MAKING MILLIMETER WAVE COMMUNICATION POSSIBLE FOR NON-LINE-OF-SIGHT SCENARIOS: 5G

by Anurag Shivam Prasad

This thesis, provides for an enhanced version of the 5G Channel Simulator, NYUSIM, developed by NYU Wireless Lab for Millimeter Wave outdoor communications at New York University. This research is performed in the physical layer for Non-Line-of-Sight scenarios. Our goal is to increase the received signal power and establish a viable transmission link, reducing the degrading effects of multipath and atmospheric noise. To achieve this goal, a search algorithm is implemented to find the main spatial energy lobe with maximum power concentration and separate it from other spatial lobes that mostly contain noise. This will act as a reference point in order to perform adaptive beamforming needed for increasing the total received signal power and noise reduction.
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Dedication

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Chapter 1

Introduction

The Fifth Generation Mobile Network (5G) is the next generation of wireless communications, which will be 10 times faster than that of the 4G LTE network, and will have the capabilities to handle 1000 times more traffic compared to today’s network. Millimeter Wave (mmWave)\(^1\) technology is one of the emerging technologies in 5G [1]. As the number of mobile devices and wireless applications have increased over the years, there is much competition for frequency bands in the existing radio frequency spectrum typically below 6 GHz. This causes issues such as slower service, dropped calls, and network congestion. The use of mmWave technology allows operation in the 30-300 GHz range, which was previously unutilized, thus opening up the radio frequency spectrum and providing higher bandwidth for increased data and information transmissions. There are challenges in this technology as these short millimeter waves are associated with strong free space path loss. Thus, it becomes crucial to understand the physical phenomenon associated with mmWave propagation. This research is basically performed in the physical layer and is an extension and enhancement of the 5G channel simulator, NYUSIM, developed by NYU wireless lab [2] for mmWave outdoor communications, in terms of achieving beamforming for Non-Line-of-Sight (NLOS) scenarios and for reducing interference. Our goal is to increase the received signal power and establish a viable transmission link, reducing the degrading effects of multipath and atmospheric noise. To accomplish this goal, as an initial step, the physical and statistical properties associated with mmWave propagation, are described in detail in Chapter 1, wherein we define the mmWave channel modeling and the development methodologies linked to NYUSIM. Chapter 2 covers the literature review part of this thesis, wherein Section 2.1, we have discussed the mathematical formulation for the statistical parameters of a mmWave channel, that

\(^1\)Millimeter in mmWave refers to the wavelength of signal used in 5G networks [1]
directly affects the performance of a wireless communication system. In Section 2.2, we discuss, in detail, the wideband mmWave measurements performed in New York City by NYU wireless laboratory. We note that the NYUSIM channel simulator was developed based on the empirical observations from NYU measurements. Chapter 3 is dedicated to the complete in-depth analysis done on NYUSIM. This crucial step allows us to perform the extensions and enhancements we implemented. In addition, it helps the reader in understanding the different scenarios and dependencies that lead to the computation of the received signal power, azimuth/elevation arrival angles, and propagation delays at the user location. In Chapter 4, we discuss the first extension performed in NYUSIM, which is basically the implementation of a search algorithm, to find the main spatial lobe with maximum power concentration, and separate it from other side lobes, which mostly constitutes noise. This step acts as a reference point in order to perform the beamforming needed for increasing the total received signal power and noise reduction. In Chapter 5, we present the details of our NYUSIM enhancements. Chapter 6 concludes our work and suggests future topics for study.

1.1 Millimeter-Wave Communication

Millimeter wave (mmWave) communication is the future of wireless technology. It provides the capability to use higher bandwidths and to achieve data rates in order of gigabits per second (Gbit/s) [3]. In the electromagnetic spectrum, the mmWave band exists in the range of 30-300 GHz and wavelengths of 1-10 mm. Spectrum for mmWave communications remained idle until recently, as it was considered unsuitable for mobile communications, due to high penetration losses and strong path loss [4].

Millimeter waves are associated with strong path loss, as per the Friis Transmission Equation [5]:

$$PL(d_0) = 20 \log_{10}(\frac{4\pi d_0}{\lambda})$$

(1.1)

where $d_0$ is the direct line of sight distance. In Eq. (1.1), Free Space Path Loss (FSPL), PL, is inversely proportional to the transmission signal’s wavelength, $\lambda$, i.e. the smaller the wavelength, the higher the path loss. Hence, strong path loss is associated with millimeter waves, as the carrier frequency is very high. To understand the physical mechanism of strong path loss, we need to first know why, in FSPL, Eq. (1.1), Line-of-Sight (LOS) path loss is inversely proportional to signal wavelength. This is due to the fact that the FSPL equation is defined for an isotropic (point
source, unity gain (0 dBi, hypothetical) receiving antenna [6]. In actuality, path loss depends on the receiving antenna aperture given by Eq. (1.2):

$$A_{\text{eff}} = G_r \times \frac{c^2}{f^2 \times 4\pi}$$  \hspace{1cm} (1.2)

where, $A_{\text{eff}}$ is the effective antenna aperture and $G_r$ is antenna gain at receiver. In Eq. (1.2), with an increase in the signal frequency, $f$, the effective measure of an antenna aperture, $A_{\text{eff}}$, decreases. Thus, to maintain unity gain, the FSPL is increased. In other words, the effective antenna aperture measures how well the electromagnetic signal can be detected and processed. So, a rise in frequency increases the FSPL between the transmitter (Tx) and the receiver (Rx) [7]. When we move from 4G LTE communication systems (operated below 6 GHz) to the mmWave range (30-300 GHz), due to a high increase in the operating frequency, the FSPL increases (from Eq. (1.2), and the $A_{\text{eff}}$ decreases). This explains the strong FSPL associated with mmWaves. We also discuss some other mechanisms of loss in the mmWave band, as listed below:

1. Blocking: Short mmWave signals (1-10 mm) show reduced diffraction and a more quasi-optical (mirror like reflections) nature of propagation than their microwave counterparts; hence, they are more sensitive to blockages around obstacles [4].

2. Rain Loss: The size of a rain drop is roughly the same as that of the wavelength of mmWaves, which causes an increase in scattering and more absorption by rain drops and; therefore, there are greater losses on rain than in a clear environment [4].

3. Atmospheric Loss: High energy mmWaves attenuate more in the air due to their higher frequency; thus, absorption due to the air is more noticeable during mmWave propagation.

4. Strong Phase Noise: This phenomenon is more prominent when there are rapid changes in the channel, which occurs due to mobility and its effect is in terms of a Doppler shift (which increases linearly with frequency) or increase in the physical orientation of devices [4].

In this thesis, we focus on the major problem of strong FSPL in the mmWave band. A resolution to this problem is to increase the gain of the receiving antenna, $G_r$. This will also allow us to increase the total received signal power. The important question
that arises here is how can we increase the gain of receiver. For this, we need to understand the basic definition of antenna gain, defined by Eq. (1.3):

\[
G = \frac{D(\theta)}{D_{iso}}
\]  

(1.3)

Equation (1.3) shows that the gain of an antenna, \(G\), is related to its directivity, \(D(\theta)\), (the measure of the concentration of the radiated power in a particular direction \((\theta, \phi)\) where \(\theta\) is the azimuth angle and \(\phi\) is the elevation angle). Isotropic Directivity, \(D_{iso}\), is the gain of an equivalent isotropic antenna [7]. So, the key approach to increasing \(G_r\) is to increase the directivity of receiver. This could be achieved by the use of highly directive antennas at the Rx, thus overcoming the strong FSPL associated with mmWaves. To summarize: Directionality is an inherent feature of mmWaves and requires multi-element antenna arrays to steer the beam energy and collect it productively (effectively increasing the gain at the Rx). For this, we need to know the desired Angle Of Arrival (AOA) of information, where the maximum signal power is received and, where a viable transmission link is established [4].

Using the path loss exponent model, we can determine the path loss over a distance \(d\) between the Tx and the Rx [5] namely

\[
PL(d) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10n\log_{10}\left(\frac{d}{d_0}\right)
\]  

(1.4)

In Eq. (1.4), \(PL(d)\) represents average path loss at a distance \(d\) between the Tx and the Rx, \(n\) is the path loss exponent that characterizes the increase in path loss as per increase in TR distance, and \(d_0\) is the direct line of sight distance (also known as the reference distance).

An important characteristic of the mmWave propagation channel is its quasi-optical nature [8]. This means that the propagation of an ElectroMagnetic (EM) wave is concerned with the size of the antenna, which can be compared in terms of its wavelength. Due to this property, most of the viable communication takes place in the LOS path and low-order reflected paths. Establishing a feasible transmission link requires steerable directional antennas to be pointed toward the LOS path or available reflected paths. As wave propagation follows the optical phenomenon, an image based ray tracing method can be used to perform spatial and temporal analysis of the channel paths [8].

An important question that arises is how these reflected rays can be analyzed to extract valuable information about the channel. For this, we need to understand the process of clustering. In channel modeling, clustering refers to the process of
grouping multipaths having some common physical characteristics such as space (angular domains) and time [8]. Statistical measurements performed in New York City, (through the NYU wireless research for mmWave communications [9]) have shown that these multipath components are very closely spaced to each other in time and angular domains after traveling through the reflected paths. For the purpose of these statistical measurements, a 400 Mega-chips-per-second (Mcps) spread spectrum based sliding correlator channel sounder was used to generate a Pseudorandom Noise (PN) sequence. To transmit and receive signals, highly directional horn-antennas were deployed. These can be steered in both azimuth and elevation directions in steps of their Half Power Beam Widths (HPBW).2

Clustering becomes an integral part of mmWave channel modeling and analysis. As time and space are two important criteria for classifications of multipaths, we are in a position to define spatial and temporal clusters based on this division. When a group of multipaths arrive closely from any arbitrary angular direction, then such a group of multipaths are known as temporal clusters. In the same line of definition, if a group of multipath signals impact along the main direction of arrival, belonging to different temporal clusters, then such category of multipaths are termed as spatial clusters [4].

Additionally polarization also plays a critical role in channel modeling, as only a single LOS path and one of the reflected NLOS path is available for reliable communication [8]. So, any polarization mismatch between the directional antennae and the channel can lead to a strong power degradation. This phenomenon also holds true for reflected paths along the receiver, which often remain highly polarized. Hence, we note that polarization characteristics are vital for the efficient analysis of mmWave propagation channel [[8], [9]].

Our next discussion focuses on the need to develop a statistical channel model for mmWave outdoor mobile communications. In addition to this, we also discuss the statistical parameters that define channel modeling and the development methodologies linked to it.

2This measurement campaign performed at NYU wireless lab, is explained in detail under Section 2.2.
1.2 Characteristics of Statistical Channel Model
For mmWave Communication

A Statistical Channel Model (SCM) for mmWave communication is required for system level design and for testing of network algorithms, which are critical for wireless industries. General requirements that characterize the need for having a channel model are:

- To obtain the space-time characteristics of the mmWave propagation environment
- To allow beamforming with steerable directional antennas while transmitting and receiving, which can support any arbitrary antenna technology
- To include polarization characteristics of antennae and signals
- To provide information about the dynamic characteristic of the propagation channel under movement of people or other time dependent variations

We are now in a position to discuss the methodologies required to develop these channel models that are mainly based on the mmWave propagation characteristics, namely, its quasi-optical nature, clustering, and polarization effects. These development methodologies include approaches to model parametric channel parameters, which are:

- Inter-Cluster Parameters: These statistical models are developed based on measurements and observance of data, as in mmWave propagation, multipath components travel very closely to each other in temporal and spatial domains [9]. The positions of clusters are modeled accordingly, taking into account the different LOS and low-order reflection propagations paths. In addition, we can accurately predict these inter-cluster parameters using strong prediction simulators such as ray tracing, to account for both the LOS and NLOS traveled distance paths [9]. Other important channel characteristics such as the propagation environment and path loss are also taken into consideration while building a ray-tracer. Data obtained from efficient ray-tracers or mmWave based statistical measurements are then processed to obtain each cluster’s time of arrival, azimuth, and elevation angle of arrival/departure. This data collection process falls into the category of inter-cluster parameters [8].

- Polarization Effect Modeling: The impact of polarization is an essential factor for characterizing mmWave propagation. Including polarization characteristics of antennae and signals is one of the key requirements to develop an efficient statistical channel model. A change in polarization for an EM wave does not
occur during free space propagation but it happens due to imperfections in antennas, which leads to cross polarization coupling. In addition, wave propagation through NLOS reflected paths can also cause changes in polarization, which are predicted by the Fresnel laws [8]. In order to measure the polarization characteristics at the antennas, we can introduce a polarization basis at the transmitter and receiver, which causes the radiated electrical \( \mathbf{E} \) field vector to decompose into two orthogonal components perpendicular to the direction of propagation and, thus, channel gain coefficients can be obtained at different orientations of the transmitter and receiver. Here, the gain of each ray in the channel is described by a 2x2 channel matrix, \( \mathbf{H} \), having elements as gain coefficients between the \( \mathbf{E} \) field vector for the corresponding orientation of the transmitter and receiver. This phenomenon can also be modeled as a polarization based ray tracer, in order to develop statistical models for \( \mathbf{H} \) [8].

- **Intra-Cluster Parameters:** The objective behind intra-cluster parameters is to group clusters with common spatial and temporal behavior. For this method to be effective, it is required to perform some data mining or post-processing schemes over the large amount of channel cluster data obtained using measurements or ray tracing schemes. These will allow some meaningful information to be extracted, thus allowing accurate channel modeling [8].
Chapter 2

Literature Review

2.1 Characterization of a 60-GHz Indoor Communication Channel

The paper entitled, “Spatial and Temporal Characteristics of 60-GHz Indoor Channels,” [5], describes one of the early statistical measurement campaigns done at mmWave frequencies. Here, the channel models were developed for 60-GHz indoor, short range communication channels. For the purpose of measurement, a 10-ns resolution sliding correlator was used, with a steerable directional antenna at the transmitter and receiver, having a HPBW of 7°. With this measurement technique, researchers were able to obtain a large number of Power Delay Profiles (PDP’s) and Power Angle Profile (PAP’s) \(^3\). After processing these measured data, high correlation between the propagation environment (for an indoor measured channel) and multipath channels structure were obtained. Although, in this paper, the authors did not mention the term ‘cluster’ for a group of multipaths having common spatial and temporal behaviors, the statistical data obtained was able to accurately describe the space-time characteristics of mmWave Channel [5].

The first half of the paper describes the experimental procedure followed for 60-GHz measurements but the part that we emphasize is the mathematical formulation for the statistical parameters of the channel and the technical definitions associated with it. These are:

\(^3\)A PDP accounts for the temporal power distribution relative to multipath Time of Arrival and a PAP records spatial power distribution relative to multipath Angle of Arrival. In other words, PDP and PAP provides the intensity of the received signal through a multipath channel as a function of time delay and multipath angle of arrival, where time delay is the difference in travel time between multipath arrivals [10].
1. Path Loss: This is a measure of the power degradation when an EM wave travels from the transmitting antenna to the receiving antennae, due to the presence of scatterers and reflectors in the path.

2. Received Signal Power: Using the same Friis Transmission Equation (Eq. (1.1)), we can compute the received signal power, which is dependent on the Path Loss between the Tx and the Rx at a distance, $d$, Tx and Rx antenna gains, and transmitted power, i.e.,

$$P_r(dBm) = P_t(dBm) + G_t(dB) + G_r(dB) - PL(d)(dB). \quad (2.1)$$

In Eq. (2.1), $P_r(dBm)$ is the received signal power in units of dBm (gain in decibels with reference of 1 milliwatt power), $P_t(dBm)$ is the transmission power in dBm, $G_t$ and $G_r$ are the gain of transmitting and receiving antennas respectively, $PL(d)$ is the average path loss at distance, and $d$, computed as per Eq. (1.4).

3. Time of Arrival Parameters: Statistical parameters that quantify the time dispersion of multipath channels are known as time-of-arrival parameters. These include parameters such as: mean excess delay($\bar{\tau}$) and Root Mean Square (RMS) delay spread ($\sigma_\tau$). These parameter directly affect the performance of a wireless communication system [5]. The mathematical expression for these time of arrival parameters are given as below in Eq. (2.2) to Eq. (2.4) [11]:

$$\bar{\tau} = \frac{\sum_{i=1}^{N} P_i \tau_i}{\sum_{i=1}^{N} P_i}, \quad (2.2)$$

$$\sigma_\tau = \sqrt{\tau^2 - (\bar{\tau})^2}, \quad (2.3)$$

and

$$\tau^2 = \frac{\sum_{i=1}^{N} P_i \tau_i^2}{\sum_{i=1}^{N} P_i}. \quad (2.4)$$

In Eqs. (2.2) and (2.4), $P_i$ and $\tau_i$ are the power and time-delay of the $i_{th}$ component of a power delay profile and $N$ is the total number of multi-paths. The RMS delay spread, $\sigma_\tau$, signifies the maximum data rate in a communication system without
equalization (required for removing the channel effect) and mean excess delay, $\bar{\tau}$, calculation is required for estimating the range of Rake receivers [5].

### 2.2 Development of Channel Models for Millimeter Wave Communication System Design

The paper, “Wideband Millimeter-Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design,” [9] discusses, in detail, the wideband mmWave measurements performed in New York City by the NYU wireless laboratory as part of its research project to develop 5G mmWave channel models. To perform these measurements, a sliding correlator channel sounder was used for each measurement campaign. The basic principle involved with a sliding correlation method is to generate two identical PN sequences at the Tx and Rx with a small difference in clock speeds or chip rate (to produce the digital PN sequence). The reason behind choosing a Pseudo-Random-Binary-Sequence (PRBS) for transmission is that it possesses a high correlation with itself and low correlation with other sequences that belong to the same set or have the same process for generation [12]. This statistical property is very similar to random noise, which satisfies the standard test of randomness [9].

The PN sequence used for transmission is a square-wave baseband sequence, having chip rate of 400 Mcps. Note that the inverse of the chip rate is the time duration of a PN square pulse, which is in units of nanoseconds. This validates the use of a wideband sliding correlator for mmWave measurements. It provides good temporal resolution in the order of nanoseconds and a large bandwidth, which are the essential characteristics of mmWave communications.

