Simulation of OFDM Transmission and Reception with Multipath Channel

COURSE: TELECOMMUNICATION SUBSYSTEM

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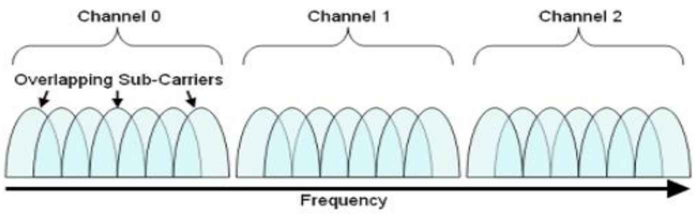
Date: 3rd March 2022

Abstract

This project covers the conceptual and experimental side of Orthogonal Frequency Division Multiplexing (OFDM). Various parameters associated in OFDM are explained in theoretical and mathematical way. OFDM without channel, with AWGN channel, and with Rayleigh multipath fading is simulated to experiment with numerous scenarios and observe behaviors on communication and Bit Error Rate (BER). In this project, *for each experiment*, the design parameters, their calculation, Simulink block diagram, MATLAB code, and results with explanation are mentioned. For experiments, the WiFi 802.11 OFDM parameters are followed. Different Modulations for a given channel condition are compared. Also, different channels for a given modulation is evaluated. Different physical phenomena related to wireless communication are simulated as well.

Introduction to OFDM

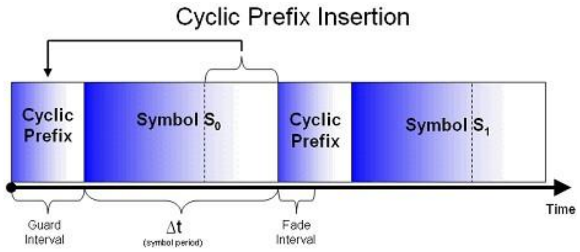
OFDM is a subset of frequency division multiplexing in which a single channel utilizes multiple sub-carriers on adjacent frequencies. In addition the sub-carriers in an OFDM system are overlapping to maximize spectral efficiency. Ordinarily, overlapping adjacent channels can interfere with one another. However, sub-carriers in an OFDM system are precisely orthogonal to one another. Thus, they are able to overlap without interfering. As a result, OFDM systems are able to maximize spectral efficiency without causing adjacent channel interference. The frequency domain of an OFDM system is represented in the diagram below.



OFDM communications systems are able to more effectively utilize the frequency spectrum through overlapping sub-carriers. These sub-carriers are able to partially overlap without interfering with adjacent sub-carriers because the maximum power of each sub-carrier corresponds directly with the minimum power of each adjacent channel. Below, we illustrate the frequency domain of an OFDM system graphically.

In an OFDM system, each channel can be broken into various sub-carriers. The use of sub-carriers makes optimal use out of the frequency spectrum but also requires additional processing by the transmitter and receiver. This additional processing is necessary to convert a serial bitstream into several parallel bitstreams to be divided among the individual carriers. Once the bitstream has been divided among the individual sub-carriers, each sub-carrier is modulated as if it was an individual channel before all channels are combined back together and transmitted as a whole

The modulation of data into a complex waveform occurs at the Inverse Fast Fourier Transform (IFFT) stage of the transmitter. Because wireless communications systems are susceptible to multi-path channel reflections, a ***cyclic prefix*** is added to reduce ISI. A cyclic prefix is a repetition of the first section of a symbol that is appended to the end of the symbol. In addition, it is important because it enables multi-path representations of the original signal to fade so that they do not interfere with the subsequent symbol.



In a traditional FDM system, each channel is spaced by about 25% of the channel width. This is done to ensure that adjacent channels do not interfere. In an OFDM system, on the other hand, the channels actually overlap. As a result, it is possible to maximize the symbol rate, and thus the throughput, for a given bandwidth.

Case-1: OFDM without channel

In this case, the OFDM implementation is simulated without a noise channel between transmitter and receiver.

1.1 Design Specifications

For reference let's follow the ***Wifi 802.11a parameters***. Here are the specifications for this particular case:

Index	Parameter	Value
1	Sampling Frequency	20MHz
2	Bandwidth	20 MHz
3	Bit rate	20Mbps
4	Sample time for Bernoulli's Binary Generator	1/20e6 = 50 ns
5	Bits per OFDM sample	192
6	Samples per frame	192
7	Modulation for each data subcarrier	QAM-16
8	Bits for each data subcarrier	4
9	Number of data subcarriers	48
10	FFT Length (Closest Multiple of 2)/Total carriers	64
11	Unused FFT bins	16
12	Left guard band bins (unused)	8
13	Right guard band bins (unused)	7
14	DC sub carrier	1 (Present)
15	Cyclic Prefix Length	0
16	Number of OFDM Symbols	1
17	Number of TX antennas	1
18	Subcarrier spacing	312.5kHz
19	OFDM baud rate	312.5 kSymbols/s
20	Period of OFDM symbol data part	$3.2\mu s$
21	FFT/IFFT Period	$3.2\mu s$
22	Guard Interval Period	0 seconds
23	Total Symbol Time	$3.2\mu s$

1.2 Parameter Explanation and Calculation

The sampling frequency for this experiment was selected to be 20MHz as indicated by parameter 1.

$$Bandwidth \ = \text{Sampling Frequency} = 20 \text{ MHz} \qquad\qquad \text{(indicated by paramater at index 2)}$$

And as we are using the Bernoulli's bit generator,

$$Bitrate = \text{Sampling frequency} = 20\text{MHz} \qquad \text{(indicated by paramater at index 3)}$$

So bitrate is 20Mbps as indicated by parameter at index 3.

$$Bit\ Period = \frac{1}{\text{Bitrate}} = \frac{1}{20\text{MHz}} = 50ns \text{ (indicated by paramater at index 4)}$$

In this experiment, it was decided to send 192 bits per OFDM symbol using QAM-16 for each subcarrier. Therefore the samples per frame for Bernoulli's generator was picked to be 24 as indicated by parameter at index 5.

Each QAM-16 modulated subcarrier contains 4 bits so for total of 24 bits so:

$$Number\ of\ data\ subcarriers = \frac{\text{Bits per OFDM symbol}}{\text{Bits per Digital Modulation}} = \frac{192}{4} = 48$$

As indicated by parameter at index 9.

It's recommended to use **<u>FFT length as power of 2 which is also equal to the total number of carriers</u>** including data, pilot, guard bands, dc null. In our example, the closest multiple of 2 from 48 is 64. Hence FFT length is 64 as indicated by parameter at index 10.

$$Total\ subcarriers = \text{Data} + \text{Pilot} + \text{Left Guard} + \text{Right Guard} + \text{DC Null}$$

Since we only need 48 subcarriers and rest of 16 subcarriers won't be used. Therefore, we will split them in left guard, right guard, and DC null with 8, 7 and 1 subcarriers respectively. This is indicated by parameters at index 12, 13, and 14 respectively.

$$Subcarrier\ spacing = \frac{\text{Sampling Frequency (Fs)}}{\text{Number of carriers}} = \frac{20}{64} = 312.5\ kHz$$

As indicated by parameter at index 18

The OFDM baud rate is also equal to subcarrier spacing as 312.5 k symbols per second as indicated by parameter at index 19.

$$OFDM\ Period = \frac{1}{\text{Subcarrier spacing}} = \frac{1}{312.5\text{kHz}} = 3.2\mu\text{s}$$

As indicated by parameter at index 20

This is also the IFFT period as indicated by parameter at index 21.

In this case, we aren't using the cyclic prefix, hence there is no guard interval. So total OFDM time is 3.2μs as indicated by parameter at index 23.

The same parameters are used in the receiver block with OFDM demodulator and QAM demodulator.

1.3 Process Flow and Design Components

Data Generation: The incoming data is represented with the binary bits with specific bitrate In Simulink, this is modeled by <u>*Bernoulli Binary Generator*</u> block.

16-QAM Modulation: The random integer are converted into bits. Each integer is represented by 4 bits making 1 complex symbol for 16-QAM using constellation diagram. This is modeled with block <u>*Rectangular QAM Modulator*</u>.

OFDM Modulation: OFDM modulator automatically converts serial incoming data to parallel streams for each subcarrier. QAM-16 modulation for each subcarrier happens. Followed by IFFT to convert N frequency bins to N time-domain discrete samples. In case there is cyclic prefix of length X then output of N+X length of time-domain symbol.

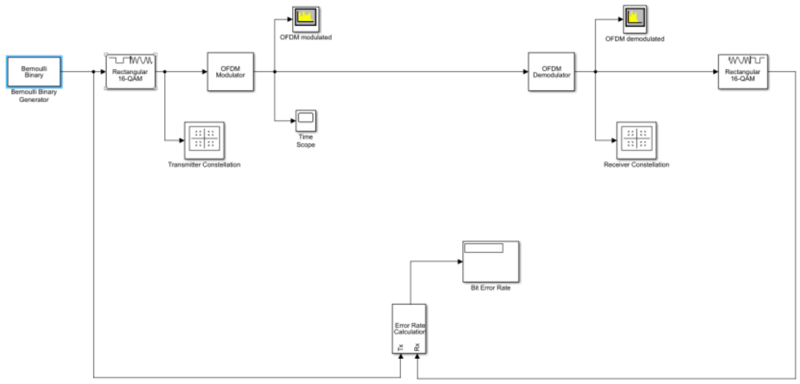
OFDM Demodulation: OFDM demodulator automatically converts OFDM symbol into multiple QAM symbols

16-QAM Demodulation: The complex symbol is demodulated using *rectangular QAM demodulator block*. This converts symbol into 4 bits from constellation diagram.

