# MmWave Transceiver Design

*A Project Report*

*submitted by*

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*for the award of the degree of*

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# THESIS CERTIFICATE

This is to certify that the thesis titled **MmWave Transceiver Design**, submitted by **MANOJ KUMAR KARNIYANA** bearing Roll No: **EE15M018**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bona fide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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I would like to thank all my professors whose lectures and discussions during course work helped me to improve my knowledge in the related area.

# ABSTRACT

Communication at millimeter wave (mmWave) frequencies is defining a new era of wireless communication. The mmWave band offers higher bandwidth communication channels. This drives the evolution of the personal wireless communication, with new standards developed to improve the spectral efficiency. However, the available spectrum below 10GHz is very limited and packing more bits per second into the same bandwidth requires larger energy consumption. As a result, such an approach is not sustainable for meeting the future demand. A natural path is to move into higher frequency bands which have larger spectrum bandwidth but less commercial usage. Signal processing is critical for enabling the next generation of mmWave communication. Because of the wider bandwidths, low complexity transceiver algorithms become important. This report provides an overview of signal processing in mmWave wireless system and the implementation of an architecture.

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# CHAPTER 1

# INTRODUCTION

MmWave communication has received increasing attentions as an important technology in the next generation Cellular Communication and the Wireless LANs. MmWaves makes use of the spectrum from 30 GHz to 300 GHz whereas most consumer wireless systems operate at carrier frequencies less than 6 GHz. The main advantage with mmWave carrier frequencies are larger spectral channels. Channels with 2 GHz bandwidth are common for systems operating in the 60 GHz unlicensed band. Larger bandwidth channels mean higher data rates.

Traditional physical layer designs for 60 GHz back-haul assume expensive directional antennas, reducing cost advantages over wired solutions. Low cost mmWave technologies with adaptive arrays, however, are actively being developed to back-haul densely distributed small cells. In this scenario, distances are very short but the operating expenditures associated with using fiber optical cable may still be prohibitive. It will be possible to establish high capacity connections using state-of-art, low cost mmWave devices. Self back-haul may even be possible in millimeter wave cellular systems.

Signal processing is of critical importance for millimeter wave cellular systems. The reasons why signal processing is different in millimeter wave frequencies than at lower frequencies are: (i) there are new constraints on the hardware in part due to the high frequency and bandwidth communication channels, (ii) the channel models are different, and (iii) large arrays will be used at both the transmitter and receivers.

The channel models at mmWave are different because the propagation environment has a different effect on the smaller wavelength signals. The arrays for mmWaves may be quite larger. To provide sufficient link margin, in most mmWave communication systems, arrays will be used at both transmitter and receiver, creating opportunities to apply MIMO communication techniques. The MIMO techniques applied will be different though due to the different channel characteristics and additional hardware constraints found at mmWave frequencies. The connection between MIMO and mmWave is the main reason that we emphasize signal processing for mmWave MIMO systems.

A fundamental challenge to mmWave communication is the extremely high path loss, due to the very high carrier frequencies in the order of 28-60 GHz. To bridge this significant link budget gap, beamforming is usually employed at both the transmitter and the receiver ends to bring large antenna array gains, which requires a large antenna array size.

In the mmWave systems, the high power consumption of mixed signal components, as well as expensive RF chains, make it difficult to realize digital baseband beamforming as used in conventional multiple-input multiple-output (MIMO) systems. So, analog beamforming is usually preferred, where all the antennas share a single RF chain and have constant amplitude on their weights.

In analog beamforming, there exist two different approaches in general. An iterative beamforming training approach, in which the beamforming vector on one side is alternatively optimized by fixing the beamforming vector on the other side, and an alternation is repeated iteratively to improve the beamforming gain over the iterations. On the other hand, a Switched beamforming approach, where the beam search space is represented by a codebook containing multiple codewords, and the best transmit/receive beams are found by searching through their respective codebooks. Both approaches have their merit and may be useful in different applications.

The combined implications of hardware constraints, channel models, and large arrays has a far-reaching impact on the design of mmWave communication systems.

**Outline:** The report describes a working model of mmWave system and the performance is evaluated by plotting Bit Error Rate(BER) versus Singal to Noise Ratio (SNR) or per Bit SNR (Eb/No). Chapter 2 deals with the design of the transmit chain which includes the baseband signal processing and the design specifications of the RF elements. Chapter 3 deals with the implementation of a superheterodyne receiver and the design specifications of the RF front end. Chapter 4 deals with the antenna array beamforming techniques, analog and digital beamforming. Chapter 5 includes the architecture and evaluation of the proposed architecture.

# CHAPTER 2

# Transmit Chain

## 2.1 Transmitter Block Diagram

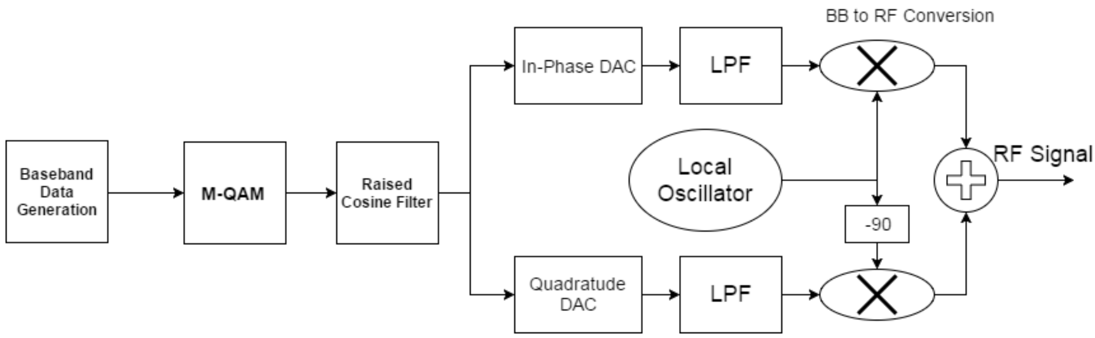


**Figure 2.1:** Transmitter Block Diagram

## 2.2 Base band Signal Generation

Random integer generator is used to generate data samples with equal probability in the set $0$ to $\mathrm{M}-1$ which is further modulated by QAM-Modulator. Samples are generated at $1$ Gsamples/sec i.e., with a duration of $1$ ns in a frame format. Each frame comprises of $2048$ samples which makes the frame duration equals $2048$ ns and the frames are transmitted at a rate of $488285$ frames/sec. A total of 25 Frames of data has been generated and transmitted.

## 2.3 M-Quadrature Amplitude Modulation

QAM is a method of combining two amplitude modulated signals in to a single channel, thereby doubling the effective bandwidth. In QAM, there are two carriers, each having the same frequency but differ in phase. The generated samples are Modulated by using a M-QAM modulation scheme and the modulated data is pulse shaped by using a Raised Cosine Filter.

The simulation uses 16-QAM and 64-QAM and the corresponding bit error rates are plotted and compared with the theoretical curves.

## 2.4 Orthogonal Frequency Division Multiplexing

Random integer generator is used to generate data samples with equal probability in the set $0$ to $\mathrm{M}-1$ which is further modulated by QAM-Modulator. Samples are generated at $1$ Gsamples/sec i.e., with a duration of $1$ ns in a frame format. OFDM modulation is used with $296$ useful sub-carriers. A guard band is introduced on both sides of length $108$ and $107$ and a dc null is introduced. FFT Length of $512$ samples and CP Length of $80$ is used which makes the frame size as $592$ samples/frame.

A total of $25$ frames are generated. Hence a total of $25 * 592 = 14800$ modulated sub-carriers are transmitted and received at the receiver and the corresponding bit error rates are plotted.

Each frame comprises of $2048$ samples which makes the frame duration equals $2048$ ns and the frames are transmitted at a rate of $488285$ frames/sec. A total of 25 Frames of data has been generated and transmitted.

## 2.5 Root Raised Cosine Filter

In Signal Processing, a Root Raised Cosine Filter (RRC) or Square Root Raised Cosine Filter (SRRC) are often used at the transmit and receive side in order to perform matched filtering. The combined response of two such filters is called Raised Cosine Filter.

To have minimum ISI (Intersymbol interference), the overall response of transmit filter, channel response and receive filter has to satisfy Nyquist ISI criterion. Raised-cosine filter is the most popular filter response satisfying this criterion.

An SRRC filter of Rolloff factor $= 0.2$, Group delay of $10$ samples and an Upconversion factor of $8$ is used to pulse shape the modulated data.

## 2.6 Digital to Analog Conversion

The band structure of the Wireless LAN system is composed of several adjacent RF carriers (especially in case of OFDM) with very high spectral density. By employing high speed, higher resolution digital-to-analog converters (DACs) multicarrier transmission through a common RF power amplifier is achieved with minimal signal distortion.

Sigma-delta modulation provides a high-resolution digital-to-analog conversion solution.

Since sigma-delta DACs provide for oversampling digital-to-analog conversion through the sampling of signals at very high frequencies (i.e., sampling at rates much greater than the Nyquist rate), high signal-to-noise ratios are achieved. The sigma delta modulator shapes the noise so that the majority of the noise falls into the very high frequencies above the Nyquist frequency leading to higher SNR performance.

No. of bits = 12 bits for better resolution hence better SNR performance and Gain tuning at Receive end.

## 2.7 BB to RF Conversion

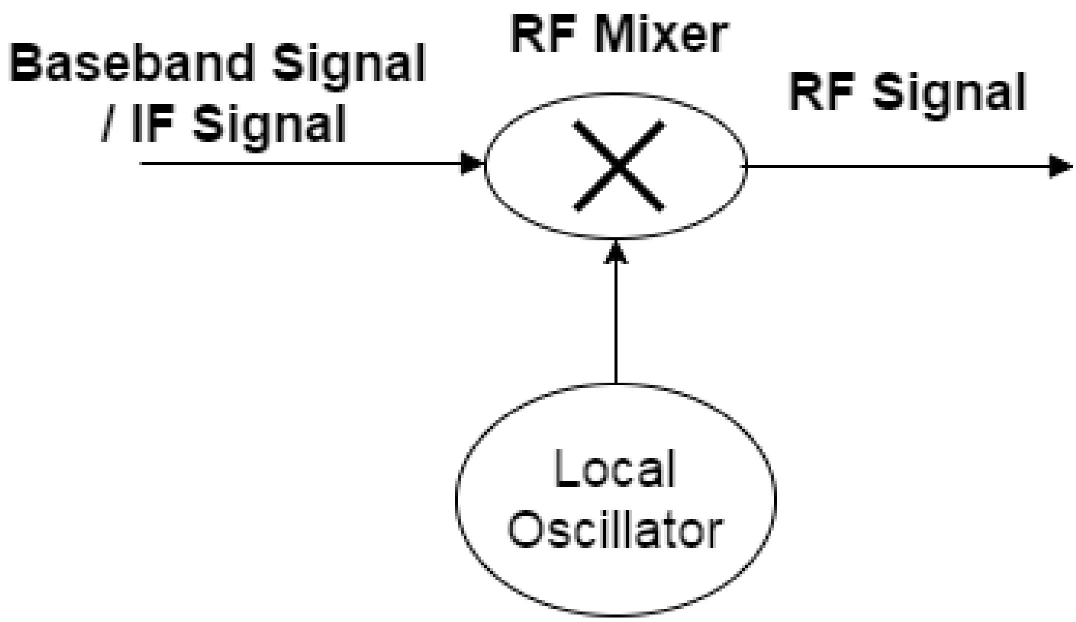


**Figure 2.2:** BB/IF to RF Upconversion

The Baseband or IF signal is up-converted to RF by using a mixer. The local oscillator produces a carrier signal of frequency $f_{\text{RF}}$ and is multiplied with the IF signal to produce the desired RF signal. The modulated signal measuring $11$ dBm at the front end of the mixer. The design of the RF elements is listed below.

