FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
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MASTER'S THESIS

ANALYSIS OF WIDEBAND PHASED ARRAY BEAMFORMING AT MILLIMETER WAVE FREQUENCIES

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ABSTRACT

Industries are undergoing an information and communication technology-driven transformation as the world becomes increasingly digitally and globally linked. 5G technology provides a common basis for providing the multiple vertical sectors with a more cost-effective, open, and wide ecosystem solutions. Due to the generally large attainable bandwidths, high frequency technologies have emerged as a promising solution for future wireless communications and attracted great interest in the literature. The millimeter wave (mmWave), i.e., the frequency range 30–300 GHz, would enable the exploitation of tens of gigahertz transmission bands, resulting in a massive channel capacities of even over one Tbps. However, one of the most challenging issues in high-frequency communication connections is the significant channel losses that require highly directional antennas and, in most cases, line-of-sight link between the transmitter and receiver. In this thesis, we study the beamforming design for wideband systems with different bandwidths. The simulation results show that with a larger bandwidth, the power loss increases with the beamforming angle. The loss of power behaviour due to beam squinting effect is quite similar over different distances.

Keywords: Beamforming, beam squinting, millimeter wave communications, phased array, received power

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FOREWORD

First of all, I would like to thanks Almighty ALLAH the most merciful and beneficent, who enabled and give guidance to me in completing this mammoth task. I would also like to acknowledge and express my sincerest gratitude to my supervisors, specially Joonas Kokkoniemi, and Nhan Thanh Nguyen for providing help, scholarly advice, support, useful comments, continuous encouragement, kind supervision and timely checking of my manuscript throughout the entire period. I Would also like to thank my colleagues Shahwaiz Ur Rehman and Hafiz Hannan Ranjha for their extended support. I dedicate this work to my parents and my sisters. Without their support and love, I could have not achieved any of the goals I had ever set in my life.

Oulu, 20th July, 2021

Asif Shakil

LIST OF ABBREVIATIONS AND SYMBOLS

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AF	Array Factor
CDMA	Code Division Multiple Access
E2E	End To End
EHF	Extremely High frequency
FCC	Federal Communication Commmission
FDMA	Frequency Division Multiple Access
GMSK	Gaussian Minimum Shift Keying
GSM	Global System For Mobile Communication
IC	Integrated Circuit
IoT	Internet Of Things
IP	Internet Protocol
ITU	International Telecommunication Union
LOS	Line Of Sight
LTE	Long Term Evolution
MAI	Multiple Access Interference
MIMO	Multiple Input Multiple Output
MMS	Multimedia Services
mmwaves	Milimeter-Waves
NLOS	Non-line-of-Sight
OFDMA	Orthognal Frequency Division Multiple Access
PC	Personal Computer
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoS	Quality Of Service
RF	Radio Frequency
RFID	Radio Frequency Identification
Rx	Receiver
SISO	Single Input Singöe Output
SMS	Short Message Service
SNR	Signal to Noise Ratio
Tx	Transmitter
USB	Universal Serial Bus
UWB	Ultra WideBand
V2I	Vehicle To Infrastructure
V2V	Vehicle To Vehicle
VHF	Very High Frequency
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WWRF	Wireless World Research Forum
α	Angular range

δ	Path gain
Γ	Desired beam direction
λ_c	Centre frequency in wavelengths
ϕ	Phase rotation
A_{tx}	Antenna element amplitude
A_i	Amplitude of transmitter
c	Speed of light
f_c	Centre frequency
G_{rx}	Receiver gain
N	Receiver noise figure
N_{tx}	Number of antenna elements
P_{tx}	Transmit power
P_{txa}	Power per antenna element
P_r	Received Power
r	Distances to users
u_{ind}	Number of user positions
u_x	User position at x-axis
u_y	User position at y-axis
W	System bandwidth
x	Input signal
y	Received Signal

1 INTRODUCTION

Wireless communication technology has come a long way and the mobile networks have been consistently developing over generations. Making individuals' personal and working lives simpler and giving extraordinary comfort and users demands keep increasing. The expenses of the services for users has decreased and in the meantime, demand for higher and higher quality of service has increased.

The world has seen a lot of changes in the domain of telecommunications. Today almost more than 60 percent of the world does not use landlines [1]. Personal cell phone have become more and more popular and used for various purposes: facilitating user connections, entertainment, as well as their work efficiency.

With the evolution of communication technologies, the requirements of end-user devices have also been increased, which pushes researchers forward to develop new, faster, and more reliable wireless systems. At the beginning of mobile communications era,basic voice services that were fulfilled with the first generation (1G) mobile communication systems [2]. Then, the need to develop a globally recognized system to support voice and data services increased. Therefore, the Global System for Mobile communication (GSM) technology was proposed [3]. The expectations of end-users did not stop there, and they thought of smartphones and global roaming with additional features of web browsing, TV, and multimedia access, and brought up third generation (3G) mobile communication technologies [4]. Today, the fourth generation (4G) is an advanced and widely spread technology being used, fulfilling the requirements of low latency, data traffic, data rates, connection density, and power efficiency, along with all the previous requirements being fulfilled by older technologies [5].

In fifth general (5G) communications systems, there are several new concepts but one of the most revolutionary idea is millimeter waves (mmWaves). The mmWaves are high-frequency waves in the extremely high frequency (EHF) band which is $30-300$ GHz. Millimeter-wave communication has a range of just 1-kilometer [6]. The millimeter band is named after the wavelengths of radio waves in the mmWave frequency band, which range from 10 to 1 mm [7]. Currently, mmWave frequencies are employed for a variety of applications such as radio astronomy, radars, military applications, imaging, security purposes, and mobile communications [8].

1.1 Thesis Problem Description

One of the main problem of the high-frequency communication links is the significant path losses that require highly directional antennas and usually Line-Of-Sight (LOS) between the Transmitter (Tx) and the Receiver (Rx). In wideband signals, There is a problem of different frequency components having different phase rotations depending on the distance from different elements. Also, the phase rotations are different from frequency to frequency, causing a loss in the achievable gain like received power for the total wideband signal. The beam squinting problem has significant impact on far field. Actually, its impact in the near field is not that well know or studied. Partially since near field is hard to predict due to spherical wave propagation. In the far field it is easier to estimate the loss due to plane wave propagation. Due to delay characteristics but also path loss variations from signals coming from different antenna elements. In this thesis, we aim to analyse the loss in the antenna gain as a function of the bandwidth of the signal.

1.2 Thesis Structure

This thesis is organized as follows: In Chapter 2, we present the background of wireless communication technologies, how communication is evolved from narrowband to wideband, ultra-wideband, and basic idea about mmWave including the applications and the propagation losses. In Chapter 3 we present the system model designed for the analysis of wideband signals and the operating principles of the phased array antennas used in mmWave. In Chapter 4, we present the simulation results of system model and Chapter 5 gives the summary of the whole thesis with possible future directions.

2 BACKGROUND

The first generation of telecommunication technologies with bulky phones and with relatively low number of users introduced analog voice calls. Then Global System for Mobile communications (GSM) introduced mobile data services such as Short Message Service (SMS) and Multi-Media Services (MMS). 2G offered digital voice services that were progressively stable and accessible to more people as it was cheaper to use. 3G presented faster mobile internet, video calls, and the development of many applications. The expectation from mobile broadband services like high definition mobile TV, gaming services, streaming video, and audio were fulfilled by Long Term Evolution (LTE) [9]. The evolution of the telecommunication industry has granted customers to experience low latency and high-speed data networks. Telecommunication industry leads towards the 5G, which will significantly affect society. It will have the technical capacity to advance in many areas, such as self-driving cars, robotics, smart city projects, health care, agriculture, and education.

Currently, LTE is available almost all over the world. It was introduced to provide a Wide Area Network (WAN) for internet access and designed mainly for packet-switched services. LTE has provided consistent Internet Protocol (IP) availability between User Equipment (UE) and the packet data network. The 4G networks provide the speed of 100 Mbps to high mobility applications (like vehicle, trains, etc.) and also 1 Gbps (theoretical value but not practically achieved) data rate for high mobility use cases with Quality of Service (QoS), and provides high network security. It gives better audio quality, and video streaming services with small latency. In most countries, it uses the 1800 MHz band, while in some countries, it operates on 900 MHz and 2300 MHz. LTE applies Orthogonal Frequency Division Multiple Access (OFDMA), Multiple Input Multiple Output (MIMO), IPv6.0, and smart antennas.

The 5G technologies have been designed with intelligent solutions that interconnect the entire world without limits. Over the past years, the bandwidths have increased from narrowband to wideband, and in near future 5G will be operating on mmWave, due to which it will have the potential to provide more than 10 Gbps user data rate [10]. This will definitely open new opportunities for applications requiring high connection speeds. For several conditions, it will have very low latency due to which many customers who need or work on a real-time network will avail of this opportunity. In previous technologies coverage was a big issue although it was catered up to some point in 4G, but it is expected in 5G that coverage issues will be mitigated (e.g cell-free technology) and due to high network power efficiency, the battery life of devices will be increased [10].

2.1 Narrowband and Wideband Communications

This section provides a brief overview of narrowband and wideband communication regarding bandwidth, data rate, and applications.

2.1.1 Narrowband Communications

Narrowband refers to radio communications where the signal bandwidth is below the channel's coherence band and experiences flat fading [11]. Applications that require stable connections in a lot of operating settings have been utilized by narrowband communications, such as military combat radios and industrial surveillance [12] and also in low data rate applications. The desire to share high-definition audio and video across the household drives the demand for ever-increasing wireless bandwidth. Narrowband signals are utilized in slower forms of communication, such as speech or slower data streams [13]. Narrowband channels are flat fading channels because they pass all spectral components with equal phase and gain. Applications are such as remote keyless entry devices in automobiles, portable mobile devices, Radio Frequency IDentification (RFID), and many more [13].

In comparison to wideband channels, very less data is being carried by narrowband channels. Those also have less noise (depending on channel bandwidth) as shown in Figure 1 [12]. Narrowband signals have a much more comprehensive reception range because tighter filters may be employed to block out undesired wideband noise [13]. Indeed, narrowband communications equipment's reduced operating-power needs make it the best choice for applications that need the Tx of limited data over long distances [12].

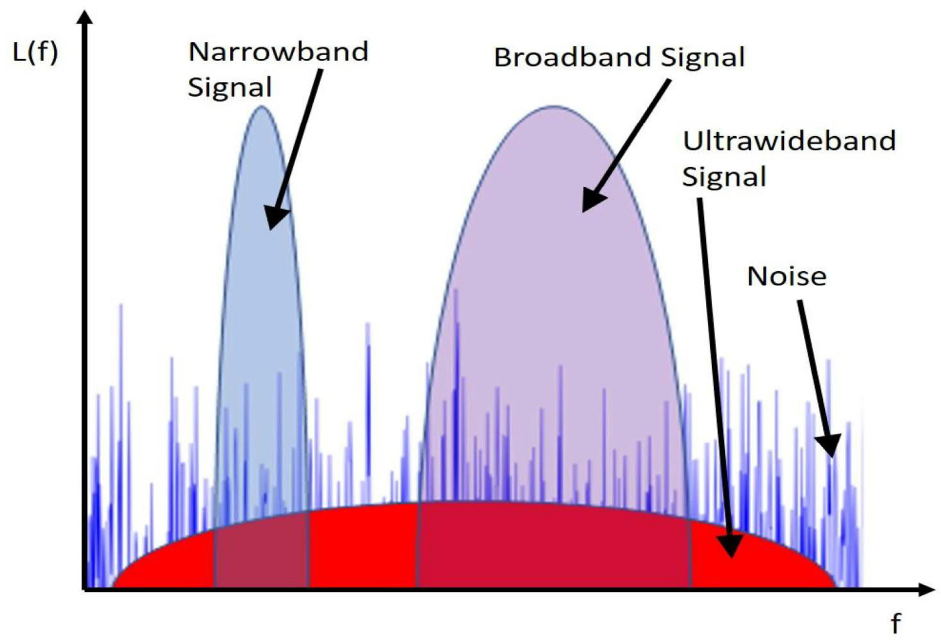

Figure 1. Narrowband, broadband, and ultra-wideband along with the illustration of the noise [12].

2.1.2 Wideband Communications

Wideband, on the other hand, refers to a communication channel with a broader frequency spectrum. The signal bandwidth in wideband communications exceeds the coherence bandwidth. The bandwidth of wideband transmissions is usually more than 1 MHz in real systems [11]. With respect to Tx and Rx signal information, more bandwidth corresponds to higher data rates [11]. Wideband communication channels become more appealing when compared to narrowband communication due to their higher data capabilities [12]. Each carrier in a wideband architecture that has access to the whole frequency spectrum or a just a single channel. Frequency Division Multiple Access (FDMA) is a narrowband architecture, whereas Code Division Multiple Access (CDMA), OFDMA, Non-orthogonal Multiple Access (NOMA) etc. are wideband architectures [11].