Bit Error Rate: The final step in this exercise is to evaluate the performance of the design. This is implemented using the block called 'Error Rate Calculator.' The transmitted bits and received (decoded) bits are its input and the vector of [error rate, no of error symbols, no of symbols checked] is outputted.

1.4 Block Diagram

The block diagram of OFDM without channel is shown below:



1.5 Results

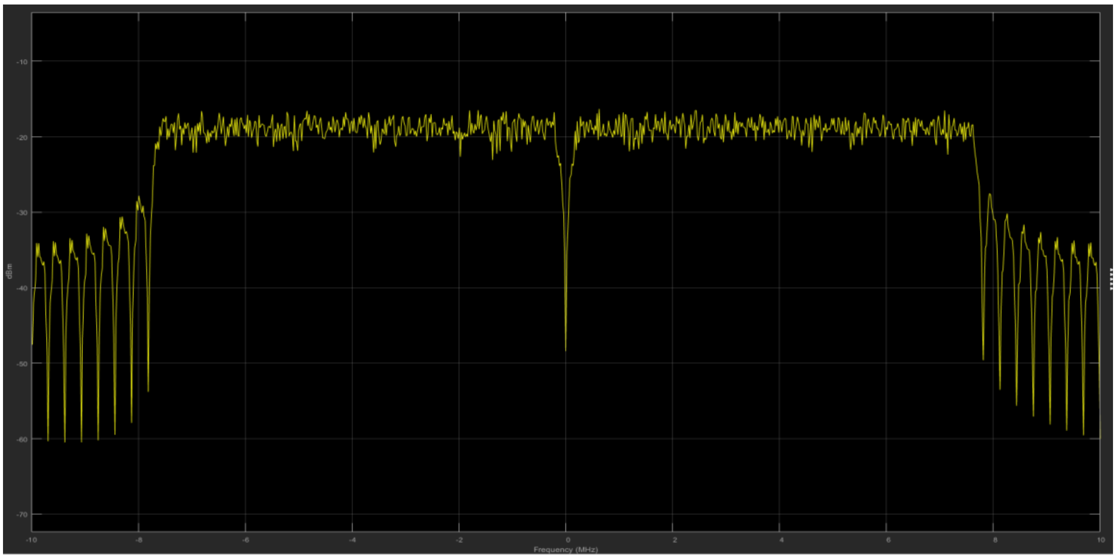


Figure-1: The figure above is the ODFM modulated symbol spectrum. As we can see the left guard, right guard and DC sub carriers are negligible in power. And the central carriers have power which are data subcarriers.

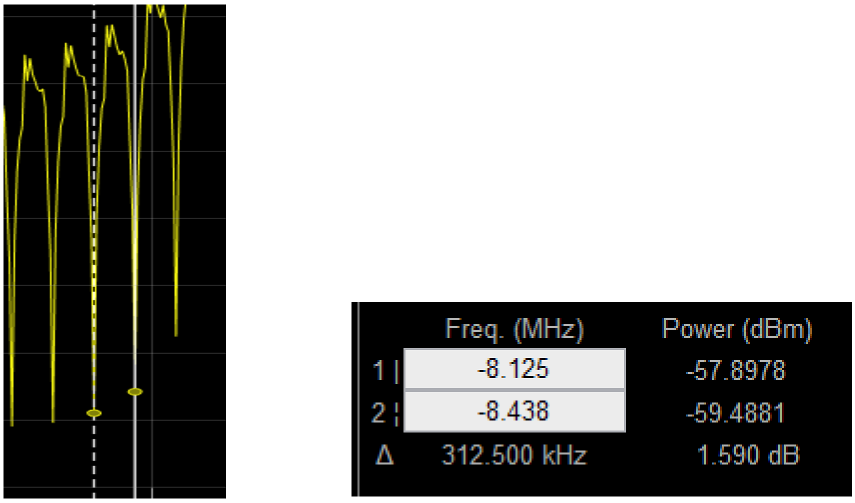


Figure-2: The figure above shows the subcarrier spacing to be 312.5 kHz which was calculated in section 1.2 above.

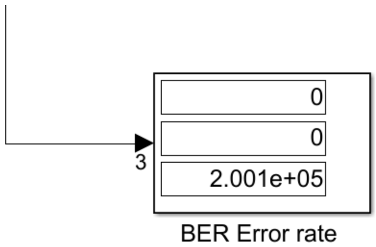


Figure-3: The figure above shows the error rate in this case without channel. As expected, it's zero.

Case-2: OFDM with AWGN channel

Now consider the case of OFDM with the AWGN channel.

2.1 Design Specifications

Here are the specifications for this particular case:

Index	Parameter	Value
1	Sampling Frequency	20MHz
2	Bandwidth	20 MHz
3	Bit rate	20Mbps
4	Sample time for Bernoulli's Binary Generator	1/20e6 = 50 ns
5	Bits per OFDM sample	192
6	Samples per frame	192
7	Modulation for each data subcarrier	QAM-16
8	Bits for each data subcarrier	4
9	Number of data subcarriers	48
10	FFT Length (Closest Multiple of 2)/Total carriers	64
11	Unused FFT bins	16
12	Left guard band bins (unused)	8
13	Right guard band bins (unused)	7
14	DC sub carrier	1 (Present)
15	Cyclic Prefix Length	0
16	Number of OFDM Symbols	1
17	Number of TX antennas	1
18	Subcarrier spacing	312.5kHz

19	OFDM baud rate	312.5 kSymbols/s
20	Period of OFDM symbol data part	3.2μs
21	FFT/IFFT Period	3.2μs
22	Guard Interval Period	0 seconds
23	Total Symbol Time	3.2μs
24	AWGN Mode	Eb/No
25	Eb/No	[0-15] dB
26	Input signal power referenced to 1 Ohm	33mW (calculated by variance)
27	AWGN Symbol Period	3.2μs

2.2 Parameter Explanation and Calculation

The sampling frequency for this experiment was selected to be 20MHz as indicated by parameter 1.

$$Bandwidth\ = \text{Sampling Frequency} = 20\text{ MHz} \qquad \text{(indicated by paramater at index 2)}$$

And as we are using the Bernoulli's bit generator,

$$Bitrate = \text{Sampling frequency} = 20\text{MHz} \qquad \text{(indicated by paramater at index 3)}$$

So bitrate is 20Mbps as indicated by parameter at index 3.

$$Bit\ Period = \frac{1}{\text{Bitrate}} = \frac{1}{20\text{MHz}} = 50ns \text{ (indicated by paramater at index 4)}$$

In this experiment, it was decided to send 192 bits per OFDM symbol using QAM-16 for each subcarrier. Therefore the samples per frame for Bernoulli's generator was picked to be 24 as indicated by parameter at index 5.

Each QAM-16 modulated subcarrier contains 4 bits so for total of 24 bits so:

$$Number\ of\ data\ subcarriers = \frac{\text{Bits per OFDM symbol}}{\text{Bits per Digital Modulation}} = \frac{192}{4} = 48$$

As indicated by parameter at index 9.

It's recommended to use **<u>FFT length as power of 2 which is also equal to the total number of carriers</u>** including data, pilot, guard bands, dc null. In our example, the closest multiple of 2 from 48 is 64. Hence FFT length is 64 as indicated by parameter at index 10.

$$Total\ subcarriers = \text{ Data + Pilot + Left Guard + Right Guard + DC Null}$$

Since we only need 48 subcarriers and rest of 16 subcarriers won't be used. Therefore, we will split them in left guard, right guard, and DC null with 8, 7 and 1 subcarriers respectively. This is indicated by parameters at index 12, 13, and 14 respectively.

$$Subcarrier\ spacing = \frac{\text{Sampling Frequency (Fs)}}{\text{Number of carriers}} = \frac{20}{64} = 312.5\ kHz$$

As indicated by parameter at index 18

The OFDM baud rate is also equal to subcarrier spacing as 312.5 k symbols per second as indicated by parameter at index 19.

$$OFDM\ Period = \frac{1}{\text{Subcarrier spacing}} = \frac{1}{312.5\text{kHz}} = 3.2\mu\text{s}$$

As indicated by parameter at index 20

This is also the IFFT period as indicated by parameter at index 21.

In this case, we aren't using the cyclic prefix, hence there is no guard interval. So total OFDM time is 3.2μs as indicated by parameter at index 23.

For AWGN, Eb/No mode is selected. Here 'Eb' is the energy of a bit and 'No' is Noise spectral density. **<u>The value is controlled through Matlab code and it changes from 0 to 15dB in step size of 3dB</u>** as indicated by parameter at index 25.

The <u>power of input signal is equal to the variance of ODFM signal because the mean power is zero</u>. Therefore variance correspond to area under the curve, hence power. Generally it revolved around 12mW as indicated by parameter at index 26.

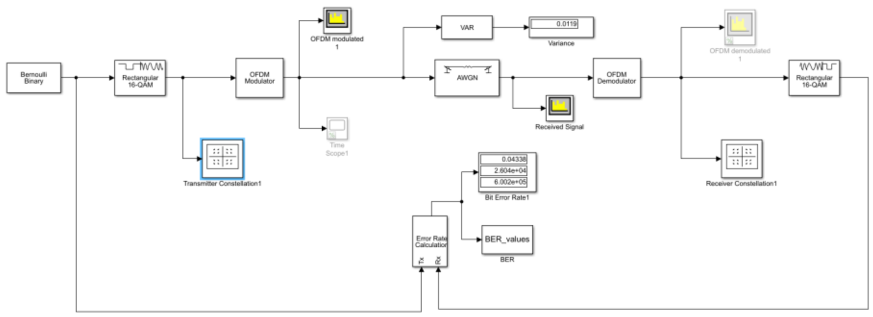
The same parameters are used in the receiver block with OFDM demodulator and QAM demodulator.