For the measurement scenario, the transmitted binary PN sequence propagates through the mmWave channel and is then received by highly directional horn antennas. This process is followed by down-conversion or demodulation of the transmitted signal. At the receiver end, the wideband signal is first down-converted to an Intermediate Frequency (IF) for post-processing, and then it is passed through a bandpass filter, in order to remove the low level noise. Once filtered, the signal is further amplified by a Low Noise Amplifier (LNA). After the signal is amplified, it is demodulated into its In-phase (I) and Quadrature (Q) phase orthogonal signal components. These extracted I and Q voltage levels are then cross-correlated with the reference PN sequence generated at a chip rate of 399.95 Mcps, which is slightly lower than that of
the transmitter. To obtain a PDP of the received signal, the conversion method in Eq. (2.5) is used:

\[ P_{\text{calculated}} = I^2 + Q^2. \]  

Equation (2.5) represents the power calculation using the cross-correlated voltage signal levels I and Q.

### 2.3 Indoor mm-Wave Wireless Communication System Design for ISI Channel Model

The paper, “OFDM-based analog multiband: a scalable design for indoor mm-wave wireless communication,” [3] discusses, in detail, the effective approach through which very high rate communication can take place over dispersive channels for indoor mmWave communication systems. Here, in order to achieve this goal the available bandwidth (in GHz) is channelized into adjacent subbands in the analog domain such that digitization is possible by utilizing suitable Analog to Digital Conversion (ADC) technology having reasonable power and cost. Furthermore, Orthogonal Frequency Division Multiplexing (OFDM) within subbands is used to reduce the intersymbol interference in an efficient way through the use of a Cyclic Prefix (CP) that compensates for channel dispersion [13]. In doing so, the authors have made certain that available bandwidth is saved by not using any guard-band within the subbands. The major challenge in this technique is to reduce the inter-band interference that arises from imperfect analog channelization and no use of large guard-bands. The paper suggests that this inter-band interference can be further suppressed by the use of adaptive linear Minimum Mean Squared Error (MMSE) techniques [14]. MMSE schemes are equalization techniques used for minimizing the mean square error between received and transmitted subcarrier symbols. The performance of this proposed architecture is evaluated using indoor channel models developed for the IEEE 802.11ad and the 60 GHz standard. The mmWave indoor communication channel model used in this paper is developed based on ray tracing simulations and experimental measurements, whose channel impulse response is modeled by Eq. (2.6) and Eq. (2.7):

\[ \text{This technique results in a bandwidth compressed signal with processing gain that greatly improves Signal to Noise (SNR) ratio.} \]
\[ h(t, \phi_{tx}, \theta_{tx}, \phi_{rx}, \theta_{rx}) = \sum_i A^{(i)} C^{(i)}(t - T^{(i)}, \phi_{tx} - \Phi^{(i)}_{tx}, \theta_{tx} - \Theta^{(i)}_{tx} - \phi^{(i)}_{rx}, \theta^{(i)}_{rx} - \Phi^{(i)}_{rx}, \theta^{(i)}_{rx}) \]

\[ C^{(i)}(t, \phi_{tx}, \theta_{tx}, \phi_{rx}, \theta_{rx}) = \sum_k \alpha^{(i,k)} \delta(t - \tau^{(i,k)}) \delta(\phi_{tx} - \phi^{(i,k)}_{tx}) \delta(\theta_{tx} - \theta^{(i,k)}_{tx}) \delta(\phi_{rx} - \phi^{(i,k)}_{rx}) \delta(\theta_{rx} - \theta^{(i,k)}_{rx}) \]

In Eqs. (2.6) and (2.7), \( C^{(i)} \) is the channel impulse response for cluster \( i \), \( T^{(i)} \), \( \Phi^{(i)}_{tx}, \Theta^{(i)}_{tx}, \phi^{(i)}_{rx}, \theta^{(i)}_{rx} \) are the time and angular characteristics of the cluster (inter-cluster parameters), \( \delta \) is the Dirac delta function, \( A^{(i)} \) is the \( 2 \times 2 \) polarization characteristic gain matrix of \( i \)-th cluster, and \( \alpha^{(i,k)}, \tau^{(i,k)}, \phi^{(i,k)}_{tx}, \theta^{(i,k)}_{tx}, \phi^{(i,k)}_{rx}, \theta^{(i,k)}_{rx} \) are the amplitude, time, and angular characteristics of the \( k \)-th ray in \( i \)-th cluster (intra-cluster parameters) [3].

At this point, we are in a position to discuss and analyze the performance of this OFDM system within subbands based upon the system architecture, as proposed in this paper by the various Bit Error Rate (BER) plots obtained. These results are produced by the authors using computer simulations and following the standard IEEE 802.11 mmWave indoor channel model. For the purpose of simulations, the OFDM transmitter for each subband has 64 sub-carriers and a symbol rate of 256 MHz is assumed, with a CP length of 16 samples. The modulation scheme used at the Tx is 16-QAM. Their results clearly show in the BER plots obtained for the 1,000 independent realizations of the conference room channel model, that the MMSE based interference technique is able to reduce the BER significantly compared to another Rx technique that uses a Zero Forcing (ZF) linear equalizer [10]. In addition, the MMSE method at the Rx provides improved performance (in terms of reduced BER), when the length of the CP is increased to 20 samples. This correlates with the fact that OFDM, with a higher CP length, is more effective in reducing Inter-Symbol Interference (ISI) [15]. Thus, the BER results produced in this paper suggests that the analog multiband structure, with OFDM and MMSE techniques employed at the Rx, presents an attractive option for high rate mmWave communication systems over dispersive channels. Moreover, the work discussed in this paper lays a good foundation for exploring the concept of diversity and multiplexing with beamforming (antenna arrays), in the context of analog multiband structure.
Chapter 3

Millimeter-Wave Channel Model Stimulator

This chapter discusses, in detail, the step-by-step physical and statistical process involved in NYUSIM, when a mmWave with a carrier frequency of 73 GHz travels from Tx to Rx under a NLOS scenario with obstacles in the path. For this process, the analysis was done by debugging the current version of NYUSIM software repeatedly for around 3 - 4 months and can be summarized in 12 steps. A major focus of a portion of this thesis are Steps 10 - 12, where the cluster lobe matrix (each of the departure/arrival energy sector lobes are comprised of subpaths) is computed (discussed in Step 11) and will act as an input matrix for our search algorithm discussed in Chapter 4. Furthermore, the power spectrum obtained in Step 12 for cluster subpaths will be used for obtaining the performance plots, namely, the PDPs and PAPs, and performing the required extensions and enhancements, directed towards increasing the received signal power. Step 1 computes the distance between the Tx and Rx, or in other words, it provides the user location, i.e., how far away from the Tx the user is standing. Each of the 10 independent users in NYUSIM represents 10 different user locations. Once the user distance is calculated, the omnidirectional received signal power (in dBm) is computed in Step 2\(^5\). Step 3 determines the number of time clusters and spatial lobes when a mmWaves travels through obstacles and reaches the Rx (user location). Since a mmWave behaves as a quasi-optical like phenomenon, it becomes more significant to analyze the temporal clusters and spatial lobes formed, in order to understand the spatial geometry involved in the propagation path and directionality, which is an inherent feature of mmWave. Multipaths associated with

\(^5\)Omnidirectional means transmitting in all directions, taking into account only the NLOS path loss which is vital in obtaining the subpath power.
these temporal clusters are generated in Step 4 and this number is crucial in analyzing the strength of a received signal. The absolute propagation delay for each multipath component is determined in Step 10, using the intra-cluster delay from Step 5 and the cluster excess time delay from Step 7. The delay calculation is important to understand the difference between intra and inter-cluster delays and the significance of a void interval, and to interpret the transmitted signal bandwidth. Furthermore, all the performance results for this research have PDP plots, so, analyzing this delay calculation helps in the perception of the physical meaning of the absolute time data generated for each subpath component. The received signal power for each multipath component is computed in Step 9, using the cluster power obtained from Step 8, which is an important part of our research, as our goal is to increase the signal power and reduce the effects of multipaths and atmospheric noise. So, it is vital to know the nature of the received signal powers that were empirically observed to be exponential decay functions from the NYU measurements. Azimuth and elevation angles of departure/arrival are computed in Step 11; these are required to understand the process involved through which these raw angles were generated. These subpath angles are later converted into suitable azimuth and elevation angles of arrival, that are required for our extension and enhancement research. Step 11 also generates the cluster lobe matrix that provides information about the various multipaths and the cluster’s corresponding spatial lobe. This data set acts as an input for our search algorithm discussed in Chapter 4, to find the spatial lobe with the maximum power concentration. Step 12 then computes the power spectrum, which tells us how the subpath power is modified with respect to the omnidirectional received power. Note, here, the complete NYUSIM is developed on the basis of empirical observations done on the experimental data obtained\(^6\), while performing real time mmWave measurements by the NYU research team. All the PDPs and PAPs plots generated for our extension and enhancement part depend upon these statistical calculations. Thus, it becomes crucial to discuss the complete process involved in NYUSIM (Appendix A (Fig. A.1)).

3.1 NYU-Simulator Version 1.1 (NYUSIM)

The NYUSIM Channel Simulator is an open source, 5G Channel Model Simulator\(^{[9] - [16]}\) that uses software developed by the NYU Wireless Lab as part of its research on prototyping a 5G mmWave statistical channel model. This section is dedicated to

\(^{6}\)http://wireless.engineering.nyu.edu/
the complete analysis done on NYUSIM using a debugging technique for an NLOS scenario at a carrier frequency of 73 GHz.

The first component of NYUSIM is the load_user inputs part, where all the initial setup for the mmWave measurement scheme under an outdoor scenario is defined. This includes the required information about the number of independent mobile users, antennae gain specifications in terms of HPBW, and antennae array type used at the Tx and the Rx. Table 3.1 lists the parameters for the outdoor mobile scenario scheme [11].

<table>
<thead>
<tr>
<th>Table 3.1: Load User Input Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Number of Independent Mobile Users</td>
</tr>
<tr>
<td>Percentage of LOS users for Joint Frequency Scenario</td>
</tr>
<tr>
<td>Maximum Possible Path Los (DynamicRange)</td>
</tr>
<tr>
<td>Transmission Power ($P_{TX}$)</td>
</tr>
<tr>
<td>Azimuth Half Power Beam width at Tx ($\theta$)</td>
</tr>
<tr>
<td>Elevation Half Power Beam width at Rx ($\phi$)</td>
</tr>
<tr>
<td>Azimuth Half Power Beam width at Tx ($\theta$)</td>
</tr>
<tr>
<td>Elevation Half Power Beam width at Rx ($\phi$)</td>
</tr>
<tr>
<td>Tx Antennae Array Type</td>
</tr>
<tr>
<td>Rx Antennae Array Type</td>
</tr>
<tr>
<td>Velocity of user</td>
</tr>
</tbody>
</table>

Next, NYUSIM evaluates the channel parameters for a 73 GHz NLOS Mobile Scenario. These channel parameters were calculated using the real time measurement data obtained from experimentation and after applying data-post processing schemes [[9]-[11]]. The channel parameters are statistical in nature and include the mean number of angles of departure and arrival, energy sector lobes formed, upper bound $X_{max}$ (required for calculation of intra-cluster subpath delays), cluster and subpath shadowing factors along with their time decay constants needed for computing subpath powers, as well as the mean and standard deviation for zenith of departure/arrival angles with their azimuth/elevation offsets required to obtain sub-path angles of departure and arrival [[9], [11], [17]]. The complete list of 73 GHz NLOS Mobile Scenario statistical parameters required to compute subpath delays, powers and angles are shown in Table 3.2 [11]:
After evaluating the statistical channel parameters for the 73 GHz NLOS Mobile Scenario, a step-wise procedure is followed in NYUSIM [11] for obtaining cluster-subpath delay, power, and azimuth/elevation angles of departure and arrival. These steps are analyzed in the following subsections.

### 3.1.1 Step 1: Calculating Distance between Tx and Rx

The Tx-Rx separation distance, \( NLOS_d \) is uniformly distributed in the NLOS Distance Range (Table 3.2), and is given by

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS Distance</td>
<td>1 m</td>
</tr>
<tr>
<td>NLOS Distance Range</td>
<td>[60,200] m</td>
</tr>
<tr>
<td>Path Loss Exponent</td>
<td>3.3</td>
</tr>
<tr>
<td>Shadow Factor ( (\sigma_{SF}) )</td>
<td>7.6 dB</td>
</tr>
<tr>
<td>Mean Number of Departure Energy Spatial Lobes</td>
<td>( \mu_{EOD} )</td>
</tr>
<tr>
<td>Mean Number of Arrival Energy Spatial Lobes</td>
<td>( \mu_{EOA} )</td>
</tr>
<tr>
<td>Upper Bound ( X_{max} ) [Uniform Dist.]</td>
<td>0.5</td>
</tr>
<tr>
<td>Mean Cluster Excess Delay ( (\mu_r) )</td>
<td>83 ns</td>
</tr>
<tr>
<td>Minimum Inter Cluster Interval ( (\text{cluster}_{\text{interval}}) )</td>
<td>25 ns</td>
</tr>
<tr>
<td>Per Cluster Shadowing ( (\sigma_{\text{cluster}}) )</td>
<td>3 dB</td>
</tr>
<tr>
<td>Time Cluster Decay Constant ( (\gamma_c) )</td>
<td>56 ns</td>
</tr>
<tr>
<td>Per Subpath Shadowing ( (\sigma_{\text{subpath}}) )</td>
<td>6 dB</td>
</tr>
<tr>
<td>Subpath Decay Constant ( (\gamma_s) )</td>
<td>15.3 ns</td>
</tr>
<tr>
<td>Mean Zenith of Departure Angle ( (\mu_{ZOD}) )</td>
<td>-4.9°</td>
</tr>
<tr>
<td>Std. of Zenith of Departure Angle ( (\sigma_{ZOD}) )</td>
<td>4.5°</td>
</tr>
<tr>
<td>Mean Zenith of Arrival Angle ( (\mu_{ZOA}) )</td>
<td>3.6°</td>
</tr>
<tr>
<td>Std. of Zenith of Arrival Angle ( (\sigma_{ZOA}) )</td>
<td>4.8°</td>
</tr>
<tr>
<td>Std. of Azimuth Offset Angle during Departure</td>
<td>( (\sigma_{\text{AODoffset}}) )</td>
</tr>
<tr>
<td>Std. of Elevation Offset Angle during Departure</td>
<td>( (\sigma_{\text{ZODoffset}}) )</td>
</tr>
<tr>
<td>Std. of Azimuth Offset Angle during Arrival</td>
<td>( (\sigma_{\text{AOAoffset}}) )</td>
</tr>
<tr>
<td>Std. of Elevation Offset Angle during Arrival</td>
<td>( (\sigma_{\text{ZOAoffset}}) )</td>
</tr>
<tr>
<td>Elevation Offset Angles Distribution Curve Type during Departure</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Elevation Offset Angles Distribution Curve Type during Arrival</td>
<td>Laplacian</td>
</tr>
</tbody>
</table>

Table 3.2: Outdoor 73 GHz NLOS Mobile Scenario
\[ NLOS_d = d_{\text{min}} + (d_{\text{max}} - d_{\text{min}}) \times r. \]  

(3.1)

In Eq. (3.1), \( d_{\text{min}} \) and \( d_{\text{max}} \) represents the minimum and maximum NLOS distances in meters and \( r \) is a uniform random variable having value between 0 and 1 [11].

3.1.2 Step 2: Computing Path Loss and Total Received Power

Once the distance between the Tx and Rx is generated, the next process is to compute the absolute path loss, \( PL(NLOS) \) as per Eq. (3.2) [11], shown below:

\[ PL(NLOS) = PL(d) + N(0, \sigma_{SF}), \]  

(3.2)

where, \( PL(d) \) is the path loss calculated from Eq. (1.4) and \( N(0, \sigma_{SF}) \) is the normal distribution having a mean of 0 and standard deviation of \( \sigma_{SF} \), as in Table 3.2. This computed path loss will never exceed the dynamic range of 180 dB, which is the maximum allowable path loss (Table 3.1) [11].

Next, is the total received power, \( Pr(dBm) \), is generated by

\[ Pr(dBm) = Pt - PL(NLOS) \]  

(3.3)

In Eq. (3.3), \( Pt \) is the transmitted power in dBm (Table 3.1) and \( PL(NLOS) \) is calculated as per Eq. (3.2) [11].

3.1.3 Step 3: Obtaining the Number of Time Clusters and Departure/Arrival Energy Sector Lobes

In this step, the initial number of time clusters, \( N \), is obtained. This parameter can take any value between 1 and 6 during an instance run of NYUSIM [11].

NYUSIM then computes the number of spatial lobes at the Tx and the Rx. For this calculation, as an initial step, the Departure/Arrival Instance, is calculated using a Poisson Distribution process and then the number of Departure/Arrival Spatial Lobes are obtained and developed as \( N_{Lobes} \); this value or parameter is always greater than or equal to 1 [11]. The relationships are shown in Eqs. (3.4) and (3.5) as

\[ Instance = Po.i(\mu_{EOD}/\mu_{EOA}) \]  

(3.4)
and
\[ N_{Lobes} = \text{Max}(1, \text{Min}(5, \text{Instance})) \]  
(3.5)

where, \( Poi \) represents a Poisson Random Distribution with rate \( \mu_{EOD}/\mu_{EOA} \), representing the mean number of Departure/Arrival Energy Spatial lobes (Table 3.2), \( \text{Min} \) represents the Minimum function, ensuring that the \( N_{Lobes} \) value cannot exceed 5 and \( \text{Max} \) represents a maximum function, such that \( N_{Lobes} \) cannot be less than 1 \([11],[16],[18] \).

### 3.1.4 Step 4: Generating Intra-Cluster Subpaths

Once the number of time clusters are obtained, intra-cluster subpaths are assigned. The number of cluster subpaths, \( N_{Subpaths} \), cannot be greater than 30 \([11]\), and are assigned as per Eq. (3.6)

\[ N_{Subpaths} = U_c[1,30] \]  
(3.6)

In Eq. (3.6), \( U_c \) represents a uniform distributed interval between 1 and 30 for each cluster, \( c \), where \( c = 1,2,3,..,N \) (number of time clusters) \([11]\).

### 3.1.5 Step 5: Generating Intra-Cluster Delays

NYUSIM next computes the intra-cluster delays. Initially, a delay factor of 2.5ns is calculated due to the time-frequency relation \([11]\):

\[ delay_{factor} = 1/BW, \]  
(3.7)

where, \( BW = 400 \text{ MHz} \) and represents the PN sequence bandwidth generated at the Tx \([9]-[11]\).