In contrast to narrowband channels, where noise inside the channel is restricted by efficient filtering so that it can minimize any noise and interference outside of the frequency band in use, in a wideband channels, higher transmit signal power is typically required to overcome the noise level. While other factors like signal propagation losses need to be compensated, so that a considerable signal level appears at the receiver and fulfill the minimal signal-to-noise-ratio (SNR) performance criteria for receiving and processing [12]. The multipath propagation affects the frequency response due to random constructive and destructive summation. This is know as frequency selective fading and that is why wideband channels are also known as selective fading [11].

2.2 Ultra Wideband Technology

The Ultra WideBand (UWB) had been studied since the early 1960s. It was referred to as a technology that was carrier-free, baseband, or impulse. The basic idea is to create, transmit, and receive a concise burst of Radio Frequency (RF) energy as a short pulse [14]. The pulses last a few tens of picoseconds to a few nanoseconds on average. [14]. The sum of power transmitted is just a few milliwatts, resulting in very low power spectral densities when combined with the spectral spread. The Federal Communication Commission (FCC) requires that emission limits between 3.1 GHz and 10.6 GHz should be less than -41.3 dBm/MHz, or 75 nW/MHz, and the power difference between the upper and lower bounds of the above band is just 0.5 mW. [14].

UWB has specific unique and distinguishing characteristics that make it appealing for several applications. UWB can provide extremely high data rates while using relatively little power and operating over a concise range, making it ideal for Wireless Personal Area Network (WPAN) applications[15, 16]. The ease and value of using PCs and laptops will be enhanced by peripheral connectivity through cable-free connections to applications such as storage, I/O devices, and wireless Universal Serial Bus (USB) [16]. High-speed data communications between computers and consumer electronics such as digital cameras, video cameras, televisions, and personal cars can offer a new entertainment level in daily life. Sensors of all kinds often provide ways for UWB to thrive. Low cost and low power are two main criteria for sensor networks, which UWB technology can easily meet [16].

A UWB multiple-access channel is depicted in Figure 2. When Multiple Access Interference (MAI) is applied to the inevitable channel noise and narrowband interference, the low-powered UWB pulses are significantly degraded, making detection extremely difficult[17, 18].

Advantages of UWB

UWB has a range of encouraging benefits that make it a more compelling approach to wireless broadband than other technologies. The following are the distinguishing characteristics:

- Since UWB has an ultra-large frequency bandwidth; it can transmit data at rates of hundreds of Mbps or even multiple Gbps over distances of 1 to 10 meters [15].
- The basic baseband design of the signal transmission results in a low cost and low complexity UWB system based on impulse radio [19].
- UWB systems operate at extremely low power transmission levels [20].
- Its low power needs make it appropriate for radio frequency-sensitive environments or scenarios, such as hospitals [20].

Disadvantages Of UWB

There are several disadvantages of UWB:

- UWB-based location and pairing tags are much more costly than tags for many other solutions like Bluetooth and RFID [20].
- Coexistence and interference with other radio-based technologies are the biggest challenges with UWB technology [21].
- It has potential interference to an existing systems and also a potential interference from existing systems.

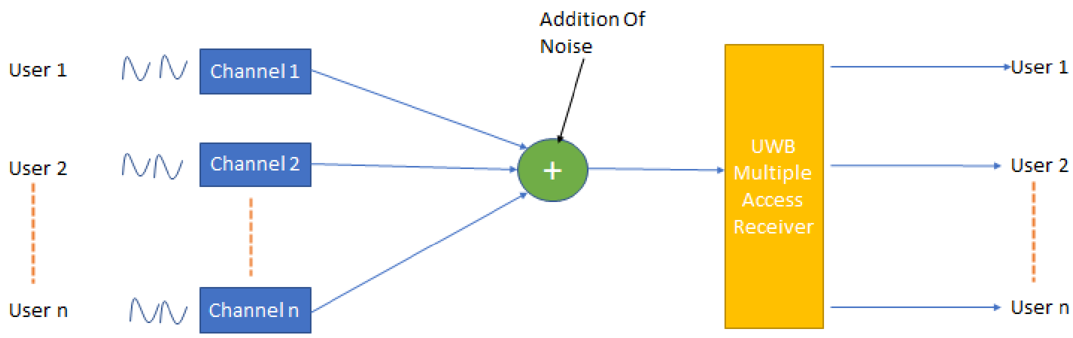

Figure 2. An UWB multiple-access channel [17].

2.3 mmWave Communications

The tremendous expansion of wireless data traffic over the last few years has provided significant problems to the design and evolution of existing wireless network architecture while simultaneously presenting the considerable potential to drive future technology innovation [7]. Wireless communication industries have proposed a new 5G standard to accommodate the demand. Over the last few years, research on the 5G wireless networks aims to address multiple unprecedented technological demands and problems. This has caught the interest of both academia and industry [22]. To satisfy the 5G needs, the present deployed 4G network, which is mainly overloaded from 600 MHz to 3 GHz, may be improved in terms of spectrum and energy efficiency. However, research suggests that certain enhancements would not be enough to match the 5G network's capacity goal. As a result, mmWave frequency ranges ranging from 30 to 300 GHz have prompted attention as a means of achieving the capacity needs of 5G networks with immense quantities of available bandwidth [22].

The International Telecommunications Union (ITU) refers to the mmWave frequency range as EHF, which lies between the super-high frequency band and the far-infrared band within the lower part of the terahertz gap. The millimeter band is named after the wavelengths of radio waves in the mmWave frequency band, which range from 10 to 1 mm [7]. Despite the enormous available bandwidth of mmWave frequencies, its propagation properties differ dramatically from those of microwave frequency bands path loss, rain attenuation, and diffraction and blockage [22].

2.3.1 mmWave Advantages

The solutions can quantify the advantages of mmWave it offers for future 5G cellular networks. Compared to the existing 4G-LTE networks, mmWave offers several remarkable benefits, as follows [23].

- Evidently, mmWave carrier frequencies allow for larger channel bandwidth allocations which directly result in higher data rates and indirectly to reduced the latency. Accordingly, service providers will be able to support data-hungry applications with minimal latency [23].

- In addition to expanding the channel bandwidth, mmWaves can be used to reduce coverage areas, i.e., establish more densely packed communication links and exploit spatial reuse to provide increased capacity gains [23].

- It decreases the size of the hardware. As we know, the size of an antenna has inversely proportional with the frequency. So, the higher the frequency, the smaller the size of the antennas [24].

Additionally, the performance gains of utilizing MIMO in standard wireless systems are also applicable to mmWave communications since mmWave frequencies may exploit massive MIMO techniques. Spatial diversity can be exploited in mmWave systems with multiple antennas at both ends to mitigate the impact of fluctuations in the channel and loss of signals. In multi-user systems, the use of multiple antennas at the transmitter and receiver increases the potential to alleviate intra-channel interference. This is achieved via precoding at the transmitter and combining at the receiver. With multiple antennas at the transmitter, parallel streams can be transmitted to the user without additional bandwidth or power.

2.3.2 Applications of mmWave

The mmWave spectrum is already in use for military, radar, and wireless backhaul applications [25]. WPAN and wireless Local Area Networks (WLAN) using the short-ranged 60-GHz unlicensed bands offered the first standardized commercial implementations of mmWave technology. The most common WPAN standard, Wireless HD, offered a high-bandwidth interface to replace cables carrying uncompressed high-definition multimedia content. IEEE 802.11ad is a WLAN protocol used to link laptops, tablets, and smartphones to the internet through a wireless access point [25]. Regardless, mmWave technology holds promise for a variety of applications, as outlined below.

While mmWave has been developed for providing gigabit data in communication systems' wireless backhaul links, conventional designs of mmWave needed costly components to provide reliable long-range communication links, reducing the cost advantages over wired backhaul solutions. Low-cost mmWave technologies are actively being researched and developed to provide high-capacity backhaul links for densely dispersed cellular networks, particularly in urban environments, as cellular systems become denser [26, 27]. Furthermore, mmWave's development isn't limited to low-cost backhaul connections; it also has many scopes for fronthaul and access links. Because of the potential benefits possible with mmWave transmissions [28].

There has recently been a surge of interest in vehicular applications, which have the potential to unlock a slew of social benefits such as autonomous vehicles, Vehicle-to-Vehicle (V2V) connectivity, and Vehicle-to-Infrastructure (V2I) connections. This may be used for traffic data sharing, collision avoidance, and pollution management [29]. Given that mmWave is already well-established in automotive radar applications [30], one can expect mmWave to play a significant role in vehicular network support.

Advances in technology are allowing wireless devices to evolve at a rapid pace. Wearable networks, which can link smart devices such as cellphones, tablets, watches, activity-tracking devices, virtual-reality headsets, and glasses, are becoming more popular due to this. To communicate with one another, these high-end devices need a high data rate and very low latency [31]. As a result, mmWave is of interest to these networks because of its ability to fulfill their needs.

The IoT is a new concept that connects physical objects in a network, affecting all aspects of society. The vast mmWave spectrum can accommodate such links at high data rates, resulting in a massive network of billions of connections. As a result, it's safe to assume that mmWave will play a key role in allowing IoT in the future.

2.3.3 mmWave Challenges

Despite the tremendous potential of mmWave communications, many problems must be overcome to realize these benefits fully. These will be addressed in the following order:

To minimize the dependence of received power on small-signal wavelengths and incorporate directional beamforming, mmWave systems need large antenna arrays. And it results directly an increase in processing power consumption. This is a significant challenge because the power consumed by signal processing devices, including data converters, mixers, and power amplifiers, grows as the number of antennas grows. For example, in a mmWave device with 16 antennas, 12-bit Analogue to Digital Converters (ADCs) would consume more than 250mW [32].

Non-linear distortions in the power amplifiers, phase noise, and IQ imbalance are additional considerations to consider when designing Integrated Circuits (ICs) for mmWave systems with high carrier frequencies and large bandwidth since the magnitude of these errors scales up with high-frequency transmissions [33].

The significant fluctuations in the channel state that arise with user mobility in mmWave communications are a big problem since channel coherence time in the mmWave range is relatively short, resulting in a high doppler spread. [32]. As a result, modulation and coding schemes used in mobile mmWave communication must account for changing channel states [34].

2.4 mmWave Propagation

As part of the quest for significant capacity improvements, the availability of wide unlicensed, semi-licensed, and licensed bandwidths in the mmWave frequency range prompted a lot of interest in industries, academics, and standardization bodies. Furthermore, the propagation qualities of mmWave frequencies differs from those of the conventional sub-3GHz range, demanding significant modeling work [35]. Understanding radio wave propagation characteristics leads to a deeper understanding of communication device architecture, power requirements, and wireless connection lengths. For a given operating frequency band, both small-scale and large-scale propagation conditions must be adequately characterized, and little is known at frequencies above 60 GHz [36]. The frequency band in which the signal is transmitted has a direct effect on its propagation. Ordinary objects such as trees and light posts become barriers to the signal due to large penetration losses in the high frequencies. Short-range communications, also known as "whisper radio" are possible since the signal drops below the thermal noise level after a short distance [23]. Rain and other environmental conditions play a significant role in deciding the cell size for long-range communications. Bands with peaks in atmospheric absorption are best suited for dense network architectures where maximum spectral frequency reuse is needed. In contrast, frequencies with low attenuation are best suited for long-distance backhaul or cellular radio applications. Penetration, reflection, and diffraction characteristics must also be understood in order to form a complete picture of channel behaviour [28].