### 2.7.1 Local Oscillator

A continuous waveform generator is used to produce a $60$GHz carrier signal that is used to produce the desired RF signal. A constant In-phase voltage of $50m$V is used to produce the LO signal. The signal is phase shifted by $-90\deg$ to obtain the quadrature LO signal, used to mix with the quadrature signal.

### 2.7.2 Mixer Design

Mixer is used to perform frequency translation.

The parameters of Mixer used are as follows.

| Sl.No | Parameter | Value | Remarks |
|---|---|---|---|
| 1 | Conversion Loss | $-7$ dB | • Considering a practical lossy mixer the Conversion loss is fixed as 7dB at fc = $60$ GHz.<br>• This is a fixed value parameter and the remaining parameters are calculated from this.<br>• A survey states that this value is achievable at comparatively low cost. |

| | | | |
|---|---|---|---|
| 2 | $\text{P1dB}_{\text{,output}}$ | 13 dBm | • The mixer P1dB is so chosen to ensure its operation in the linear region. The input power is 7dBm and the linearity margin is assumed to be 9 dB. The saturation output power is kept at 22dBm.<br>• Linearity margin = P1dB − IF Power + Conversion Loss<br>• Linearity margin $= 13 - 11 + 7 = 9$dB<br>• Since transmitter has no uncertainty in its input power, the output saturation power is an optimal choice. |
| 3 | OIP3<br>(3rd Order output intercept point) | 29 dBm | For OIP3 being 16dB higher than the 1-dB compression point inorder to obtain negligible intermod products. |
| 4 | Noise Figure | 6 dB | This value arrived at considering the SNR requirements. |

**Table 2.1:** Mixer RF specifications

### 2.7.3 Band Pass Filter

A Band Pass Filter is needed to reject the harmonics and difference products produced by the mixer. Following are the design characteristics of the Band Pass Filter used in the architecture.

| **Sl.No** | **Parameter** | **Value** | **Remarks** |
|---|---|---|---|
| 1 | Center Frequency | 60 GHz | To cater any channelization needed. |
| 2 | Pass Band | 8 GHz | To pass the desired signal |
| 3 | Pass Band Attenuation | 0 dB(Approx.) | In-order to reproduce the signals in the Band of interest. |
| 4 | Stop Band Attenuation | 40 dB | To attenuate harmonics and difference products. |

| | | | |
|---|---|---|---|
| 5 | Input Impedance | $50\Omega$ | Source Impedance. |
| 6 | Output Impedance | $50\Omega$ | Matched Load. |

**Table 2.2:** Band Pass Filter Specifications

## 2.8 Power Amplifier

Since the up-converted signal needs to travel a long distance in free space it experience severe attenuation, to overcome this issue a Power Amplifier (PA) in 60GHz range is added to compensate this loss.

| Sl.No | Parameter | Value | Remarks |
|---|---|---|---|
| 1 | $\text{P1dB}_{,\text{output}}$ | 16 dBm | The EIRP at 60 GHz is assumed to be $+34$ dBm.<br>Antenna Beam-forming will provide a gain of 18 dB directive gain.<br>$\text{EIRP}_{\text{max}} = \text{P}_{\text{o/p}} + \text{Gain}_{\text{Antenna}}$<br>So, $\text{P}_{\text{o/p}} = \text{P1dB}_{,\text{output}} = 34 - 18 = 16\text{dBm}$. |
| 2 | RF Gain | 17 dB | $\text{P}_{\text{o/p}} = \text{P}_{\text{i/p}} + \text{Gain}_{\text{PA}}$<br>Maximum input power = $-1$ dBm.<br>Maximum output Power of the Power Amplifier, $\text{P}_{\text{max. o/p}} = \text{P}_{\text{i/p}} + \text{Gain}_{\text{PA}}$.<br>$\text{P}_{\text{max. o/p}} = -1 + 17 = 16\text{dBm}$ |
| 3 | Input Back-off | 3 dB | $\text{P}_{\text{in,saturation}} = \text{P1dB} - \text{Gain}_{\text{PA}}$<br>So, $\text{P}_{\text{in,saturation}} = 16 - 17 = -1\text{dBm}$.<br>The Amplifier is operated at 3dB back-off, so that the PA does not saturate when it is operated in the non-linear region.<br>Thus the PA output power is $+13$dBm and will be in more linear region compared to saturation region |

| | | | |
|---|---|---|---|
| 4 | OIP3 | 36 dBm | To have very low intermod products, we need to have OIP3 = P1dB + 20 dB = 36dBm. |
| 5 | IIP3 | 19 dBm | $\text{IIP3} = \text{OIP3} - \text{Gain}_{\text{PA}} = 36-17 = 19\text{dBm}$. |
| 6 | Noise Figure | 10 dB | To meet the SNR requirements. |

**Table 2.3:** Power Amplifier specifications

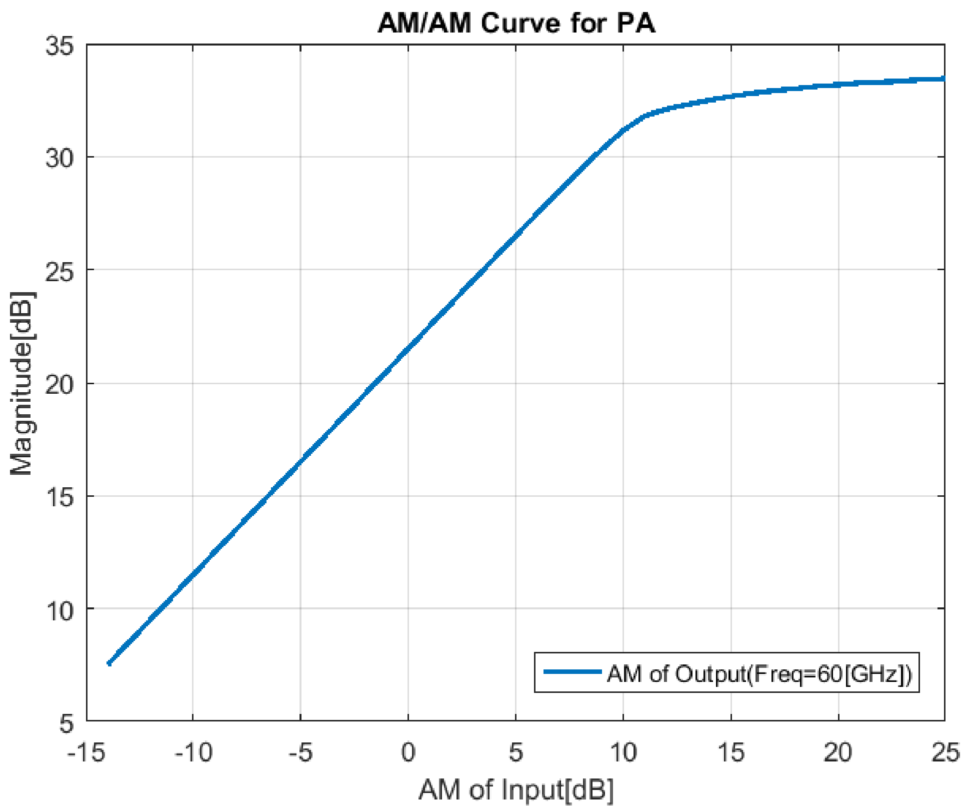


**Figure 2.3:** AM/AM Curve for the PA

## 2.9 Harmonic Reject Filter

Since the PA produces harmonic components, a Harmonic rejection filter is required after PA stage. Two major choices on the filter function is possible i.e., BPF or LPF.

But realizing a Narrow BPF calls for complex filter function, further, maintaining a high power handling simultaneously is another challenge. To alleviate this problem we can employ a LPF design where power handling can be achieved at comparatively less complex circuit design.

| Sl.No | Parameter | Value | Remarks |
|---|---|---|---|
| 1 | Cut-off Frequency | 70 GHz | To reject harmonic components. |
| 2 | Stop Band Attenuation | 40 dB | Harmonic components are severely attenuated. |
| 3 | Pass Band Attenuation | 0 dB(Approx.) | Inorder to reproduce the Band of interest. |
| 3 | Filter tyoe | Butterworth Lowpass | |
| 5 | Input Impedance | 50Ω | Source Impedance. |
| 6 | Output Impedance | 50Ω | Matched Load. |

**Table 2.4:** Harmonic Reject Filter Specifications

## 2.10 Transmitted signal Spectrum

The transmitted channel power measured to be 16 dBm and the spectral mask is shown in the following figure.