The \( delay_{factor} (1/BW = 2.5 \text{ ns}) \) is used to compute the intra-cluster delays, \( \rho_c \), as shown in Eqs. (3.8) and (3.9) namely,

\[ X = X_{max} \times r, \]  
(3.8)

and

\[ \rho_c = (2.5 \times [1 : N_{Subpath_c}])^{1+X} \]  
(3.9)

In Eq. (3.8), \( X_{max} \) is the upper bound parameter (Table 3.2 ) and \( r \) is a uniform random variable taking values between 0 and 1. In Eq. (3.9), \( N_{Subpath_c} \) is the
number of subpaths for each cluster, $c$. Here, the intra-cluster subpath delay, $\rho_c$, is always sorted in ascending order and starts from 0 ns [[11], [16], [18]].

### 3.1.6 Step 6: Generating Subpath Phases

Subpath phase, $\text{phase}_c$, for each cluster, $c$, is calculated by Eq. (3.10) as:

$$\text{phase}_c = 2 \times \pi \times r(1, N\text{Subpath}_c)$$  \hspace{1cm} (3.10)

where, $r$ is a uniform random variable, with dimension $[1 \times N\text{Subpath}_c]$ and $N\text{Subpath}_c$ is the number of cluster subpaths [[11], [16], [18]].

### 3.1.7 Step 7: Obtaining Cluster Excess Time Delay

In this functional component of NYUSIM, the intercluster excess time delay is calculated based on an exponential distribution identified for the PDP data obtained via the NYU experimentation process [[9], [11]]. As a first step, the void interval between consecutive clusters is calculated from Eq. (3.11),

$$\text{void interval} = \text{cluster interval} + 2.5,$$ \hspace{1cm} (3.11)

where, $\text{cluster interval}$ is the minimum cluster interval from Table 3.2, and 2.5 ns is the $\text{delay factor}$ as per Eq. (3.7).

The next step is to generate the cluster excess delays $\tau_c$. To do this, the simulator proceeds as follows in Eqs. (3.12) - (3.14):

$$\tau_{\text{exp}} = \text{exp}(\mu_r, [1, N]),$$ \hspace{1cm} (3.12)

$$\tau_c = \tau_{\text{exp}} + \rho_{\text{temp}} + \text{void interval},$$ \hspace{1cm} (3.13)

$$\rho_{\text{temp}} = \tau_c + \rho_c(\text{endtime}).$$ \hspace{1cm} (3.14)

In Eqs. (3.12) - (3.13), $\tau_{\text{exp}}$ represents the exponential time delay calculated from the exponential distribution, $\text{exp}$, having the mean parameter $\mu_r$ (mean cluster excess delay from Table 3.2). Additionally, $\tau_{\text{exp}}$ is sorted in ascending order and starts from 0 ns with dimension $[1 \times N]$. In Eqs. (3.13) - (3.14), $\rho_{\text{temp}}$ is calculated recursively (initialized to 0 ns) for each time cluster, taking the sum of the cluster excess delay,
3.1.8 Step 8: Obtaining Cluster Power

After obtaining the cluster excess time delay, the next important component of NYUSIM is to compute the cluster power. For this calculation, the power ratio is obtained from an exponential decay function taking into account the shadow factor, which is calculated for each cluster as per the below steps:

\[ S_c = \sigma_{\text{cluster}} \times \text{Norm}(1, N), \]  
\[(3.15)\]

\[ \text{PowerRatio}_c = 10^{(S_c/10)} \times e^{-\tau_c/\gamma_c}, \]  
\[(3.16)\]

\[ \text{ClusterPower}_c = \frac{\text{PowerRatio}_c}{\sum \text{PowerRatio}_c}. \]  
\[(3.17)\]

In Eqs. (3.15) and (3.16), \( S_c \) is the shadow factor for each cluster calculated from the normal distribution, \( \text{Norm} \), and having a standard deviation of \( \sigma_{\text{cluster}} \) (per cluster shadowing in dB from Table 3.2), dimensions of \( [1 \times N] \). In Eqs. (3.16) and (3.17), the parameter \( \text{PowerRatio}_c \) for each cluster is obtained from the exponential decay function having a decay constant given as \( \gamma_c \) (time cluster decay constant from Table 3.2) and is a function of cluster excess time delay, \( \tau_c \), from Eq. (3.13). It also includes the per cluster shadowing, \( S_c \), converted from dB to a linear scale. In Eq. (3.17), \( \text{ClusterPower}_c \) is the normalized cluster power for each cluster such that the sum will be equal to 1, with a dimension of \( [1 \times N] \).

3.1.9 Step 9: Obtaining Cluster Subpath Powers

Once the normalized cluster power is calculated, the next step in NYUSIM is to calculate the normalized cluster subpath power. For this determination, the initial intra-cluster delays \( \rho_c \) is extracted and then its size is determined, having a dimension of \( [1 \times N_{\text{Subpath}}] \). Here, similar to the cluster-power calculation, the subpath shadowing factor is determined and then the power ratio is calculated from the exponential decay function, as follows in Eqs. (3.18) - (3.21):

\[ S_{\text{subpath}} = \sigma_{\text{subpath}} \times \text{Norm}(1, N_{\text{Subpath}}), \]  
\[(3.18)\]
PowerRatio_{subpath} = 10^{(S_{subpath}/10)} \times e^{-\rho_c/\gamma_s}, \quad (3.19)

Power_{subpath} = \frac{\text{PowerRatio}_{subpath}}{\sum \text{PowerRatio}_{subpath}} \times \text{ClusterPower}_c, \quad (3.20)

Subpath_{power} = \text{Max}(\text{Power}_{subpath}, 10^{(P_{TX}-\text{DynamicRange})/10}). \quad (3.21)

In Eqs. (3.18) and (3.19), $S_{subpath}$ is the shadow factor for cluster subpaths calculated from the normal distribution, $\text{Norm}$, having standard deviation as $\sigma_{subpath}$ (per subpath shadowing in dB from Table 3.2), dimension of $[1 \times N_{Subpath_c}]$. In Eqs. (3.19) and (3.20), $\text{PowerRatio}_{subpath}$ is obtained from the exponential decay function having a decay constant given as $\gamma_s$ (subpath decay constant from Table 3.2) and a function of intra-cluster delays, $\rho_c$, from Eq. (3.9). It also includes per subpath shadowing, $S_{subpath}$, converted from dB to a linear scale. In Eq. (3.20), $\text{Power}_{subpath}$ is the normalized subpath power for each cluster, $c$, such that the sum will be equal to 1, and is obtained by multiplying the corresponding normalized cluster power $\text{ClusterPower}_c$, from Eq. (3.17). Equation (3.21) gives the resultant subpath power $\text{Subpath}_{power}$, where $\text{Max}$ represents the maximum function, $P_{TX}$ is the transmission power and Dynamic Range is the maximum possible path loss (from Table 3.1). This step will ensure that the subpath power will not go below the Dynamic Range [[11], [16], [18]].

3.1.10 Step 10: Obtaining Absolute Propagation time of multipath components

Intra-cluster absolute propagation time (in ns) is obtained from Eqs. (3.22) and (3.23) as

$$t_0 = \frac{NLOS_d}{c \times 10^{-9}}, \quad (3.22)$$

and

$$t_{\text{abs}} = t_0 + \rho_c + \tau_c. \quad (3.23)$$

In Eq. (3.22), $t_0$ represents the free space electromagnetic wave propagation time (in ns), $NLOS_d$ is the Tx-Rx separation distance calculated from Eq. (3.1) and $c$ is the speed of light whose value is equal to $3 \times 10^8$ m/s. In Eq. (3.23), $t_{\text{abs}}$ represents the intra-cluster absolute propagation time (in ns) or the time of arrival for cluster
subpaths, $\rho_c$ is the intra-cluster delays from Eq. (3.9) and $\tau_c$ is the cluster excess delay from Eq. (3.13) [[11], [16], [18]].

### 3.1.11 Step 11: Generating Azimuth ($\theta$) and Elevation ($\phi$) Angles for multi-path components during Departure and Arrival

In this functional part of NYUSIM, subpath angles (azimuth ($\theta$) and elevation ($\phi$)) are calculated during departure and arrival events, similar to the process involved for mmWave measurements [[9], [11], [18]]. The overall steps involved with angle computation can be divided into 3 parts, which are listed below:

#### 3.1.11.1 Part 1: Obtaining the Mean Azimuth and Elevation Angles during departure/arrival events for each spatial lobes $N_{Lobes}$

This part initially involves the fixing of an azimuth plane, as per Eqs. (3.24) and (3.25):

\[
\theta_{\text{min}} = 360 \times \left( \frac{1}{N_{\text{Lobes}}} - 1 \right), \quad (3.24)
\]

and

\[
\theta_{\text{max}} = 360 \times \left( \frac{1}{N_{\text{Lobes}}} \right), \quad (3.25)
\]

In Eqs. (3.24) and (3.25), $N_{\text{Lobes}}$ represent the number of departure/arrival spatial lobes from Eq. (3.5). The dimension of $\theta_{\text{min}}$ and $\theta_{\text{max}}$ is $[1 \times N_{\text{Lobes}}]$ [11].

Now, once the azimuth plane is discretized, the next step is to calculate the mean azimuth angle $\mu_{Azi}$ as

\[
\mu_{Azi} = \theta_{\text{min}} + (\theta_{\text{max}} - \theta_{\text{min}}) \times r. \quad (3.26)
\]

In Eq. (3.26), $r$ is a uniform random variable taking values between 0 and 1 [11]. After calculating the mean azimuth angle, NYUSIM calculates the mean elevation angle, $\mu_{Ele}$ as

\[
\mu_{Ele} = \mu_{Z} + \sigma_{Z} \times \text{Norm}(N_{\text{Lobes}}, 1). \quad (3.27)
\]

In Eq. (3.27), $\mu_{Z}$ represents the mean zenith of departure/arrival angle ($\mu_{ZOD}$, $\mu_{ZOA}$ from Table 3.2) and $\sigma_{Z}$ is the standard deviation zenith of departure/arrival
angle \((\sigma_{ZOD}, \sigma_{ZOA} \text{ from Table 3.2})\), with a dimension of \([N_{Lobes} \times 1]\) having mean of \(\mu_{ZOD}/\mu_{ZOA}\) and standard deviation of \(\sigma_{ZOD}/\sigma_{ZOA}\) [[11], [16], [18]].

3.1.11.2 Part 2: Generating Azimuth and Elevation Offset from spatial lobe centroid for each cluster and its subpath components

For each cluster sub-path, azimuth offsets from the spatial lobe centroid are computed from a Gaussian distribution. Elevation offset, in the case of a departure event, is calculated from a Gaussian distribution, while, for an arrival event it is extracted from a Laplacian distribution as shown in Eqs. (3.28 - 3.30) [[11], [18]]

\[
\delta_{Azimuth} = \sigma_{AziOffset} \times \text{Norm}
\]  
(3.28)

\[
\delta_{Elevation} = \sigma_{EleOffset} \times \text{Norm}
\]  
(3.29)

\[
\delta_{Elevation} = -\left(\frac{\sigma_{EleOffset}}{\sqrt{2}}\right) \times \text{sgn}(-0.5 + r) \times \ln(1 - 2 \times \text{abs}(-0.5 + r)).
\]  
(3.30)

In Eq. (3.28), \(\delta_{Azimuth}\) is the azimuth offset angle, \(\sigma_{AziOffset}\), and represents the standard deviation of the azimuth offset angle during departure/arrival (\(\sigma_{AOAOffset}\) \(\text{from Table 3.2}\)). \(\text{Norm}\) is the normal (or Gaussian) distribution having standard deviation of \(\sigma_{AOAOffset}/\sigma_{AOAOffset}\) [[11], [16], [18]].

Equation (3.29) represents the computation of elevation offset angle \(\delta_{Elevation}\) during departure event, which is from a normal distribution having a standard deviation of \(\sigma_{EleOffset}\) (\(\sigma_{ZODoffset}\) \(\text{from Table 3.2}\)) [[11], [16], [18]].

In Eq. (3.30), \(\delta_{Elevation}\) refers to the elevation angle offset extracted from the Laplacian random distribution during an arrival event for each cluster subpath. Additionally, we note that, \(\sigma_{EleOffset}\) represents the standard deviation of the elevation offset angle during arrival (\(\sigma_{ZOAoffset}\) \(\text{from Table 3.2}\)), \(\text{sgn}\) is the sign function, and \(r\) is a uniform random variable taking values between 0 and 1 [[11], [16], [18]].

3.1.11.3 Part 3: Calculating resultant Azimuth and Elevation Angles for each subpath component during departure/arrival

Once the mean azimuth/elevation angles (\(\mu_{Azi}/\mu_{Ele}\)) along with their offsets (\(\delta_{Azimuth}/\delta_{Elevation}\)) from the spatial centroid are obtained in NYUSIM, the next step is to obtain the resultant subpath angles as per Eqs. (3.31) - (3.32), given by
\[ \text{Azimuth}_{\text{subpath}} = \text{Mod}(\mu_{\text{Azi}} + \delta_{\text{Azimuth}}, 360), \]  

(3.31)

and

\[ \text{Elevation}_{\text{subpath}} = \text{Min}(\text{Max}(\mu_{\text{Ele}} + \delta_{\text{Elevation}}, -60), 60). \]  

(3.32)

In Eq. (3.31), \text{Mod} is the modulo operator which returns the remainder. This operation forces the subpath azimuth angle \text{Azimuth}_{\text{subpath}} to lie within the range of: \([0^\circ, 360^\circ]\), in the azimuth plane [11].

In Eq. (3.32), \text{Max} and \text{Min} represents the maximum and minimum function respectively. This step will ensure that the subpath elevation angle \text{Elevation}_{\text{subpath}} lies between: \([-60^\circ, 60^\circ]\) [11].

After the computation of the subpath angles, a cluster lobe mapping matrix is generated whose values are assigned recursively for each cluster and its multipath, as per Eq. (3.33) [11]:

\[ \text{ClusterLobeMapping} = [N_{\text{index}}, \text{Subpath}_{\text{index}}, Lobe_{\text{index}}]. \]  

(3.33)

In Eq. (3.33), \(N_{\text{index}}\) is the cluster number, \(\text{Subpath}_{\text{index}}\) is the index of multipath for the current cluster, and \(Lobe_{\text{index}}\) represents the randomly assigned lobe from \(N_{\text{Lobes}}\) (from Eq. (3.5) for departure/arrival). \text{ClusterLobeMapping} has a dimension of \([N_{\text{subpaths}} \times 3]\), \(N_{\text{subpaths}}\) being the total number of subpath components [11].

### 3.1.12 Step 12: Generating Power Spectrum for cluster subpaths

After computation of the subpath time delays, power, phase, and angles of departure/arrival, a power spectrum is formed in NYUSIM [[11], [18]] as per the steps below, indicated in Eqs. (3.34) and (3.35):

\[ \text{PowerSpectrum} = [t_{\text{abs}}, \text{Power}_{\text{subpath}}, \text{phase}_c, \text{Azimuth}_{\text{subpath}}, \text{Elevation}_{\text{subpath}}], \]  

(3.34)

\[ \text{Power}_{\text{subpath}} = \text{Subpath}^{\text{power}} \times 10^{\frac{Pr(dBm)}{10}}. \]  

(3.35)
In Eq. (3.34), $t_{abs}$ represents the absolute propagation time of the multi-path components as per Eq. (3.23), $\text{phase}_c$ is the subpath phase from Eq. (3.10), $\text{Azimuth}_{subpath}$ and $\text{Elevation}_{subpath}$ are the azimuth/elevation angles of departure/arrival. Equation (3.35) shows the calculation of subpath power $\text{Power}_{subpath}$ from the omnidirectional received power, $Pr(dBm)$, obtained from Eq. (3.3) and $\text{Subpath}_{power}$ from Eq. (3.21).

### 3.1.13 NYUSIM steps: Block Diagram

![Block Diagram](image)

---

7 In a multipath channel model, the absolute propagation time is defined as the total time taken by a multipath to reach from Tx to Rx and is obtained from the cluster excess time delay and intra-cluster delays, where clusters are formed due to nature of obstacles present between Tx and Rx path [19].
Figure 3.1: NYUSIM steps: Block Diagram

Step 5: Generate Intra-Cluster Delays (from PN sequence BW = 400 MHz)
\[ \text{Delay} = \left( \frac{1}{\text{Number of Subpaths} \times \left(1/BW\right)} \right) \]

Step 6: Generate Subpath phases:
\[ 2 \times \pi \times r \left( 1, \text{Number of Subpaths} \right) [r \text{ is uniform random variable}] \]

Step 7: Obtain Cluster Excess Time Delay (from: Exponential Distribution, cluster void interval = 27ns, and intra-cluster delay)

Step 8: Obtain Cluster Power (from: exponential decay function, shadowing factor, normal distribution)

Step 9: Obtain Subpath powers (from: exponential decay function, shadowing factor, cluster power)

Step 10: Obtain absolute propagation time/Subpath time delay (sum of: free space wave propagation time, intra-cluster delay and cluster excess delay)

Step 11: Generate Subpath angles for departure/arrival (Azimuth and elevation) [from: number of departure/arrival sector lobes, Gaussian distribution] and computing cluster lobe matrix (comprised of subpaths and randomly assigned departure/arrival lobes)
Chapter 4

Millimeter-Wave Channel Model
Stimulator Extension & Enhancement

Chapter 4 discusses the first extension we made in NYUSIM, which is the implementation of a search algorithm in order to find the spatial lobe with the maximum power concentration and separate it from the side lobes that mainly constitute noise. The overall process steps involved with this search algorithm are summarized into three parts. Part 1 finds all the multipaths belonging to each of the spatial lobes, Part 2 returns the maximum power of each spatial lobe and its corresponding azimuth/elevation arrival angle using the grouped multipath spectrum. This part is crucial as it allows the selection of the main lobe, which has the maximum signal power. The main energy lobe information obtained will be used to perform a comparative analysis after implementation of the beamforming algorithms, oriented towards increasing the received signal power. In addition to this, the azimuth/elevation angle of arrival obtained for the main energy lobe will act as a desired arrival angle, where the maximum signal power is obtained. This, in turn, will help to achieve adaptive beamforming in order to steer the signal towards main energy lobe and, thus, increase the overall received signal power. Directionality is an inherent feature of mmWave technology and can be best modeled through spatial lobes in order to find the best possible path for transmission and reception [[11], [16], [18]]. Performance plots obtained in Part 2 show the maximum power vs azimuth/elevation arrival angle for each spatial lobe that help in selecting the main lobe index, validating our search algorithm and power delay/angle profile plots for the main energy lobe. These act as a reference point for our comparative analysis, mainly in terms of the received signal power and the
4.1 Obtaining Main Energy Sector Lobe with Maximum Power for an Arrival Event

This functionality is inserted in the module: getting Lobe Power Spectrum part of NYUSIM (Constructing 3-D Lobe power spectra at Tx and Rx) [[11], [16]]. Here, the data post-processing steps are implemented for an arrival event in order to select the energy lobe (from $N_{Lobes}$, Eq. (3.5)) with the maximum power concentration and finding its corresponding azimuth/elevation angle of arrival.