2.4.1 Atmospheric Losses

At mmWave frequencies, especially in the 60 GHz band, atmospheric effects contribute to signal degradation [36]. Due to the short wavelength, the molecular constituents of

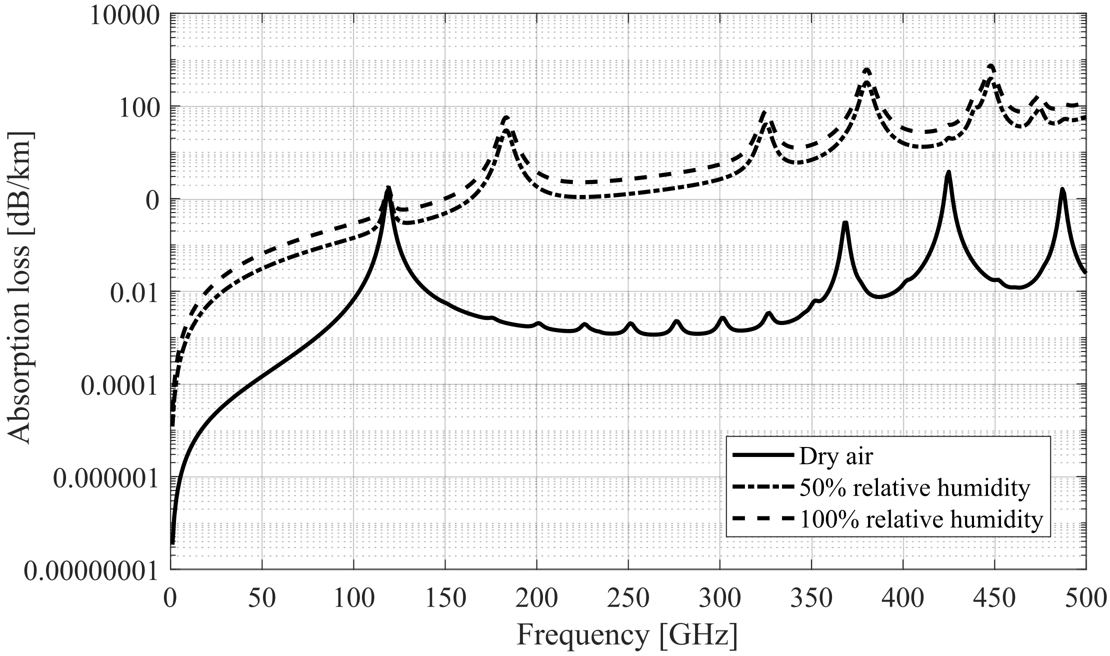

Figure 3. Average mmWave atmospheric absorption.

air and water play a role in deciding the coverage gap in high-frequency bands. Some of the atmospheric attenuation properties of mmWave propagation are shown in Figure 3.

As shown in Figure 3, dry air and humidity impact on the signal in some mmWave bands. At the E-band, for example, heavy rain can result in an additional attenuation [28]. For outdoor mmWave connections, increasing the antenna gain by beamforming will be needed to overcome the rain effect.

2.4.2 Diffraction and Penetration

Indoor users in cellular networks link to the network through an outside base station, which necessitates signal transmission via walls and windows, resulting in high penetration loss, which is exacerbated in mmWave bands [37]. Measurement of the penetration characteristics of mmWave channels for next-generation mobile communication has been a focus of research. In 5G cellular architecture, outdoor and indoor scenarios are likely to be segregated [37]. When a signal bends around the objects in its direction, it is called diffraction. Diffraction occurs at lower frequency bands due to factors like the earth's curved surface, hilly or irregular terrain, building edges, or obstructions blocking the LOS route between the transmitter and receiver [38].

In addition, several small objects in the imperfect medium can be called scatterers, displaying a highly reflective and scattering behavior to establish viable alternate communication path [39]. Millimeter wave frequencies are similarly sensitive to penetration loss, and when compared to low frequency waves, the mmWave cannot penetrate most solid materials well, like doors, walls, and furniture [40] as shown in Table1.

Table 1. Penetration losses measurements by [41]

Indoor/Outdoor	**Location**	**Material**	**Penetration losses (dB)**	**Thickness (m)**
Indoor	MetroTech Center	Crystal Glass	3.9	<0.013
	Warren Weaver Hall	shaded Glass	24.5	<0.013
		Crystal Glass	3.6	<0.013
		Wall	6.8	0.38
Outdoor	Othmer Residence Hall	shaded Glass	3.8	0.038
	Warren Weaver Hall	Brick	1.85	28.3

2.4.3 Foliage Losses

At millimeter wave frequencies, foliage losses are substantial. In fact, in some situations, foliage loss may be a limiting propagation impairment. An empirical relation was discovered in [42] that may be utilized to forecast or determine foliage losses. This was given by CCIR Report 236-2 [42], which gives the loss for below 400 meter links as:

$$L = 0.2f^{0.3}R^{0.6}dB, \tag{1}$$

where f is the frequency in MHz and its range varies between 200 MHz – 95 GHz and R is the foliage depth in meters (R<400 m). There is an example in [42], which indicates that at foliage loss at 40 GHz is around 19 dB for a penetration of 10 meters (about similar to a large tree). These values demonstrate that mmWave foliage loss is severe enough and it, like other types of losses, should never be overlooked when designing a network.

2.4.4 Small Scale Propagation

Small scale fading is the rapid fluctuation of a signal caused by interference between various copies of the transmitted signal arriving at the receiver at slightly different times. On different signal versions, multi-path waves produce additional minor fading effects such as time dispersion due to multi-path delays and random frequency modulation due to Doppler shifts [38]. The Channel Impulse Response (CIR) is directly affiliated to the wireless channel's small-scale fading. CIR contains all of the information needed to simulate or analyze any radio transmission that passes through the channel [38]. The received signal will appear as a pulse train if a single pulse is transmitted over a multi-path channel, with each pulse in the train corresponding to the LOS portion or a separate multi-path wave associated with a distinct scatterer or cluster of scatterers [38]. The CIR of a multi-path channel is shown in Figure 4.

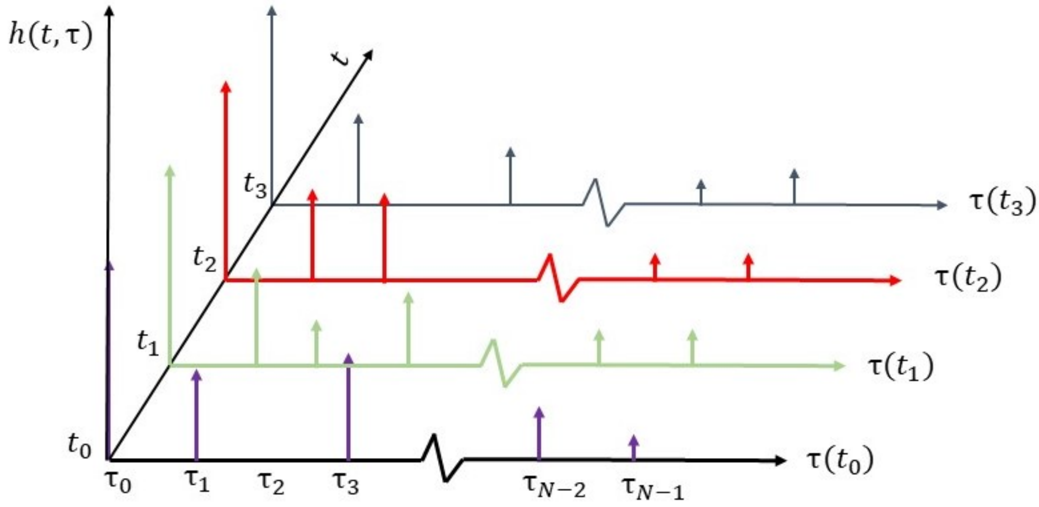

Figure 4. Time varying impulse response model for a multi-path radio channel [43].

2.4.5 Delay Spread

The arrival times and energy of the received propagation paths are included in the time delay spread of a wireless channel. Coherence bandwidth is inverse of the delay spread, and vice versa. Similarly as the coherence time is proportional to inverse of the doppler spread, and vice versa. There is little time spreading in the received signal if the delay spread is tiny compared to the inverse of the signal bandwidth. However, when the delay spread is considerable, the received signal experiences extensive time spreading, which can result in considerable signal distortion [38]. The minimum excess delay time, which is the time associated with the first path arrival, is one of the parameters used to describe the signal's delay spread; the maximum delay indicates the longest delay between initial reception and the last measurable multi-path component of a given amplitude. The root mean square delay spread is a parameter that describes a channel's propagation delays. It can be used to determine whether a channel may create inter-symbol interference without using an equalizer.

Several measurement experiments have been carried out to better understand the mmWave channel's delay spread behavior. The delay spread behavior is shown to be relatively independent of the receiver location in the interior environment [44]. On the other hand, it has been shown to be proportional to the room size and the wall reflection coefficient [36].

3 THEORETICAL BEAMFORMING PERFORMANCE

With the speedy evolution in technology, the higher frequency systems are becoming more popular in research in order to improve the capacity and bandwidth for future communication systems. With the passage of time the the data requirement is increasing so the high frequencies are very attractive as they provide high capacity for future applications etc, but with high frequencies the losses are higher which impact the overall gain with comparison to lower frequencies. In mmWave or wideband signal different frequency components have different phase rotations which depends on the distance from different elements. As all systems are frequency dependent, the effect of beam squinting (which is discussed in Section 3.2.3) has impact on the overall gain by changing antenna pattern points at different frequencies. This chapter includes the system model for analysing of signal behaviour with reference to bandwidth and distance variation at different angle.

3.1 System Model

We consider a phased array system in which an input signal will be transmitted through multiple antennas with considering the phase and gain of transmitter. A wideband channel model is considered so that higher frequencies behaviour can be analysed in this channel.More over a single receiver has been considered with different distances to antenna and variation of angle so that a clear comparison between higher frequencies can be studied. Block diagram of system model is shown in figure 5.

The large path losses that need highly directed antennas and generally LOS between the Tx and the Rx are one of the primary problems of high-frequency communication systems. This system model aims to study the loss of received power in higher frequencies with the angle variations in phased arrays. Various frequency components have distinct phase rotations based on the distance between different elements in wideband communications. Furthermore, the phase rotations change from one frequency to another, as a result it causes the reduction in overall wideband signal's attainable gain, such as received power. Moreover the impact of distance on the loss is also considered in this work. This system model will also analyse the loss occurred in higher frequencies due to beam squinting effect at different distances. Overall this model will analyse the loss in the antenna gain as a function of the bandwidth of the signal.

The received signal in the above system model can be expressed mathematically as:

$$y = \sum_{i=0}^{N-1} A_i \phi_i \sqrt{\delta_i} \sqrt{G} x, \tag{2}$$

where A_i is the amplitude, ϕ_i is the phase rotation, G is the receiver gain, x and y are the transmit and received signals, and δ_i represents the wideband channel model, respectively.

The system model components are the most important part in any model to develop the basic understanding. The components illustrates how the system model has been built up. The detail component models of system are given below.

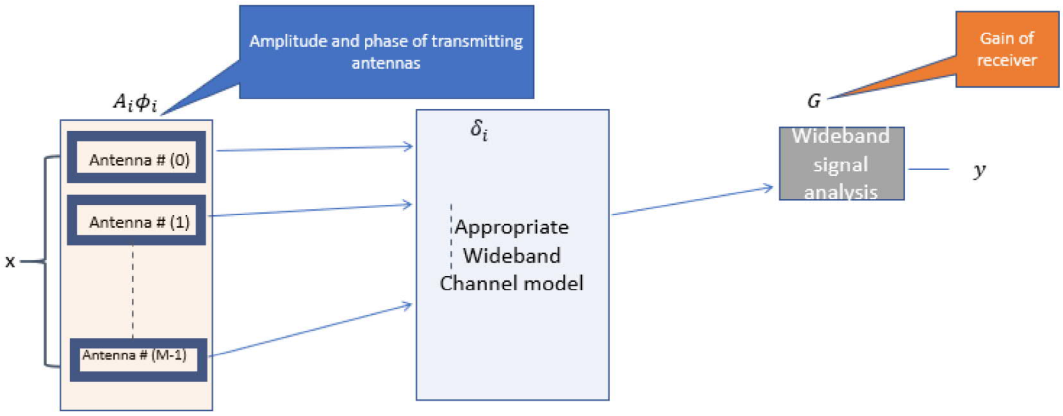

Figure 5. System model considered in this work.

Transmitter Properties

In the transmitter side, multiple components have been set for simulation. Centre frequency and bandwidth were varying in different simulations in order to get comparison. In this system model, Tx antenna is assumed to be a linear phased array and also beamforming at the Tx is studied in this work. The number of antenna elements and transmit power are key components of transmitter. So per antenna element power P_{txa} is calculated as:

$$P_{txa} = \frac{P_{tx}}{N_{tx}}, \tag{3}$$

where P_{tx} is transmit power and N_{tx} is number of antenna elements. Antenna element amplitudes are considered unitary and matrix size is $1 \times N_{tx}$. The geometry of antenna is defined as the the initial zeros matrix size $[1 \times N_{tx}]$ for x coordinates whereas y coordinates are defined as $(0 : d : (N_{tx} - 1)d) - (N_{tx} - 1)d/2$, where d is the distance between the antennas element, $d = \lambda_c/2$ and λ_c is the wavelength in centre frequency. The antenna models are later discussed in this chapter.

As discussed above the we assume phased array antennas in this work. Mathematically, the antenna gain at a certain azimuth angle of observation α is given as [45]:

$$G(\alpha) = |AF(\alpha)|^2, \tag{4}$$

where $AF(\alpha)$ is the array factor. The array factor can be given as [45]:

$$AF(\alpha) = \beta(\Gamma)^H a(\alpha) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} e^{-j\frac{2\pi}{\lambda}dn(\sin\alpha - \sin\Gamma)}, \tag{5}$$

where $a(\alpha)$ is the steering vector and $\beta(\Gamma)$ is a vector consisting of the beamforming weights and Γ is the desired beam steering direction [45].