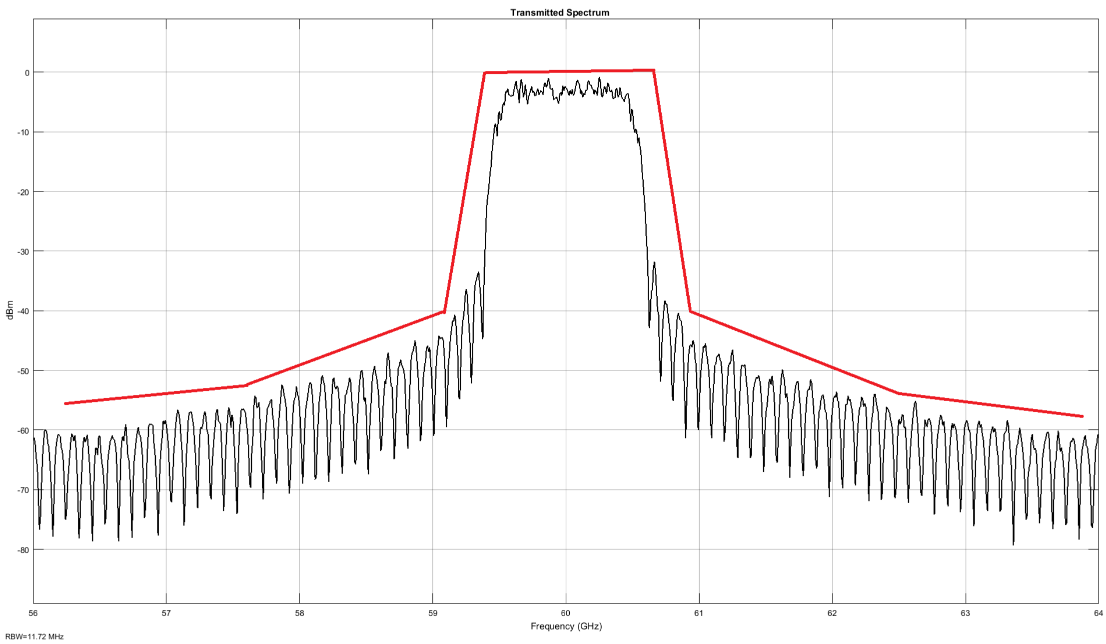


**Figure 2.4:** Transmitted spectrum mask for SC

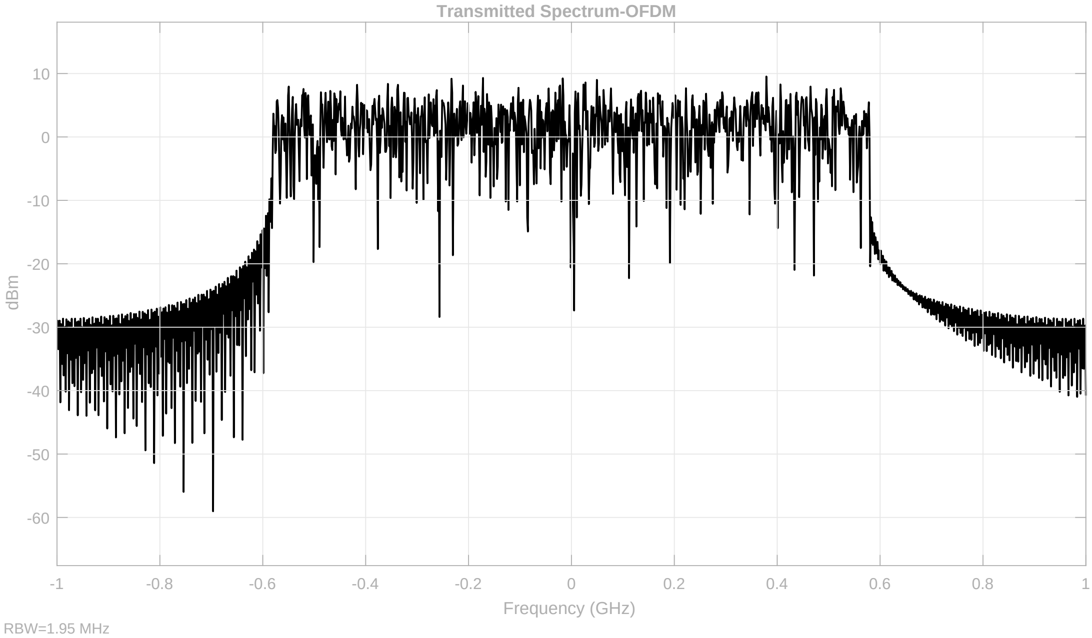


**Figure 2.5:** Transmitted spectrum mask for OFDM modulation

# CHAPTER 3

# Receive Chain

## 3.1 Receiver Sensitivity

Receiver sensitivity is the lowest power level at which the receiver can detect an RF signal and demodulate data. Sensitivity is purely a receiver specification and is independent of the transmitter. As the signal propagates away from the transmitter, the power density of the signal decreases, making it more difficult for a receiver to detect the signal as the distance increases. Improving the sensitivity of the receiver will allow the radio to detect weaker signals, and can dramatically increase the transmission range. Sensitivity is vitally important in the decision making process since even slight differences in sensitivity can account for large variations in the range.

Sensitivity = $10\log10(\mathrm{kT}) + 10\log10(\mathrm{BW})$ + NF + SNR.

BW $=$ BandWidth in Hz.

NF $=$ Noise Figure in dB.

k $=$ Boltzmann Constant $= 1.38\text{x}10^{-23}$.

T $=$ Temperature $= 300$°K

So, Sensitivity $= -174$ dBm/Hz $+10\log10(\mathrm{BW})$ + NF + SNR.

For BER (Bit Error Rate) in the order of $10^{-1}$, the SNR required is $6$ dB. For a Noise Figure (NF) of $10$ dB and Band Width of $1$ GHz, the receiver sensitivity is

Sensitivity $= -174$ dBm/Hz $+10\log10(10^9)+10 + 6 = -68$ dBm.

For BER (Bit Error Rate) in the order of $10^{-3}$, the SNR required is $16$ dB. For a Noise Figure (NF) of $10$ dB and Band Width of $1$ GHz, the receiver sensitivity is

$\text{Sensitivity}_{\text{max}} = -174$ dBm/Hz $+10\log10(10^9)+10 + 16 = -58$ dBm.

For BER (Bit Error Rate) in the order of $2 * 10^{-1}$, the SNR required is $0$ dB. For a Noise Figure (NF) of $10$ dB and Band Width of $1$ GHz, the receiver sensitivity is

$\text{Sensitivity}_{\text{min}} = -174$ dBm/Hz $+10\log10(10^9)+10 + 0 = -74$ dBm.

## 3.2 Band Select Filter

Most receiver front ends do incorporate a Band Select Filter, which selects the entire receive band and rejects out-of-band interferers, thereby suppressing components that may be generated by users that do not belong to the band of interest. In order to eliminate the out of band noise and to prevent saturating the succeeding amplifier, a BPF with the following specifications is employed.

| Sl.No | Parameter | Value | Remarks |
|---|---|---|---|
| 1 | Center Frequency | 60 GHz | To cater any channelization needed. |
| 2 | Pass Band | 10 GHz | To pass the desired signal |
| 3 | Pass Band Attenuation | 0 dB(Approx.) | In-order to reproduce the signals in the Band of interest. |
| 4 | Stop Band Attenuation | 40 dB | To attenuate harmonics and difference products. |
| 5 | Input Impedance | 50Ω | Source Impedance. |
| 6 | Output Impedance | 50Ω | Matched Load. |

**Table 3.1:** Band Select Filter Specifications

## 3.3 Low Noise Amplifier

Since the signal has been attenuated on the flight in free space a high gain with lower noise contribution, in order not to drown the signal, is needed. As the first active stage of receivers, LNAs play a critical role in the overall performance and their design is governed by the following parameters.

| Sl.No | Parameter | Value | Remarks |
|---|---|---|---|
| 1 | RF Gain | 10 dB | This value is arrived at by considering the following factors:<br>• To boost the lower range signals.<br>• To suppress the Noise figure effects of subsequent stages.<br>• Availabilty |

| | | | |
|---|---|---|---|
| 2 | Input Dynamic Range | $-62$ to $-22$ dBm | At $60$ GHz, the Free Space Path Loss for a distance of $200$m is $114$dB. Hence<br>$P_{in,min}$ = EIRP $-$ FSPL $+$ Rx.Antenna Gain<br>$P_{in,min}$ = $34 - 114 + 18 = -62$dBm.<br>Free Space Path Loss for a distance of 2m is $74$dB.<br>$P_{in,max}$ = $34 - 74 + 18 = -22$dBm.<br>Considering an additional margin of 2dB, the maximum input at the receiver input is $-20$dBm. |
| 3 | Input Saturation Drive | 19dBm | This level is $3$dB above the maximum input level hence Non-linear distortion doesn't occur. Saturation is identified by $1$dB Gain compression with respect to linear gain. |
| 4 | $P1dB_{out}$, Saturated Output Power | $-10$dBm | $P1dB_{out} = P_{in,sat} + \text{Gain} = -20 + 10 = -10$dBm. |
| 5 | OIP3 | 10 dBm | OIP3$=$ P1dB$+20 = -10 + 20 = 10$dBm |
| 6 | IIP3 | 0 dBm | OIP3$-$Gain $= 10 - 10 = 0$dBm |
| 7 | Noise Figure | 10 dB | The LNA's Noise figure has a significant impact in the entire Receive chain. This is because the Noise factor for a cascaded stage is given by:<br>F=F1+(F2$-$1)/G1 +(F3$-$1)/(G1$*$G2)<br>This value is arrived at by considering the optimum Noise figure value for a $60$GHz LNA. |

## 3.4 RF Down Conversion

The RF signal is Down-converted to BB/IF by using a mixer. The local oscillator produces a carrier signal of frequency $f_{RF}$ and is multiplied with the RF signal to produce the desired RF signal and an Image Frequency component. The design of the RF elements is listed below.

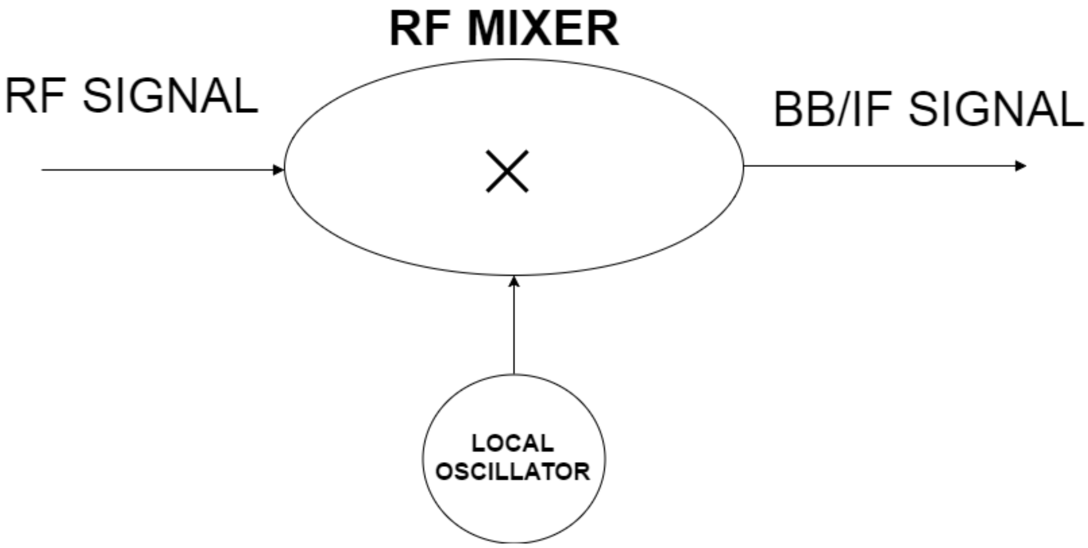


**Figure 3.1:** RF to BB/IF DownConversion

### 3.4.1 Local Oscillator

A continuous waveform generator is used to produce a $60$GHz carrier signal that is used to produce the desired Down-converted signal. A constant In-phase voltage of $50m$V is used to produce the LO signal. The signal is phase shifted by $-90\deg$ to obtain the quadrature LO signal, used to mix with the quadrature signal.

### 3.4.2 Mixer

Mixer is used to perform frequency translation.