2.3 Process Flow and Design Components

The blocks used here are same as mentioned in prior section 1.3. Only additional block is **<u>AWGN Channel</u>** to add a Guassian noise. The value of **<u>EbNo is controlled from 0 to 15dB with step size of 3dB</u>** and the BER was observed.

2.4 Block Diagram

The block diagram is given below:



2.5 Results

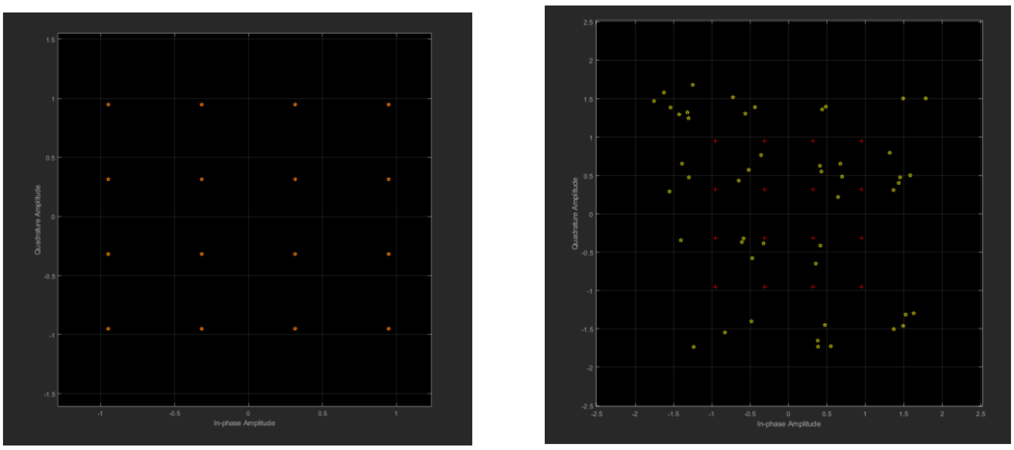


Figure-4: The figure compares the transmitted (left) and received (right) constellation diagram of QAM symbols. On left, everything is perfect. But because of noise channel, the received symbols (yellow) are quite imperfect from expected (red).

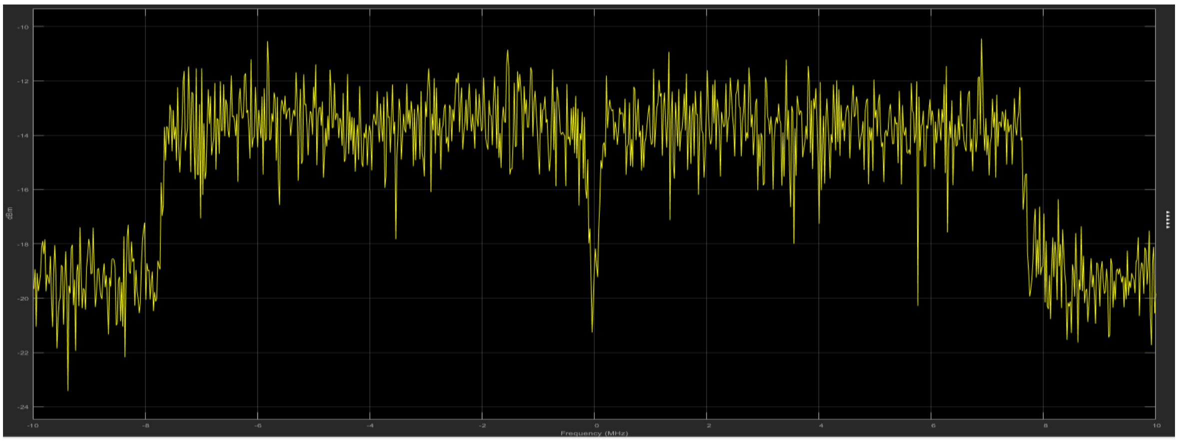


Figure-5: The received OFDM signal after AWGN channel with SNR 2dB. As you can see the noise of the signal is increased. It has been disrupted and quite different which was transmitted as shown in Figure-1

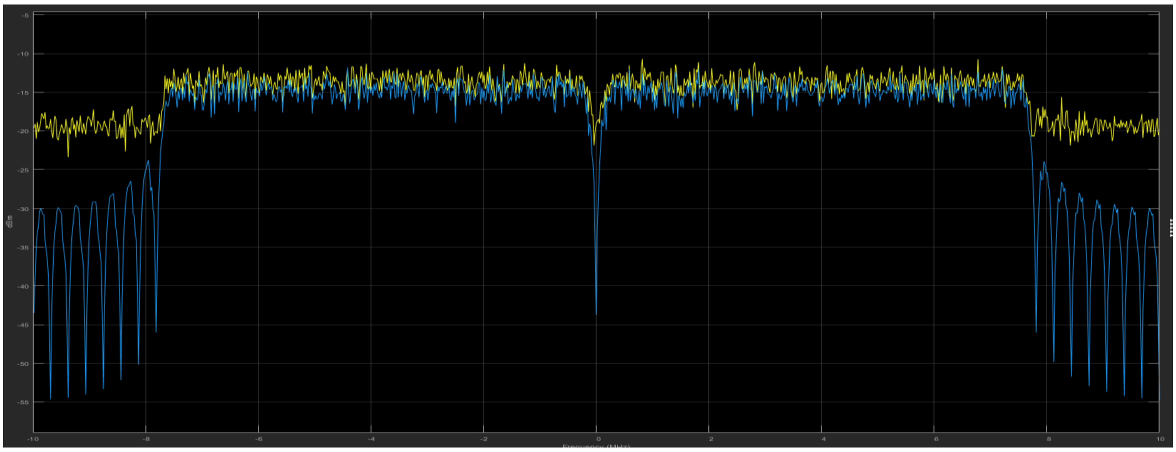


Figure-6: The OFDM symbol <u>transmitted vs received</u> following 802.11 protocol. The blue one was transmitted and have very low power for NULL subcarriers. The difference in power levels of data subcarriers and NULL subcarriers is large. The yellow one is received after AWGN channel with SNR = 2dB. It has increased the noise in carriers and increased the power levels of NULL subcarriers. Now, the difference in power levels of data subcarriers and NULL subcarriers is reduced.

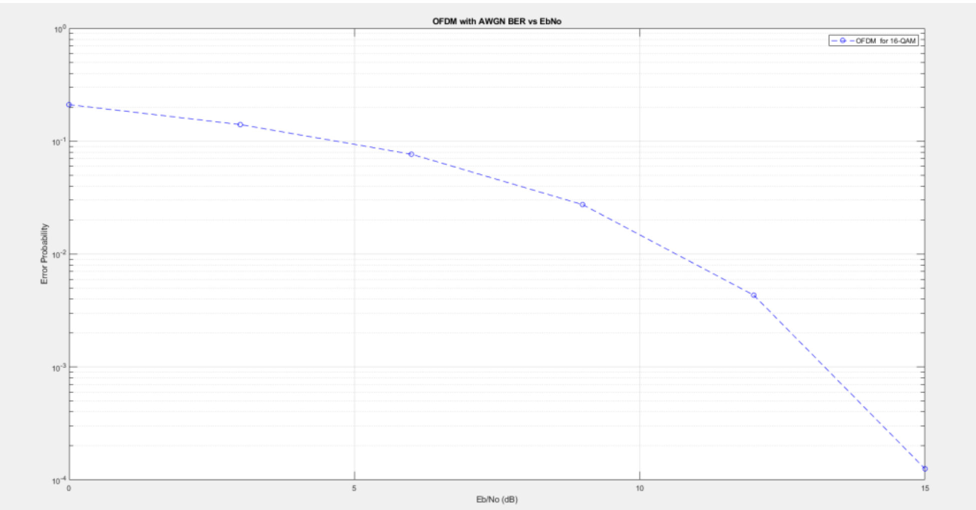


Figure-7: OFDM for 16-QAM <u>Bit Error rate vs EbNo</u>. As EbNo increases errors reduce exponentially as expected. Eb/No varies from 0 to 15 dB in steps of 3dB. Error goes very low around 15dB.

2.6 MATLAB Code

```
clear; clc;
close all;

EbNoVec = [0:3:15];
maxNumErrors = 1e6;
maxNumBits = 1e10;

for n = 1: length(EbNoVec)
    EbNo = EbNoVec (n);
    output = sim ('OFDM_project');
    BERVEC(n,:) = BER_values6(10417,1);
end
semilogy(EbNoVec,BERVEC(:,1), 'ob--');
legend('OFDM  for 16-QAM');
ylabel('Error Probability');
xlabel('Eb/No (dB)');
title('OFDM with AWGN BER vs EbNo');
grid on;
```

SIMULATION TIME : 0.1s

Simulink Block : AWGN Channel
Parameter Name : Eb / No (dB)
Parameter Value: <<EbNo>>

Case-3: OFDM with AWGN and 64-QAM

3.1 Design Specifications

In this case, number of **data subcarriers become 32 each containing 6 bits**. Rest remains same. The **unused frequency bins are 32**. The **effective bandwidth is reduced by 33%** as data subcarriers are decreased from 48 to 32.