As an initial step, a sub-part of $Power_{Spectrum}$ (from Eq. (3.34)) is extracted taking only the arrival event into consideration:

$$Subpath_{Arrival} = [t_{abs}, Power_{subpath}, \text{phase}_c, Azimuth_{subpath/arrival}, Elevation_{subpath/arrival}]$$

(4.1)

In Eq. (4.1), the dimension of $Subpath_{Arrival}$ is $[N_{subpaths} \times 5]$ and represents the subpath arrival spectrum where $N_{subpaths}$ is the total number of subpath components. $Azimuth_{subpath/arrival}$ and $Elevation_{subpath/arrival}$ are the azimuth and elevation angles of arrival [[11], [16]].

The NYUSIM extension is basically a search algorithm in order to determine the lobe with the maximum power which then extracts the corresponding angles of arrival information. This process can be broken down into three parts as listed below:

4.1.1 Part 1: Finding the Subpath Components belonging to each $N_{Lobes}$ during an arrival event

The subpath components ($Subpath_{samelobe}$) are found by mapping the $ClusterLobeMapping$ structure (from Eq. (3.33)) for each lobe index from $N_{Lobes}$:

$$Subpath_{samelobe} = ClusterLobeMapping[Lobe_{index} == 1 : N_{Lobes}]$$

(4.2)

In Eq. (4.2), $N_{Lobes}$ represents the number of arrival spatial lobes (from Eq. (3.5)), and $Lobe_{index}$ is the randomly assigned lobe number in the $ClusterLobeMapping$ structure [11].
4.1.2 Part 2: Finding the Maximum Power for each arriving spatial lobes and its corresponding azimuth/elevation angle

After computing Subpath\textsubscript{samelobe}, mapped Subpath\textsubscript{Arrival} components are extracted to recover the time, power, phase, and angle of arrival information for the same lobe as per the step in Eq. (4.3):

\[
\text{Subpath Spectrum}_{\text{samelobe}} = \text{Subpath}_{\text{Arrival}}(\text{Subpath}_{\text{samelobe}}) \tag{4.3}
\]

Equation (4.3), provides the subpath spectrum for each lobe from \(N\text{Lobes}\), where Subpath\textsubscript{Arrival} represents the sub-path spectrum during an arrival event (Eq. (4.1)).

Now, after the extraction of Subpath\textsubscript{samelobe}, data-post processing steps are performed in order to obtain suitable azimuth/elevation angles and then to find the maximum power for each lobe index from the arrival energy sector lobes. In addition to this, the azimuth and elevation angles of arrival corresponding to the maximum power are also obtained. As an initial data post-processing step, the azimuth/elevation angles of arrival are modified as per the steps in Eqs. (4.4) and (4.5):

\[
\text{Subpath Spectrum}_{\text{samelobe}}(\text{Azimuth}_{\text{arrival}}) = \text{Subpath Spectrum}_{\text{samelobe}}(\text{Azimuth}_{\text{arrival}})^{180^\circ} - 180^\circ \tag{4.4}
\]

and

\[
\text{Subpath Spectrum}_{\text{samelobe}}(\text{Elevation}_{\text{Arrival}}) = 90^\circ - \text{Subpath Spectrum}_{\text{samelobe}}(\text{Elevation}_{\text{Arrival}}) \tag{4.5}
\]

Equations (4.4) and (4.5), ensure that the azimuth angle of arrival lie in the range of: \([0^\circ, 180^\circ]\) and the elevation angle of arrival will be \(\leq 90^\circ\), avoiding negative angles. The next post-processing step is to arrange the Subpath\textsubscript{samelobe} matrix, according to the azimuth/elevation angles of arrival as per the steps followed in Eqs. (4.6) and (4.7):

\[
A_{\text{Azimuth}} = \text{sort}(\text{Subpath Spectrum}_{\text{samelobe}}, \text{Azimuth}_{\text{arrival}}) \tag{4.6}
\]

and

\[
B_{\text{Elevation}} = \text{sort}(\text{Subpath Spectrum}_{\text{samelobe}}, \text{Elevation}_{\text{arrival}}) \tag{4.7}
\]
In Eqs. (4.6) and (4.7), \( \text{SubpathSpectrum}_{\text{samelobe}} \) is sorted according to the azimuth/elevation angles of arrival without changing the order of the sub-path spectrum. Thus, \( A_{\text{Azimuth}} \) is the sub-path spectrum corresponding to azimuth angle of arrival and \( B_{\text{Elevation}} \) is the structure which corresponds to sorted elevation angle of arrival. After this, the maximum power and the azimuth/elevation angle of arrival corresponding to the maximum power for each lobe index from the arrival energy sector lobes are obtained, as per Eqs. (4.8) - (4.11):

\[
\text{Power}_{\text{Azimuth}}(N_{\text{Lobesi}}) = \text{Max}(A_{\text{Azimuth}}, \text{Power}_{\text{subpath}}) \quad (4.8)
\]

\[
\text{Power}_{\text{Elevation}}(N_{\text{Lobesi}}) = \text{Max}(B_{\text{Elevation}}, \text{Power}_{\text{subpath}}) \quad (4.9)
\]

\[
\text{Angle}_{\text{Azimuth}}(N_{\text{Lobesi}}) = (A_{\text{Azimuth}}, \text{Azimuth}_{\text{arrival}})_{\text{maxpower}} \quad (4.10)
\]

\[
\text{Angle}_{\text{Elevation}}(N_{\text{Lobesi}}) = (B_{\text{Elevation}}, \text{Elevation}_{\text{arrival}})_{\text{maxpower}} \quad (4.11)
\]

In Eqs. (4.8) and (4.9): Maximum power for each lobe index \( i \) from \( N_{\text{Lobesi}} \) (number of arrival energy sector lobes, Eq. (3.5)) is obtained, by finding maximum subpath power \( \text{Power}_{\text{subpath}} \) from the sorted sub-path spectrum structure: \( A_{\text{Azimuth}} \) and \( B_{\text{Elevation}} \) (\text{Max} represents maximum function). The dimensions of \( \text{Power}_{\text{Azimuth}} \) and \( \text{Power}_{\text{Elevation}} \) are \([1 \times N_{\text{Lobesi}}]\) and its entries correspond to maximum power of each lobe.

Equations (4.10) and (4.11) find the characteristic azimuth/elevation angle of arrival corresponding to maximum power obtained from \( \text{Power}_{\text{Azimuth}} \) and \( \text{Power}_{\text{Elevation}} \) for each arrival lobe index \( i \). The dimensions of \( \text{Angle}_{\text{Azimuth}} \) and \( \text{Angle}_{\text{Elevation}} \) are \([1 \times N_{\text{Lobesi}}]\), and its entries are azimuth/elevation arrival angles corresponding to maximum power.

Now, after computation of the maximum power for each arrival of the energy sector lobes, the \( \text{Power}_{\text{Azimuth}} \) and \( \text{Power}_{\text{Elevation}} \) vectors are plotted against their corresponding azimuth/elevation angles of arrival, as shown in Figs. 4.1 - 4.6.
Figure 4.1: Maximum Power vs Azimuth Angle For Each Energy Lobe (User3)

Figure 4.2: Maximum Power vs Azimuth Angle For Each Energy Lobe (User5)
Figure 4.3: Maximum Power vs Azimuth Angle For Each Energy Lobe (User6)

Figure 4.4: Maximum Power vs Elevation Angle For Each Energy Lobe (User3)
Figure 4.5: Maximum Power vs Elevation Angle For Each Energy Lobe (User5)

Figure 4.6: Maximum Power vs Elevation Angle For Each Energy Lobe (User6)
Figures 4.1, 4.2, 4.3 show the Maximum Power ($Power_{Azimuth}(N_{Lobesi})$) vs corresponding azimuth angle of arrival ($Angle_{Azimuth}(N_{Lobesi})$) plots generated for each of the 5 energy sector lobes obtained representing Users 3, 5 and 6 at three different Rx locations. Clearly, the main lobe can be identified from the plots obtained, namely, the one with the maximum power. Table 4.1 summarizes the main lobe power data obtained:

<table>
<thead>
<tr>
<th>User Number</th>
<th>Power (dBm)</th>
<th>Azimuth Angle ($\theta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-131.5</td>
<td>143°</td>
</tr>
<tr>
<td>5</td>
<td>-140.1</td>
<td>27°</td>
</tr>
<tr>
<td>6</td>
<td>-154.8</td>
<td>16°</td>
</tr>
</tbody>
</table>

Similar to the maximum power vs azimuth angle plots for each arrival lobes, Figs. 4.4, 4.5, 4.6 represent the Maximum Power ($Power_{Elevation}(N_{Lobesi})$) vs elevation angles ($Angle_{Elevation}(N_{Lobesi})$) plots for each of the 5 energy sector lobes obtained. The main lobe power data and its corresponding elevation angle for Users 3, 5 and 6 are listed in Table 4.2:

<table>
<thead>
<tr>
<th>User Number</th>
<th>Power (dBm)</th>
<th>Elevation Angle ($\phi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-131.5</td>
<td>85°</td>
</tr>
<tr>
<td>5</td>
<td>-140.1</td>
<td>89°</td>
</tr>
<tr>
<td>6</td>
<td>-154.8</td>
<td>85°</td>
</tr>
</tbody>
</table>

Figures 4.7, 4.8 and 4.9: show the PDP plots obtained for the main energy lobe and are plotted against the sorted absolute propagation time $t_{abs}$ (from Eq. (3.23)). Here the main lobe index is identified by finding the maximum of $Power_{Azimuth}(N_{Lobesi})/Power_{Elevation}(N_{Lobesi})$ and then the corresponding multi-paths are mapped, as per Eqs. (4.12) - (4.14):

$$Subpath_{mainlobe} = ClusterLobe_{Mapping}[Lobe_{index} == MainLobe_{index}],$$  

(4.12)
\[ SubpathSpectrum_{\text{mainlobe}} = Subpath_{\text{Arrival}}(Subpath_{\text{mainlobe}}), \quad (4.13) \]

and

\[ Spectrum_{\text{mainlobe}} = \text{sort}(SubpathSpectrum_{\text{mainlobe}}, t_{\text{abs}}). \quad (4.14) \]

In Eqs. (4.12), (4.13), \textit{Subpath}_{\text{mainlobe}} refers to the multi-paths extracted from \textit{ClusterLobeMapping} (Eq. (3.33)) for the main lobe index (obtained from our selection algorithm: lobe with maximum power). \textit{SubpathSpectrum}_{\text{mainlobe}} is the subpath arrival spectrum corresponding to main lobe subpaths, using \textit{Subpath}_{\text{Arrival}} structure (Eq. (4.1)). In Eq. (4.14), \textit{Spectrum}_{\text{mainlobe}} is the sorted main lobe spectrum, according to absolute propagation time \( t_{\text{abs}} \). Thus, \textit{Spectrum}_{\text{mainlobe}}(\text{Power}_{\text{subpath}}) vs \textit{Spectrum}_{\text{mainlobe}}(t_{\text{abs}}) plots are generated for Users 3, 5 and 6.

![Figure 4.7: Power Delay Profile For Main Energy Lobe(User3)](image-url)
Figure 4.8: Power Delay Profile For Main Energy Lobe (User5)

Figure 4.9: Power Delay Profile For Main Energy Lobe (User6)
Next, the generation of the main lobe index PAPs plots (Power vs Elevation Angle ($\phi$)) is presented. For this, the initial steps are very similar to the ones followed for obtaining PDP plots (Eqs. (4.12), (4.13)) namely, extracting the subpaths for main lobe index and finding its corresponding subpath spectrum. Now, in order to get the required plots, the subpath power spectrum is sorted against the elevation angles of arrival as per Eq. (4.15):

\[
Spectrum_{\text{mainlobe}} = \text{sort}(\text{SubpathSpectrum}_{\text{mainlobe}}, \text{Elevation}_{\text{subpath/arrival}}) \quad (4.15)
\]

Hence, the plots of Figs. 4.10 and 4.11 are obtained:

![Power vs Elevation Angle (Main Lobe)](image)

Figure 4.10: Power Angle Profile For Main Energy Lobe(User2)
Figures 4.10, 4.11, represent the PAPs at user locations 2 and 4 for the main energy sector lobe. The main lobe maximum power for the second user is -148.8 dBm (reference to 1mW power) at an elevation angle of 89° and for the fourth user it is -154.3 dBm at an elevation angle of 82°. The significance of obtaining maximum signal power for user location 2 at an elevation angle of arrival: 89° is that when a mmWave signal travels from Tx to Rx (where user 2 is located), the maximum signal strength is observed at an AOA of 89°. Thus, PAP plots are crucial to gather directional information (AOD/AOA) when a mmWave travels in a fixed geometry between the Tx and Rx.

4.1.3 Part 3: Discussion of Results Obtained

The main lobe received power after the mmWave travels through the NLOS distance (\(NLOS_d\)) at the Rx location for user number 3 is -131.5 dBm while that of user locations 5 and 6 are -140.1 dBm and -154.8 dBm. This shows that the received power for third user is higher than that of users 5 and 6. Note, here, the NLOS setting means there is no straight path between the Tx and Rx with obstructions in the path. User number 3 receives a higher signal power as compared to others is due to the fact that there are less number of multi-paths. Now, this result can be further validated through the PDPs obtained for the main energy lobe at Rx location for 3 different users. For instance, analyzing the PDP generated for user number 3, the absolute propagation time is around 327 ns (Fig. 4.7), while that for users 5 and 6 are around 611.8 ns and 675.7 ns (Figs. 4.8, 4.9). We note that the longer the propagation
time, the more the number of multi-paths arrive at the user location. Thus, a weaker signal is received as the high energy mmWave gets destroyed due to the presence of obstacles between the Tx and Rx site.

We now analyze the PDP plots obtained in Figs. 4.7, 4.8 and 4.9. Observing these PDPs at different time intervals, we can see some patterns formed, which actually depict the temporal clusters obtained for the main energy sector lobe. This phenomenon occurs when a group of subpaths arrive closely in the time domain from arbitrary angular directions. In Fig. 4.8 checking the number of clusters formed, we count around 5 under time intervals: [(611.8 ns to 700 ns), (700 ns to 950 ns), (950 ns to 1100 ns), (1100 ns to 1400 ns), (1400 ns to 1500 ns)]. Similarly, for PDPs obtained in Figs. 4.7 and 4.9, temporal clusters can be identified and counted. One other important reason to implement the search algorithm is to group the maximum amount of temporal clusters, which in turn provides vital information about the dynamic range of the signals at the receiver (range of signal levels over which it can operate). For example in the PDP obtained for user 3 (Fig. 4.7), we can fix a noise threshold around -160 dBm thus; the dynamic range of Rx will lie between: -160 dBm and -131.5 dBm. Here, we have fixed the noise threshold as: -160 dBm, considering the fact that the minimum signal power that Rx can detect is: -173.9 dBm/Hz (thermal noise power)

Next, we validate the implemented search algorithm to find the main energy lobe with the maximum power concentration. From Tables 4.1 and 4.2, it is clear that the main lobe Power(dBm) for user locations 3, 5 and 6 remains the same for Azimuth ($\theta$) and Elevation ($\phi$) angle of arrival. Hence, max($Power_{Azimuth}(N_{Lobesi})$) vs $Angle_{Azimuth}(N_{Lobesi})$ and max($Power_{Elevation}(N_{Lobesi})$) vs $Angle_{Elevation}(N_{Lobesi})$ does not change and are equal. Also, the search algorithm returns the same main lobe index/number either using azimuth or elevation angles of arrival information. In addition to this, the total number of subpath components obtained (from Eq. (4.12)) for user 3 is less when compared to users 5 and 6. This again validates the fact that higher the number of multi-paths, the greater the reduction in received signal strength. Thus, the proposed search algorithm is verified.
4.1.4 Search Algorithm: Block Diagram

Figure 4.12: Search Algorithm: Block Diagram
Chapter 5

NYUSIM Enhancement: Addition of Tx and Rx Gains, MIMO: Beamforming & Adaptive Beamforming Scheme

Chapter 5 discusses the next set of enhancements we performed in NYUSIM, which are oriented towards increasing the received signal power and reducing the effects of multipath and atmospheric noise. These improvements are the primary focus for this research. To achieve the goal of increased receiver power and lower noise power, beamforming and adaptive beamforming schemes are implemented inside the function module: getLocalCIR part of NYUSIM [2], discussed in Section 5.2. In Section 5.1, the Tx and Rx antenna gains are added into the Friis equation, which is a workaround solution to ensure the mmWave signal is at least received at a User/Rx location, as the amount of thermal noise present in PDP/PAP results discussed in Chapter 4 was significantly high. Section 5.2.1 discusses the computation of the resultant signal voltage across 10 elements of an antenna array at the Rx, using a MIMO system architecture. For computing the channel matrix, $H$, first, the phase information is computed based on the geometry of the antenna array used at the Tx (linear array) and the Rx (rectangular array) along with the signals AOD/AOA, and then the spatial correlation matrices are computed at both the Tx and Rx. The entries in these spatial correlation matrices indicate the level of similarity in signal levels between the antenna elements. Next, a MIMO channel matrix, $H_l$, for each multipath is calculated using a Kronecker model [[19], [20]]. Section 5.2.2, then discusses the implementation of beamforming and our adaptive beamforming scheme. For the
beamforming scheme, all the signal voltages across the 10 elements of an antenna array at the Rx are added and then the resultant multipath power is calculated. After this, all the multipath powers are added to compute the total signal power received at Rx/User location. For the adaptive beamforming scheme, a phased array antenna architecture is employed, where the steering action is performed at the Tx and adaptive weights are computed at the Rx, based on the desired angle of arrival information, where we are getting the maximum signal power at a particular Rx/user location (obtained from the search algorithm implemented in Chapter 4). Then, the resultant multipath power and total signal power received at the Rx location is calculated. This approach will enable a very directional transmission and reception at the Tx and Rx, thus increasing the overall gain of the Rx and then increasing the received signal power. Section 5.2.3, then discusses the results obtained by implementation of beamforming and adaptive beamforming schemes, mainly using the performance plots: resultant multipath vs number of subpath components, PDP & PAP plots for the main energy lobe, total signal power for each of the arrival sector lobes, and total signal power received at Rx location for 10 different users. The results discussion in Section 5.2.3, is basically a comparative analysis based on received signal power strength, temporal clusters, dynamic range, and total number of subpaths for the performance plots obtained using beamforming & adaptive beamforming schemes.