The parameters of Mixer used are as follows.

| Sl.No | Parameter | Value | Remarks |
|---|---|---|---|
| 1 | Conversion Loss | $-7$ dB | • Considering a practical lossy mixer the Conversion loss is fixed as 7dB at fc = $60$ GHz.<br>• This is a fixed value parameter and the remaining parameters are calculated from this. |

| | | | |
|---|---|---|---|
| 2 | $P1dB_{,output}$ | $-10$ dBm | • The mixer P1dB is so chosen to ensure its operation in the linear region.<br>• The maximum RF input power is $-10$dBm and the linearity margin is,<br>Linearity Margin = $P1dB_{,output}-$ Max. RF input $-$ Conversion Gain<br>$= -10 - (-13) - (-7) = 10$ dB. |
| 3 | OIP3<br>(3rd Order output intercept point) | 10 dBm | For OIP3 being 20dB higher than the 1-dB compression point inorder to obtain negligible intermod products. |
| 4 | Noise Figure | 6 dB | This value arrived at considering the SNR requirements. |

**Table 3.3:** Mixer RF specifications

### 3.4.3 Low Pass Filter

A Low Pass Filter is needed to reject the harmonics and sum products produced by the mixer operation. Following are the design characteristics of the Low Pass Filter used in the architecture.

| Sl.No | Parameter | Value | Remarks |
|---|---|---|---|
| 1 | Cut-Off Frequency | 10 GHz | 10 GHz is chosen for ease of implementing LPF. |
| 2 | Pass Band Attenuation | 0 dB(Approx.) | In-order to reproduce the signals in the Band of interest. |
| 4 | Stop Band Attenuation | 40 dB | To attenuate harmonics and sum products. |
| 5 | Input Impedance | $50\Omega$ | Source Impedance. |
| 6 | Output Impedance | $50\Omega$ | Matched Load. |

**Table 3.4:** Low Pass Filter Specifications

## 3.5 Image Rejection

$$\text{IF Frequency} = \text{RF Frequency} - \text{LO Frequency}$$
$$= 60 \text{ GHz} - 53 \text{ GHz} = 7\text{GHz}.$$
$$\text{Image Frequency} = \text{RF Frequency} - 2*\text{IF Frequency}$$
$$= 60 - (2 * 7) = 46\text{GHz}.$$

But the $46$ GHz signal is attenuated by the Band Select Filter present at the front end of the receiver. Hence an additional Image Rejection Filter is not required in this design.

## 3.6 Automatic Gain Control (AGC)

Automatic Gain Control is employed to adjust the amplifier gain based on the incoming signal. This results in a fixed output power which is required for the Base band data extraction.
In Simulink, the AGC function is simulated as below

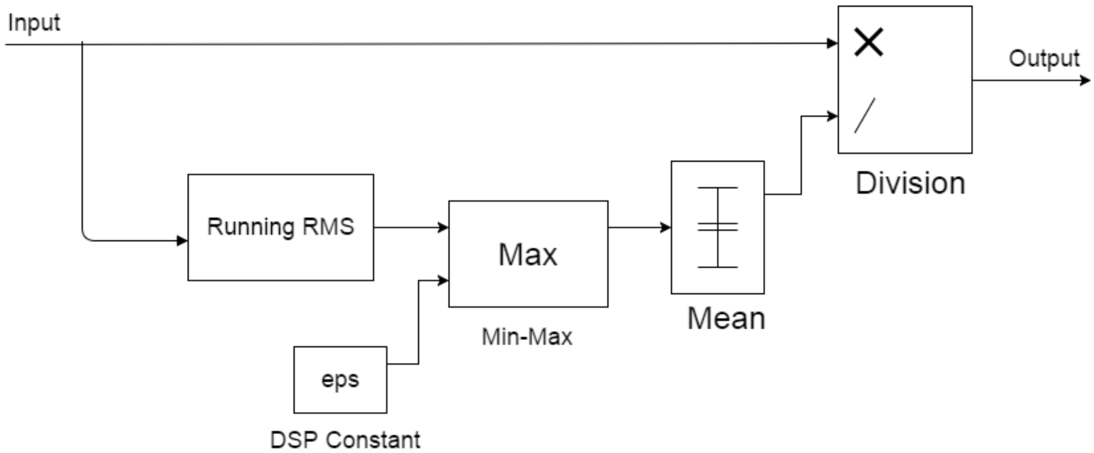


**Figure 3.2:** Automatic Gain Control

## 3.7 Analog-Digital Conversion (ADC)

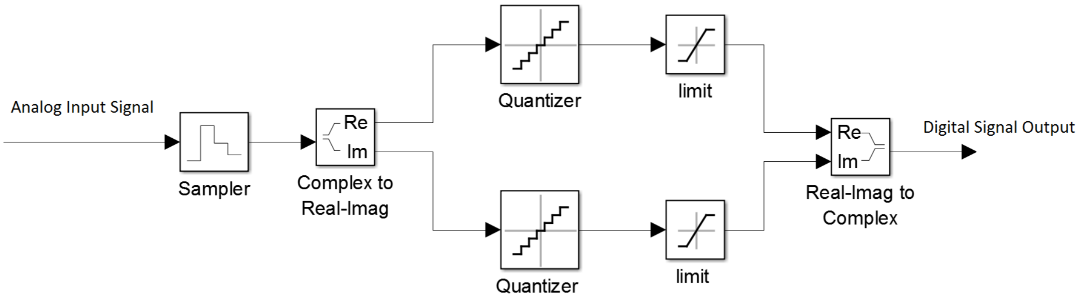


**Figure 3.3:** Analog to Digital Converter

Number of Bits used in ADC $= 8$ bits for better resolution. The Simulink model used for the ADC is shown in the above figure.

## 3.8 Demodulation

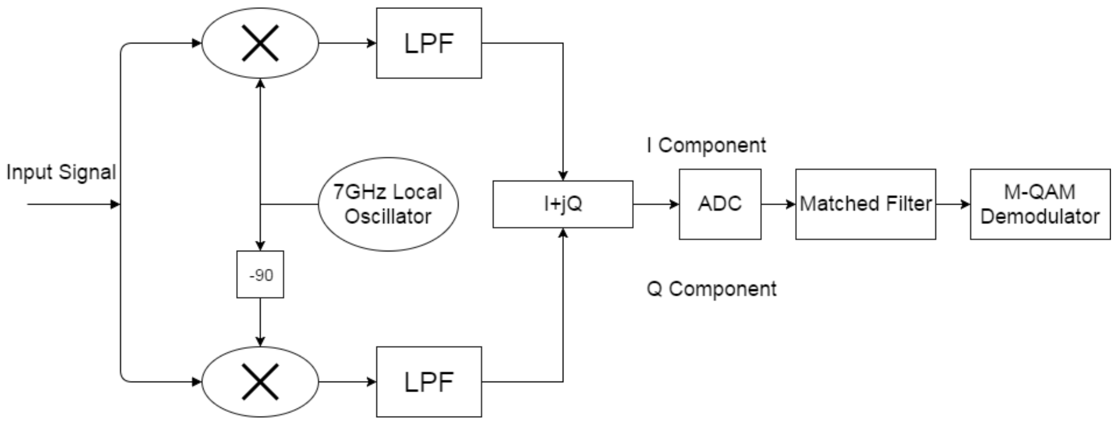


**Figure 3.4:** Baseband M-QAM Demodulation

### 3.8.1 Matched Filter

The digital data coming out from the ADC is filtered using a matched filter. A Square Root Raised Cosine (SRRC) Filter with the same parameters used at the transmitted side is used to achieve the same.

### 3.8.2 M-QAM Demodulation

The complex data coming out from the ADC is demodulated using rectangular M-QAM with average power as the threshold to obtain the estimated data which is then fed in to a error rate calculator along with the transmit symbols to obtain the Symbol Error Rate (SER) or Bit Error Rate (BER).

# CHAPTER 4

# Antenna Array and Beam Forming Mechanism

Antenna Beamforming is the process to steer the antenna beam in the desired direction thereby achieving higher directive gain compared to radiation pattern without beamforming. Also one more interesting aspect here is to apply a Null in the radiation pattern corresponding to the Interfering signal. Depending on the beamformer architecture, the weighting can be done either in the digital domain or in the analog domain.

The Antenna Beamforming can be done in any one of the following methods:

1. Analog Beamforming
    1.1 RF Phase shifting
    1.2 LO Phase shifting
    1.3 IF Phase shifting
2. Digital Beamforming

## 4.1 Analog Beamforming

### 4.1.1 RF Phase shifting

In this architecture, the signals at the antenna elements are phase-shifted and combined in the RF domain. The combined signal is then down converted to Baseband using heterodyne or homodyne mixing.

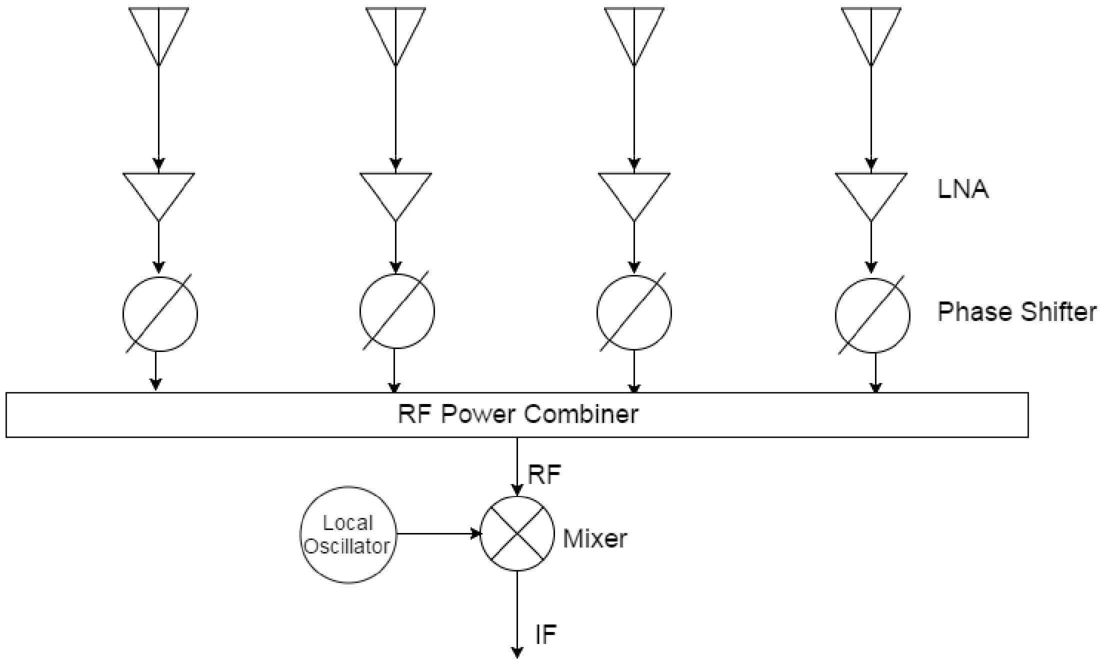


**Figure 4.1:** RF Phase Shifting

**Advantage**

- Since this technique requires only a single mixer and there is no need of LO signal distribution, it usually results in the most compact architecture among other phase array designs.
- It provides insulation of a larger portion of the receiver chain from interference emanating from undesired directions.
- Since phase shifting and the signal combining are performed prior to down conversion in the RF phase shifting architecture, the interferer is filtered at RF stage prior to the mixer; therefore, the requirement on dynamic range of down conversion mixer is not as stringent as other types of phased array architectures.

