3 = 4.*2.16.*log2(1 + 10.^(120.6-PL3NLOS));
Capacity3b = 4.*4.*2.16.*log2(1 + 10.^(120.6-PL3NLOS));
figure(12);
plot(d3,Capacity3b,'-r');
grid on;
title('802.11ad Shannon capacity NLOS 4 channel bonded 4x4 MIMO vs One channel 4X4
MIMO');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
indexmax = find(max(Capacity3b) == Capacity3b);
xmax = d3(indexmax);
ymax = Capacity3b(indexmax);
strmax = ['60GHZ Bonded Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d3,Capacity3,'--');
legend('60GHZ Channel Bonded','60GHZ Single Channel');
indexmax = find(max(Capacity3) == Capacity3);
xmax = d3(indexmax);
ymax = Capacity3(indexmax);
strmax = ['60GHZ Single Channel Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

13. LOS Capacity 60GHz 4 channel bonded vs. single channel code

```
d3 = 0.00001:0.001:50;
sigmaLOS3 = 0.00000000001;
x3 = (0.00001:0.001:50);
SFLOS3 = normpdf(x3,0,sigmaLOS3);
PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d3) + SFLOS3;
Capacity3b = 4.*4.*2.16.*log2(1 + 10.^(120.6-PL3LOS));
Capacity3 = 4.*2.16.*log2(1 + 10.^(120.6-PL3LOS));
figure(13);
plot(d3,Capacity3b,'-r');
grid on;
title('802.11ad Shannon capacity LOS 4 channel bonded 4x4 MIMO vs One channel 4X4
MIMO');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
legend('60GHZ');
indexmax = find(max(Capacity3b) == Capacity3b);
xmax = d3(indexmax);
ymax = Capacity3b(indexmax);
strmax = ['60GHZ Bonded Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d3,Capacity3,'--');
legend('60GHZ Channel Bonded','60GHZ Single Channel');
indexmax = find(max(Capacity3) == Capacity3);
xmax = d3(indexmax);
ymax = Capacity3(indexmax);
strmax = ['60GHZ Single Channel Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

14. LOS Capacity 60GHz 4 channel bonded vs. single channel code

```
d3 = 0.00001:0.001:50;
sigmaNLOS3 = 3.4;
sigmaLOS3 = 0.00000000001;
x3 = (0.00001:0.001:50);
SFNLOS3 = normpdf(x3,0,sigmaNLOS3);
SFLOS3 = normpdf(x3,0,sigmaLOS3);
PL3NLOS = 44.7 + 20.*log10(60) + 15.*log10(d3) + SFNLOS3;
PL3LOS = 32.5 + 20.*log10(60) + 20.*log10(d3) + SFLOS3;
CapacityNLOS3b = 4.*4.*2.16.*log2(1 + 10.^(120.6-PL3NLOS));
CapacityLOS3b = 4.*4.*2.16.*log2(1 + 10.^(120.6-PL3LOS));
figure(13);
plot(d3,CapacityNLOS3b,'-r');
grid on;
title('802.11ad Shannon capacity 4 channel bonded 4x4 MIMO NLOS vs LOS');
xlabel('distance(m)');
ylabel('Shannon capacity in Mbps');
indexmax = find(max(CapacityNLOS3b) == CapacityNLOS3b);
xmax = d3(indexmax);
ymax = CapacityNLOS3b(indexmax);
strmax = ['60GHZ NLOS Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
hold on;
plot(d3,CapacityLOS3b,'--');
legend('60GHZ NLOS','60GHZ LOS');
indexmax = find(max(CapacityLOS3b) == CapacityLOS3b);
xmax = d3(indexmax);
ymax = CapacityLOS3b(indexmax);
strmax = ['60GHZ LOS Maximum = ',num2str(ymax)];
text(xmax,ymax,strmax,'HorizontalAlignment','left');
```

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