5.1 Addition of Transmitter and Receiver Antenna Gain

Upon evaluating the results obtained in Chapter 4 for the first extension performed using our search algorithm to find the main energy lobe, we note that the amount of thermal noise (KTB noise) [21] present in the received signal is still significantly high at three different user locations (Tables 4.1, 4.2). To compute the minimum signal power that the Rx antenna can receive, we use the NoiseFloor expression in dB:

$$\text{NoiseFloor} = 10 \times \log10(k \times T \times B) \quad (5.1)$$

In Eq. (5.1), $k$ is the Boltzmann’s constant having value of $1.38 \times 10^{-23}$ Joules/K, $T$ is the absolute temperature having value of 290 K, and $B$ is the signal bandwidth, whose value is 400 MHz. Substituting $KTB$ values in Eq. (5.1), we obtain a value of: -117.956 dB. Converting this minimum received signal power into dBm we have
-87.956 dBm. Now, in order for the mmWave signal to be detected at the Rx location, the power should be higher than: -87.956 dBm. We note that the main energy lobe received signal power as per Tables 4.1 and 4.2 is still lower than -87.956 dBm. The first workaround for this problem is to add the Tx and Rx Antenna Gains, while computing the omnidirectional received signal power (from Eq. (3.3)). Thus, Eq. (3.3) will be modified, as per the Friis Transmission Equation to become Eq. (5.2),

\[
Pr(dBm) = Pt - PL(NLOS) + G_t(dB) + G_r(dB) .
\]  

(5.2)

In Eq. (5.2), \(Pt\) is the transmitted power in dBm (Table 3.1) and \(PL(NLOS)\) is calculated as per Eq. (3.2). \(G_t\) is the Tx Antenna Gain = 27 dBi, and \(G_r\) is the Rx Antenna Gain = 27 dBi (these values are obtained from the hardware specifications from measurements done at 73 GHz [9]).

The PDP plots obtained for the main energy lobe from the search algorithm module, after addition of the Tx and Rx gains are shown in Figs. 5.1 and 5.2.

Figure 5.1: Power Delay Profile For Main Energy Lobe (User 5)

<table>
<thead>
<tr>
<th>Table 5.1: User 5/Receiver Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx- Rx Distance</td>
</tr>
<tr>
<td>Total Number of Multipaths</td>
</tr>
<tr>
<td>Total Number of Time Clusters</td>
</tr>
<tr>
<td>Omnidirectional Power</td>
</tr>
<tr>
<td>Main Energy Lobe Power</td>
</tr>
</tbody>
</table>
The main energy lobe received signal power obtained at user locations 5 and 2 (Figs. 5.1 and 5.2), are now within the detectable range of the receiver. As, the minimum signal power that a Rx antenna can receive is -87.95 dBm, the main lobe power for User 5 is: -79.61 dBm, which is around 9.48% higher than minimum and for User 2 is: -80.05 dBm, which is around 8.98% higher than minimum and are, thus, detectable. Also, the omnidirectional received signal power for users 5 and 2 (Tables 5.1, 5.2) are: -77.44 dBm and -76.98 dBm respectively. These values are significantly above the minimum power that an Rx antenna can detect.

### 5.2 MIMO: Beamforming & Adaptive Beamforming Scheme

The primary focus of this research is to increase the signal power levels at the Rx location, as mmWaves are associated with strong FSPL. As discussed in Chapter 1, the solution to overcome this problem is to increase the gain of the antenna receiver.
For this, we need to increase the directivity of the receiver (Eq. (1.3)). In other words, the Rx requires highly directional transmission and reception. Hence, a next logical approach is to implement beamforming and adaptive beamforming schemes, such that multielement antenna arrays steer towards the beam energy and collect it coherently, thus increasing the gain of Rx antenna [4]. In the context of NYUSIM, Multi-Input and Multi-Output (MIMO) [20] channel coefficients are generated inside the function module: getLocalCIR, where antenna arrays are used both at the Tx and Rx. The Tx antenna array type used is a Uniform Linear Array (ULA), having 4 antenna elements and the Rx is a Uniform Rectangular Array (URA), having 10 antenna elements (Table 3.1). Now, before discussing the enhancements performed in the module: getLocalCIR, we need to first understand how the MIMO channel coefficients or Channel Matrix, $H$, is computed. The MIMO channel matrix, $H_l$, for each subpath component, $l$, is generated using the Kronecker model (non-parametric channel model) [20], as per the expressions below Eqs. (5.3) to (5.6):

$$H_l = R_{r,l}^{1/2} \times H_{w,l} \times R_{t,l}^{1/2},$$

(5.3)

$$H_{w,l} = H_{RicianLos} + \sqrt{\frac{1}{2}} \times H_{Rayleigh},$$

(5.4)

$$H_{Rayleigh} = \text{Norm}(N_r, N_t) + j \times \text{Norm}(N_r, N_t),$$

(5.5)

$$H_{RicianLos} = \sqrt{\frac{k}{k+1}} \times \exp(j \times \frac{\pi}{4}).$$

(5.6)

In Eq. (5.3), $R_{r,l}$ and $R_{t,l}$ are the spatial correlation matrices at the transmitter and receiver, respectively, for a user defined antenna array, which signifies the spatial correlation of the transmit/receive multipath signal across antennae array elements. The $H_{w,l}$ ($N_r \times N_t$) entries are independently distributed according to the complex Gaussian distribution and correspond to small scale spatial path amplitudes (voltage) and phase [22]. For LOS and NLOS environments, $H_{w,l}$ entries are commonly assumed to obey small-scale random Rician and Rayleigh distributions as per Eqs. (5.4), (5.5), and (5.6), specified by $H_{RicianLos}$ and $H_{Rayleigh}$. In Eqs. (5.4) and (5.6), $k$ represents the Rician factor and its value denotes the ratio of signal power in LOS path to the power in other scattered paths. A phase shift of $\pi/4$ implies equal power of the LOS component in both the real and imaginary parts of $H_{RicianLos}$ entries. In Eq. (5.5), $\text{Norm}$ is the normal distribution having dimension of $[N_r \times N_t]$, where $N_r/N_t$ is the
Before discussing the implementation of the beamforming and adaptive beamforming schemes in module: getLocalCIR, we need to first understand how the spatial correlation matrices, $R_{r,l}$ and $R_{t,l}$, are computed and the phase shift is calculated based on a mmWave signal’s AOA and AOD. Also, we need to describe how the MIMO channel signal output is computed at Rx (Rectangular Array having 10 antenna elements). These are discussed in Section 5.2.1. Then, in Section 5.2.2 we talk about the implementation of beamforming and our adaptive beamforming scheme (using weight estimation), in order to steer the signal towards the main energy lobe and, thus increase the overall received signal power.

5.2.1 Computing Phase Shift based on the geometry of Antenna Array used at Tx/Rx

In NYUSIM [2], the spatial correlation matrices at the Tx and Rx for computing the MIMO Channel Matrix (using Kronecker model (Eq. (5.3))), $H$, is obtained using a best fit exponential model as shown in Eq. (5.7):

$$[R_{r,l}, R_{t,l}] = e^{-j\Phi \times (A e^{-B \Delta r} - C)}, \quad (5.7)$$

where $\Phi$ is the phase difference between the antenna array elements due to spacing and is computed as a uniform distribution between $[-\pi, \pi]$ taking into account the antennae element distance offset; in other words, the phase is computed randomly. The constants; $A$, $B$ and $C$, are determined using the MMSE method and $\Delta r$ represents the distance between the antenna array elements [23]. For a NLOS scenario, $A = 0.9$, $B = 1$, $C = -0.1$ in NYUSIM.

For our enhancement, work we compute the phase shift, $\Phi$, based on the geometry of the antenna array used at the Tx/Rx (Linear/Rectangular). The phase shift of the $m$th array element with respect to the reference antenna as a function of AOA, can be expressed as shown in Eq. (5.8).

$$\Phi_m(\phi) = k \times d \times m \times \sin(\phi), \quad (5.8)$$

where, $k = 2 \times \pi / \lambda$ ($k$ is the wavenumber and $\lambda$ is the wavelength of mmWave signal), $d$ is the distance between antenna array elements ($m$th array element and reference antenna), having a factor of $\lambda/2$, and $\phi$ is the AOA in case of the Rx and AOD.
in the case of the Tx [20]. Substituting, the values of \(k\), and \(d\) (minimum distance wavelength factor = \(\lambda/2\)) in Eq. (5.8), it is further reduced that shown in Eq. (5.9) as

\[
\Phi_m(\phi) = pi \times d_{\text{act}} \times m \times sin(\phi),
\]

(5.9)

where, \(d_{\text{act}}\) is the actual distance between the \(m\)th array element (signal departure/arrival) and the reference antenna. Now, \(d_{\text{act}}\) is calculated based on the geometry of the antenna array used at the Tx (linear) and Rx (rectangular). In order to understand the distance calculation between the antenna array elements at the Rx, let us consider the arrangement of a rectangular array as illustrated below in Fig. 5.3.

Figure 5.3: Rectangular Array Geometry at Receiver

In Fig. 5.3, assuming each antenna element in the rectangular array is equidistant to its neighbors (unit distance). If the \(m\)th array element index is odd and the reference antenna index is also odd, then, \(d_{\text{act}}\), is just the absolute linear distance between two odd indexed elements. For example: if the \(m\)th array element is 3 and the reference antenna is 7, then \(d_{\text{act}}\) is 2 units \((l_{37} = 2 \text{ units})\). The same concept is applied when the \(m\)th array element is even and the reference antenna is even. Then \(d_{\text{act}}\) is the absolute linear distance between two even indexed elements. In the case where when one array element is an odd index and the other is an even index, then the distance between them is calculated using the Pythagorean Theorem. For example: the distance between array elements 1 and 6 is \(l_{16} = 3.1623 \text{ units} \left(\sqrt{1^2 + 3^2}\right)\).

Similar to the technique used at the Rx, the distance between the antenna array elements at Tx, \(d_{\text{act}}\), is calculated using the absolute linear distance between the array elements.

Once the actual distance between the antenna array elements is calculated based on
the geometry of the array elements at the Tx and Rx, the next step is to compute the phase shift, $\Phi_m(\phi)$, (from Eq. (5.9)) between the array elements at the Tx and Rx. To calculate the phase shift at the Rx, the AOA of a subpath component, $\phi$, is the Angle Elevation corresponding to the arrival energy sector lobes (from Eq. (4.11)), as each subpath component belongs to one of the characteristic arrival spatial lobes (from Eq. (3.33)). The basic idea of this approach is that there are only 10 array elements at the Rx and directionality is an inherent feature of mmWaves technology. Thus, the subpath components can be best modeled through the arriving spatial lobes (each of the arrival energy sector lobes are comprised of multipaths). In the case of the Tx, $\phi$, is the AOD of a subpath [90° - Elevation subpath] (from Eq. (3.32)) for a departure event (avoiding negative angles). After computing the phase shift, $\Phi_m(\phi)$, between the antenna array elements, at the Rx and Tx, $\Phi_m$ is substituted into Eq. (5.7), $\Phi$ (Phase Information), and then the spatial correlation matrices $R_{r,l}$, $R_{t,l}$ are calculated. The phase difference between the array elements are now computed based upon the geometry of the antenna array type used at Rx and Tx. Correlation matrix plots obtained at Rx and Tx for the same are shown in Figs. 5.4 and 5.5.

Figure 5.4: Correlation Matrix Plot for 5th Array Element at Receiver [Rectangular Array]
In Fig. 5.4, for a rectangular array at the Rx, the correlation value of the 5th antenna array index element with itself is 1, while, in Fig. 5.5, for a linear antenna array at the Tx, the correlation value of the 3\textsuperscript{rd} array index element with itself is 1. This validates that the phase shift calculation between array elements at the Rx and Tx based on its geometry is correct. Now, once the spatial correlation matrices, $R_{r,t}$, $R_{t,t}$, are re-computed for each subpath, $l$, after the calculation of the phase shift based on the geometry of the antenna array elements at Rx and Tx. The next step is to generate the MIMO channel matrix, $H_l (N_r \times N_t)$, using Eq. (5.3).

The next process involved, after generation of the MIMO channel matrix, $H_l$, is to compute the output signal voltage at the Rx (across the rectangular antenna array arrangement). In order to understand how the MIMO output is calculated, let us consider the MIMO system architecture as illustrated in Fig. 5.6.
In Fig. 5.6, Tx is a linear array having 4 elements and Rx is a rectangular array having 10 antenna elements. Now, the output of this MIMO system, $y'$, can be computed in Eq. (5.10),

$$y' = H_l \times x' + n$$  \hspace{1cm} (5.10)

where,

$$H_l = \begin{bmatrix}
h_{11} & h_{12} & h_{13} & h_{14} \\
h_{21} & h_{22} & h_{23} & h_{24} \\
h_{31} & h_{32} & h_{33} & h_{34} \\
\vdots & \vdots & \vdots & \vdots \\
h_{101} & h_{102} & h_{103} & h_{104}
\end{bmatrix}$$

$y = [y_1, y_2, y_3, y_4, \ldots y_{10}]$ and $x = [x_1, x_2, x_3, x_4]$.

In Eq. (5.10), $y'$ represents the MIMO channel output at Rx (the received vector) with the dimension of $[10 \times 1]$, $x'$ represents the MIMO channel input at Tx (the transmit vector) with the dimension of $[4 \times 1]$ and $n$ is the noise vector. $H_l$ is the MIMO channel matrix for a subpath component, $l$, with a dimension of $[N_r \times N_t]$, where $N_r$ is the number of antenna array elements at Rx, $N_r = 10$, and $N_t$ is the number of array elements at Tx, $N_t = 4$. Thus, the dimension of $H_l$ is $[10 \times 4]$. Now, each element in the channel matrix, $H_l$, represents the channel coefficient between the receive antenna and the transmit antenna. For example, matrix element $h_{32}$ represents the channel coefficient between the $3^{rd}$ receive antenna array element and the $2^{nd}$ transmit antenna element. Now, the MIMO signal output across the
array elements at the Rx can be computed as
\[ y_j = \sum_{j=1}^{10} \sum_{i=1}^{4} h_{ji} \times x_i \text{, e.g., } y_1 = h_{11} \times x_1 + h_{12} \times x_2 + h_{13} \times x_3 + h_{14} \times x_4. \]
Hence, the resultant will be 10 output signals (with its amplitude and phase information) \( y_1, y_2, \ldots, y_{10} \). Note: for the purpose of computation of the received vector, \( y' \), \( x \) is considered as \( \sqrt{\text{Power}_{\text{subpath}}} \) (multipath signal voltage), where \( \text{Power}_{\text{subpath}} \) is the multipath power obtained from Eq. (3.35). The subpath signal is already comprised of the noise component, due to the presence of obstacles in the path when a mmWave signal travels from the Tx to the Rx. Now, the received vector is calculated and is in sync with the MIMO system architecture (Fig. 5.6) [7, 24, 25, 26].

5.2.2 Implementation of Beamforming and Adaptive Beamforming Scheme (Weight Estimation and Steering through the Main Energy Lobe)

In this section, we discuss the method used to compute the resultant signal power of a multipath and total signal power at a User/Rx location by using techniques of beamforming and adaptive beamforming. Once the received output vector is computed. The next step is to implement a beamforming scheme. As a first step, we need to determine the resultant power of a subpath, which is calculated as shown in Eq. (5.11):

\[
P_{1n} = \left| \sum_{i=1}^{10} y_i \right|^2.
\]  

In Eq. (5.11), \( P_{1n} \) represents the resultant power of the \( n^{th} \) multipath. Next, we compute the total power at User/Rx location, which is calculated by summing the subpath power of all the multipath components (\( N_{\text{Subpaths}} \), from Eq. (3.6)), as in Eq. (5.12):

\[
P_{1\text{user}} = \sum_{n=1}^{N_{\text{Subpaths}}} P_{1n} \]  

In Eq. (5.12), \( P_{1\text{user}} \) represents the total power computed at User/Rx location, where \( P_{1n} \) is subpath resultant power using the beamforming scheme (from Eq. (5.11)) [9] (non-coherent beamforming approach).

Once, the beamforming scheme is implemented and the resultant subpath power/total signal power at the Rx location is computed, the next implementation is to perform adaptive beamforming. This is done by steering through the main energy...
lobe at the Tx and computing the adaptive weights at Rx. Now, we discuss the method used to perform this steering action at the Tx. For this we need to first calculate the desired phase shift between the antenna array elements at the Tx, using Eq. (5.13), namely

$$\Phi_{\text{desired}}(\phi_{\text{max}}) = \pi \times d_{\text{act}} \times m \times \sin(\phi_{\text{max}}).$$  (5.13)

In Eq. (5.13), $\Phi_{\text{desired}}$ represents the desired phase shift between array elements at the Tx and its calculation is similar to the phase shift calculation in Eq. (5.9), except for the fact that instead of $\phi$, which is the elevation AOD, it is replaced with $\phi_{\text{max}}$. Here, $\phi_{\text{max}}$ represents the elevation angle of arrival corresponding to main (maximum) energy lobe power obtained from the search algorithm implemented in Chapter 4 (elevation angle corresponding to maximum (Power\_Elevation) vector (Eq. 4.10)). The next step is to compute the Steering Factor (SF), $SF = \Phi_{\text{desired}}(\phi_{\text{max}}) - \Phi_m(\phi)$, where $\Phi_m(\phi)$ is the actual phase shift obtained from (Eq. (5.9)). Now, the phase information, $\Phi_m(\phi) + SF$, is substituted into Eq. (5.7), which will lead to the re-computation of the spatial correlation matrix at the Tx ($R_{t,l}$). After computing, $R_{t,l}$, the MIMO channel matrix is generated for multipath, $l$, $H_t$, from Eq. (5.3). Next, we compute the MIMO system output (received vector: $y'$), using Eq. (5.10). This process will ensure that the linear antenna array at the Tx will perform a focused transmission and, thus, the steering action is carried out. The manner in which the Tx will perform the steering action can also be visualized as a transmitting antenna that is changing its orientation each time depending on the specific User/Rx location and the main energy lobe available information, ensuring focused transmission. In other words, the Tx will point in the direction through which the Rx can receive the maximum signal strength. Note, for implementing this steering approach we have assumed that the Channel State Information (CSI) and the user location is known at the Tx. Also, this approach is very similar to the time-shift property of the Fourier transform, i.e. providing a time delay to the signal is similar to a change in the phase in the frequency/complex domain. Now, after completing the steering action by the array elements at the Tx for a particular user/Rx location (from main lobe energy information: $\phi_{\text{max}}$), the next step involved is the adaptive weight estimation at the Rx, and then computation of the resultant signal multipath power. In order to understand how the weight is estimated and the signal output voltage is calculated, let us first consider the phased array antenna architecture at the Rx as illustrated in Fig. 5.7.
Figure 5.7, represents the general architecture of a phased array antenna having adaptive weight elements, $w_i$, connected to each of the 10 elements of an antenna array at Rx. These adaptive weights also act as phase shifters in order to steer the beam energy and collect it coherently, thus increasing the gain of the receiver (from Eq. (1.3)). This same phased array antenna architecture is followed here, in order to estimate the weights and, hence, achieve adaptive beamforming at the Rx [[27], [28]].