3.2 Results

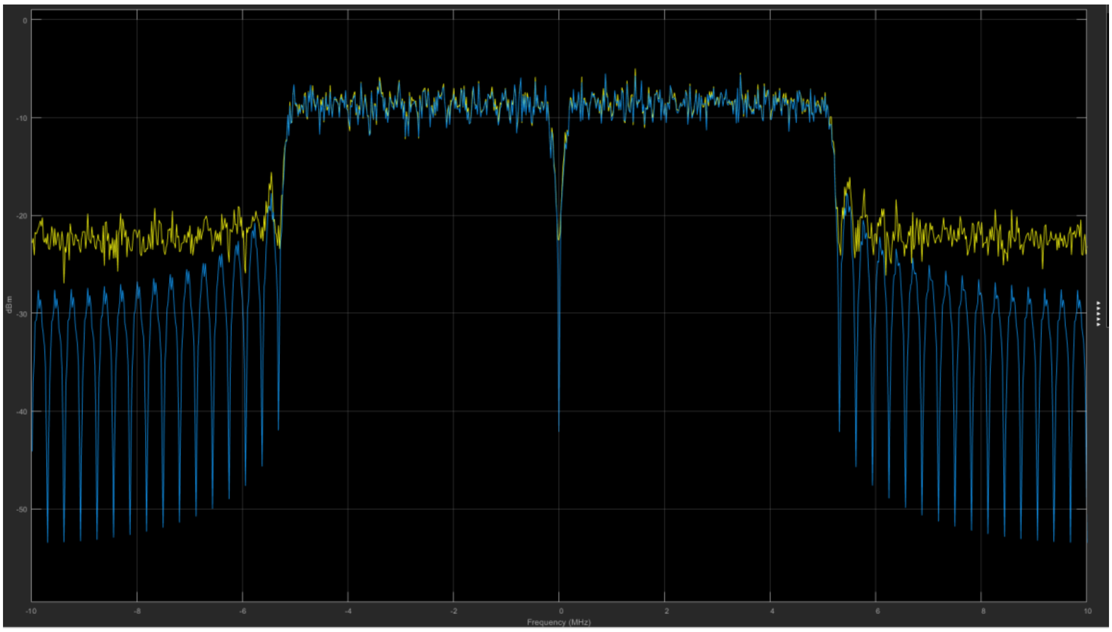


Figure-8: OFDM symbol for 64-QAM with 32 data carriers. The blue one is transmitted and yellow one is received with AWGN having Eb/No = 2dB.

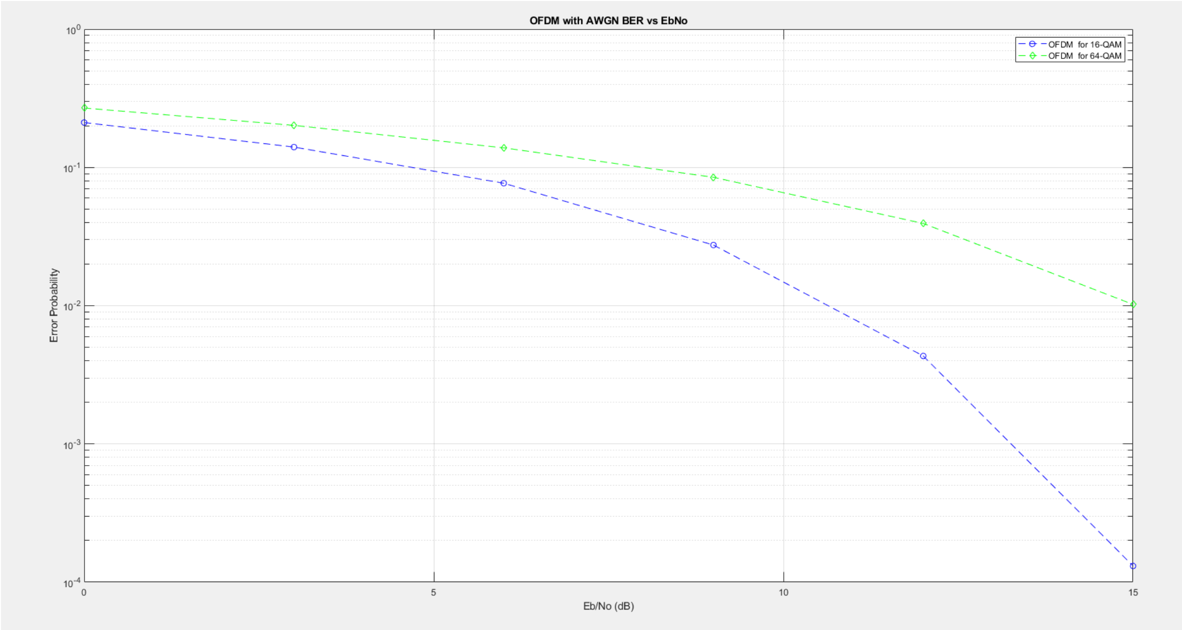


Figure-10: The Bit Error rate vs EbNo for 64-QAM vs 16-QAM. As EbNo increases errors reduce exponentially as expected. The blue is OFDM for 16-QAM and green is OFDM for 64-QAM. The error rate for given Eb/No is much higher for 64-QAM than 16-QAM. This makes sense with an intuition as higher modulations leads to higher errors.

3.3 MATLAB Code

```
clear; clc;
close all;

EbNoVec = [0:3:15];
maxNumErrors = 1e6;
maxNumBits = 1e10;

for n = 1: length(EbNoVec)
    EbNo = EbNoVec (n);
    output = sim ('OFDM_project');
end
semilogy(EbNoVec,BERVEC(:,1), 'ob--');
legend('OFDM  for 16-QAM');
ylabel('Error Probability');
xlabel('Eb/No (dB)');
title('OFDM with AWGN BER vs EbNo');
grid on;

hold;
semilogy(EbNoVec,BERVEC1(:,1), 'dg--');
legend('OFDM  for 16-QAM','OFDM  for 64-QAM');
```

SIMULATION TIME : 0.1s

Simulink Block : AWGN Channel
Parameter Name : Eb / No (dB)
Parameter Value: <<EbNo>>

Case-4: OFDM with AWGN channel and cyclic prefix

4.1 Design Specifications

Here are the specifications for this particular case:

Index	Parameter	Value
1	Sampling Frequency	20MHz
2	Bandwidth	20 MHz

3	Bit rate	20Mbps
4	Sample time for Bernoulli's Binary Generator	1/20e6 = 50 ns
5	Bits per OFDM sample	192
6	Samples per frame	192
7	Modulation for each data subcarrier	QAM-16
8	Bits for each data subcarrier	4
9	Number of data subcarriers	48
10	FFT Length (Closest Multiple of 2)/Total carriers	64
11	Unused FFT bins	16
12	Left guard band bins (unused)	8
13	Right guard band bins (unused)	7
14	DC sub carrier	1 (Present)
15	Cyclic Prefix Length	16
16	Number of OFDM Symbols	1
17	Number of TX antennas	1
18	Subcarrier spacing	250kHz
19	OFDM baud rate	250 kSymbols/s
20	Period of OFDM symbol data part	3.2μs
21	FFT/IFFT Period	3.2μs
22	Guard Interval Period	800ns
23	Total Symbol Time	4μs
24	AWGN Mode	Eb/No
25	Eb/No	[0-15] dB
26	Input signal power referenced to 1 Ohm	33mW (calculated by variance)
27	AWGN Symbol Period	3.2e-6 seconds

2.2 Parameter Explanation and Calculation

The sampling frequency for this experiment was selected to be 20MHz as indicated by parameter 1.

$$Bandwidth\ = \text{Sampling Frequency} = 20\text{ MHz} \qquad \text{(indicated by paramater at index 2)}$$

And as we are using the Bernoulli's bit generator,

$$Bitrate = \text{Sampling frequency} = 20\text{MHz} \qquad \text{(indicated by paramater at index 3)}$$

So bitrate is 20Mbps as indicated by parameter at index 3.

$$Bit\ Period = \frac{1}{\text{Bitrate}} = \frac{1}{20\text{MHz}} = 50ns \text{ (indicated by paramater at index 4)}$$

In this experiment, it was decided to send 192 bits per OFDM symbol using QAM-16 for each subcarrier. Therefore the samples per frame for Bernoulli's generator was picked to be 24 as indicated by parameter at index 5.

Each QAM-16 modulated subcarrier contains 4 bits so for total of 24 bits so:

$$Number\ of\ data\ subcarriers = \frac{\text{Bits per OFDM symbol}}{\text{Bits per Digital Modulation}} = \frac{192}{4} = 48$$

As indicated by parameter at index 9.

It's recommended to use **<u>FFT length as power of 2 which is also equal to the total number of carriers</u>** including data, pilot, guard bands, dc null. In our example, the closest multiple of 2 from 48 is 64. Hence FFT length is 64 as indicated by parameter at index 10.

$$Total\ subcarriers = \text{Data} + \text{Pilot} + \text{Left Guard} + \text{Right Guard} + \text{DC Null}$$

Since we only need 48 subcarriers and rest of 16 subcarriers won't be used. Therefore, we will split them in left guard, right guard, and DC null with 8, 7 and 1 subcarriers respectively. This is indicated by parameters at index 12, 13, and 14 respectively.

In this case, we are considering 16 samples of cyclic prefix as indicated by parameter at index 15. Hence total samples are 64+16 = 80.

$$Subcarrier\ spacing == \frac{20}{80} = 250\ kHz$$

As indicated by parameter at index 18

The OFDM baud rate is also equal to subcarrier spacing as 312.5 k symbols per second as indicated by parameter at index 19.

$$OFDM\ Period = \frac{1}{\text{Subcarrier spacing}} = \frac{1}{250\text{kHz}} = 4\mu\text{s}$$

As indicated by parameter at index 20

This is also the IFFT period as indicated by parameter at index 21.