**Disadvantage**

- The main challenge of using phase shifting at RF stage in the design of phased arrays is implementing high performance phase-shifters capable of operating at RF frequencies.
- Regardless of the technology used to implement phase shifters such as BST, MEMS, GaAs or CMOS, passive phase shifters, in general, tend to be excessively lossy at mi-

crowave and millimeter regime.

- Active phase shifters usually suffer from low dynamic range. Dynamic range of phase shifters is particularly important in the operation of phased arrays as phase shifters are required to operate in the presence of strong interferers.
- Furthermore, phase shifter used in receive phase arrays are in the RF signal path and therefore, their noise performance can be critical for the sensitivity of receivers.
- Another factor that should be taken into consideration is the amplitude variation of the signal at each channel. As the signal combining and null forming at undesired directions is significantly affected by the amplitude of the signal at each channel, the phase shifters are required to not just have a low insertion loss but also maintain a constant loss within their phase tuning range.

### 4.1.2 LO Phase shifting

The phase of RF signal at each channel is basically the sum of phases of IF and LO signals. Therefore, tuning the phase of LO signals would translate into changing the phase of RF signals.

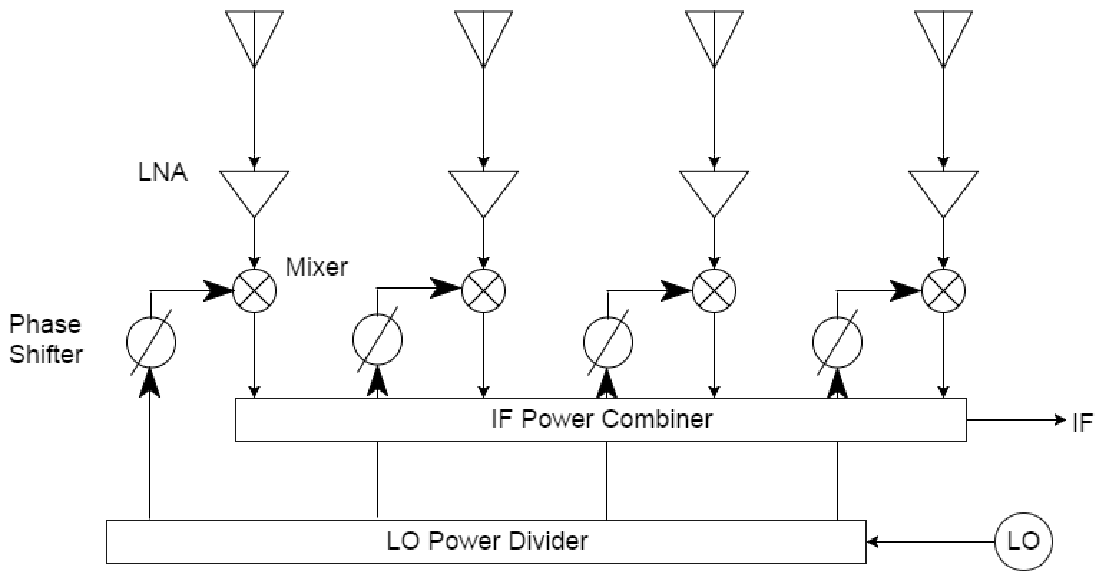


**Figure 4.2:** LO Phase Shifting

#### Advantage

- The phase-shifters are not placed on the signal path, as a result, the loss, nonlinearity and the noise performance of the phase-shifters would not have a direct impact on the overall system performance.

- The performance of the required phase shifter on LO signal path, such as bandwidth, linearity and noise figure will not be as stringent as the phase shifters on the signal path.

**Disadvantage**

- However, this method compared to RF phase shifting requires a large number of mixers, therefore; in general, the overall complexity and power consumption will be higher than phased array based on RF stage phase shifting.

### 4.1.3 IF Phase shifting

As mentioned before, the phase of RF signal at each channel is the sum of phases of IF and LO signals. Therefore, tuning the phase of RF signals can be achieved by tuning through tuning the phase of IF signal.

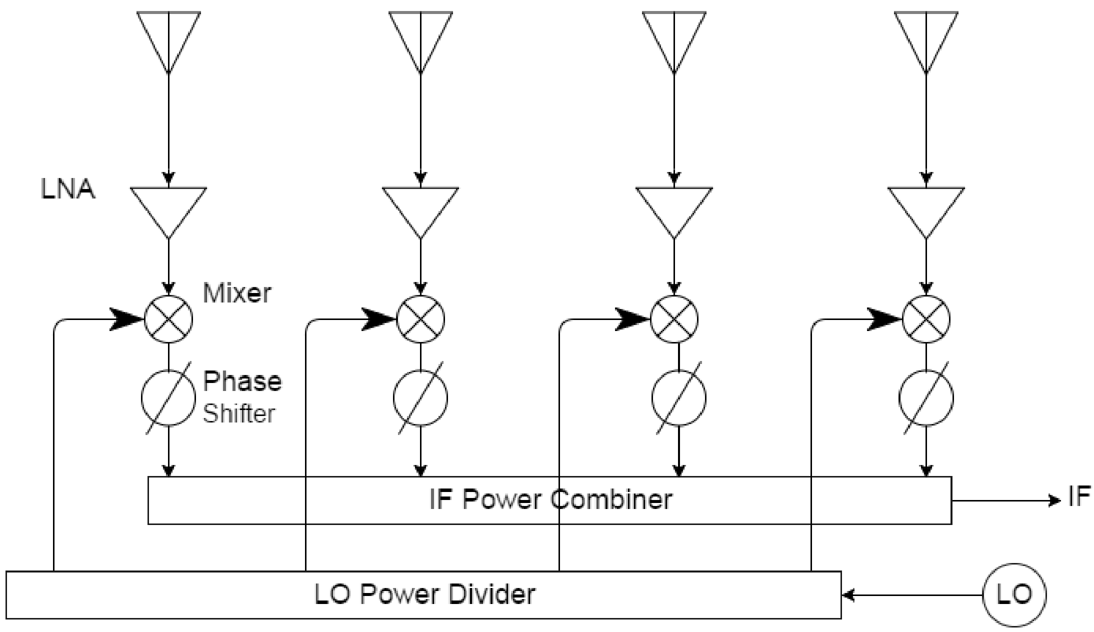


**Figure 4.3:** IF Phase Shifting

**Advantage**

- The main advantage of this approach over RF and LO phase shifting is that the phase-shifting is performed at much lower frequencies, therefore, designing phase shifters with much better performance can be possible at IF path.

- As a result, the loss, nonlinearity and the noise performance of the phase shifters can be much better when IF phase shifting is used.

**Disadvantage**

- However, in this architecture similar to LO phase shifting phased arrays large number of mixers are required that can add to the overall system complexity and power consumption.
- Since the interfere cancellation occurs only after the IF stage, all the mixers are required to have a high level of linearity capable of handling strong interference emanating from undesired directions.

## 4.2 Digital Beamforming

In digital phased array design, the signal at each array element after RF signal conditioning is digitized using an Analog-to-Digital Converter (ADC) and the digital signal are then processed using a Digital Signal Processing unit (DSP).

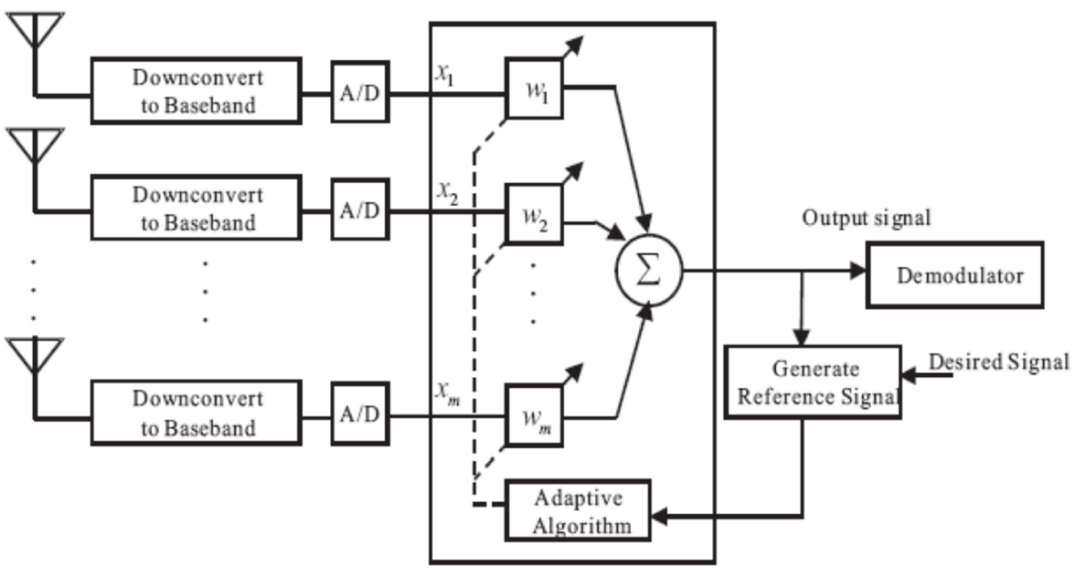


**Figure 4.4:** Digital Beamformer

**Advantage**

- The main advantage of the digital array is its multi function capability such as creating many beams.
- An extensive variety of complex, signal-processing algorithms can be implemented using DSP units. For instance, multi-beam and multiple-input multiple-output (MIMO) functionality can be achieved by the digital phased arrays. Such phased arrays can be capable of distinguishing among desired signals, multipath and interfering signals, as well as demonstrating their directions of arrival.
- Furthermore, digital phased arrays can adaptively update their beam patterns, so as to track the desired signal with the beamâĂŹs main lobe and track the interferers by placing nulls in their directions.
- For higher throughput communication such as WiGig a higher SNR is required at Receiver input. This high SNR is obtained by directing the Main lobe in the desired direction and there by attaining higher directivity. The stringent beam steering can be achieved by applying weighting function in the digital domain.

**Disadvantage**

- Each channel requires the entire RF chain front end circuits. As a result, power consumption is relatively high in this architecture.

Among the architectures, RF phase shifting (RF Analog Beamforming) is employed in the current design since it results in the most compact architecture and its capability of filtering the interferer prior to the mixer.