Now, we need to first compute the adaptive weights, as per Eq. (5.14):

$$w_i = \frac{\pi \times \sin(\phi_{\text{max}})}{\phi(y_i)}.$$  \hspace{1cm} (5.14)

In Eq. (5.14), $(\pi \times \sin(\phi_{\text{max}}))$ represents the approximated version of the desired phase, $\Phi_{\text{desired}}(\phi_{\text{max}})$, (from Eq. (5.13)), where $\phi_{\text{max}}$ is the elevation angle of arrival corresponding to the main energy lobe power obtained from the search algorithm implemented in Chapter 4 and $\phi(y_i)$ is the phase of the arriving signal across each of the 10 array elements at the Rx. Note, here, the received vector, $y_i$ is computed after steering through the main energy lobe at the Tx. Equation (5.14), is obtained from the fact that it is the specific factor that needs to be multiplied with the phase of arriving signals so the desired phase is obtained. Thus, the division operation results in computation of the adaptive weights. Now, after computing the adaptive weights, $w_i$, the next step is to calculate the resultant signal power of a multipath from Eq. (5.15):

$$ P2 = \left| \sum_{i=1}^{10} w_i \times y_i \right|^2 $$ \hspace{1cm} (5.15)
In Eq. (5.15), $P_{2n}$ represents the resultant power of the $n^{th}$ multipath, where $w_i$ is the adaptive weight estimate (Eq. (5.14)) and $y_i$ is the MIMO channel output computed after steering through the main energy lobe at Tx (Eq. (5.10)). Next, is the calculation of the total signal power at the User/Rx location. This is calculated in a similar way as done in the case of our beamforming scheme, that is, by adding the resultant subpath power of all the multipath components under the adaptive beamforming scheme namely, $P_{2\text{user}} = \sum_{n=1}^{N_{\text{Subpaths}}} P_{2n}$, where $P_{2n}$ is the resultant multipath power (from Eq. (5.15)) and $N_{\text{Subpaths}}$ is the total number of subpath components (calculated using Eq. (3.6)). Thus, $P_{2\text{user}}$ represents the total signal power received at Rx/User location under the adaptive beamforming scheme [[27], [28]].

Once, the beamforming and adaptive beamforming scheme is implemented inside the module: getLocalCIR of NYUSIM [2], the performance plots obtained are: Resultant multipath power vs number of subpath components, PDP plots for the main energy lobe, PAP plots for the main energy lobe, Total Signal Power for each of the arrival energy sector lobes, and Total Signal Power received at Rx/User location. The results are discussed below in Section 5.2.3

5.2.3 Performance Plots and Discussion of Results Obtained: Beamforming & Adaptive Beamforming Scheme

In this subsection we discuss the performance plots generated by our enhancement work namely, the implementation of the beamforming and adaptive beamforming signal processing schemes. Figures 5.8 and 5.9, represent the resultant multipath power plots at Rx/User locations 2 and 3, where the subpath power is computed from Eqs. (5.11) and (5.15). Note, here, for comparison purposes, we have also plotted the resultant multipath power when the phase is calculated randomly as a uniform distribution between $[-\pi, \pi]$ as it is done in the current version of NYUSIM (from Eq. (5.7)), and then the beamforming steps are followed to compute the subpath power (from Eq. (5.11)). Now, in Fig. 5.8 (resultant multipath power plot for User 2), comparing the signal power levels obtained for adaptive beamforming, beamforming (AOA/AOD), and beamforming (random phase) schemes, the received signal power levels obtained under adaptive beamforming is higher than that of the other two schemes. The maximum signal power for User 2/Rx location (64.27 m (from Table 5.3)) is -42.88 dBm under the adaptive beamforming approach, while that for beamforming (AOA/AOD) is -48.13 dBm and beamforming (random phase) is -62.59 dBm. Thus, there is a 10.9 % increase in maximum signal power for adaptive beam-
forming implementation as compared to the maximum signal power obtained due to beamforming (AOA/AOD) and there is a 31.49 % increase in maximum signal power (adaptive beamforming) as compared to that of the beamforming (random phase) approach. Note, here that beamforming (AOA/AOD) represents resultant multipath power due to beamforming when a phase difference is calculated from the subpath AOA/AOD and the beamforming (random phase) represents resultant multipath power due to beamforming when phase is calculated randomly. In Fig. 5.8, we also observe the resultant multipath power curve for the adaptive beamforming scheme and that clearly it is higher than that of the other two schemes (beamforming (AOA/AOD) and beamforming (random phase) at every subpath instance (for every mmWave multipaths) and closely follows the other two multipath power curves. Hence, there is a sharp increase in signal power due to adaptive beamforming implementation for User 2. Now, in Fig. 5.9 (resultant multipath power plot for User 3), comparing the signal power levels obtained for adaptive beamforming, beamforming (AOA/AOD), and beamforming (random phase) schemes, similar results are obtained like those in Fig. 5.8. Thus, the adaptive beamforming approach results in an increase in the multipath signal power. For User 3/Rx location (110.34 m from Table 5.4), the maximum signal power for the adaptive beamforming scheme is -33.86 dBm, while that for the beamforming (AOA/AOD) scheme is -49.35 dBm and for the beamforming (random phase) scheme is -62.81 dBm. Thus, there is a 31.39 % increase in maximum signal power using the adaptive beamforming approach compared to that of the beamforming (AOA/AOD) scheme and a 46.09 % increase in maximum signal power (adaptive beamforming) compared to that of beamforming (random phase). Also, the resultant multipath power curve in Fig. 5.9, for the adaptive beamforming scheme is higher at every subpath instance, compared to that of the beamforming (AOA/AOD) and beamforming (random phase) power curves. Hence, the resultant multipath power plots obtained in Figs. 5.8 and 5.9 are consistent, as the adaptive beamforming approach results in an increase in signal power levels throughout each multipath.
Figure 5.8: Resultant Multipath Power vs Subpath components (User 2)

Figure 5.9: Resultant Multipath Power vs Subpath components (User 3)
Table 5.3: User 2/Receiver Specifications (Beamforming and Adaptive Beamforming Scheme)

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx- Rx Distance</td>
<td>64.27 mts</td>
</tr>
<tr>
<td>Total Number of Multipaths</td>
<td>75</td>
</tr>
<tr>
<td>Total Number of Time Clusters</td>
<td>4</td>
</tr>
<tr>
<td>Main Energy Lobe Power (Search Algorithm)</td>
<td>-85.75 dBm</td>
</tr>
<tr>
<td>Elevation Angle Main Lobe (Search Algorithm)</td>
<td>93.57°</td>
</tr>
<tr>
<td>Main Lobe Index (Search Algorithm)</td>
<td>1</td>
</tr>
<tr>
<td>Main Energy Lobe Power (Adaptive Beamforming)</td>
<td>-42.88 dBm</td>
</tr>
<tr>
<td>Main Energy Lobe Power (Beamforming (AOA/AOD))</td>
<td>-48.13 dBm</td>
</tr>
<tr>
<td>Main Energy Lobe Power (Beamforming (Random Phase))</td>
<td>-62.59 dBm</td>
</tr>
</tbody>
</table>

Table 5.4: User 3/Receiver Specifications (Beamforming and Adaptive Beamforming Scheme)

<p>| | |</p>
<table>
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</thead>
<tbody>
<tr>
<td>Tx- Rx Distance</td>
<td>110.34 mts</td>
</tr>
<tr>
<td>Total Number of Multipaths</td>
<td>44</td>
</tr>
<tr>
<td>Total Number of Time Clusters</td>
<td>5</td>
</tr>
<tr>
<td>Main Energy Lobe Power (Search Algorithm)</td>
<td>-86.24 dBm</td>
</tr>
<tr>
<td>Elevation Angle Main Lobe (Search Algorithm)</td>
<td>83.73°</td>
</tr>
<tr>
<td>Main Lobe Index (Search Algorithm)</td>
<td>5</td>
</tr>
<tr>
<td>Main Energy Lobe Power (Adaptive Beamforming)</td>
<td>-33.86 dBm</td>
</tr>
<tr>
<td>Main Energy Lobe Power (Beamforming (AOA/AOD))</td>
<td>-49.35 dBm</td>
</tr>
<tr>
<td>Main Energy Lobe Power (Beamforming (Random Phase))</td>
<td>-62.81 dBm</td>
</tr>
</tbody>
</table>

Next, we discuss the PDP plots obtained in Figs. 5.10 and 5.11 for the main energy lobe (Users 2 and 3). To obtain the PDP plots, the approach is similar to one followed in Chapter 4, i.e., we find the subpath components belonging to main lobe index, where the main lobe index is found by our search algorithm implemented in Chapter 4 (arrival energy lobe index corresponding to maximum of: $Power_{Azimuth}(N_{Lobes_i})/Power_{Elevation}(N_{Lobes_i})$ power vectors obtained from Eqs. (4.8), (4.9)), and then the extracted subpaths are used to obtain the corresponding multipath powers from the vectors $P_{1n}$ and $P_{2n}$ (Eqs. (5.11) and (5.15)). Later, these computed multipath powers (belonging to the beamforming and adaptive beamforming schemes), are plotted against the corresponding total propagation time, $t_{abs}$ (from Eq. (3.23)) and, thus, the PDP plots are obtained for the main energy lobe index. Now, in
Fig. 5.10, comparing the PDP plots obtained for User 2/Rx location (64.27 m (from Table 5.3)) under the adaptive beamforming, beamforming (AOA/AOD) and beamforming (random phase) schemes, the total number of temporal clusters obtained/observed for all these three schemes are the same and have a value of 4 (Table 5.3). Note, the formation of temporal clusters happen when a group of subpaths arrive closely in the time domain from an arbitrary angular direction (i.e., a formation of patterns at different time intervals). Also, in comparing the received signal strength, we find the main energy lobe signal power obtained under adaptive beamforming scheme is -42.88 dBm, while that for the beamforming (AOA/AOD) is -48.13 dBm and beamforming (random phase) is: -62.59 dBm. Thus, again, the adaptive beamforming approach leads to a sharp increase in the main energy lobe received power. Now, in Fig. 5.11, we can perform similar PDP plots comparison for User 3/Rx location (110.34 m (from Table 5.4)). Again, the same number of temporal clusters are obtained/observed under the adaptive beamforming, beamforming (AOA/AOD), and beamforming (random phase) schemes having a value of 5 (Table 5.4). Also, the adaptive beamforming approach once again results in an increase of main energy lobe power, as the main lobe power obtained for the adaptive beamforming scheme is -33.86 dBm, while that for the beamforming (AOA/AOD) is -49.35 dBm and beamforming (random phase) is -62.81 dBm. Another key observation which could be made from the PDP plots obtained in Figs. 5.10 and 5.11 is that in regards to the dynamic range at the Rx (range of signal levels in which Rx can operate). Certainly, using the MIMO system architecture model (Fig. 5.6) for the beamforming and adaptive beamforming schemes, enhances the dynamic range of Rx. Consider the example of the PDP plot obtained in Fig. 5.11 for User 3; the dynamic range of the receiver can lie between -70 dBm to -30 dBm, by fixing the noise threshold to around -70 dBm, thus enhancing the dynamic range compared to PDP plots obtained in Figs. 5.1 and 5.2 (discussed in Section 5.1).
Figure 5.10: PDP profile for the Main Energy Lobe (User 2)

Figure 5.11: PDP profile for the Main Energy Lobe (User 3)
Next, is the analysis of PAP plots for the main energy lobe index obtained in Figs. 5.12 and 5.13 at Rx location for Users 2 and 3. To obtain the PAP plots, the approach is again similar to one followed in Chapter 4 wherein subpath powers (belonging to beamforming and adaptive beamforming scheme) from the main lobe index (obtained from the search algorithm) is plotted against the elevation angle of arrival. In Figs. 5.12 and 5.13, the PAP plots are compared under two schemes: adaptive beamforming and beamforming (AOA/AOD). For User 2 (Fig. 5.12), the maximum signal powers of -42.88 dBm and -48.13 dBm are obtained at an elevation AOA of 93.57° under adaptive beamforming and beamforming (AOA/AOD) scheme. Now, checking the elevation AOA corresponding to the main lobe index obtained from the search algorithm (Table 5.3), we see that the value is 93.57°. This shows that our adaptive beamforming and beamforming (AOA/AOD) schemes implementation are correct, as we are able to obtain the maximum signal power at the desired AOA corresponding to main energy lobe power obtained from the search algorithm implemented in Chapter 4. Thus, Eqs. (5.13) and (5.14), are validated for the steering action at the Tx and the computation of the adaptive weights at the Rx, where \( \phi_{max} = 93.57° \). Similar results could be observed for User 3, wherein Fig. 5.13, we are getting the maximum signal power of -33.86 dBm (adaptive beamforming) and -49.35 dBm (beamforming (AOA/AOD)) at an elevation AOA of 83.73°. So, now checking the elevation AOA value corresponding to the main energy lobe power obtained from our search algorithm (from Table 5.4), it is 83.73°. This, further validates the correct implementation of adaptive beamforming scheme.

Figure 5.12: PAP profile for the Main Energy Lobe (User 2)
Now, after discussing the PAP plots for the main energy lobe index and validating the adaptive beamforming scheme, we can further validate the performance plots obtained for Users 2 and 3, by comparing the resultant multipath power plots, as well as the PDP and PAP plots for the main energy lobe with each other, under the beamforming and adaptive beamforming schemes. Now, for User 2, the maximum signal power in Fig. 5.8 under the adaptive beamforming, beamforming (AOA/AOD), beamforming (random phase) schemes does not change when comparing it with the main lobe energy power obtained in Figs. 5.10 and 5.12. For example in Fig. 5.8, the maximum signal power received for User 2/Rx location under the adaptive beamforming scheme is -42.88 dBm, while the main energy lobe signal power from the PDP and PAP plots (in Figs. 5.10 and 5.12), is also -42.88 dBm. This shows that the main lobe index computed from the search algorithm in Chapter 4 is correct, as the maximum signal power value is not changing for the PDP and PAP plots. The same holds true for User 3/Rx scenario (Figs. 5.9, 5.11 and 5.13). Now, we can also compare the maximum signal power/main energy lobe power between Users 2 and 3 under the adaptive beamforming scheme. The main energy lobe power obtained for User 2 is -42.88 dBm, while that for User 3 is -33.86 dBm (Tables 5.3 and 5.4). Thus, User 3 receives a higher signal power under the adaptive beamforming approach when compared to User 2. This is due to the fact that total number of multipaths obtained at User 2/Rx location is higher than that of User 3/Rx location. From Table 5.3, the total number of multipaths obtained at User 2 location is 75, while that for User 3/Rx location is 44 (Table 5.4). So, the more the number of multipaths at our User 2
location the larger the reduction in signal strength and, thus, a lower received signal power.