The guard interval is:

$$Guard\ Interval == \frac{\text{16 cyclic samples}}{\text{20MHz}} = 800\ ns$$

So total OFDM time is 3.2 + 0.8 = 4μs as indicated by parameter at index 23.

For AWGN, Eb/No mode is selected. Here 'Eb' is the energy of a bit and 'No' is Noise spectral density. **The value is controlled through Matlab code and it changes from 0 to 15dB in step size of 3dB** as indicated by parameter at index 25.

The power of input signal is equal to the variance of ODFM signal because the mean power is zero. Therefore variance correspond to area under the curve, hence power. Generally it revolved around 12mW as indicated by parameter at index 26.

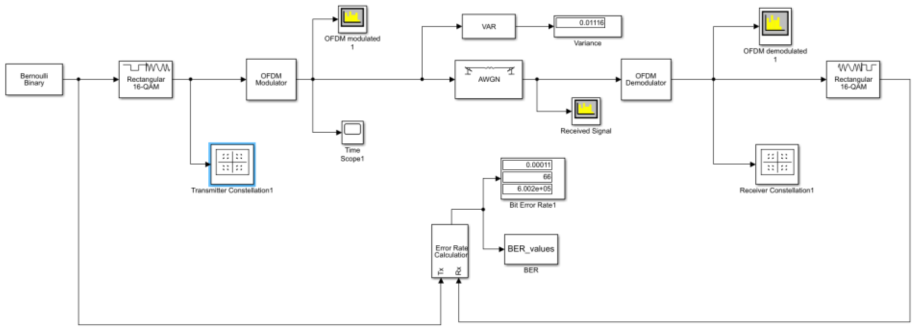
The same parameters are used in the receiver block with OFDM demodulator and QAM demodulator.

4.3 Process Flow and Design Components

The blocks used here are same as mentioned in prior section 2.3.

4.4 Block Diagram

The block diagram is given below:



4.5 Results

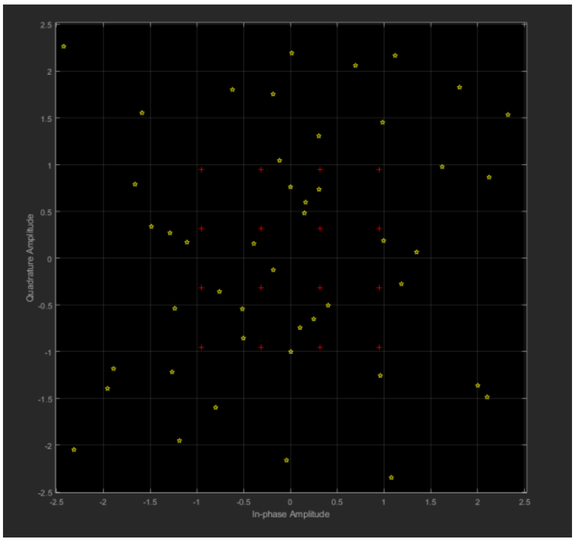


Figure-11: The received constellation diagram after adding the cyclic prefix. It still has some errors but not large enough as found without cyclic prefix in Figure-4. As most of the symbols are closer to expected value, hence errors will be less.

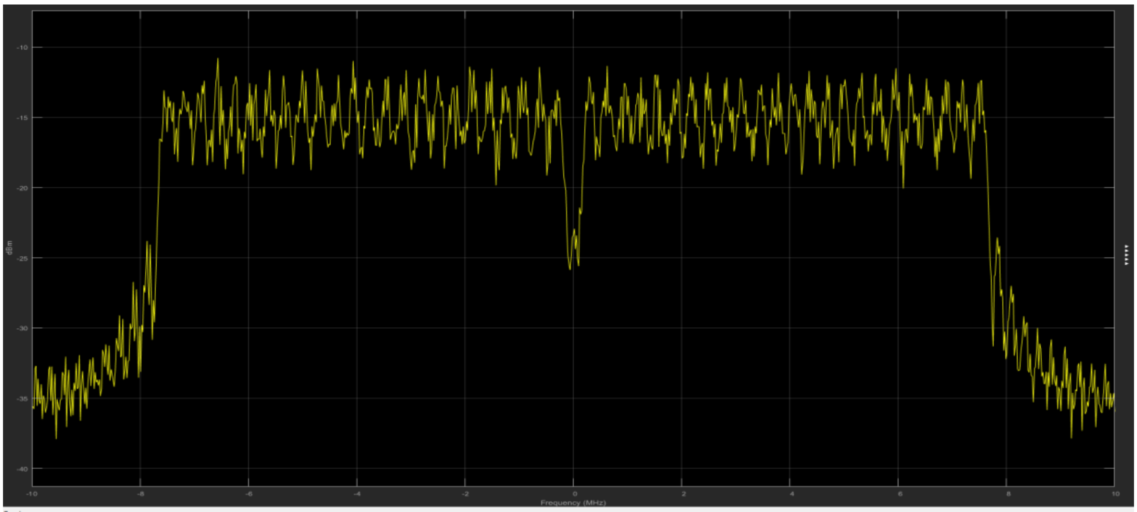


Figure-12: The OFDM symbol after the addition of cyclic prefix. As you can see the spectrum after cyclic prefix is different from one we got before in figure-1. It has more perturbations. And overall bandwidth after cyclic prefix is also increased.

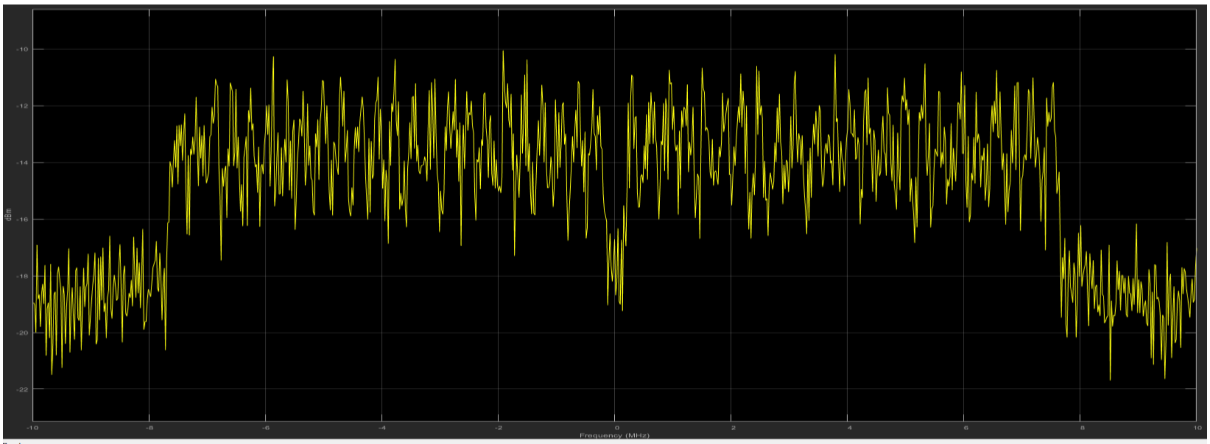


Figure-13: The OFDM symbol received after the AWGN channel in the presence of cyclic prefix. Here the signal is preserved relatively more than the case without cyclic prefix.

4.6 MATLAB Code

```
clear; clc;
close all;
EbNoVec = [0:2:12];
maxNumErrors = 1e6;
maxNumBits = 1e10;

for n = 1: length(EbNoVec)
    EbNo = EbNoVec (n);
    output = sim ('test');
    BERVEC(n,:) = BER_values(313);
end

BERVEC = BERVEC*100;
plot(EbNoVec,BERVEC(:,1), 'ob--');
ylabel('BER %age');
xlabel('EbNo');
title('OFDM with AWGN BER vs EbNo (cyclic prefix present)');
```

SIMULATION TIME : 0.1s

Simulink Block : AWGN Channel
Parameter Name : Eb / No (dB)
Parameter Value: <<EbNo>>

Case-5: OFDM with Rayleigh fading channel

Now we are going to experiment with **fading alongside prior AWGN channel**. For the experiment of fading, **Rayleigh fading channel is used**.

5.1 Design Specifications

The parameters relevant to Rayleigh fading are:

Index	Parameter	Value
1	Discrete Path Delays	0 seconds
2	Average Path Gains	0 dB
3	Fading Distribution	Rayleigh
4	Maximum Doppler Shift	0 Hz
5	Doppler Spectrum	Jakes

5.2 Parameter Explanation and Calculation

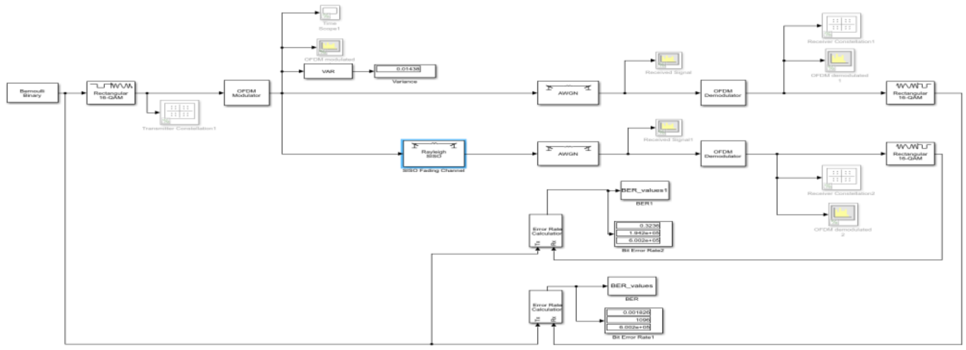
In the **first experiment, no delays and path gains (losses) are added**.