Due to constructive accumulation of individual antenna element strengths in the beamforming direction, the maximum attainable gain of a linear phased array antenna is equal to the number of antenna elements.

Path Loss Model

The free space propagation model is the most simple model for radio signal propagation. They are regarded to go outwards from the antenna's radiated point in this case. The way they spread is similar to how ripples in a pond spread outwards from the place where a stone is thrown in.

In free space propagation as the signal travels away from the place where it was emitted, the level of the signal decreases. It decreases at a pace proportional to the inverse of the square of the distance traveled. Mathematically it can be represented as:

$$|y|^2 = \left(\frac{P_{tx}}{r^2}\right), \tag{6}$$

where r here is considered as the distance from transmitter.The path loss between a transmitter and a receiver can be calculated. As seen above, path loss is proportional to the square of the distance between the transmitter and receiver, as well as the square of the frequency in use.

The wavelength and frequency can both be used to describe the free space route loss. Below is the equation in wavelength:

$$\delta = \left(\frac{\lambda}{4\pi r}\right)^2, \tag{7}$$

where r is the distance from transmitter and λ is the wavelength.

Linear Phase Shift

In beamformer the array factor is designed based on centre frequency and also as a function of angle. With reference to centre frequency, the linear phase shift ϕ is represented as:

$$\phi = e^{-j\frac{2\pi f_c r}{c}}, \tag{8}$$

where r is the distance and c is the speed of light. The phase rotation is caused by the signal rotating with respect to the frequency and the distance has impact on how many rotations certain distance corresponds to. This causes frequency and distance dependent phase rotation.

3.2 Antenna Array

To address the demands of communication in mmWave communication systems, antennas with extremely directional properties (enormous gains) are required. The additional gain can be achieved by increasing the antenna's electrical size by arranging the radiating elements in a specific electrical and geometrical configuration. An array is a type of antenna that is made up of several antenna elements. The overall pattern of the antenna can be shaped in a variety of ways in an array of identical pieces. The overall array's geometrical configuration, the relative displacement between the elements, the signal amplitude and excitation phase of the individual antennas, and the associated pattern of the individual elements are all examples of such methods [46].

3.2.1 Uniform Linear Array

The simplest and most practical array is made by aligning the antennas in a straight line. The overall field of the array is equal to the field of a single element centered at the origin multiplied by a factor known as the array factor. It can be expressed as [46]:

$$E_T = E_e \times \text{AF}, \tag{9}$$

where E_e is the single antenna element at reference point and AF is the array factor. The array factor is determined by the array's shape and excitation phase. The features of the array factor, and thus the total field, of the array, can be modified by adjusting the separation and/or phase between the elements. There is an array factor for each array. In general, the array factor is determined by the number of elements, their geometrical arrangement, the relative magnitudes and phases of the components, and the spacing between the components. Because the array factor is independent of the directional features of the radiating elements [46].

3.2.2 Phased Arrays

A phased array is a computer-controlled array of antennas that produces a beam of radio waves that can be electrically guided to point in various directions without moving the antennas [46].

Let us consider a simple phased array beam steering example. Figure 6 and 7 depicts a wavefront impacting three antenna components from two different directions. A time delay is introduced after each antenna portion in the receive direction, and then all three signals are merged. The time delay in Figure 6 shows the time difference between the wavefronts striking each section [47]. In this scenario, the added delay enables the four signals to arrive in phase at the time of adding. This combining results in a larger signal at the output of combiner. Figure 7 uses the same delay as Figure 6, but the wavefront is perpendicular to the antenna components this time. As a result of the added delay, the four signals' steps are now misaligned, and the combiner's performance is considerably diminished.

For required beam steering time delay is the measurable delta in a phased array. However, a phase shift can be utilized to simulate time delay, which is common and realistic in many implementations.

Figure 8, shows a phased array configuration that does not employ time delay and instead uses phase shifters. The direction of boresight ($\theta = 0°$) is specified as parallel to the antenna's face.

For better visualization of phase shift required for beam steering a collection of right triangles can be drawn between adjacent elements by applying a basic concepts of trigonometry, as shown in Figure 9 .

Figure 9, depicts the trigonometry between the elements, with each element separated by a distance d. The beam is pointed away from boresight and at a 45° angle to the horizon. As illustrated in Figure 9(b), that $\cos(\phi) = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{L}{d}$, and the sum of $\theta + \phi = 90$. $L = d\sin(\theta)$ is used to determine L, the wave propagation delta distance. The time it takes the wavefront to travel the distance, L, is the same as the time it takes us to direct our beam. We can substitute the time delay with a phase delay if we take

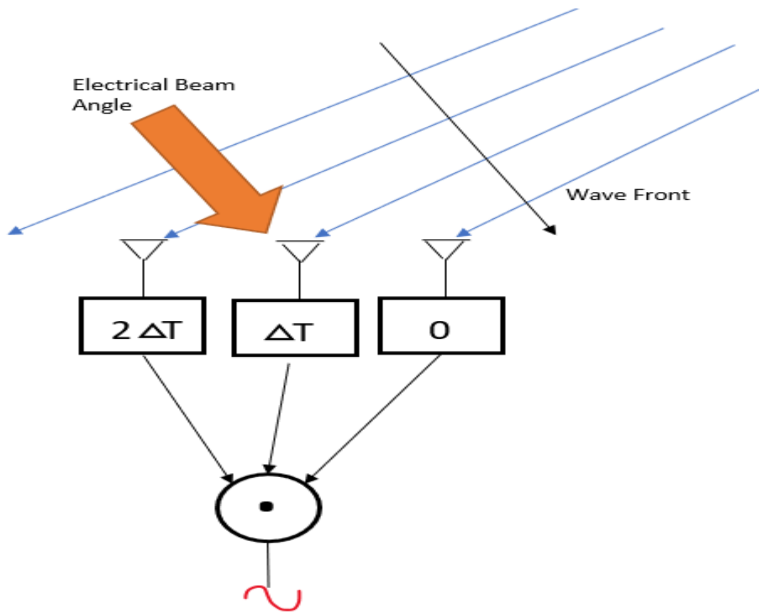

Figure 6. Steering angle [47].

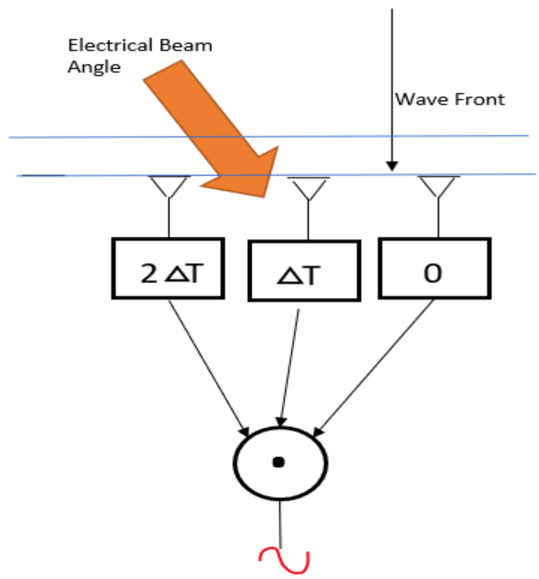

Figure 7. (b) Steering angle when no longer in phase [47].

L to be a fraction of the wavelength. The equations for and can then be represented relative to each other, as shown in Figure 9 (c) and repeated in Equation (10):

$$\Delta\phi = \frac{2\pi d \sin(\theta)}{\lambda}, \tag{10}$$

If the spacing between elements is exactly one half of the signal wavelength ($d = \lambda/2$), then this can further be simplified to:

$$\Delta\phi = \pi \sin(\theta), \tag{11}$$

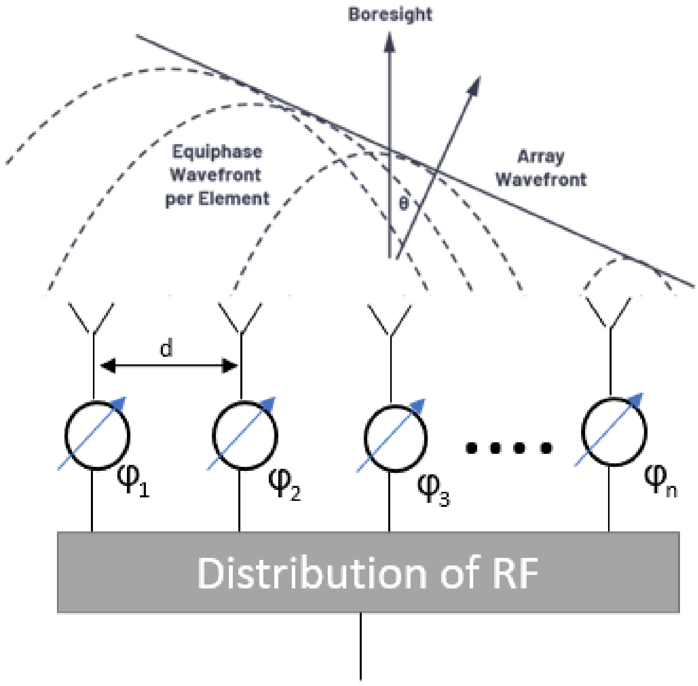

Figure 8. Phased array using RF shifters [47].

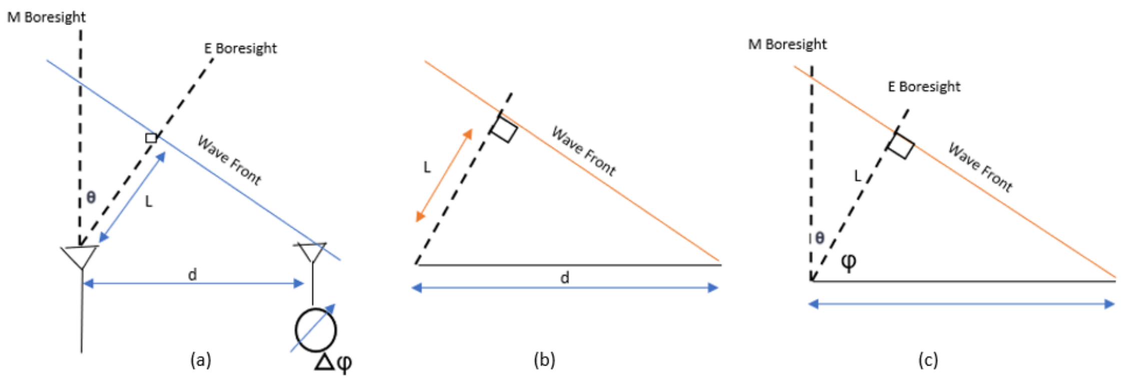

Figure 9. Phase shift vs. Beam steering angle.

3.2.3 Beam Squinting

There are wide range of applications for phased array antenna systems in various communication systems. An important phenomenon that can limit bandwidth in phased array antenna systems is beam squinting [48]. It is the change in beam direction as a function of operating frequency, polarization, or orientation in simple words. From Figure 10, we can understand the beam squinting effect that changing of antenna pattern points from original pointing direction θ at particular frequency. It can also be viewed in figure 10, a reduction in gain in the direction of θ, restricting the system's usable bandwidth.

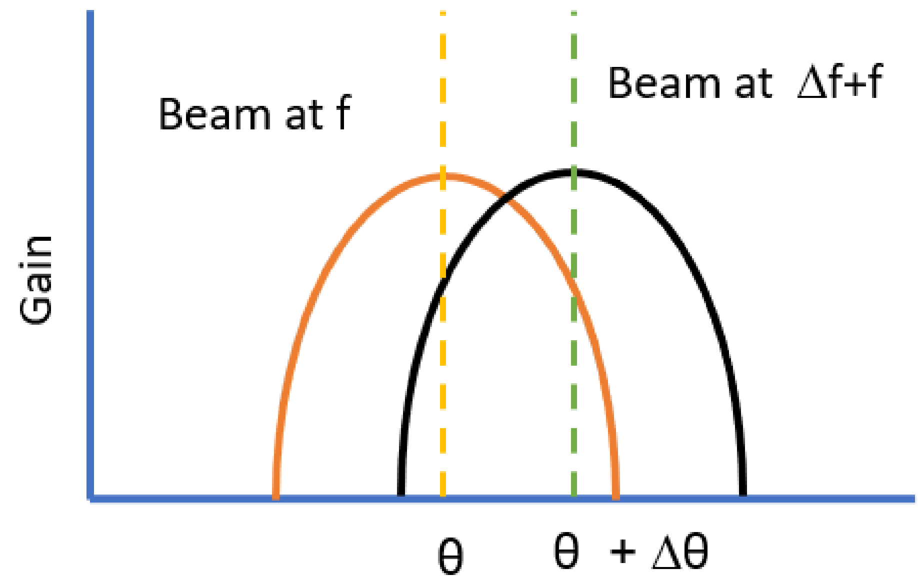

Figure 10. Beam squint illustration [48].