Next, we discuss and analyze the total signal power for each arrival spatial lobes plots obtained at User 2 and User 3 Rx locations under the adaptive beamforming, beamforming (AOA/AOD) and beamforming (random phase) schemes. To obtain these plots, the subpaths are extracted from the ClusterLobeMapping matrix (from Eq. 3.33), for each $N_{Lobes}$ (from Eq. (3.5)). Then the corresponding subpath powers are extracted from the $P1_n$ and $P2_n$ vectors (from Eqs. (5.11) and (5.15)), then the sum of the computed subpath powers for each $N_{Lobes}$ (beamforming and adaptive beamforming approach) will give the resultant total signal power at each arrival spatial lobes. In Fig. 5.14, for User 2, the maximum signal power is obtained at lobe number 1 for the adaptive beamforming and beamforming (AOA/AOD) schemes. Now, comparing the signal power obtained at Lobe 1 (Table 5.5), for the adaptive beamforming scheme, it is -41.91 dBm, while that for the beamforming (AOA/AOD) scheme is -47.64 dBm and that for the beamforming(random phase) scheme is -60.67 dBm. Thus, there is a 12.02% increase in the total signal power at Lobe 1 under the adaptive beamforming approach as compared to the beamforming (AOA/AOD) scheme and a 30.92% increase in the total signal power at Lobe 1 using adaptive beamforming, compared to that of the beamforming (random phase) approach. Table 5.5 represents the total signal power received at each arrival spatial lobe for User 2 under the adaptive beamforming, beamforming (AOA/AOD), and beamforming (random phase) schemes. Now, for the adaptive beamforming approach, clearly the total signal power at each arrival spatial lobe is higher than that of the other two schemes (Fig. 5.14). Also, checking the main lobe index value (obtained from the search algorithm), Table 5.3, is 1, which is in accordance with the results obtained in Fig. 5.14 and, thus, the adaptive beamforming approach is able to increase the main lobe energy power. Now, the same analysis for our User 3 scenario reveals that, the adaptive beamforming approach is able to increase the main energy lobe power at lobe index 5 (from Fig. 5.15), where, in Table 5.6, the total signal power received at each arrival spatial lobe for the adaptive beamforming scheme is higher than that of the beamforming (AOA/AOD) and beamforming (random phase) schemes.
Figure 5.14: Total Signal Power for Each Arrival Spatial Lobes (User 2)

Figure 5.15: Total Signal Power for Each Arrival Spatial Lobes (User 3)
Table 5.5: Total Signal Power at each Arrival Spatial Lobe (User 2)

<table>
<thead>
<tr>
<th>Spatial Lobe Index</th>
<th>Total Signal Power (Adaptive Beamforming)</th>
<th>Total Signal Power (Beamforming (AOA/AOD))</th>
<th>Total Signal Power (Beamforming (Random Phase))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-41.91 dBm</td>
<td>-47.64 dBm</td>
<td>-60.67 dBm</td>
</tr>
<tr>
<td>2</td>
<td>-50.46 dBm</td>
<td>-57.02 dBm</td>
<td>-68.33 dBm</td>
</tr>
<tr>
<td>3</td>
<td>-47.97 dBm</td>
<td>-56.18 dBm</td>
<td>-57.98 dBm</td>
</tr>
<tr>
<td>4</td>
<td>-45.75 dBm</td>
<td>-57.34 dBm</td>
<td>-59.41 dBm</td>
</tr>
<tr>
<td>5</td>
<td>-47.13 dBm</td>
<td>-59.05 dBm</td>
<td>-67.03 dBm</td>
</tr>
</tbody>
</table>

Table 5.6: Total Signal Power at each Arrival Spatial Lobe (User 3)

<table>
<thead>
<tr>
<th>Spatial Lobe Index</th>
<th>Total Signal Power (Adaptive Beamforming)</th>
<th>Total Signal Power (Beamforming (AOA/AOD))</th>
<th>Total Signal Power (Beamforming (Random Phase))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-46.53 dBm</td>
<td>-69.15 dBm</td>
<td>-77.23 dBm</td>
</tr>
<tr>
<td>2</td>
<td>-49.07 dBm</td>
<td>-66.39 dBm</td>
<td>-72.59 dBm</td>
</tr>
<tr>
<td>3</td>
<td>-37.29 dBm</td>
<td>-55.48 dBm</td>
<td>-70.53 dBm</td>
</tr>
<tr>
<td>4</td>
<td>-39.91 dBm</td>
<td>-68.60 dBm</td>
<td>-71.03 dBm</td>
</tr>
<tr>
<td>5</td>
<td>-33.86 dBm</td>
<td>-49.34 dBm</td>
<td>-62.78 dBm</td>
</tr>
</tbody>
</table>

Now, the final plot/result to be discussed in this section is Fig. 5.16, namely the total signal power obtained at the Rx for 10 different user locations, which is a comparison plot between our beamforming (AOA/AOD) and the adaptive beamforming schemes, where the total signal power at the Rx for a particular user location is calculated from $P_{1_{\text{user}}}$ (from Eq. (5.12)) and $P_{2_{\text{user}}}$. 
Figure 5.16: Total Signal Power obtained at Rx for 10 different User locations

Table 5.7 summarizes the total signal power received in dBm at 10 different user locations under our beamforming (AOA/AOD) and adaptive beamforming schemes. The fourth column in Table 5.7 (Percentage Increase in Signal Power (Adaptive Beamforming)), lists the percentage increase in the total signal power at the Rx, due to our adaptive beamforming approach. Now, from Fig. 5.16 and Table 5.7, it is clear that User 6 has the highest percentage increase in total signal power compared to the total power received due to beamforming (AOA/AOD), which is around 59.73 %, and the total signal power at the Rx for User 6 with our adaptive beamforming approach is -18.68 dBm, which is the maximum signal power obtained. To understand the reason for such a high increase in signal power for User 6, we use Table 5.8 User 6/Rx Specifications. Checking Table 5.8, the total number of subpaths obtained at User 6 location is 27 and there is only one temporal cluster formed here. This indicates that, compared to the other User location scenarios, there is a lower number of multipaths obtained for User 6 with a few obstacles around, thus leading to a high increase in the received signal power due to our adaptive beamforming scheme. Also, the total signal power obtained at 10 different Rx locations, in Fig. 5.16, is very stable for every first execution of NYUSIM. In other words, the total signal power plot obtained in Fig. 5.16 does not change.
Table 5.7: Total Signal Power at Rx: Beamforming & Adaptive Beamforming Scheme Comparison Table

<table>
<thead>
<tr>
<th>User Index</th>
<th>Total Signal Power at Rx (Beamforming (AOA/AOD)) [dBm]</th>
<th>Total Signal Power at Rx (Adaptive Beamforming) [dBm]</th>
<th>Percentage Increase in Signal Power (Adaptive Beamforming)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-42.97</td>
<td>-32.58</td>
<td>24.19%</td>
</tr>
<tr>
<td>2</td>
<td>-46.07</td>
<td>-38.69</td>
<td>16.03%</td>
</tr>
<tr>
<td>3</td>
<td>-48.25</td>
<td>-31.34</td>
<td>35.05%</td>
</tr>
<tr>
<td>4</td>
<td>-55.38</td>
<td>-52.71</td>
<td>4.82%</td>
</tr>
<tr>
<td>5</td>
<td>-64.02</td>
<td>-43.45</td>
<td>32.13%</td>
</tr>
<tr>
<td>6</td>
<td>-46.37</td>
<td>-18.68</td>
<td>59.73%</td>
</tr>
<tr>
<td>7</td>
<td>-62.94</td>
<td>-46.99</td>
<td>25.35%</td>
</tr>
<tr>
<td>8</td>
<td>-48.02</td>
<td>-34.77</td>
<td>27.59%</td>
</tr>
<tr>
<td>9</td>
<td>-40.69</td>
<td>-26.88</td>
<td>33.93%</td>
</tr>
<tr>
<td>10</td>
<td>-50.10</td>
<td>-35.57</td>
<td>29.01%</td>
</tr>
</tbody>
</table>

Table 5.8: User 6/Rx Specifications (Maximum Received Signal Power: -18.68 dBm)

<table>
<thead>
<tr>
<th></th>
<th>80.40 mts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx- Rx Distance</td>
<td></td>
</tr>
<tr>
<td>Total Number of Multipaths</td>
<td>27</td>
</tr>
<tr>
<td>Total Number of Time Clusters</td>
<td>1</td>
</tr>
</tbody>
</table>
5.2.4 Beamforming & Adaptive Beamforming: Block Diagram

Start

Addition of Tx and Rx antenna gains in Friis transmission equation (omnidirectional received power computation)

getLocalCIR module: implementation of beamforming and adaptive beamforming scheme

Getting Subpath AOA using spatial energy sector lobes AOA (spatial energy lobe: comprised of multipaths)

Phase Shift Calculation based on geometry of antenna array used at Tx and Rx (distance b/w elements and signal AOA/AOD)

Spatial Correlation Matrix computation at Tx and Rx. Adaptive Beamforming: Steering Factor Calculation = Desired Phase – Actual Phase & spatial correlation matrix calculation at Tx

Computation of MIMO Channel Matrix, H, using Kronecker model
Figure 5.17: Beamforming & Adaptive Beamforming: Block Diagram

- **Signal output calculation across 10 antenna elements.**
  \[ Y = H \times x + \text{noise} \]

- **Adaptive beamforming weight computation.**
  \[ w = \text{desired phase/phase of arriving signal} \]

- **Resultant multipath power computation for beamforming and adaptive beamforming approach** (\( w \times Y \))

- **Total signal power calculation at Rx (sum of all multipath powers)**

- **Plot:** Resultant multipath power, PDPs and PAPs for main energy lobe index, total signal power for each arrival energy sector lobe, and total signal power obtained at Rx (main lobe index is from search algorithm)
Chapter 6

Future Work & Conclusion

Chapter 6 discusses the future work which could be performed for NYUSIM [2] as part of our extension and enhancement plan to increase the received signal power and to reduce the effects of noise. One probable work is to implement a Zero-Forcing (ZF) Receiver [29] inside the function module: getLocalCIR, where the MIMO channel coefficients are generated (from Eq. (5.3)). The objective behind implementation of a ZF receiver is to minimize the measurement error between the received and transmitted signals. The least squared error, $e$, can be computed from Eq. (6.1), as

$$e = \| y - Hx \|^2$$

(6.1)

In Eq. (6.1), $H$ is the MIMO channel matrix calculated from Eq. (5.3), $y$ is the measured output signal vector (from Eq. (5.10)) and $x$ is the transmitted signal vector. Now, to minimize the least square error, $e$, an appropriate $x$ is required to be chosen. The approximate solution that minimizes the least square error, $e$, also termed as the ZF receiver, is given by Eq. (6.2).

$$x = (H^T H)^{-1} H^T y$$

(6.2)

In Eq. (6.2), $H^T$ represents the transpose operation on channel matrix, $H$. Also, this approximate solution for $x$ to minimize the least square error, $e$, is applicable for the scenario wherein the number of receive antenna elements is greater than the number of transmit antenna elements ($N_r \geq N_t$). In this case, the number of equations are greater than the number of unknowns; thus, there is no exact solution and an approximate $x$ is required to be chosen for the ZF receiver. In addition to this, when the channel matrix, $H$, is complex, then Eq. (6.2) is modified to become
\( \mathbf{x} = (H^H H)^{-1} H^H \mathbf{y} \), where \( H^H \) represents the Hermitian form of the channel matrix, \( H \) \([29], [30]\).

In conclusion, we are able to make mmWave communication possible for Non-Line-Of-Sight Scenarios operating at a 73 GHz carrier frequency using beamforming and adaptive beamforming schemes, as the received signal power level is increased significantly. This research shows that by setting the right amplitude and phase of a mmWave signal and performing directional transmission and reception in a mobile environment, reliable 5G communication can take place. In addition to this, the results obtained in this thesis work for the proposed phased array antenna architecture can also be used for future 5G system level design and testing of network algorithms, which are critical for 5G based wireless industries.
Appendix A

NYUSIM Process Diagram

Figure A.1: NYUSIM Process Diagram

Cluster Excess Time Delay

Intra-Cluster Delays

Cluster Void Interval

Cluster Void Interval

Temporal Clusters comprised of multipaths. Maximum number of clusters possible in NYUSIM = 6

Departure/Arrival Energy Sector Lobes are comprised of multipaths

Absolute propagation time = free space electromagnetic wave propagation time + intra-cluster delays + cluster excess time delay

Maximum Number of Multipaths Possible in NYUSIM = 30 for each cluster (Intra-Cluster Subpaths)
Appendix B

Search Algorithm Code

function [lobePowerSpectrum_struct,Max_Power,
    Azimuth_Max_Power,Elevation_Max_Power,Main_Lobe_Index,
    Spatail_Lobe_Mapping] = ...
getLobePowerSpectrum(numberOfLobes,
    cluster_subpath_lobes_mappings,powerSpectrum,
    angleType)

% Generate the lobe power angular spectra

% Inputs:
% - numberOfLobes: the number of spatial lobes
% - cluster_subpath_lobes_mappings: a structure containing
%     the mapping
% - powerSpectrum: an array containing all multipath
%     parameters
% - angleType: 'AOD' or 'AOA'

% Output:
% - lobePowerSpectrum_struct: a structure containing
%     lobe angular spectra
%
if strcmp(angleType,'AOD') == true
    subpathSpectrum = powerSpectrum(:,1:5);
```matlab
elseif strcmp(angleType,'AOA') == true
    subpathSpectrum = powerSpectrum(:,[1:3 6:7]);
else
end

%%% initialize lobe power spectrum
lobePowerSpectrum_struct = struct;

for lobeIndex = 1:numberOfLobes
    indSameLobe = find(cluster_subpath_lobe_mapping(:,3) == lobeIndex);

    null_chk = isempty(indSameLobe);

    %%% Start of Changes Anurag Prasad Miami University
    %%% End of Changes Anurag Prasad Miami University

    subpathSpectrum_SameLobe = subpathSpectrum(indSameLobe,:);

    if (strcmp(angleType,'AOA') == true) && (null_chk ~= 1)
        lobeAzi = subpathSpectrum_SameLobe(:,4);
        lobeAzi(lobeAzi > 180) = lobeAzi(lobeAzi > 180) - 180;
        subpathSpectrum_SameLobe(:,4) = lobeAzi;
        subpathSpectrum_SameLobe(:,5) = 90 - subpathSpectrum_SameLobe(:,5);
        A = sortrows(subpathSpectrum_SameLobe,4);
        B = sortrows(subpathSpectrum_SameLobe,5);
        [~, indx1] = max(A(:,2));
```

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Finding Maximum Power corresponding to Sorted Elevation Angle

[val2, indx2] = max(B(:,2));
powerAzimuth(lobeIndex) = val1;
angleAzimuth(lobeIndex) = A(indx1,4); % Corresponding Azimuth Angle
powerElevation(lobeIndex) = val2;
angleElevation(lobeIndex) = B(indx2,5); % Corresponding Elevation Angle

end

%%% Start of Changes Anurag Prasad Miami University Oxford Ohio
if (strcmp(angleType, 'AOA') == true)
    num_lobes = length(powerAzimuth);
    v1 = [1:num_lobes] powerAzimuth' angleAzimuth';
    v2 = [1:num_lobes]' powerElevation' angleElevation';
    v3 = sortrows(v1,3);
    v4 = sortrows(v2,3);
    figure(1);
    plot(round(v3(:,3)), 10*log10(v3(:,2)),'o--');
    title('Max Power vs Azimuth Angle Profile For Each Lobes');
    xlabel('Azimuth Angle');
    ylabel('Max. Power at Each Lobe (dBm)');
grid on;
figure(2);
plot(round(v4(:,3)),10*log10(v4(:,2)),'o--');
title('Max Power vs Elevation Angle Profile For Each Lobes');
xlabel('Elevation Angle');
ylabel('Max. Power at Each Lobe (dBm)');
grid on;
[maxPower,pos1] = max(v3(:,2));
[maxPower,pos2] = max(v4(:,2));

%% Start of Changes Anurag Prasad Miami University
12/05/2016

disp('Max Power Obtained is:'); disp(10*log10(maxPower));
disp('Azimuth AOA/maxPower is:'); disp(v3(pos1,3));
disp('Elevation AOA/maxPower is:'); disp(v4(pos2,3));
Max_Power = 10*log10(maxPower);
Azimuth_Max_Power = v3(pos1,3);
Elevation_Max_Power = v4(pos2,3);
Main_Lobe_Index = v3(pos1,1);
Spatail_Lobe_Mapping = v2;

%% End of Changes Anurag Prasad Miami University
12/05/2016

%% Getting The Subpaths belonging to Main Lobe having Maximum Power
ind1Azi = find(cluster_subpath_lobe_mapping(:,3) == v3(pos1,1));

Spectrum1 = subpathSpectrum(ind1Azi,:);
mainLobeAzi = Spectrum1(:,4);
mainLobeAzi( mainLobeAzi > 180 ) = mainLobeAzi( mainLobeAzi > 180 ) - 180;
Spectrum1(:,4) = mainLobeAzi;
Spectrum1(:,5) = 90 - Spectrum1(:,5);
C = sortrows(Spectrum1,1);
D = sortrows(Spectrum1,5);

figure(3);
plot(C(:,1),10*log10(C(:,2)));
title('Power vs Absolute Propagation Time (Main Lobe)');
xlabel('Propagation Time (ns)');
ylabel('Power (dBm)');
grid on;
figure(4);
plot(round(D(:,5)),D(:,2));
title('Power vs Elevation Angle Profile (Main Lobe)');
xlabel('Elevation Angle');
ylabel('Power');
grid on;

end

%%% End of Changes Anurag Prasad Miami University Oxford
Ohio
end
Appendix C

Addition of Tx and Rx Gains Code

```matlab
function [Pr_dBm, PL] = getRXPower(f_str,n,SF,TXPower,dist,d0,dynamicRange)
% Generate the omnidirectional received power and path loss
%
% Inputs:
% - f_str: a string specifying the frequency of interest
% - n: the frequency-dependent path loss exponent
% - SF: the shadow factor, in dB
% - TXPower: the transmit power, typically set to 0 dBm
% - dist: the T-R separation, in meters
% - d0: the free space reference distance, typically 1 meter
% - dynamicRange: the maximum allowable path loss, typically 180 dB in
% the NYU measurements
% Output:
% - Pr_dBm: the omnidirectional received power, in dBm
% - PL: the omnidirectional path loss, in dB
%
switch f_str
    case '28_GHz'
        f_ = 28e9;
    case '73_GHz'
```
\begin{verbatim}
22     f_ = 73e9;
23     case '2873_GHz'
24         f_ = 28e9; % For the joint scenario, use the 28 GHz frequency and path loss parameters
25     otherwise
26     end
27
28     % constants
29     c = 3e8; %% speed of light (m/s)
30     lambda = c/f_; %% wavelength (m)
31
32     % free space path loss at d0 (dB)
33     PLref = 20*log10(4*pi*d0/lambda);
34
35     % absolute path loss at distance dist
36     PL = min (PLref + n*10*log10(dist/d0)+SF*randn, dynamicRange);
37
38     % total received power (dBm) at distance dist
39     Pr_dBm = TXPower - PL;
40
41     %%% Start of Changes Anurag Shivam Prasad Miami University
42     05/29/2017
43     %%% Addition of Transmitter and Recevier Gain
44     if (f_ == 73e9)
45         Gtx = 27; % Actual Outdoor Measurement Specifications horn antenna at Tx
46         Grx = 27; % Actual Outdoor Measurement Specifications horn antenna at Rx
47         Pr_dBm = TXPower - PL + Gtx + Grx;
48     end
49     %%% End of Changes Anurag Shivam Prasad Miami University
50     05/29/2017
51 end
\end{verbatim}
Appendix D