5.3 Process Flow and Design Components

Only additional block we need is **SISO Fading Channel**.

5.4 Block Diagram

The block diagram is given below:



5.5 Results

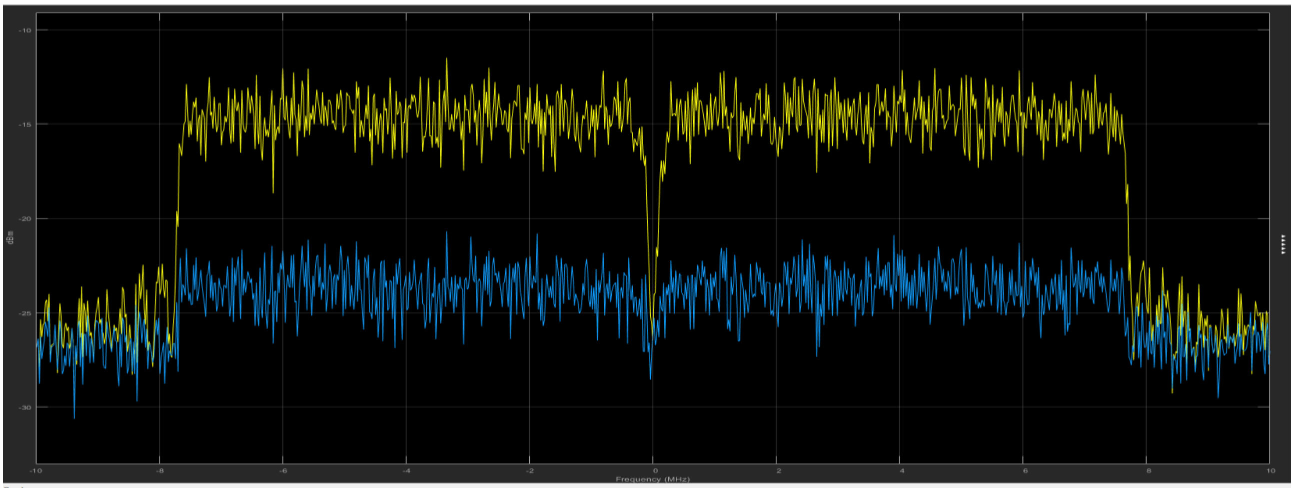


Figure-14: The upper is received signal after just AWGN channel. The bottom is after Rayleigh and AWGN path. As you can see the Rayleigh has massively decreased the signal power levels for all frequencies. That's why we observe very high error rates in Rayleigh channel in comparison to pure AWGN channel. Therefore, to understand the channel condition, <u>receiver must have equalizer to estimate the channel</u> to improve the performance.

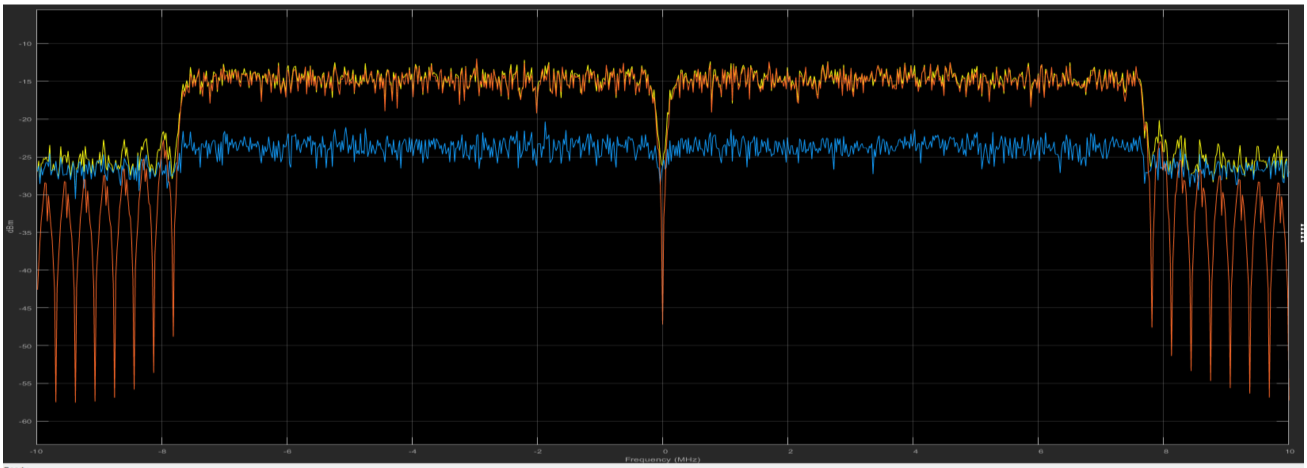


Figure-15: <u>Three stages of OFDM signals</u>. Orange is the transmitted (very low power NULL subcarriers). Yellow signal received after pure AWGN channel (noise is additively increased and power of NULL subcarriers is increased). Blue is signal received after Rayleigh path which has decreased the power levels for all carriers excessively and hence causing higher error rates.

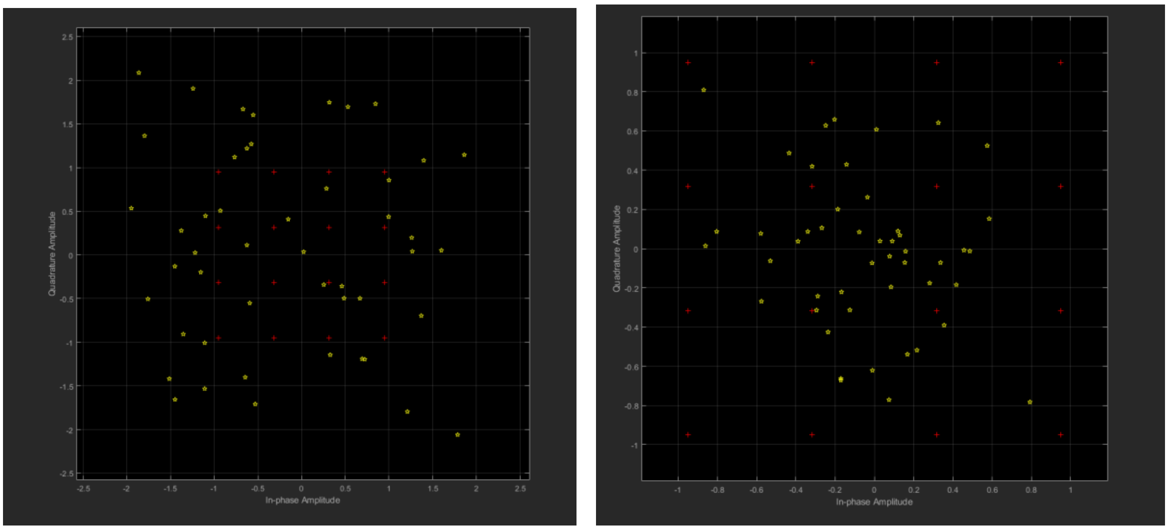


Figure-16: With Eb/No = 10dB Received Constellations of AWGN (left) and Rayleigh right). Both have errors but fading has decreased more the performance hence more errors are expected.

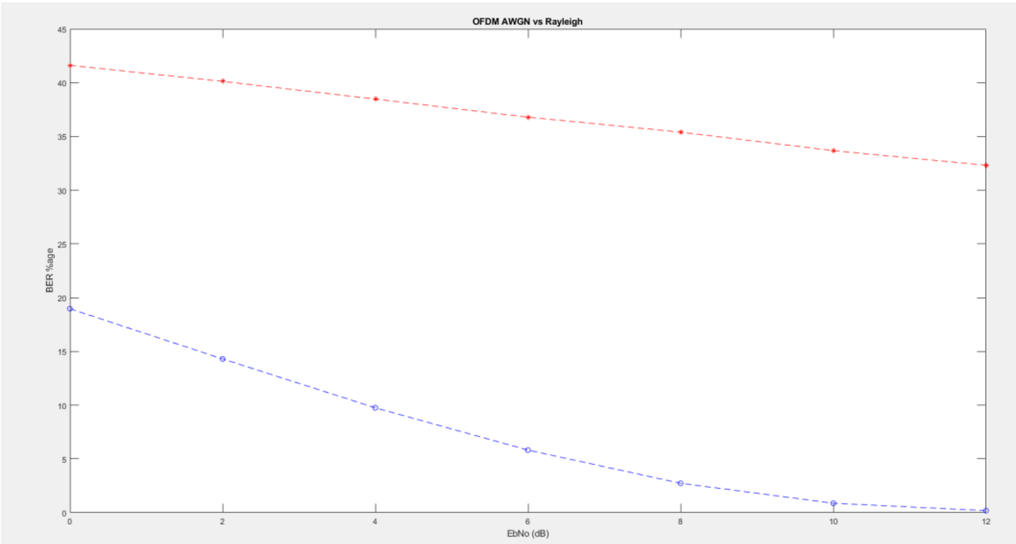


Figure-17: BER performance of AWGN vs Rayleigh. The latter (red) is far worse as expected.

Case-6: OFDM Multipath Delay vs BER

In this section, we are going to see how **BER varies when the multipath has different delays**. The delays correspond to the distance in real life. The extra distance for the delayed path to arrive at the receiver.