Several research ongoing in order to mitigate or limit the beam squinting effect in systems either with some hardware implementations or with some delaying techniques like Tapped delay line or true time delay.

The beamformer is designed about some center frequency. The wideband signals have a wide range of frequencies and the frequency offset at different frequencies cause the beamforming direction to change as the optimal phase of the beamformer is different at all the frequencies. However, the beamformer can only be designed based on one center frequency. Notable is that in the zero beamforming direction, all the phases are zeros for all the frequencies. Therefore, at zero beamforming angle there is no beam squinting.

3.3 Antennas in mmWave Systems

With the advancements in telecommunication, antennas play an increasingly vital part in any wireless system. Because the requirements for antennas in mobile communication are changing as technology advances, extensive research and development is being done to design antennas for both academic and industrial telecommunication communities.

In simple words it can be said that antenna converts electromagnetic waves into electrical signals in receiving part and vice versa in transmission. Antennas are essential part in communication systems, Following are some basics of antenna [46]. This section describes the some basics and fundamental parameters of antenna.

3.3.1 Basics of Antenna

An antenna is a conductor or series of conductors that transmits electrical signals. An antenna is defined as “a medium for radiating or receiving radio waves” [46] by the

IEEE standard definitions of words for antennas. In other words, a transmitting antenna receives signals from a transmission line, turns them into electromagnetic waves, and then broadcasts them into free space. The antenna gathers incident electromagnetic waves and turns them back into signals when in receiving mode. Following are the basics for understanding about antenna.

3.3.2 Fundamental Antenna Parameters

Antenna characterization and performance depends on several parameters some of them are described below [46].

Transmitting Antenna

According to role of the transmitting antenna it can be said as a transducer because it converts the guided electromagnetic power from a generator into a radiated power.

Receiving Antenna

The function of receiving antenna is vice versa, as receiving antenna can pick up the radiated power and transforms it in electromagnetic power.

Gain

The parameter which measures the directionality of an antenna is called gain. A low gain antenna radiates at about the same power in all directions, but a high gain antenna radiates in specific directions. The ratio of the intensity of the signal radiated by the antenna in a particular direction at an arbitrary distance divided by the intensity radiated at the same distance by a hypothetical isotropic lossless antenna is defined as the gain, directive gain, or power gain of an antenna. Because the intensity of radiation from a lossless isotropic antenna equals the power into the antenna divided by a solid angle of 4π steradians [46], so mathematically it can be expressed as:

$$\mathrm{G} = \frac{P_T}{4\pi U}, \tag{12}$$

where P_T is the total transmit power and U is the radiation intensity.

Directivity

The antenna's directivity is defined as "the antenna's radiation intensity in a given direction divided by the antenna's radiation intensity averaged over all directions." [46], mathematically it can expressed as:

$$D = \frac{P_{Tr}}{4\pi U}, \tag{13}$$

where P_{Tr} is the total radiated power (in W) and D is the directivity of antenna [46].

3.4 Total Received Power

The receiver is assumed to be single antenna receiver with gain G_{rx}. So than received power can be given as:

$$P_r(f,\alpha) = \frac{P_{t_{xa}} G_{rx}}{WN} \left| \sum_{n=0}^{N-1} A_{t_x} \sqrt{\delta_i} \phi e^{-j\frac{2\pi}{\lambda} dn \sin\alpha - j\frac{2\pi}{\lambda_c} dn \sin\Gamma} \right|^2, \tag{14}$$

where P_{txa} is the per antenna element power, A_{tx} is the antenna element amplitude, W is the system bandwidth and $P_r(f,\alpha)$ is the total received power calculated at different α and f, that is, the center frequency of the user with beam steering vector and the observation angle is associated with the observation frequency as well.

4 NUMERICAL RESULTS

Despite the enormous available bandwidth of mmWave frequencies, its propagation properties differ dramatically from microwave frequency bands, as discussed in Chapter 2. The beam squinting effect can limit the bandwidth in these high frequencies, as discussed in Chapter 3. To simulate the behavior of these high-frequency bands, MATLAB simulations were performed for bandwidths from 1 GHz to 100 GHz, considering the distance to users of 20 m and 80 m for the system model defined in the previous chapter. Following are the constants and variables used in the simulation.

4.1 Simulation Parameters

On the transmitter side, multiple components have been set for simulation. Centre frequency f_c set to 140 GHz. The number of antenna elements set to 128, whereas transmit power is 1 W. The receiver's temperature was set to 300 K and the receiver gain was 20 dB and the noise figure set to 10 dB.

The antenna geometry user positioning and beamforming design regarding centre frequency are already discussed in Chapter 3. The angular range set for α has been set in each simulation from 0 to 90 degrees, and the representation of ϕ is already shown in equation (8). For the analysis of higher frequencies we variate the bandwidth from 1 GHz to 100 GHz in order to show the behaviour of power loss in in high frequencies where as the distance value was set to 20 m in first run and 80 m in second simulation run.

Table 2. List of constant parameters

Parameter Name	**Symbol**	**Value**	**Unit**
Speed of light	c	299792458	m/s
Boltzman Constant	kB	1.38065×10^{-23}	J/K
Angular range	α	0−90	degree
Center frequency	f_c	140	GHz
Number of antenna elements	N_{tx}	128	-
Transmit power	P_{tx}	1	W
Receiver temperature	T	300	K
Receiver gain	G_{rx}	20	dB
Noise Figure	NF	10	dB

Table 3. List of variables used in the numerical results

Parameter Name	**Symbol**	**Value**	**Unit**
System bandwidth	W	1−100	GHz
Frequency	f	$f_c - \frac{W}{2}, f_c + \frac{W}{2}$	Hz
Distance to users	r	20 & 80	m

4.2 Simulation Results

The Figures 11 to 14 shows the results when r set to 20 m at angle range from 0 to 90 degrees. In figure 11 the response of 1 GHz bandwidth and 3 GHz bandwidth has been shown. For comparison, we take a 20-degree angle as a reference point, so it is visible that at 1 GHz, the integrated power is -37.33 dBm, and at 3 GHz, it drops -37.56 dBm. It can be seen from figure 12 that as the bandwidth is increased to 10 and 20 GHz, the loss increased to -39.73 and -42.54 dBm respectively, which shows clearly about 47.64% loss from 10 to 20 GHz bandwidth. To check this behavior in higher bandwidths, we can see that in figure 13 that there is a difference of 1.7 dB among 40 and 60 GHz bandwidths as in 40 GHz result shows the value of -45.41 dBm, and for 60 GHz it is -47.11 dBm which is 32.39% loss. Moving up to 100 GHz, the simulated integral power is -49.28 dBm, whereas 70 GHz calculated power is -47.77 dBm, which is more than 100 GHz as the difference is about 1.51 dBm which is almost 29.37% loss.

Moreover, if we compare the minimum bandwidth of 1 GHz with the maximum bandwidth of 100 GHz it is clearly evident that in higher frequency, the power is more as we can see that it dropped from -37.33 to -49.28 that is almost 93.62% loss. This research also reveals how much power is lost when the angle changed from 0 to 90 degrees. The data clearly demonstrates how the power has decreased as a function of angle. For 3 GHz bandwidth, we can see that from 0 to 20 degrees, there is a 5% loss, while at 60 degrees, the loss increases to 28.71%, and at 90 degrees, it reaches 36.47%. Similarly, at 60 GHz, at 20 degrees, we see a loss of nearly 89.48% as compared to 0 degrees. At 60 degrees, the power loss increases to 95.90%, while at 90 degrees, it rises to 96.51%. The maximum losses were recorded in the 100 GHz bandwidth, with a loss of almost 93.62% at 20 degrees, rising to 97.29% at 60 degrees and 97.85% at 90 degrees.

3D plots have been shown in figures 15 to 18, which describes the behavior of signal over frequency, angle, and power over a distance of 20 m. Figure 15 shows a 3 GHz signal behavior over the frequency with power and angle. So as the angle is increasing, the power is decreasing, and at the centre frequency point, maximum received power can be achieved at any angle. As the bandwidth increased, we can see that in figure 16 an evident change in signals behavior. The frequency pattern has expanded and power over the angle has changed dramatically, which is clearly the same as the results shown in 2D plots. Similarly, figure 17 shows the response of 60 GHz bandwidth signal, and figure 18 demonstrates the 100 GHz power behavior over angle and frequency. We can observe the 3dB bandwidth loss when we shift the observation angle from 0 to 20 degrees as shown in figures 15 to 18. When observation angle changed from 0 to 20 degrees at 20 GHz the estimated bandwidth loss was nearly 5 GHz, as shown in figure 16. The loss of approximately 8 GHz observed at 20 degrees and when bandwidth of 60 GHz is shown in Figure 25. In the 100 GHz simulation, we can see that at 20 degrees, approximately 10 GHz loss is recorded 26.

The results of setting distance r to 80 m at angles ranging from 0 to 90 degrees are shown in figures from 19 to 22. Figure 19 depicts the response of a 1 GHz bandwidth and a 3 GHz bandwidth. As mentioned earlier that for comparison, we use 20-degree angle as a reference point, thus the integrated power at 1 GHz is -49.37 dBm, and it decreases to -49.6 dBm at 3 GHz. Figure 20 indicates that when the bandwidth is raised to 10 and 20 GHz, the loss increases to -51.77 and -54.58 dBm, respectively, indicating a nearly 47.64% loss from 10 to 20 GHz. To verify this behavior at higher bandwidths, we can

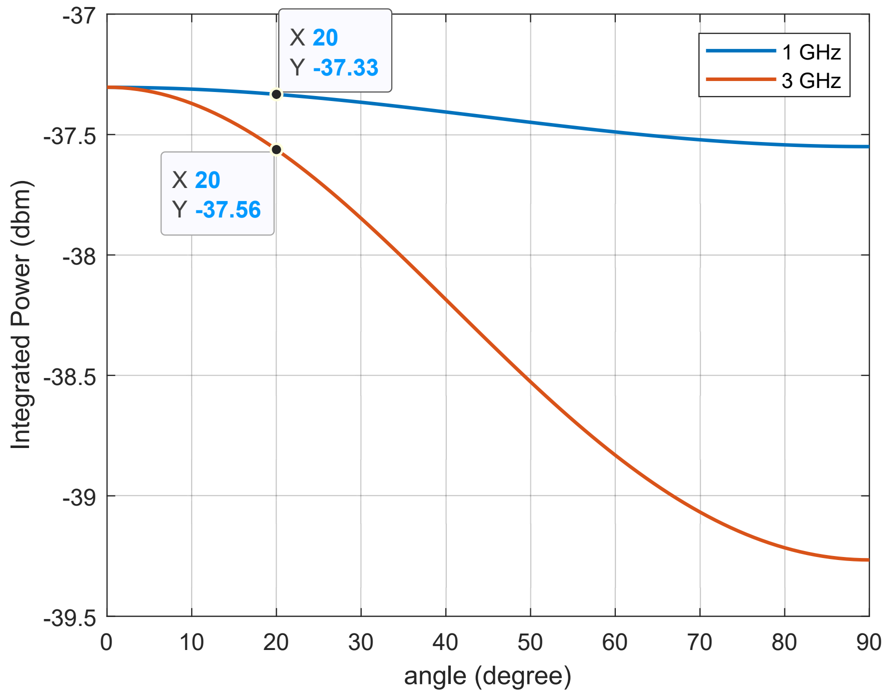

Figure 11. Received power as a function of beamforming angle (r = 20 m, W = 1 and 3 GHz).

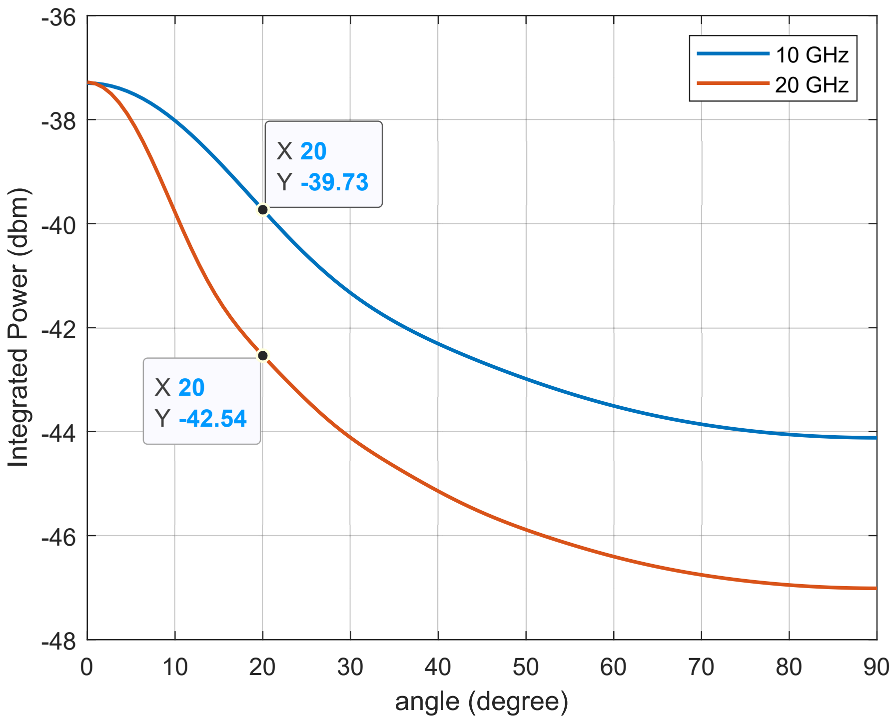

Figure 12. Received power as a function of beamforming angle (r = 20 m, W = 10 and 20 GHz).