## 4.3 Antenna Array Radiation Pattern

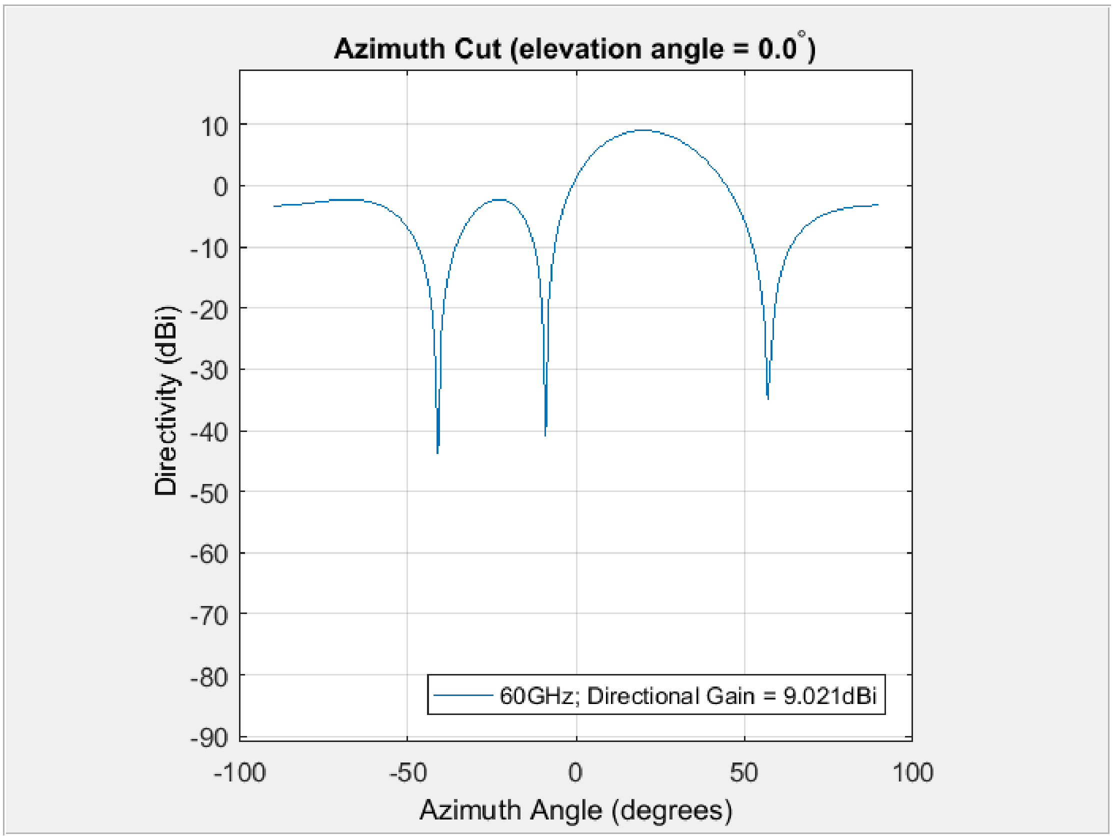


**Figure 4.5:** Radiation Pattern of ULA with 4 Isotropic Antenna Elements

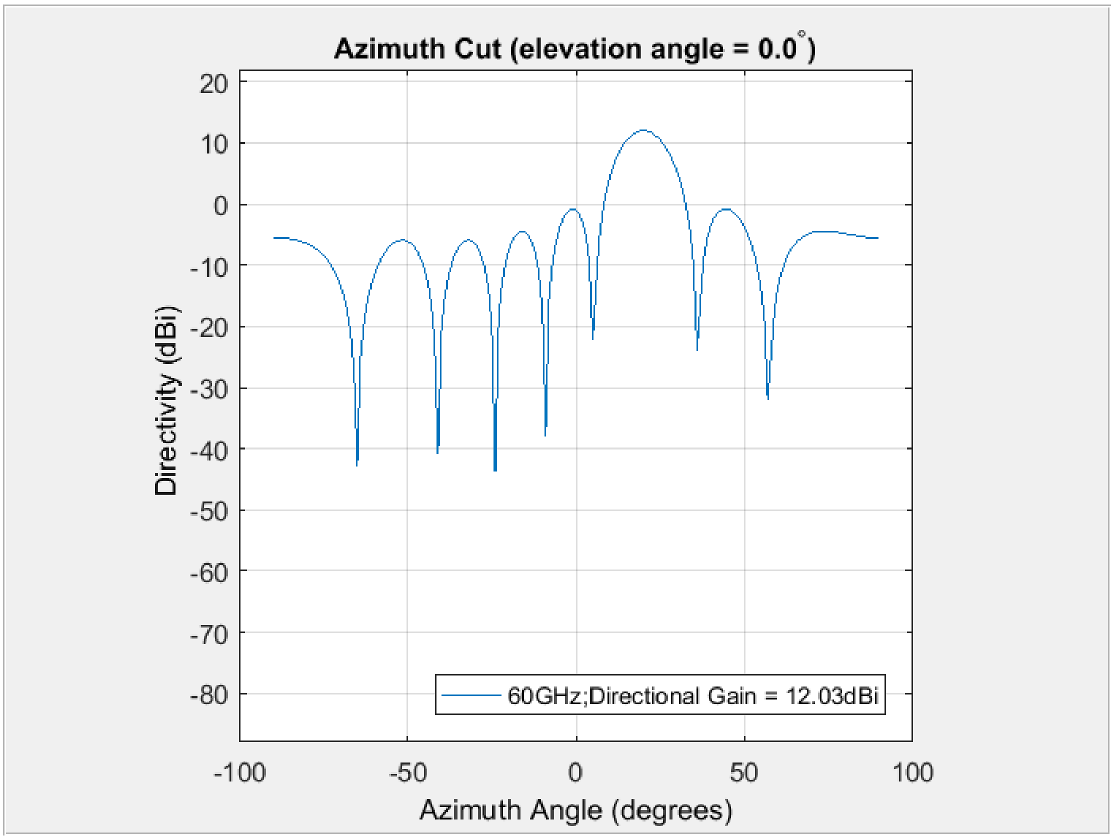


**Figure 4.6:** Radiation Pattern of ULA with 8 Isotropic Antenna Elements

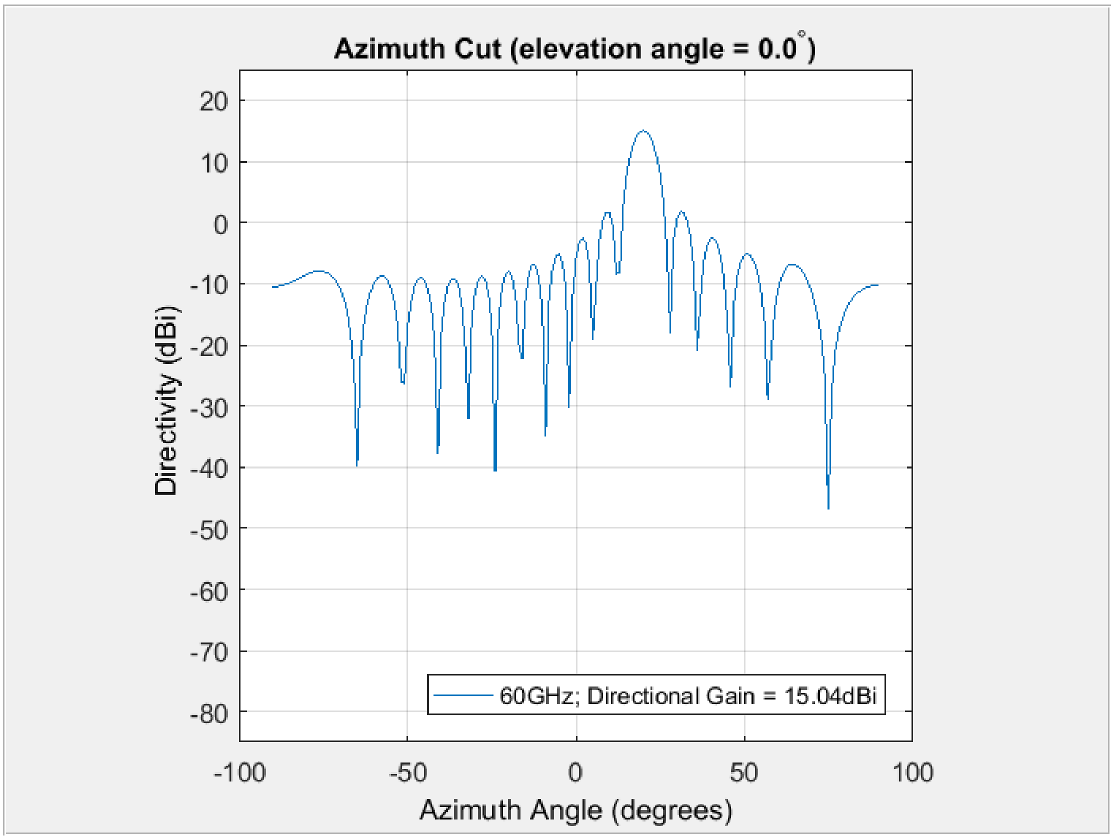


**Figure 4.7:** Radiation Pattern of ULA with 16 Isotropic Antenna Elements

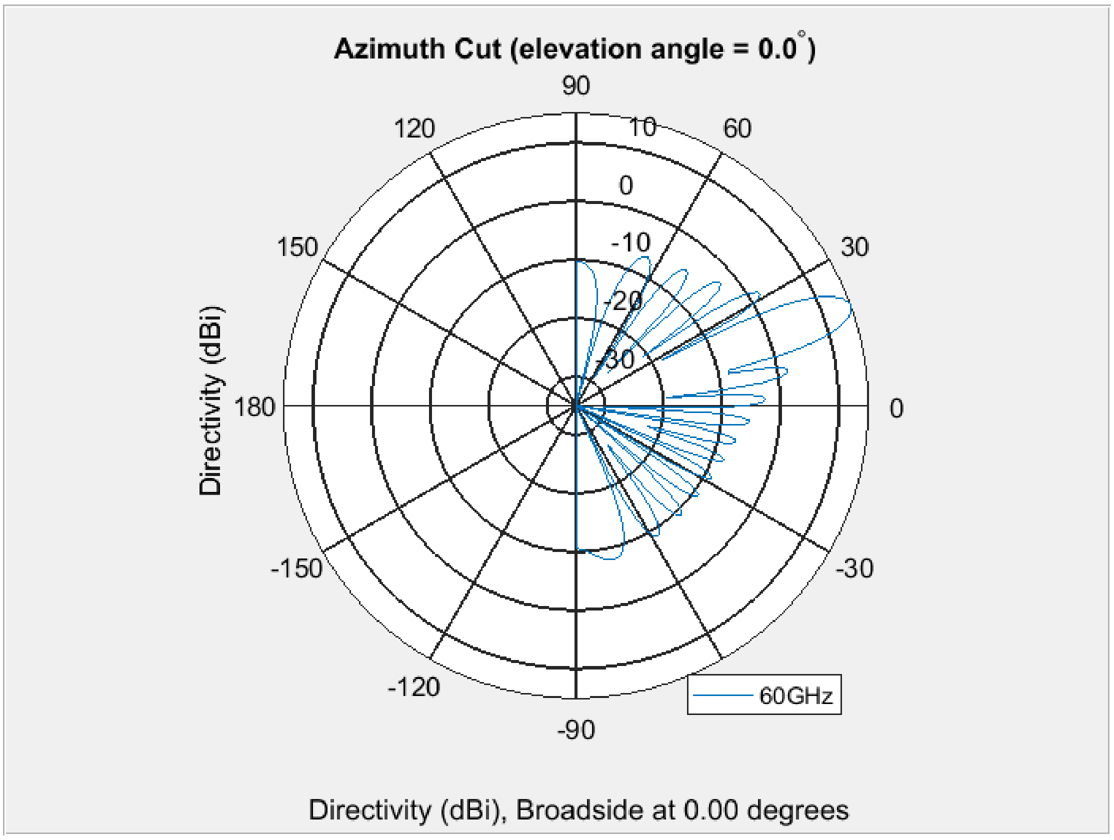


**Figure 4.8:** Radiation Pattern of ULA with 16 Isotropic Antenna Elements (Polar Plot)

# CHAPTER 5

# Transceiver Architecture and Evaluation

## 5.1 Transceiver Block Diagram

### 5.1.1 Transmitter

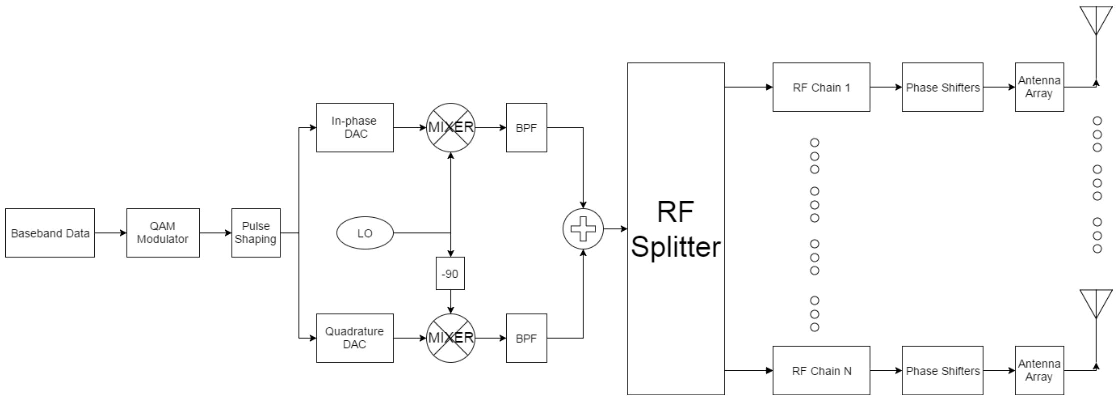


**Figure 5.1:** Transmitter Block Diagram

### 5.1.2 Receiver

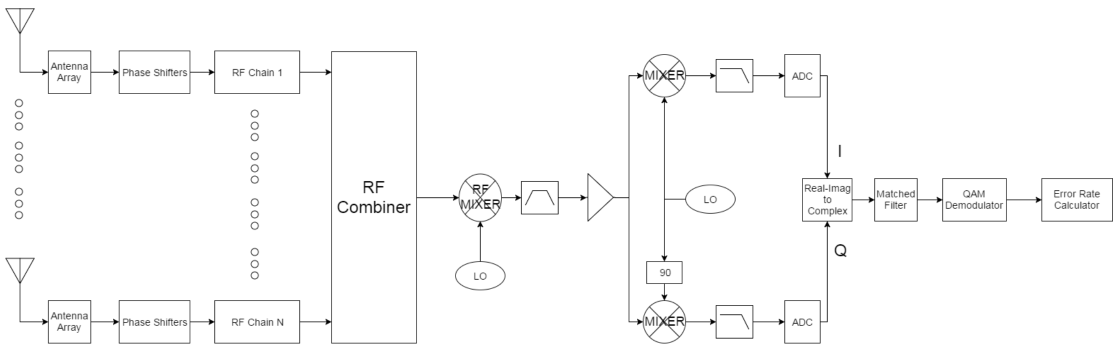


**Figure 5.2:** Receiver Block Diagram

## 5.2 Results

### 5.2.1 Constellation Diagrams

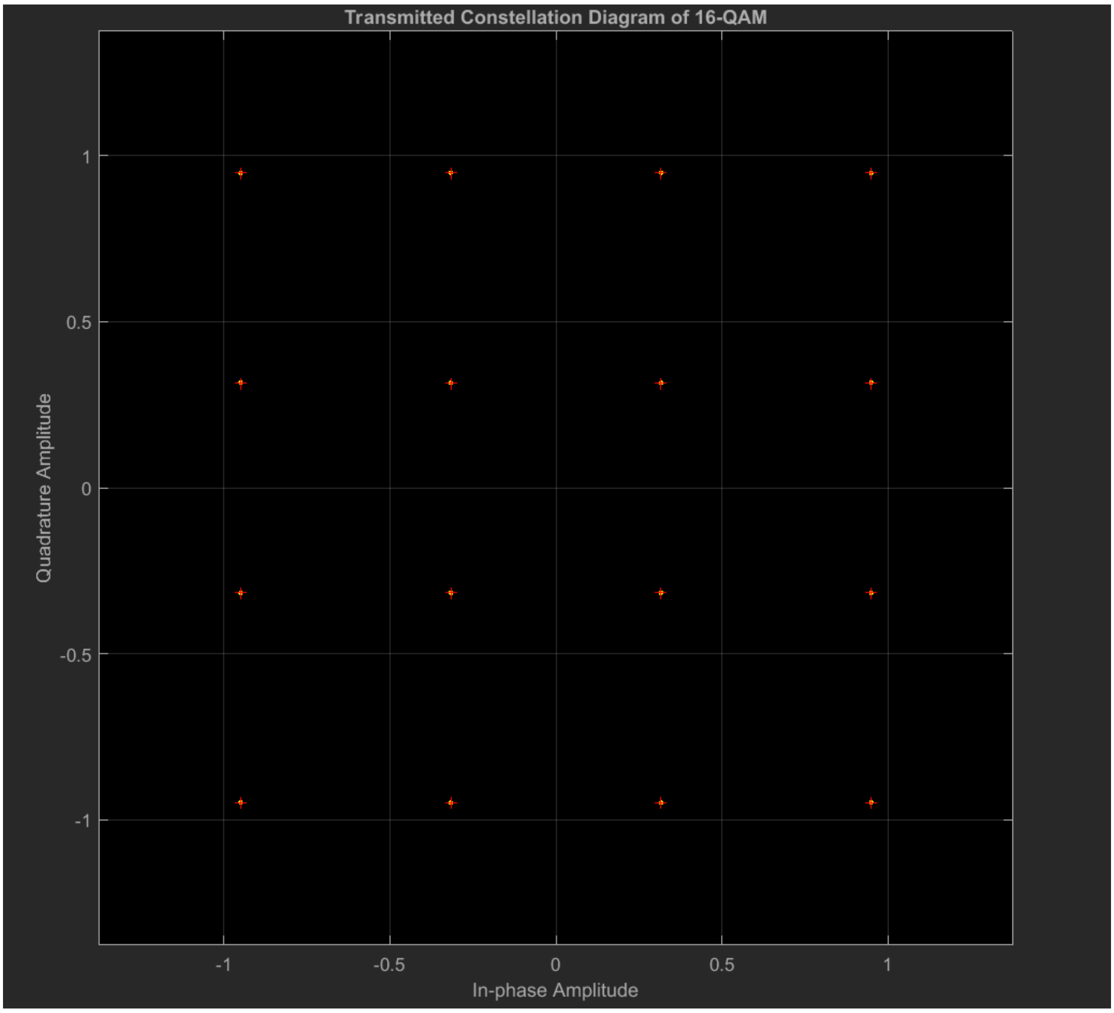