6.1 Results

Two paths are selected. The first has 0 delay. **2nd path has delay in range 0.2ns to 2µs**. This second path delay is tunable and we want to see the effect on BER with its variation in this experiment. The gains are 0dB and -3dB for each path respectively. Our guard interval is 100ns in this experiment.

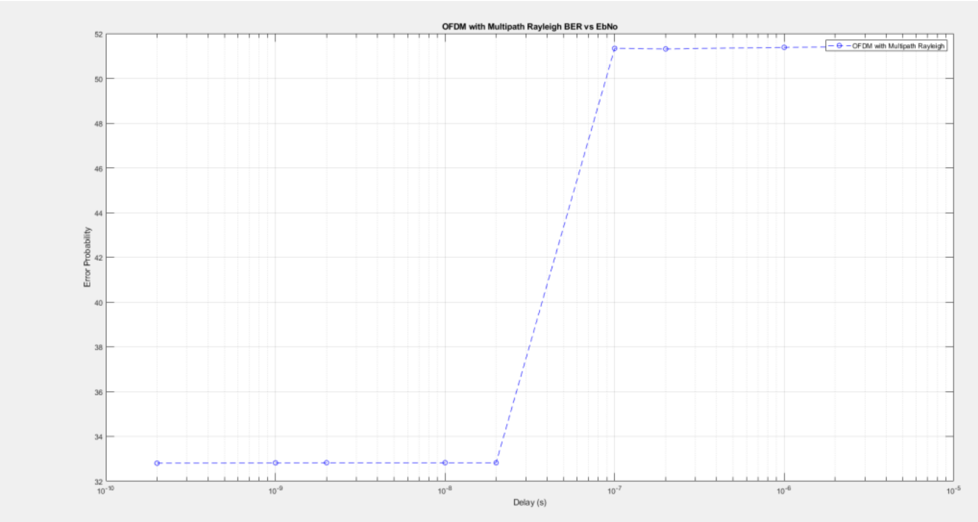


Figure-18: This shows that after a certain delay, the BER shoots very high. Initially it has a base value because of general baseline fading of around 32% BER (equalizer needed!). But for paths longer than 100ns (cyclic prefix length), the error become around 53%. This is due to OFDM inter symbol interference (ISI).

In practical life, the longer the path the lesser the gain (higher loss). With inverse linear relationship, I got the same results as shown above. This is understandable.

Now let's add 3 multipath but each has delay less than guard interval, hence we will not experience the error beyond the baseline fading error.

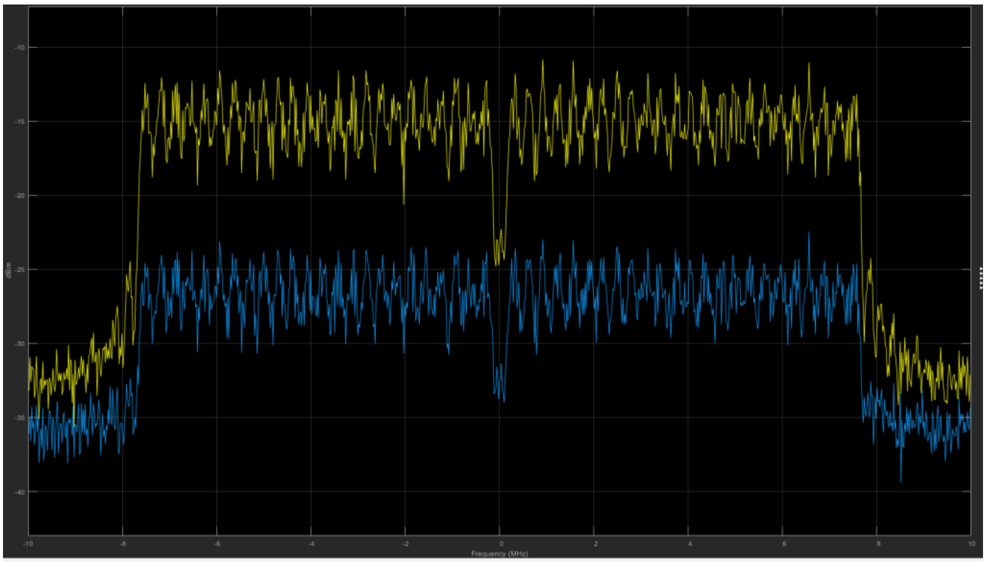


Figure-18: As you can see the difference between AWGN (yellow) and Rayleigh (blue) is power levels which needs to be solved through equalizer at the receiver. But here we don't observe ISI. This is similar to the case with baseline fading effect as observed in figure-14. The three paths have delays 0, 1ns, and 10ns. All are less than cyclic prefix. The BER is baseline 29.4%. Also we observe the flat fading here since maximum delay is smaller than symbol period. All the frequencies got affected similarly.

<u>Now let's add fourth path with max delay which is more than cyclic prefix</u>.

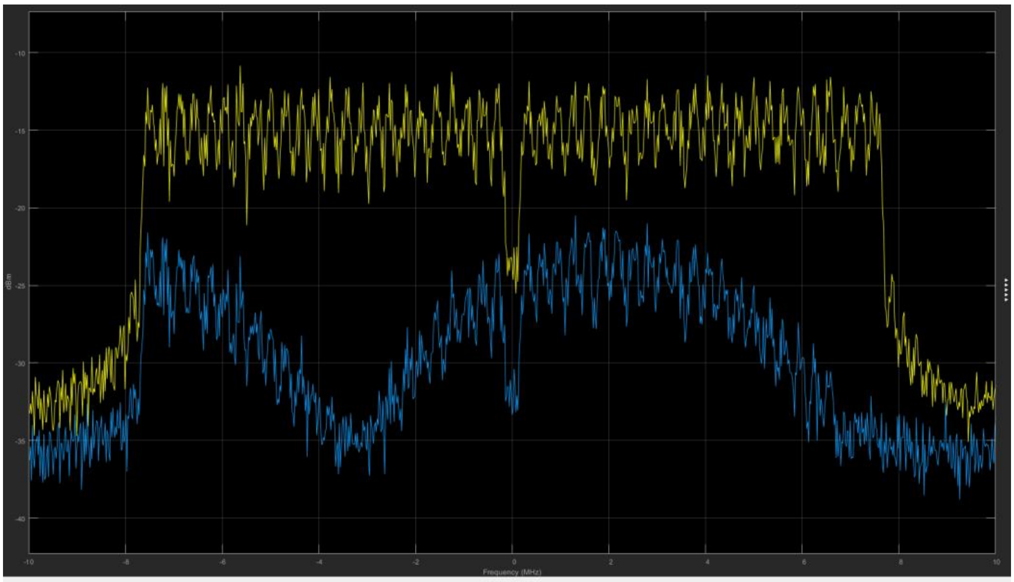


Figure-19: Now here <u>we observe ISI.</u> The four delays with delay higher than cyclic prefix. The BER shoots to 46.02%. Also now we observe the <u>selective fading</u> here since maximum delay is higher than symbol period. Different frequencies got affected differently. As seen with the blue spectrum.

6.2 MATLAB Code

```
clear; clc;
close all;

% IMPORTANT NOTE: SIMULAITON TIME IN SIMULINK: 0.1s %
% Uncomment the path you need to experiment (SNR, Delay, or Doppler) %
% By Default EB/No vs BER %

DelayVec = [0.2 1 2 10 20 100 200 1000 2000];
GainVec = [1 2 3 4 5 6 7 8 9];
MaxDopplerShiftVec = [0 0.0000001 0.000001 0.00001 0.0001 0.001 0.01 0.1 1
10 100 1000 10000 100e3];
DelayVec = DelayVec*(1e-9);
GainVec = GainVec*(-1.5);
EbNoVec = [0:3:15];
maxNumErrors = 1e6;
maxNumBits = 1e10;

% To vary the Eb/No (dB) parameter of AWGN Channel block with parameter
name <<EbNo>>
for n = 1: length(EbNoVec)
    EbNo = EbNoVec (n);
    output = sim ('OFDM_project');
    BERVEC(n,:) = BER_values6(10417,1);
    BERVEC1(n,:) = BER_values7(10417,1);
    disp(BER_values6(10417,1));
    disp(BER_values7(10417,1));

end

% To vary the Discrete path delays (s) parameter of SISO Fading Channel
block with parameter name <<Delay>>

% for n = 1: length(DelayVec)
```

```
%     Delay = DelayVec (n);
%     output = sim ('OFDM_project');
%     BERVEC(n,:) = BER_values6(10417,1);
%     BERVEC1(n,:) = BER_values7(10417,1);
%
% end

% To vary the Maximum Doppler shift (Hz) parameter of SISO Fading Channel
block with parameter name <<MaxDopplerShift>>

% for n = 1: length(MaxDopplerShiftVec)
%     MaxDopplerShift = MaxDopplerShiftVec (n);
%     output = sim ('OFDM_project');
%     BERVEC(n,:) = BER_values6(10417,1);
%     BERVEC1(n,:) = BER_values7(10417,1);
%
% end

%Plot BER vs Eb/No
semilogy(EbNoVec,BERVEC(:,1), 'ob--');
legend('OFDM with AWGN');
ylabel('Error Probability');
xlabel('Eb/No (dB)');
title('OFDM with AWGN BER vs EbNo');
grid on;

hold;
semilogy(EbNoVec,BERVEC1(:,1), 'dg--');
legend('OFDM with AWGN','OFDM  with AWGN and Rayleigh');

%Plot BER vs Multipath delay

% BERVEC1 = BERVEC1*100;
% semilogx(DelayVec,BERVEC1(:,1), 'ob--');
% legend('OFDM with Multipath Rayleigh');
% ylabel('Error Probability');
% xlabel('Delay (s)');
% title('OFDM with Multipath Rayleigh Delay vs BER');
% grid on;

%Plot BER vs Doppler shift

% BERVEC1 = BERVEC1*100;
% semilogx(MaxDopplerShiftVec,BERVEC1(:,1), 'ob--');
% legend('OFDM with Multipath Rayleigh');
% ylabel('BER %age');
% xlabel('Max Doppler Shift (Hz)');
% title('OFDM Rayleigh Doppler Shift vs BER');
% grid on;
```

Case-7: Flat Fading and Selective Fading

In small scale fading, spreading of the signal in time delay spread results in flat or selective fading. If the maximum delay is less than symbol period, channel is flat fading. It means it affect all frequencies in same manner. However if the maximum delay is greater than the symbol period (cyclic prefix in the case of OFDM), channel is selective fading since it affects different frequencies in different manner resulting in losing orthogonality of subcarriers and ISI.