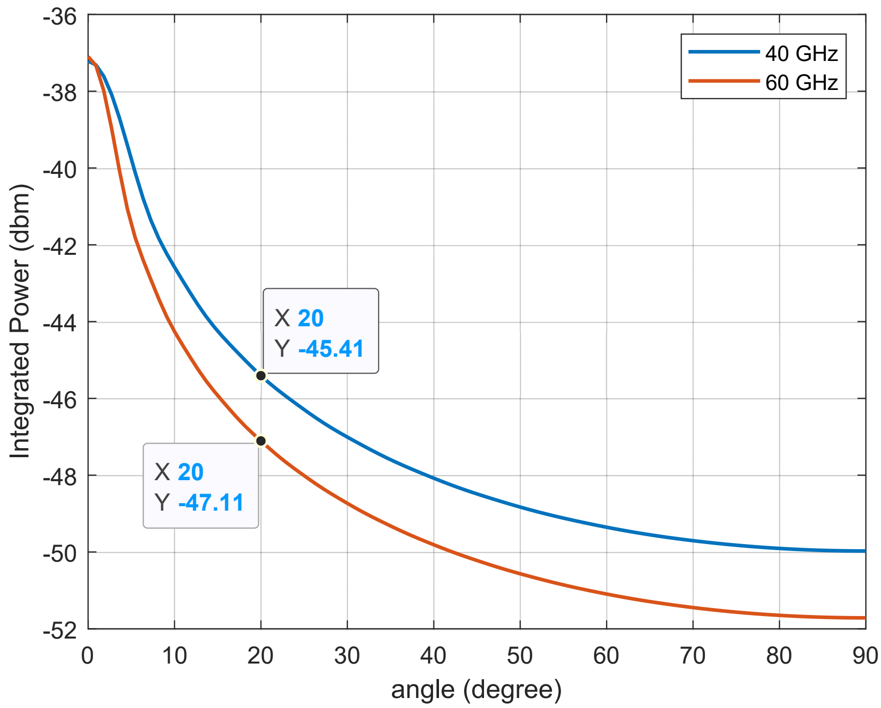

Figure 13. Received power as a function of beamforming angle (r = 20 m, W = 40 and 60 GHz).

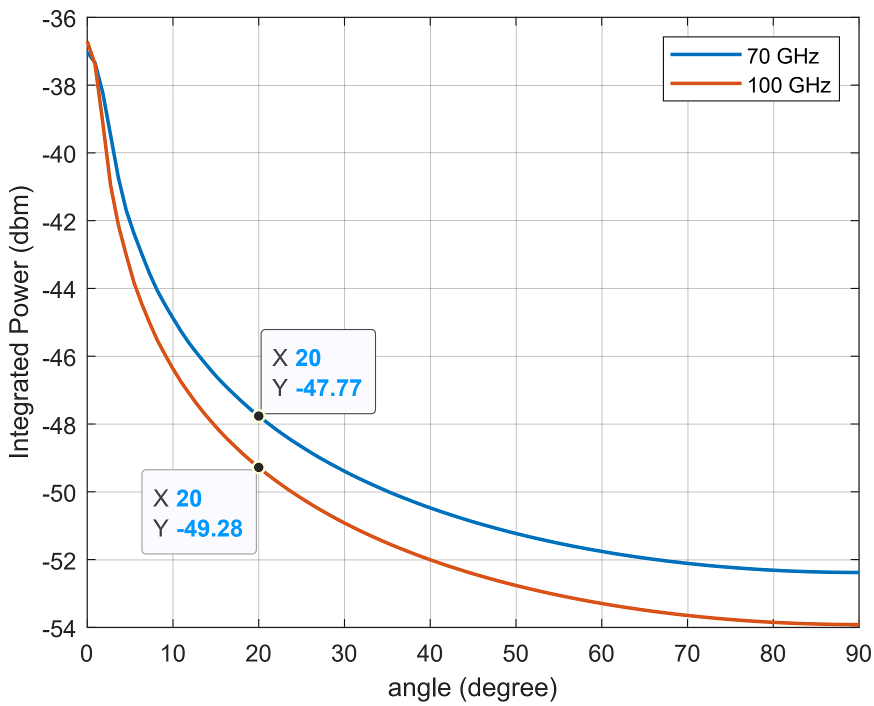

Figure 14. Received power as a function of beamforming angle (r = 20 m, W = 70 and 100 GHz).

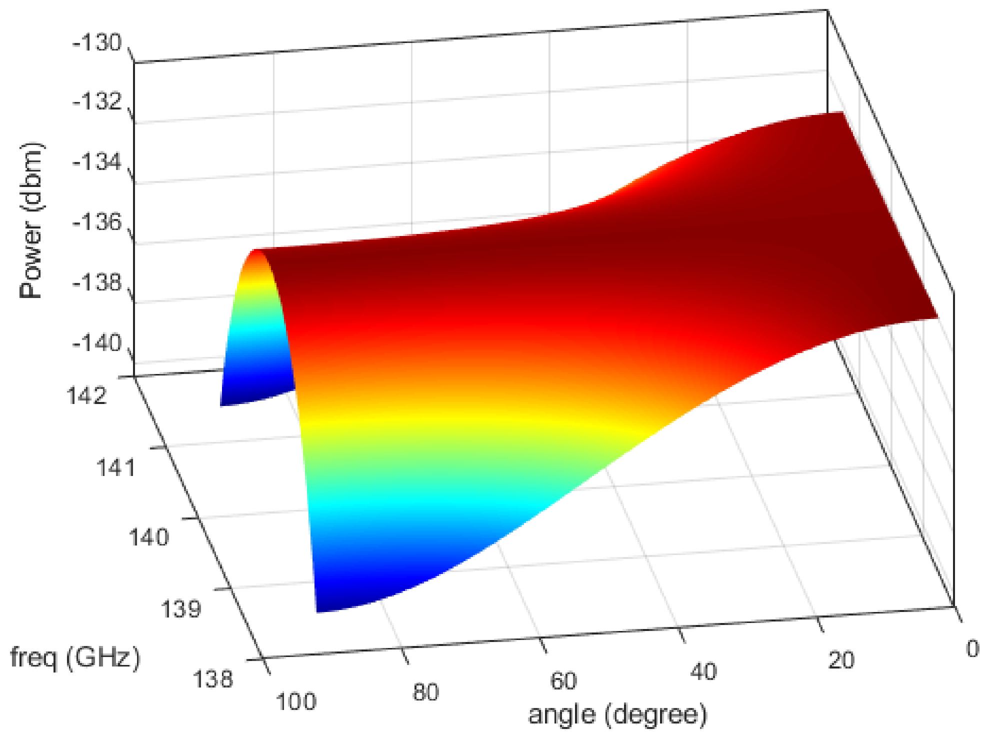

Figure 15. 3D plot of received power behaviour over frequency and angle (r = 20 m, W = 3 GHz).

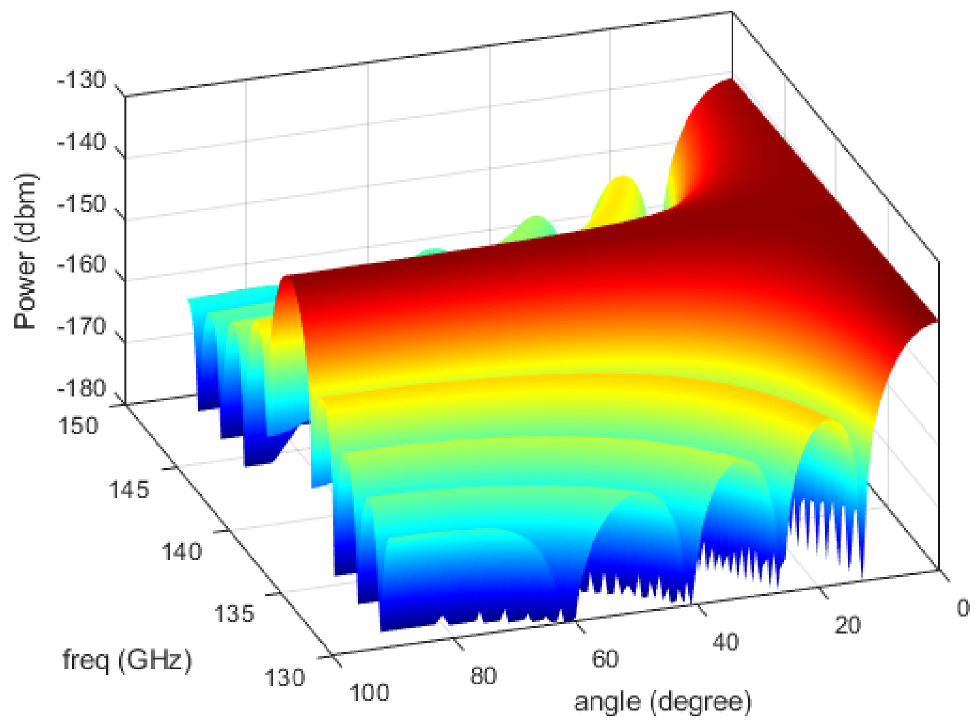

Figure 16. 3D plot of received power behaviour over frequency and angle (r = 20 m, W = 20 GHz).

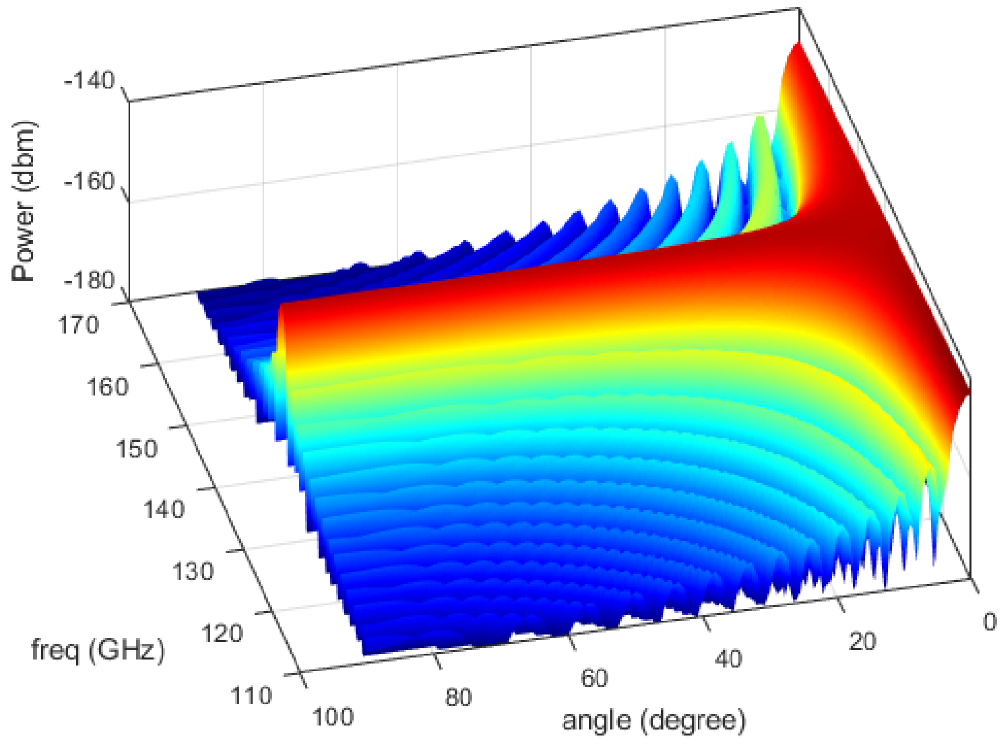

Figure 17. 3D plot of received power behaviour over frequency and angle (r = 20 m, W = 60 GHz).