MIMO: Beamforming and Adaptive Beamforming Scheme Code

```
function CIR_Struct = getLocalCIR(CIR_Struct, TxArrayType, RxArrayType, Nt, Nr, Wt, Wr, dTxAnt, dRxAnt)
%
% This function generates the local area CIRs.
%
% Inputs:
% - TxArrayType: a string, specifying the type of TX antenna array
%   (e.g., 'ULA', 'URA')
% - RxArrayType: a string, specifying the type of RX antenna array
%   (e.g., 'ULA', 'URA')
% - Nt: the number of TX antennas
% - Nr: the number of RX antennas
% - Wt: the number of TX antennas in the azimuth dimension
% - Wr: the number of RX antennas in the azimuth dimension
% - dTxAnt: the spacing between adjacent TX antennas in units of wavelengths
```
\%
- \texttt{dRxAnt}: the spacing between adjacent TX antennas in
units of wavelengths
\%
\textbf{Output:}
\%
- \texttt{CIR}: structure containing the MIMO channel
coefficients
\%
\textbf{Example input parameters (for test purpose only)}:
\%
\texttt{TxArrayType} = 'ULA'; \texttt{RxArrayType} = 'URA'; \texttt{Nt} = 4; \texttt{Nr} =
10; \ldots
\%
\texttt{dTxAnt} = 1/2; \texttt{dRxAnt} = 1/2; \texttt{Wt} = 1; \texttt{Wr} = 2;
\%
\%
\%
imaginary unit
\texttt{j} = \texttt{sqrt(-1)};
\%
speed of light (m/s)
\texttt{c} = 3e8;
\%
Rician K factor
\texttt{K} = 10^{(10/10)};
\%
Number of CIRs to process
\texttt{N} = \texttt{size(fieldnames(CIR_Struct),1)};
\%
for \texttt{CIRIdx} = 1: \texttt{N}
\%
Extract n-th CIR
\texttt{CIR} = \texttt{CIR_Struct.(['CIR_',num2str(CIRIdx)])};
\%
carrier frequency (GHz)
\texttt{f} = \texttt{str2double(CIR.frequency(1:2))*1e9};
\%
carrier wavelength
\texttt{wl} = \texttt{c/f};
47  % determine if the environment is LOS
48  if strcmp(CIR.environment,'LOS') == true
49      % spatial correlation coefficients for LOS
50          A = 0.99; B = 1.95; C = 0;
51  elseif strcmp(CIR.environment,'NLOS') == true
52      % spatial correlation coefficients for NLOS
53          A = 0.9; B = 1; C = -0.1;
54  else
55  end
56
57  % number of paths
58  nTap = length(CIR.pathDelays);
59
60  % absolute propagation time delay of each path
61  timeDelay = CIR.pathDelays.*1e-9;
62
63  % received power in mW of each path
64  Pr_lin = CIR.pathPowers;
65  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
66  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
67  Azimuth_A0A = CIR.AOAs;
68  Azimuth_A0D = CIR.AODs;
69  Zenith_AOA = CIR.ZOAs;
70  Azimuth_A0A(Azimuth_A0A > 180) = Azimuth_A0A(Azimuth_A0A > 180) - 180;
71  Elevation_AOA = 90 - Zenith_AOA;
72  Elevation_AOD = 90 - CIR.ZODs;
73  Azimuth_A0D(Azimuth_A0D > 180) = Azimuth_A0D(Azimuth_A0D > 180) - 180;
74  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
75  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
76  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
77  %Start of Changes by Anurag Shivam Prasad 06/30/2017
cluster_subpath_Angle_Lobe_mapping = CIR.
subpath_lobe_mapping;
for lobei = 1:CIR.AOA_Lobes
    SameLobe = find(CIR.subpath_lobe_mapping(:,3) == lobei);
null_chk = isempty(SameLobe);
    if (null_chk ~= 1)
        cluster_subpath_Angle_Lobe_mapping(SameLobe,3) = CIR.
        Spatail_Lobe_Mapping(lobei,3);
        end
end

Subpath_Lobe_Angles =
cluster_subpath_Angle_Lobe_mapping(:,3);

% End of Changes by Anurag Shivam Prasad 06/30/2017

% Calculate local area CIRs and the corresponding
parameters in a path-by-path manner
for a = 1:nTap
    % Determine the Tx and Rx antenna array types
    if strcmp(TxAArtype,'ULA') == true && strcmp(RxArraytype,'ULA') == true
        % Calculate Rx spatial correlation matrix Rr
        for i = 1:Nr
            for m = 1:Nr
                % Spatial correlation between Rx
                antenna elements i and m in a ULA
                Rr(i,m) = (A.*exp(-B.*dRxAnt.*wl.*abs(i
                -m))-C).*exp(-j.*unifrnd(-pi,pi).*(i
                -m));
            end
        end
    end
end

% Calculate Tx spatial correlation matrix \( \mathbf{R}_t \)
for \( i = 1: \text{N}_t \)
    for \( m = 1: \text{N}_t \)
        % Spatial correlation between Tx antenna elements \( i \) and \( m \) in a ULA
        \( \mathbf{R}_t(i,m) = (A.\exp(-B.\text{d}_{\text{Tx Ant}}.\text{wl}.\text{abs}(i - m)) - C).\exp(-j.\text{unifrnd}(-\pi,\pi).*(i - m)) \);
    end
end

% Determine the Tx and Rx antenna array types
elseif strcmp(TxArrayType, 'ULA') == true && strcmp(RxArrayType, 'URA') == true
% Calculate Rx spatial correlation matrix \( \mathbf{R}_r \)
for \( i = 1: \text{N}_r \)
    for \( m = 1: \text{N}_r \)
        % Spatial correlation between Rx antenna elements \( i \) and \( m \) in a URA
        \( \mathbf{R}_r(i,m) = (A.\exp(-B.\text{d}_{\text{Rx Ant}}.\text{wl}.\text{sqrt}((\text{mod}(i,\text{Wr}) - \text{mod}(m,\text{Wr}))^2 + (\text{fix}(i/\text{Wr}) - \text{fix}(m/\text{Wr}))^2)) - C).\exp(-j.\text{unifrnd}(-\pi,\pi).*(i - m)) \);
    end
end

%%% Start of Changes by Anurag Shivam
phi_AOA = pi*sqrt(((mod(i,Wr)-mod(m,Wr))^2+(fix(i/Wr)-fix(m/Wr))^2)*i*sin(Subpath_Lobe_Angles(a));
Rr_1(i,m) = (A.\exp(-B.\text{d}_{\text{Rx Ant}}.\text{wl}.\text{sqrt}((\text{mod}(i,\text{Wr}) - \text{mod}(m,\text{Wr}))^2 + (\text{fix}(i/\text{Wr}) - \text{fix}(m/\text{Wr}))^2)) - C).\exp
(-j.*phi_AOA);

%%% End of Changes by Anurag Shivam
Prasad Miami University
12/05/2016

end
end

% Calculate Tx spatial correlation matrix Rt
for i = 1:Nt
  for m = 1:Nt
    % Spatial correlation between Tx
    % antenna elements i and m in a ULA
    Rt(i,m) = (A.*exp(-B.*dTxAnt.*wl.*abs(i
    %m))-C).*exp(-j.*unifrnd(-pi,pi).*(i
    %m));
    
   %%% Start of Changes by Anurag Shivam
    Prasad Miami University 12/05/2016
    phi_AOD = pi*abs(i-m)*i*sin(
    Elevation_AOD(a));
    phi_desired = pi*abs(i-m)*i*sin(CIR.
    Elevation_Max_Power);
    S_F = phi_desired - phi_AOD;
    Rt_1(i,m) = (A.*exp(-B.*dTxAnt.*wl.*
    abs(i-m))-C).*exp(-j.*phi_AOD);
    Rt_2(i,m) = (A.*exp(-B.*dTxAnt.*wl.*
    abs(i-m))-C).*exp(-j.*(phi_AOD +
    S_F));
    
   %%% End of Changes by Anurag Shivam
    Prasad Miami University 12/05/2016
  end
end

% Determine the Tx and Rx antenna array types
elseif strcmp(TxArrayType,'URA') == true &&
  strcmp(RxArrayType,'ULA') == true
% Calculate Rx spatial correlation matrix \( R_r \)
for \( i = 1: \text{Nr} \)
    for \( m = 1: \text{Nr} \)
        \% Spatial correlation between Rx antenna elements \( i \) and \( m \) in a ULA
        \( R_r(i,m) = (A.*\exp(-B.*dRxAnt.*wl.*\abs(i-m))-C).*\exp(-j.*\text{unifrnd}(-\pi,\pi).*(i-m)); \)
    end
end

% Calculate Tx spatial correlation matrix \( R_t \)
for \( i = 1: \text{Nt} \)
    for \( m = 1: \text{Nt} \)
        \% Spatial correlation between Tx antenna elements \( i \) and \( m \) in a URA
        \( R_t(i,m) = (A.*\exp(-B.*dTxAnt.*wl.*\sqrt{((\mod(i,Wt)-\mod(m,Wt))^2+(\fix(i/Wt)-\fix(m/Wt))^2)}-C).*\exp(-j.*\text{unifrnd}(-\pi,\pi).*(i-m)); \)
    end
end

% Determine the Tx and Rx antenna array types
elseif strcmp(TxArrayType,'URA') == true && strcmp(RxArrayType,'URA') == true
% Calculate Rx spatial correlation matrix \( R_r \)
for \( i = 1: \text{Nr} \)
    for \( m = 1: \text{Nr} \)
        \% Spatial correlation between Rx antenna elements \( i \) and \( m \) in a URA
        \( R_r(i,m) = (A.*\exp(-B.*dRxAnt.*wl.*\sqrt{((\mod(i,Wr)-\mod(m,Wr))^2+(\fix(i/Wr)-\fix(m/Wr))^2)}-C).*\exp(-j.*\text{unifrnd}(-\pi,\pi).*(i-m)); \)
    end
end
% Calculate Tx spatial correlation matrix Rt
for i = 1:Nt
    for m = 1:Nt
        % Spatial correlation between Tx
        % antenna elements i and m in a URA
        Rt(i,m) = (A.*exp(-B.*dTxAnt.*wl.*sqrt((mod(i,Wt)-mod(m,Wt))^2+(fix(i/Wt)-fix(m/Wt))^2))-C).*exp(-j.*unifrnd(-pi,pi).*(i-m));
    end
end

end%% end of if statement

% eigenvalue decomposition of Rr and Rt
[Ur,Dr] = eig(Rr); [Ut,Dt] = eig(Rt);

% random Rayleigh distribution (to be incorporated in the Rician distribution)
randRayleigh = randn(Nr,Nt)+j*randn(Nr,Nt);

% H matrix with independent Rician distribution
Hw_RC{a,1} = sqrt(K/(K+1))*exp(j*pi/4)+sqrt(1/2/(K+1))*randRayleigh;

% H matrix for the a-th path, where the elements obey the small-scale Rician distribution
% specified by Hw_RC and spatial correlation specified by Rt and Rr
H_RC{a,1} = sqrt(Pr_lin(a))*Ur*Dr^((1/2)*Hw_RC{a,1}*Dt^((1/2)*Ut');

%%% Start of Changes by Anurag Shivam Prasad Miami University 12/05/2016
194 \% H_RC_1{a,1} = sqrt(Pr_lin(a))*Ur_1*Dr_1^(1/2)*Hw_RC{a,1}*Dt_1^(1/2)*Ut_1';
195 H_RC_1{a,1} = sqrt(Pr_lin(a))*Rr_1^(1/2)*Hw_RC{a,1}*(Rt_1^(1/2))';
196
197 \%\% End of Changes by Anurag Shivam Prasad Miami University 12/05/2016
198
199 \%\% Start of Changes by Anurag Shivam Prasad Miami University
200 \%\% 06/19/2017
201 \%H_RC_2{a,1} = sqrt(Pr_lin(a))*Ur_2*Dr_2^(1/2)*Hw_RC{a,1}*Dt_2^(1/2)*Ut_2';
202 H_RC_2{a,1} = sqrt(Pr_lin(a))*Rr_1^(1/2)*Hw_RC{a,1}*(Rt_2^(1/2))';
203
204 \%\% End of Changes by Anurag Shivam Prasad Miami University
205 University 06/19/2017
206 \% time delay for the a-th path
207 CIR.HDelays{a,1} = CIR.pathDelays(a);
208
209 \% received power between each Tx antenna and each Rx antenna for the a-th path
210 CIR.HPowers{a,1} = abs(H_RC{a,1}).^2;
211
212 [r,c] = size(H_RC{a,1});
213
214 \textbf{for} i = 1 : r
215 \quad P_Rx(i) = sum(H_RC{a,1}(i,:));
216 \quad P_Rx_1(i) = sum(H_RC_1{a,1}(i,:));
217 \quad P_Rx_2(i) = sum(H_RC_2{a,1}(i,:));
218 \textbf{end}
219
220 \% w_estimate = (pi*sin(CIR.Elevation_Max_Power))./angle(P_Rx_2);
221 Power_Subpath(a,:) = abs(sum(P_Rx)).^2;
222 Power_Subpath_1(a,:) = abs(sum(P_Rx_1)).^2;
Power_Subpath_2(a,:) = abs(sum(w_estimate.*P_Rx_2)).^2;

%% End of Changes by Anurag Shivam Prasad Miami University 12/05/2016

% phase between each Tx antenna and each Rx antenna for the a-th path
CIR.HPhases{a,1} = CIR.pathPhases(a)+angle(H_RC{a,1});
CIR.HAODs{a,1} = CIR.AODs(a); % AOD for the ath path
CIR.HZODs{a,1} = CIR.ZODs(a); % ZOD for the ath path
CIR.HAOAs{a,1} = CIR.AOAs(a); % AOA for the ath path
CIR.HZOAs{a,1} = CIR.ZOAs(a); % ZOA for the ath path
end % end of aTap for loop

%%% Start of Changes by Anurag Shivam Prasad Miami University 12/05/2016

figure(5);
plot(1:nTap,10*log10(Power_Subpath),'k'); hold on;
plot(1:nTap,10*log10(Power_Subpath_1),'b');
hold on; plot(1:nTap,10*log10(Power_Subpath_2),'r');
xlabel('mmWave Multipaths ');
ylabel('Recieved Power (dBm)');
grid on;

%%% End of Changes by Anurag Shivam Prasad Miami University 12/05/2016

%%% Start of Changes by Anurag Shivam Prasad 06/09/2017

%%% Creating the power Delay Profile (PDPs) for comparisons
Time_Delay = CIR.pathDelays;
Main_Lobe = find(CIR.subpath_lobe_mapping(:,3) == CIR.Main_Lobe_Index);
beam_delay = [Time_Delay(Main_Lobe,1)
              Power_Subpath_2(Main_Lobe,1)];
beam_delay_profile = [Time_Delay(Main_Lobe,1)
                      Power_Subpath(Main_Lobe,1)];
beam_delay_profile_1 = [Time_Delay(Main_Lobe,1)
                       Power_Subpath_1(Main_Lobe,1)];
beam = sortrows(beam_delay,1);
beam_set = sortrows(beam_delay_profile,1);
beam_set_1 = sortrows(beam_delay_profile_1,1);

figure(6);
plot(beam(:,1),10*log10(beam(:,2)),'r'); hold on; plot(
              beam_set(:,1),10*log10(beam_set(:,2)),'k');
              hold on; plot(beam_set_1(:,1),10*log10(
                           beam_set_1(:,2)),'b');
xlabel('Propagation Time(ns)');
ylabel('Recieved Power (dBm)');
grid on;

%%% End of Changes by Anurag Shivam Prasad 06/09/2017

%%% Start of Changes by Anurag Shivam Prasad Miami University 12/05/2016
numberOfLobes = CIR.AOA_Lobes;
cluster_subpath_AOAlobe_mapping = CIR.
subpath_lobe_mapping;

for lobei = 1:numberOfLobes
    SameLobe = find(
                   cluster_subpath_AOAlobe_mapping(:,3) ==
                 lobei);
    Power_Subpath_SameLobe = Power_Subpath
                           (SameLobe,1);
Power_Subpath_1_SameLobe = Power_Subpath_1(SameLobe,1);
Power_Subpath_2_SameLobe = Power_Subpath_2(SameLobe,1);
Power_Subpath_Rx(lobei) = sum(Power_Subpath_SameLobe);
Power_Subpath_Rx_1(lobei) = sum(Power_Subpath_1_SameLobe);
Power_Subpath_Rx_2(lobei) = sum(Power_Subpath_2_SameLobe);
end

for lobei = 1:numberOfLobes
    SameLobe = find(cluster_subpath_AOAlobe_mapping(:,3) == lobei);
    Power_SameLobe = Pr_lin(SameLobe,1);
    Power_Total_Rx(lobei) = sum(Power_SameLobe);
end

% beamforming results
% Total Signal Power at each spatial lobes
figure(7);
plot(10*log10(Power_Subpath_Rx),'k--o'); hold on; plot(10*log10(Power_Subpath_Rx_1),'b--o ');
hold on; plot(10*log10(Power_Subpath_Rx_2),'r--o ');
xlabel('Lobe Number '); ylabel('Received Power (dBm)'); grid on;
beam_angle_1 = [Elevation_AOA(Main_Lobe,1) Power_Subpath_1(Main_Lobe,1)];
beam_angle_2 = [Elevation_AOA(Main_Lobe,1) Power_Subpath_2(Main_Lobe,1)];
angle_profile_1 = sortrows(beam_angle_1,1);
angle_profile_2 = sortrows(beam_angle_2,1);
figure(8);
plot(angle_profile_1(:,1), 10*log10(angle_profile_1(:,2))); hold on;
plot(angle_profile_2(:,1), 10*log10(angle_profile_2(:,2)),'r');
grid on;
xlabel('Angle of Arrival ');
ylabel('Received Power (dBm)');
Total_Power_1(CIRIdx) = sum(Power_Subpath_1);
Total_Power_2(CIRIdx) = sum(Power_Subpath_2);
CIR.H = H_RC;

% Store the updated CIR
CIR_Struct([CIR', num2str(CIRIdx)]) = CIR;

%%% Start of Changes by Anurag Shivam Prasad
06/06/2017
%%% Clearing Intermediate Variables

Abs_Array_Power = [];
Abs_Array_Power_1 = [];
Abs_Array_Power_2 = [];
P_Rx = [];
P_Rx_1 = [];
P_Rx_2 = [];
Power_Subpath = [];
Power_Subpath_1 = [];
Power_Subpath_2 = [];
H_RC = [];
H_RC_1 = [];
H_RC_2 = [];
Rr_1 = [];
Rr_2 = [];
Rr = [];
Rt_1 = [];
Rt_2 = [];
Rt = [];
Subpath_Lobe_Angles = [];

%%% End of Changes by Anurag Shivam Prasad 06/06/2017

end % end of CIRIdx

figure(9);
plot(10*log10(Total_Power_1)); hold on ; plot(10*log10(Total_Power_2), 'r');
grid on;
xlabel('User Index');
ylabel('Recieved Total Signal Power (dBm)');
end% end of function
Appendix E

Power Angle Profile Code

```matlab
clc;
clear all;
close all;

A = xlsread('testdata4.xls');

B = round(A(:,5));

azimuth_axis = round(linspace(0,180,100000));
C = zeros(1,100000);
Z = [azimuth_axis' C'];

for i = 1:length(A)
    for j = 1:length(C)
        if (B(i) == Z(j,1))
            Z(j,2) = A(i,2);
        end
    end
end

power_dBm = 10*log10(Z(:,2));
```
figure(1);  
plot(Z(:,1),(power_dBm));  
grid on;  
xlabel('Elevation Angle');  
ylabel('Main Lobe Received Power (dBm)');
Bibliography


less communication system design,” *IEEE Transactions on Communications*, vol. 63, no. 9, pp. 3029–3056, Sept 2015.