For Selective fading, the frequency response is shown as below:

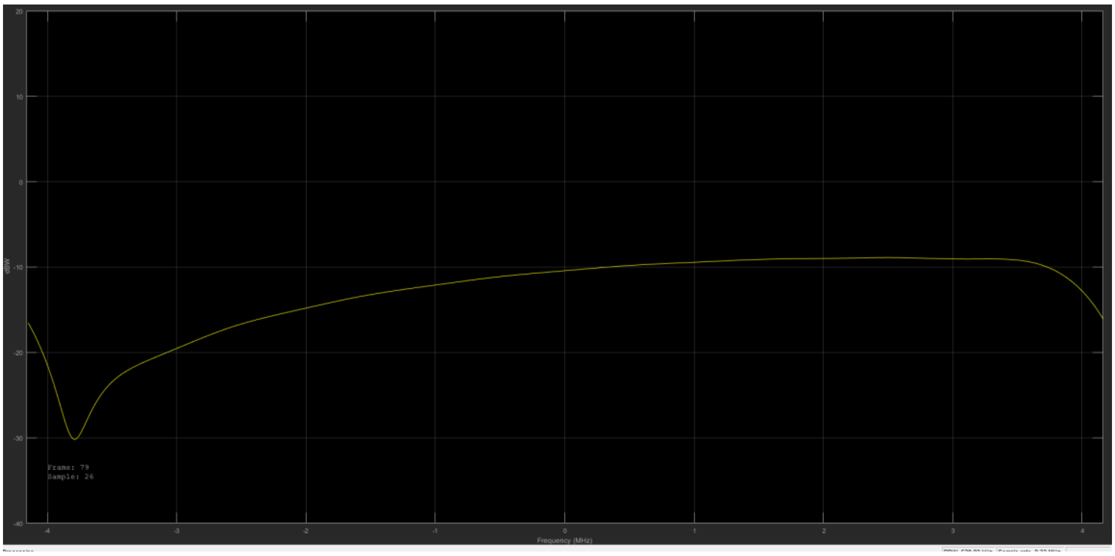


Figure-20: Selective fading when maximum delay is higher than cyclic prefix causing ISI and high BER of 46.02%. The OFDM signal spectrum resembling to this case is shown in figure-19.

For flat fading, the frequency response is shown as below:

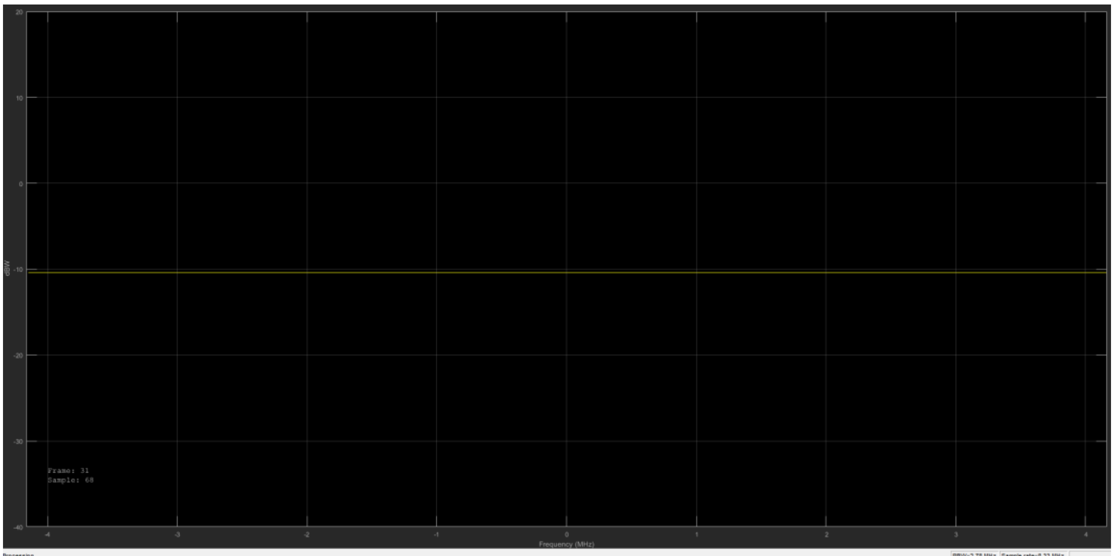


Figure-21: Flat fading when maximum delay is lower than cyclic prefix and low base level BER of 29.4%. The OFDM signal spectrum resembling to this case is shown in figure-18.

Case-8: Slow Fading vs Fast Fading

The Doppler spread is due to the relative motion of transmitter and receiver. If the Doppler spread is higher than signal bandwidth, it leads to fast fading. Otherwise it's slow fading. Signal distortion is high in case of fast fading.

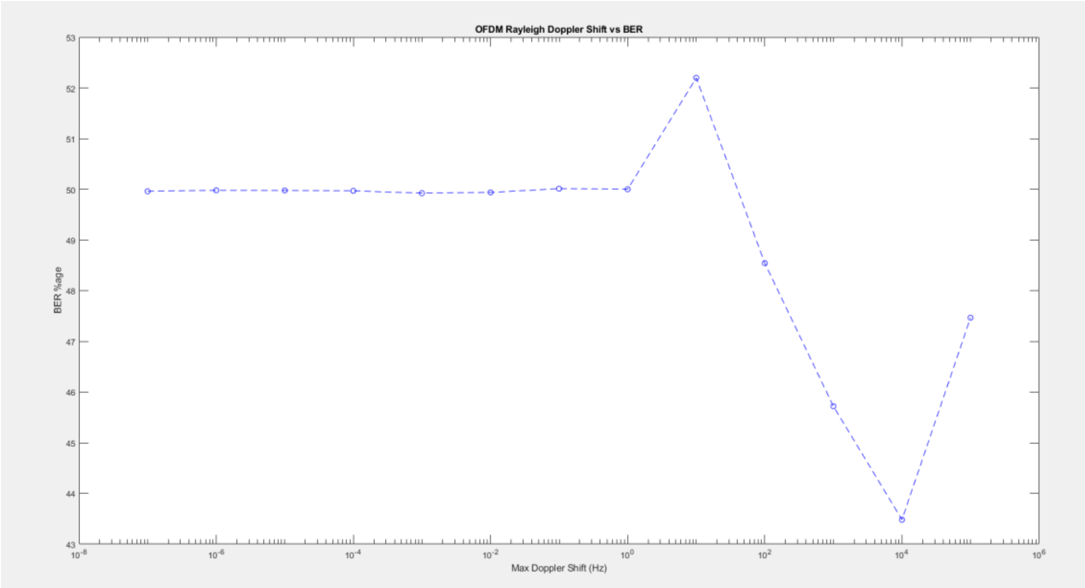


Figure-22: BER in relation to max Doppler shift. The BER remains same for a while as Max Doppler shift increases. Beyond a threshold of shift = 10Hz, the BER reduces.

Conclusions and Remarks

1. Without channel, OFDM communication is error free.
2. AWGN channel affects with respect to Eb/No value. Hence most significant effect is for subcarriers which have low power (Guard, DC NULL) as shown in Figure-6.
3. AWGN reduces the power level difference in data subcarriers and NULL subcarriers. Higher the value of Eb/No, higher the reduction hence lesser difference between the power levels.
4. Higher modulations for a given channel lead to higher error rates.
5. For higher order modulation say 64-QAM vs 16-QAM with same FFT size, the effective bandwidth is reduced as lesser number of data subcarriers are needed with each subcarrier transmitting more bits than 16-QAM subcarrier.
6. The error rate for higher order modulation (64-QAM) is more than lower order modulation 16-QAM. In other words, you would require channel with much better quality in case of 64-QAM to meet the same performance as for 16-QAM.
7. Addition of cyclic prefix increases the effective bandwidth of the OFDM signal.
8. Rayleigh block decreases the signal power levels massively hence error rate rises sharply as shown in Figure-14.
9. AWGN always performs better than Rayleigh for all modulations in terms of bit error rates.
10. It's necessary to have an equalizer at the receiver in wireless communication. Though it wasn't part of this project.
11. Equalizer is a filter which has an impulse response inverse of channel's impulse response.
12. The path delays due to multipath have inverse relation with gains. Higher the delay, lower the path gain.
13. If the multipath has maximum delay higher than the cyclic prefix of OFDM symbol, the phenomenon is selective fading otherwise flat fading.
14. The Doppler shift is a measure of relative motion between transmitter and receiver. Valid if either of them is mobile.

15. If the Doppler spread is higher than signal bandwidth, it leads to fast fading. Otherwise it's slow fading. Signal distortion is high in case of fast fading.

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