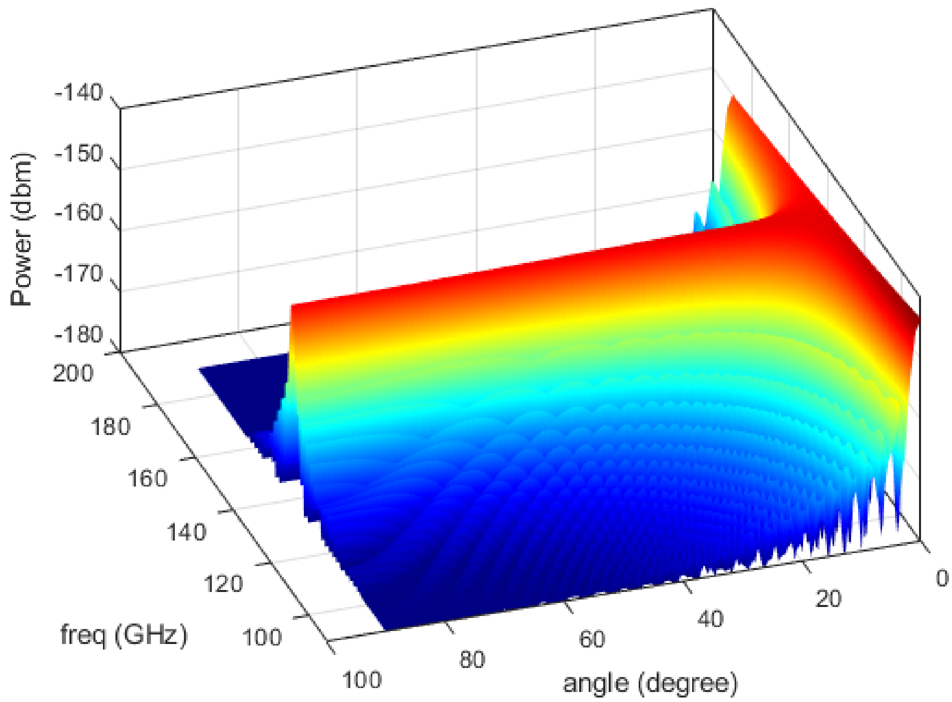

Figure 18. 3D plot of received power behaviour over frequency and angle (r = 20 m, W = 100 GHz).

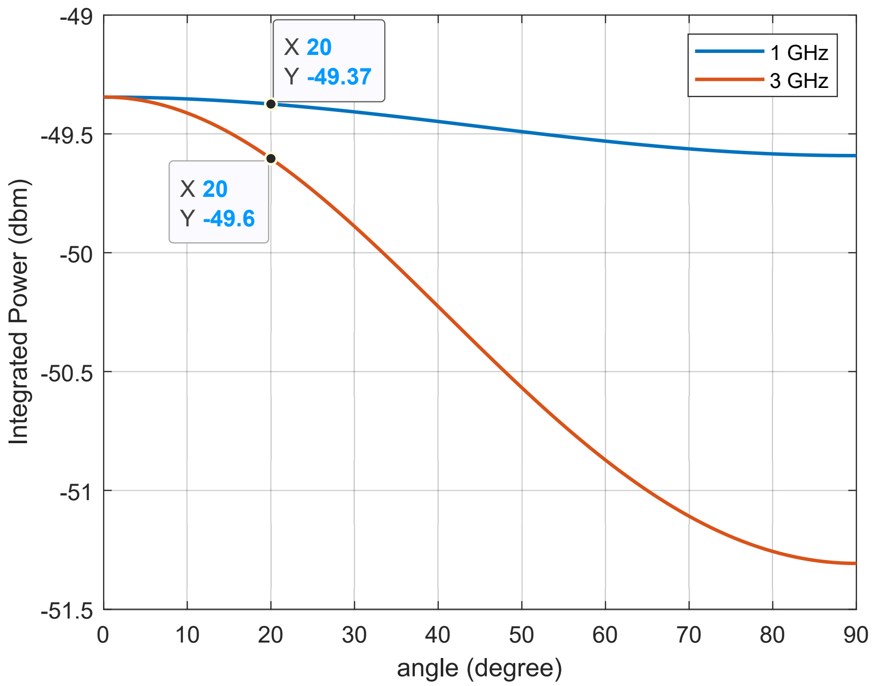

Figure 19. Received power as a function of beamforming angle (r = 80 m, W = 1 GHz and 3 GHz).

see in figure 21 that there is a 1.7 dBm difference between 40 and 60 GHz bandwidths, with the 40 GHz result showing a value of −57.45 dBm and the 60 GHz result showing a value of −59.15 dBm, a loss of nearly 2.87%. This lossy behaviour continues when we increase bandwidth to 100 GHz, the simulated integral power is −61.32 dBm, while the estimated power for 70 GHz is −59.81 dBm, which is higher than 100 GHz since the difference is approximately 1.51 dBm, or nearly 29.37%. Furthermore, when comparing the lowest bandwidth of 1 GHz to the maximum bandwidth of 100 GHz, it is obvious that the power loss is greater at higher frequencies, as shown by the fact that it fell from −49.37 to −61.32 dBm , a loss of almost 94%. This study also shows the power loss reference to 0 degrees. The results clearly shows how the power has been dropped with reference to angle. For 3 GHz bandwidth the we can see that from zero 0 to 20 degrees about 94% loss is observed, whereas at 60 degrees this loss increased to 95.37% and at 90 degrees this loss reach to 95.77%. Similarly at 60 GHz at 20 degrees we observe almost 99.34% loss with reference to 0 degrees. At 60 degrees the power loss jumps up to 99.71% whereas as at 90 degrees the losses increased to 99.78%. The highest losses were observed in 100 GHz bandwidth as at 20 degrees the loss was almost 99.6% which rise up to 99.81% at 60 degrees and 99.86% at 90 degrees.

Figures 23 to 26 provide a three-dimensional depiction of signal behavior with frequency, angle, and power at a 80 m distance. Figure 15 depicts the behavior of a 3 GHz signal as a function of frequency, power, and angle. As the angle increases, the power decreases, and maximum received power may be reached at any angle at the center frequency point. Figure 24 shows an obvious shift in signal behavior as the bandwidth increased. The frequency pattern has grown significantly, and the power across the angle has changed dramatically, which is consistent with the findings presented in 2D

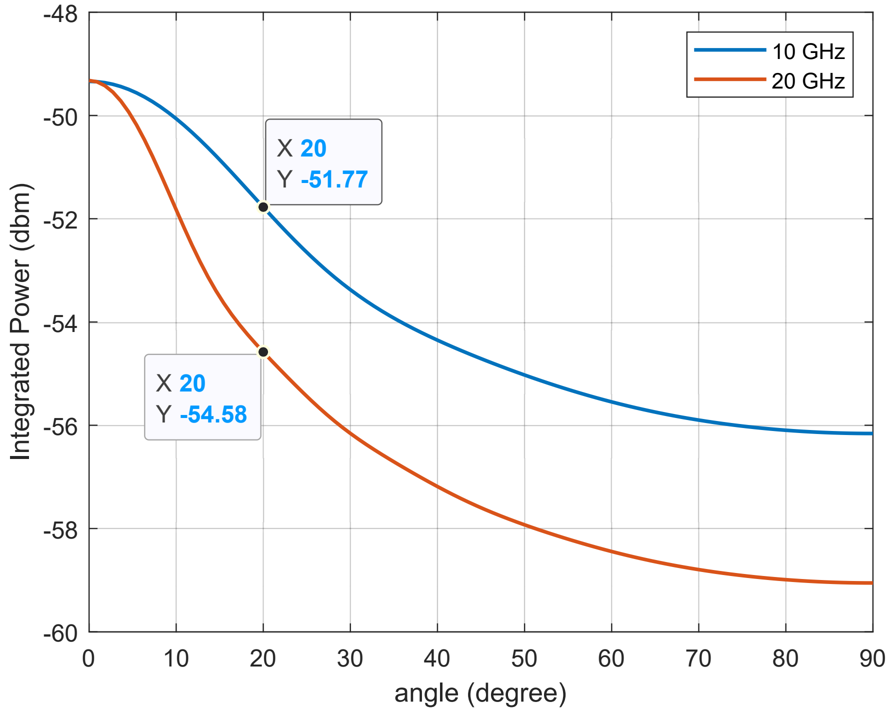

Figure 20. Received power as a function of beamforming angle (r = 80 m, W = 10 GHz and 20 GHz).

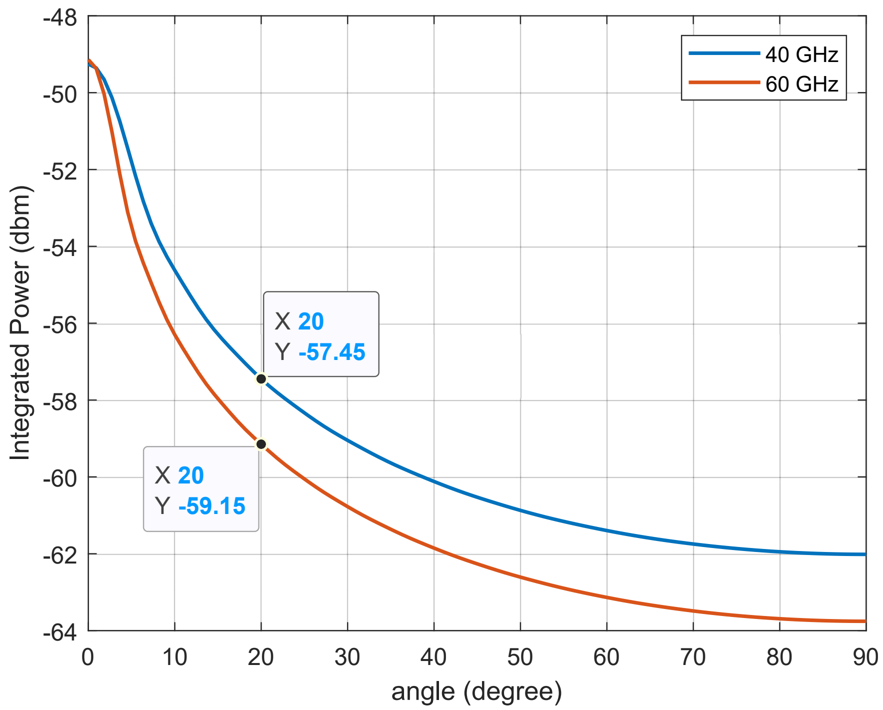

Figure 21. Received power as a function of beamforming angle (r = 80 m, W = 40 GHz and 60 GHz).

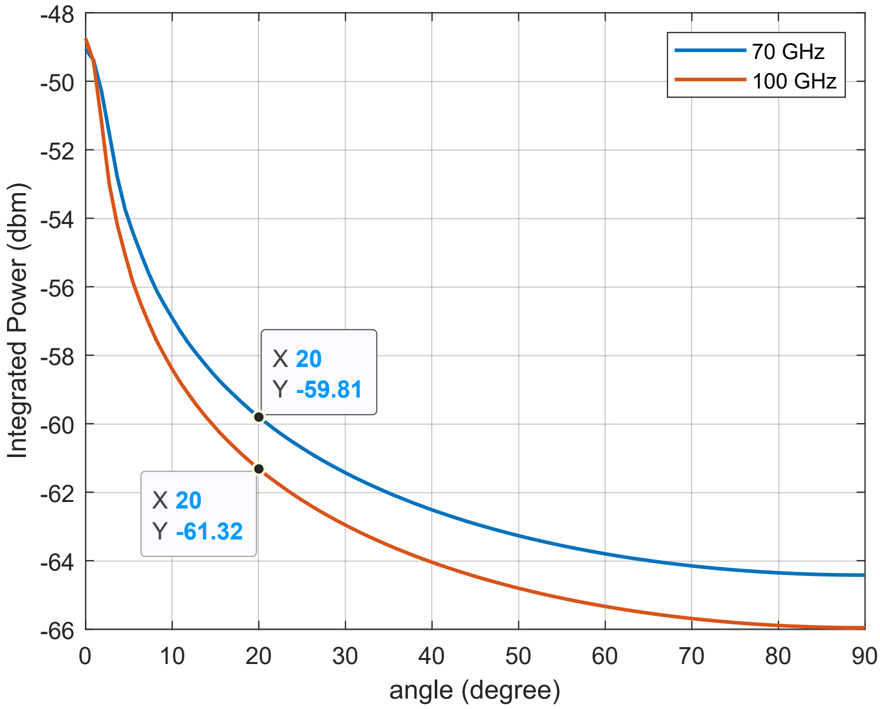

Figure 22. Received power as a function of beamforming angle (r = 80 m, W = 70 and 100 GHz).

graphs. Figure 25 depicts the 60 GHz response, whereas Figure 26 depicts the 100 GHz power behavior across angle and frequency.From figures 23 to 26 we can also see the 3dB bandwidth loss as we change the observing angle. When bandwdith is set to 20 GHz the calculated bandwidth loss was almost 5 GHz when the observing angle changed from 0 to 90 degrees as shown in figure 24. Figure 25 demonstrates the loss of about 8 GHz at 20 degrees and at bandwidth of 60 GHz. For 100 GHz simulation, we can see that in figure 26 at 20 degrees about 10 GHz loss observed.