**Figure 5.3:** Transmitted Constellation for 16-QAM

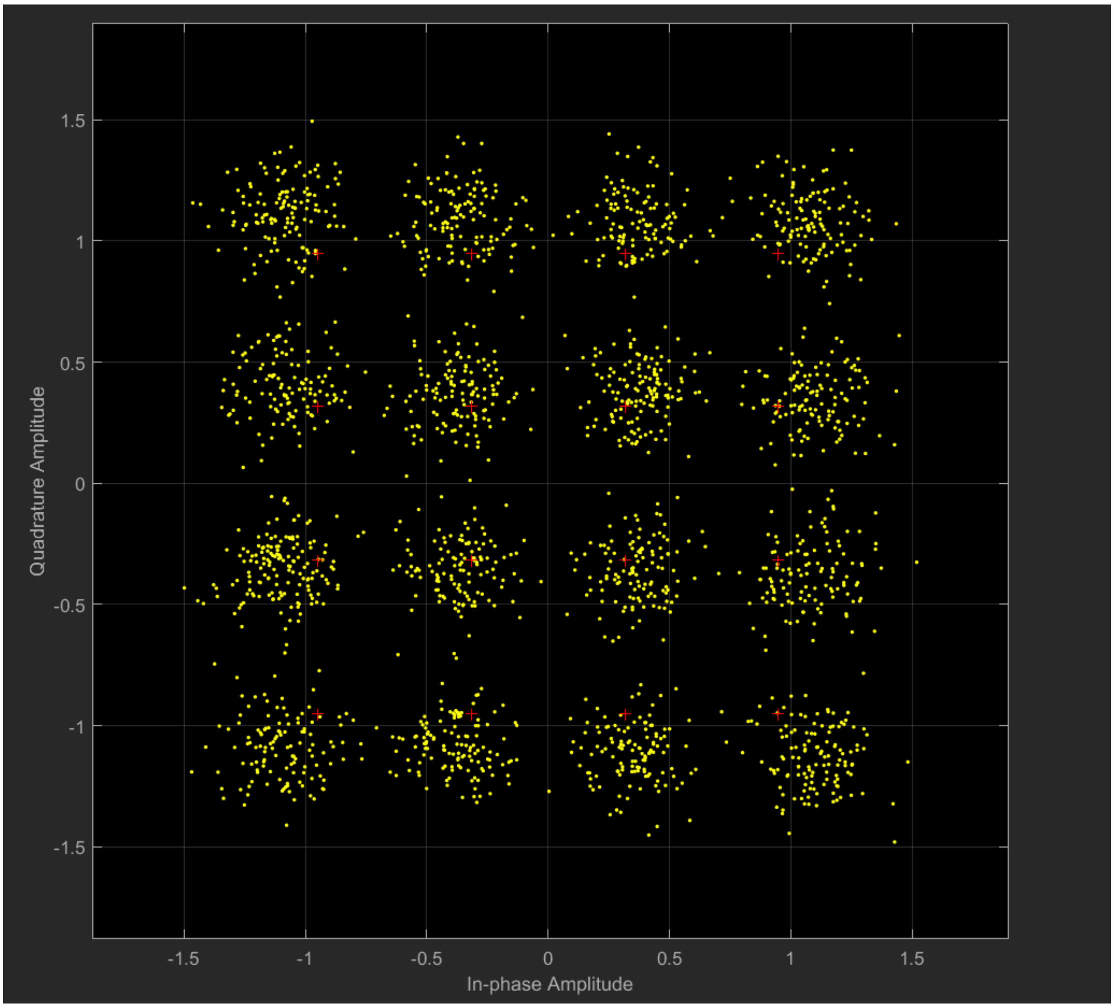


**Figure 5.4:** Received Constellation for 16-QAM for SNR = 10dB

### 5.2.2 Transmitted Spectral Mask

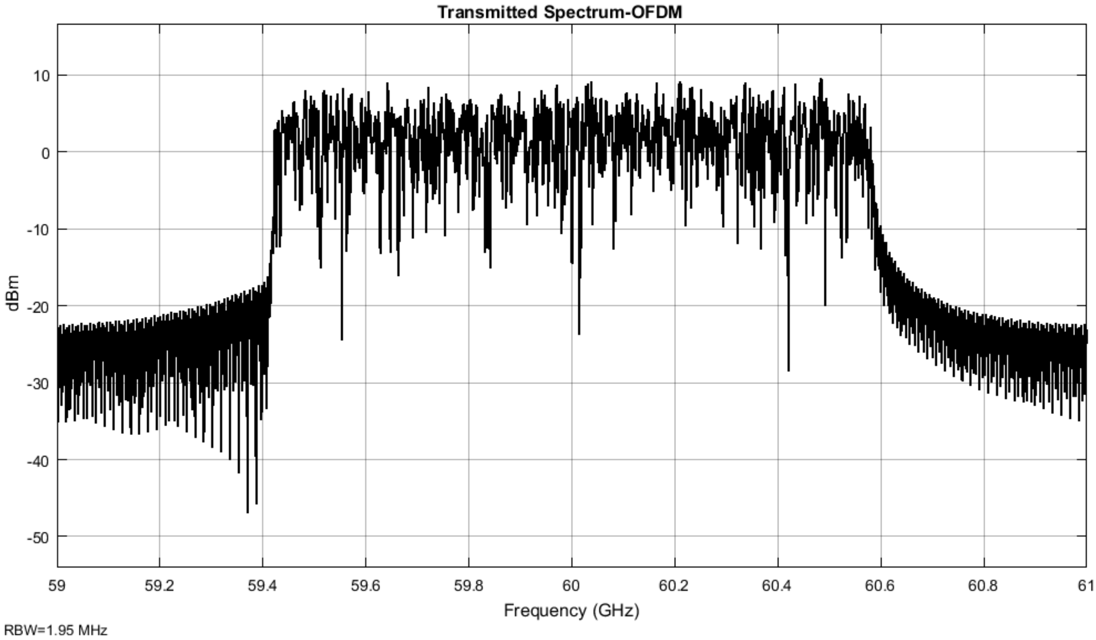


**Figure 5.5:** Transmitted Spectrum-OFDM

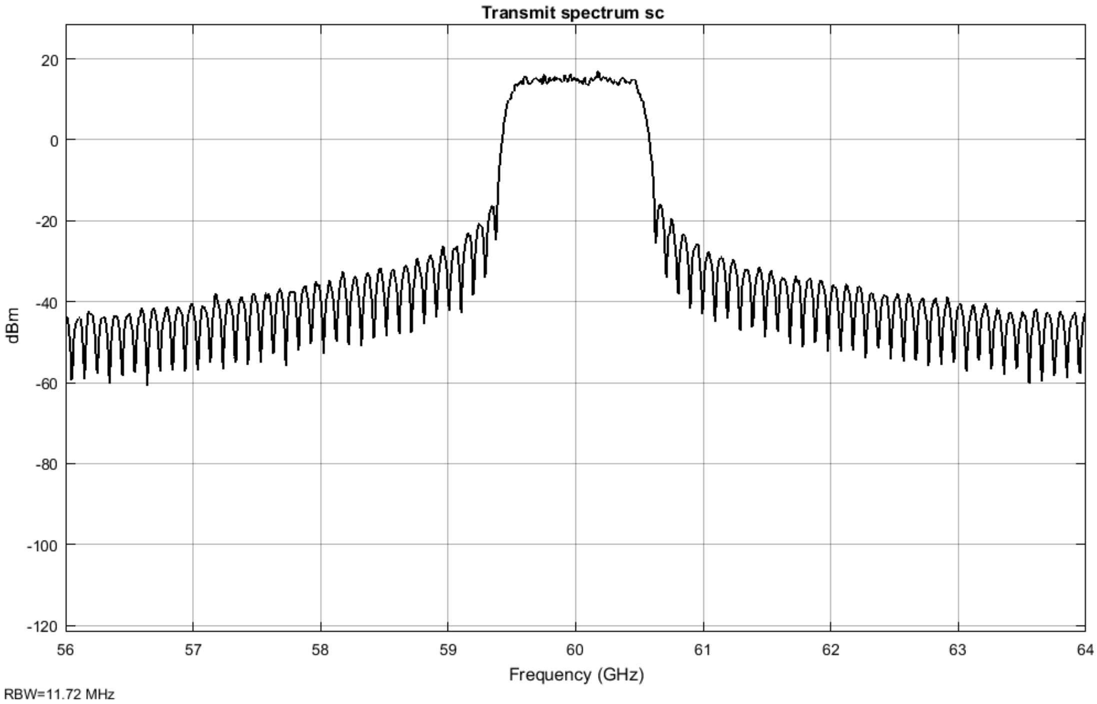


**Figure 5.6:** Wide-Band Transmit Spectrum-SC

### 5.2.3 BER Curves

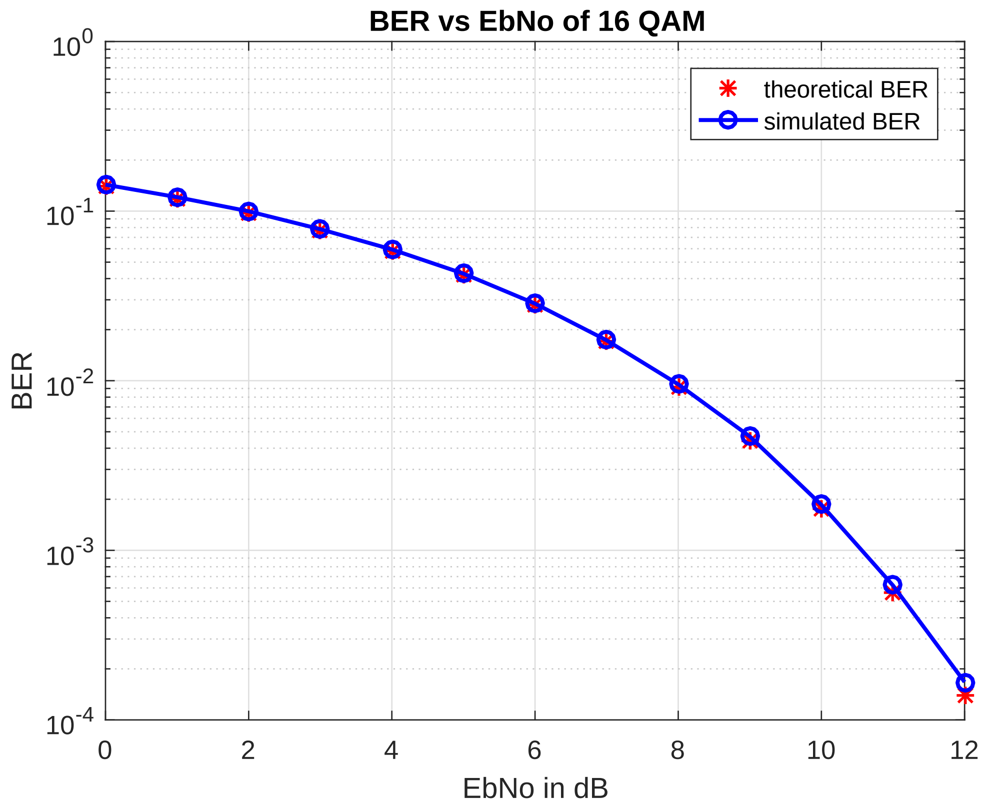


**Figure 5.7:** BER Curve for 16-QAM

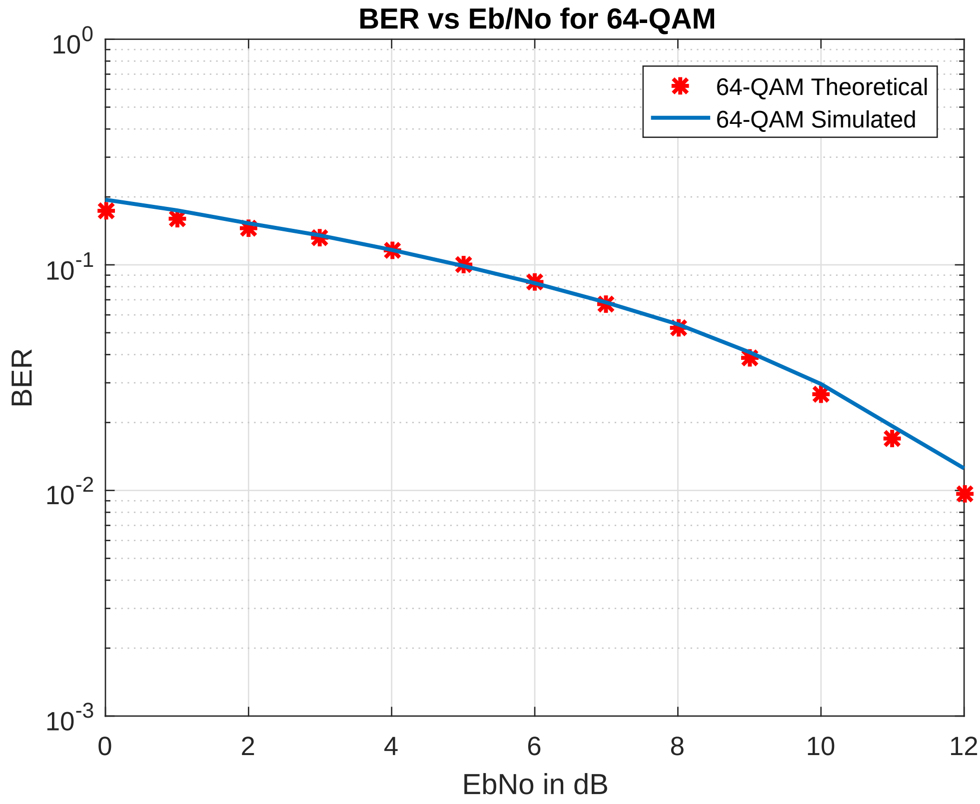


**Figure 5.8:** BER Curve for 64-QAM

# CHAPTER 6

# Conclusion

Communication at mmWave frequencies is not just a matter of changing the carrier frequency but it involves a prior development in signal processing for communication at these frequencies. The radio frequency hardware introduces constraints that have ramifications on the beamforming, precoding, and channel estimation algorithms. The propagation channel has higher dimension, with much more spatial diversity, different path-loss characteristics, and highly sensitive to blockage. The usage of large antenna arrays at both transmitter and receiver, reestablish the importance of MIMO communication. There is a requirement for better signal processing algorithm for mmWave communication systems.

The end-to-end mmWave system model for mmWaves has been designed and evaluated by plotting the BER Curves. Antenna Beamforming has been discussed and the improvement in SNR was shown. An iterative algorithm for Beamsteering has been proposed and the corresponding SNR was improved. The transmitted spectral mask was shown for both OFDM and single carrier modulation. The received constellation for 16-QAM for an SNR of 10dB has been show. The BER Curves for 16-QAM and 64-QAM have been plotted and shown that the BER is sufficiently good by comparing with the theoretical BER.