It is undeniable that higher frequency systems suffer from more significant losses. Also, if we regard distance as a loss factor, it is imperative. When comparing Figures 11 and 19 at the angle of 20 degrees, we can see that a difference of 60 m results in a power loss of almost 32.25% in 1 GHz bandwidth. Comparing 3 GHz at both distances results in a loss of approximately 32.06%. For 10 GHz bandwidth the change of distance from 20 m to 80 m caused about 30% loss. The loss observed at 20 GHz bandwidth was almost 28%. Figure 13 and 21 shows that at 40 GHz received power loss was 26.51% and in 60 GHz it was about 25% considering the distance change from 20 m to 80 m. When bandwidth increased to 100 GHz, the loss percentage was 24.43%. The whole summary for all computed bandwidths can be seen in Table 4.

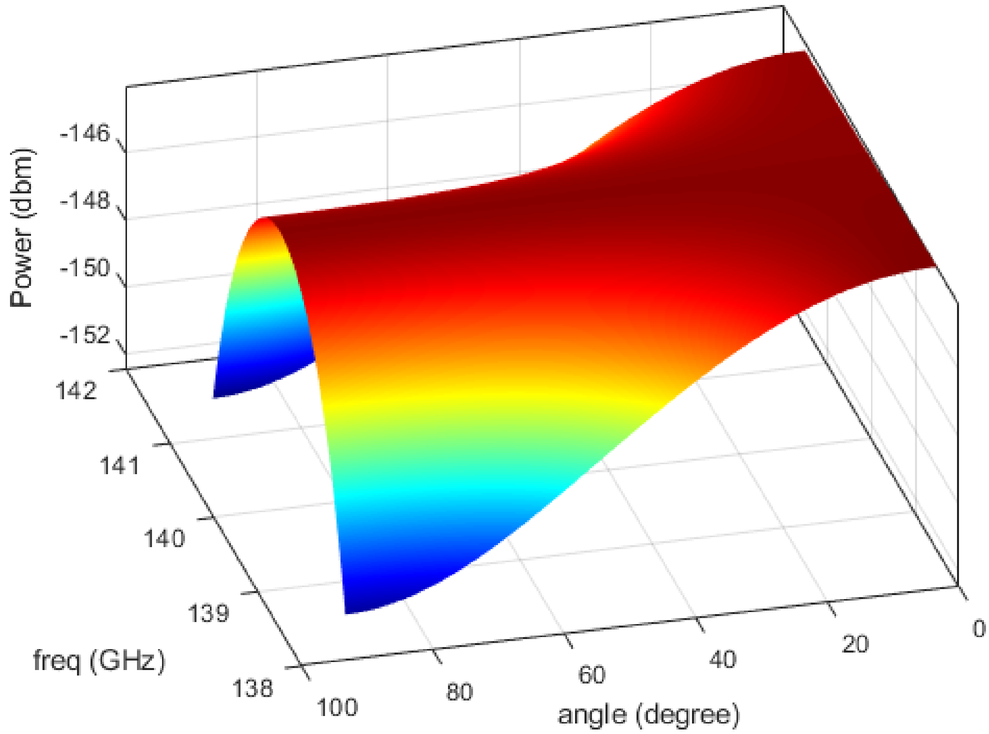

Figure 23. 3D plot of received power behaviour over frequency and angle (r = 80 m, W = 3 GHz).

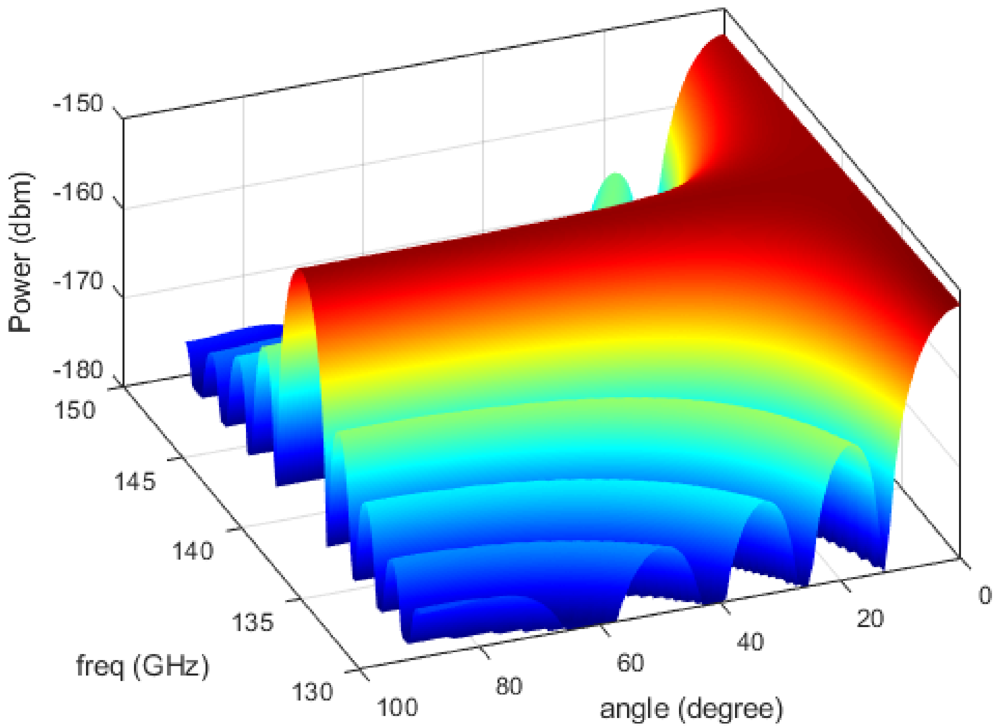

Figure 24. 3D plot of received power behaviour over frequency and angle (r = 80 m, W = 20 GHz).

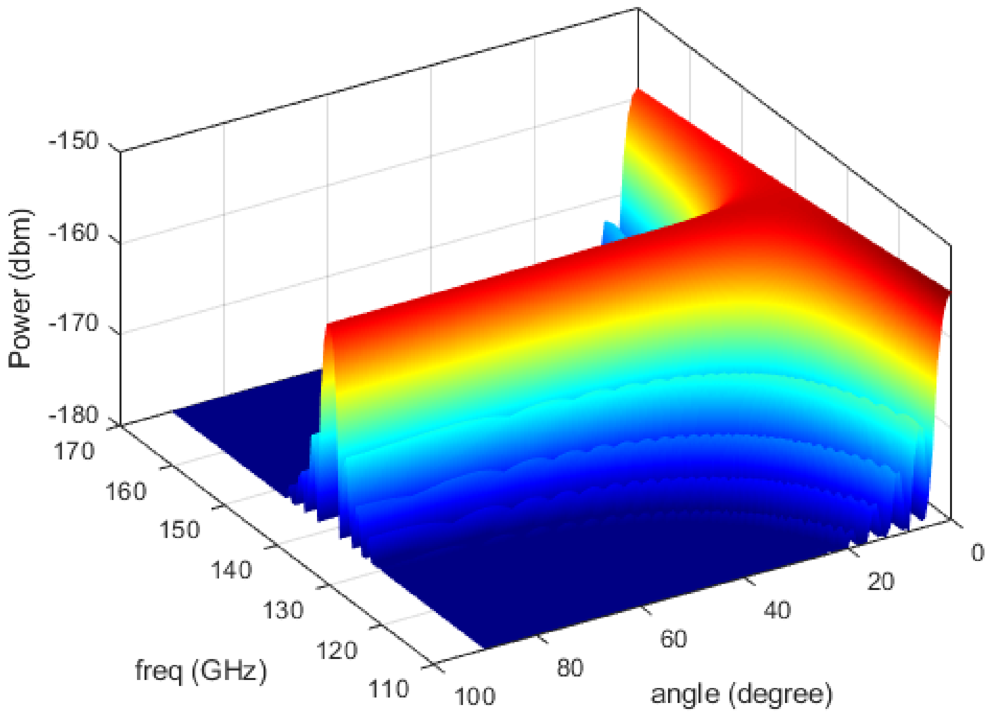

Figure 25. 3D plot of received power behaviour over frequency and angle (r = 80 m, W = 60 GHz).

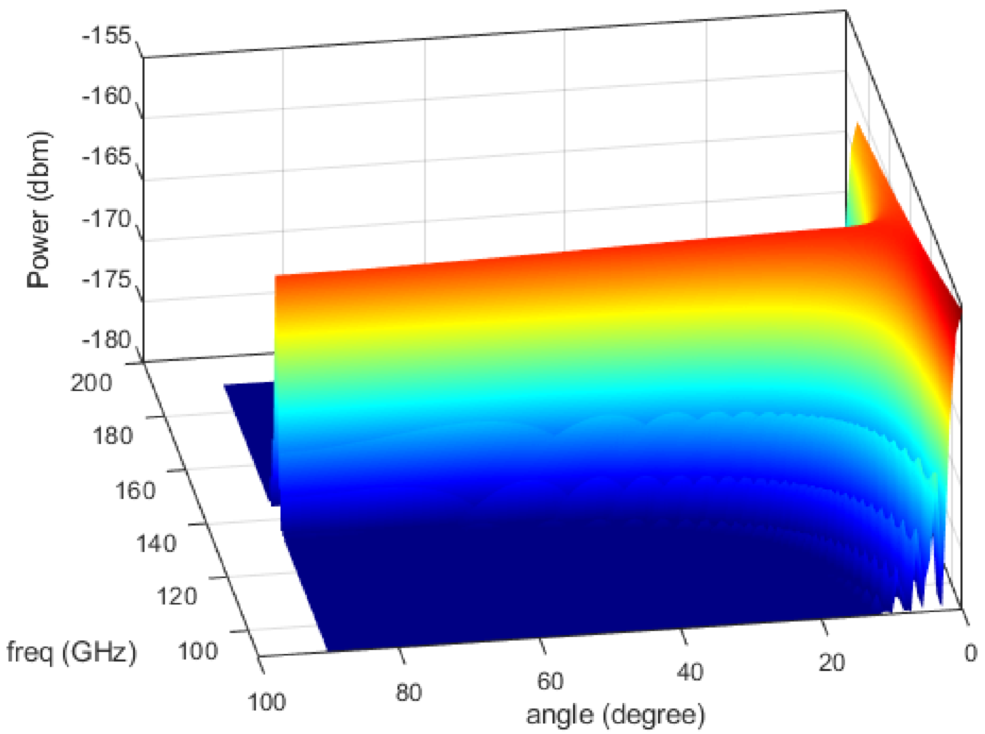

Figure 26. 3D plot of received power behaviour over frequency and angle (r = 80 m, W = 100 GHz).

Table 4. Power loss comparison over distance

Bandwidth	**Integrated Received Power (dBm)**		**Loss of Power reference to zero degree (%)**	
	r = 20 m	**r = 80 m**	**r = 20 m**	**r = 80 m**
1 GHz	-37.33	-49.37	0.00	93.75
3 GHz	-37.56	-49.6	5.16	94.07
10 GHz	-39.73	-51.77	42.46	96.40
20 GHz	-42.54	-54.58	69.87	98.12
40 GHz	-45.41	-57.45	84.44	99.03
60 GHz	-47.11	-59.15	89.48	99.34
70 GHz	-47.77	-59.18	90.96	99.35
100 GHz	-49.28	-61.32	93.62	99.60

5 SUMMARY

The future 5G and beyond networks will be featured with intelligent technologies that interconnect the whole world without limits. Millimeter-waves are high-frequency waves that are used in the future communication systems. Due to operation on the millimeter wave, it will potentially obtain around 10 Gbps data rate. MmWave frequencies are employed for various applications like radars, military applications, imaging, mobile communications, and many others.

Applications of high-frequency communications are exciting as the data rate is enormous, but its major problem is the channel losses. We designed a system model to simulate the problem that compares bandwidths from 1 GHz to 100 GHz as we move towards higher bandwidths, the main lobes and side-lobes behavior changes over frequency and angles. As the beamformer is designed at center frequency of 140 GHz, it is visible in results how the beam behaves around center frequency. In wideband signals, we have different frequency components having different phase rotations depending on the distance from different elements. Also the phase rotations are different from frequency to frequency, causing a loss in the achievable gain for the total wideband signal. This particular problem has a major impact on far field near field is hard to predict due to spherical wave propagation. In the far field it's easier to estimate the loss due to plane wave propagation, due to delay characteristics and path loss variations from signals coming from different antenna elements.

In this thesis, we performed simulation from 1 GHz to 100 GHz and it concluded that as the bandwidth increase, the power loss is increased. Moreover, the distance factor also matters, as the channel losses increase with distance.

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