COMMUNICATION SYSTEM DESIGN LAB (EE 534)

EXPERIMENT - 5

LAB REPORT

Submitted by- Group 5

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AIM: To observe the OFDM modulation and demodulation through LabView simulation and USRP 2900/2901 boards to build the understanding about the impact of key parameters on the system performance.

OBJECTIVE:

1. Design a OFDM-QAM transmitter block Fig.1 to transmit a random bit stream without and with additive noise. Demodulate the received RF signal and recover the correct bit stream for the corresponding receiver in Fig.2.
2. Understand the impact of important OFDM parameters (i.e. symbol period, FFT length, cyclic prefix, guard bands, AWGN) on the channel bandwidth and system performance.
3. Observe the time domain behavior (In-phase/Quadrature phase signals) and constellation diagram of QAM signal, without noise and with additive white noise.
4. Plot the eye diagram for the received RF signal.
5. Observe the errors and record the results to perform the bit error analysis and plotting the graphs.
6. Repeat the process with PN sequence. You can transmit a user-defined message and can observe it through your design, similar to the YouTube videohttps://youtu.be/HpgLJACaBaw.

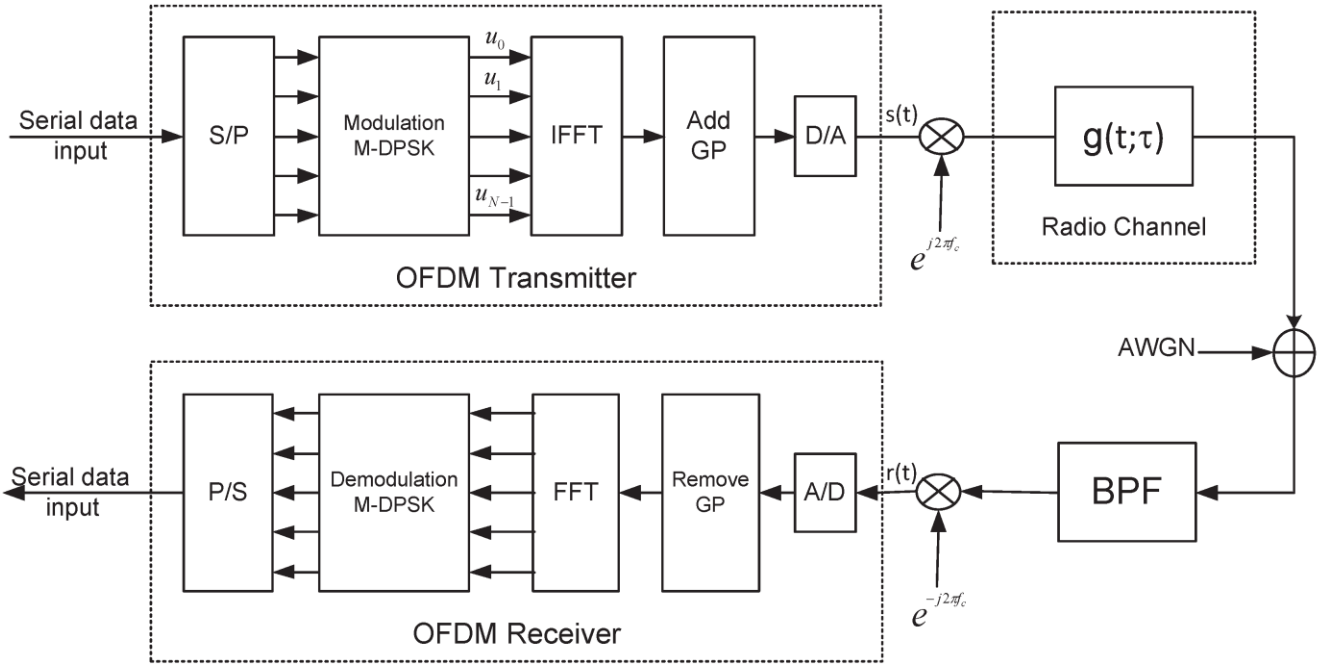
THEORY OF OFDM:

OFDM, Orthogonal Frequency Division Multiplexing is a form of signal waveform or modulation that provides some significant advantages for data links.

Accordingly, OFDM, Orthogonal Frequency Division Multiplexing is used for many of the latest wide bandwidth and high data rate wireless systems including Wi-Fi, cellular telecommunications and many more.

The fact that OFDM uses a large number of carriers, each carrying low bit rate data, means that it is very resilient to selective fading, interference, and multipath effects, as well providing a high degree of spectral efficiency.

Early systems using OFDM found the processing required for the signal format was relatively high, but with advances in technology, OFDM presents few problems in terms of the processing required.

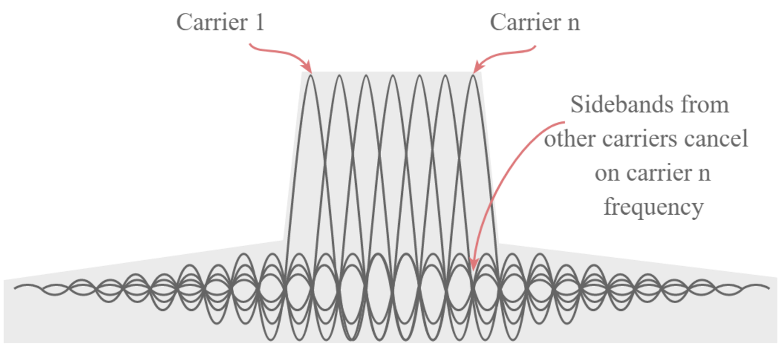


WHAT IS OFDM?

OFDM is a form of multicarrier modulation. An OFDM signal consists of a number of closely spaced modulated carriers. When modulation of any form - voice, data, etc. is applied to a carrier, then sidebands spread out either side. It is necessary for a receiver to be able to receive the whole signal to be able to successfully demodulate the data. As a result when signals are transmitted close to one another they must be spaced so that the receiver can

separate them using a filter and there must be a guard band between them. This is not the case with OFDM. Although the sidebands from each carrier overlap, they can still be received without the interference that might be expected because they are orthogonal to each another. This is achieved by having the carrier spacing equal to the reciprocal of the symbol period.

To see how OFDM works, it is necessary to look at the receiver. This acts as a bank of demodulators, translating each carrier down to DC. The resulting signal is integrated over the symbol period to regenerate the data from that carrier. The same demodulator also demodulates the other carriers. As the carrier spacing equal to the reciprocal of the symbol period means that they will have a whole number of cycles in the symbol period and their contribution will sum to zero - in other words there is no interference contribution



One requirement of the OFDM transmitting and receiving systems is that they must be linear. Any non-linearity will cause interference between the carriers as a result of inter-modulation distortion. This will introduce unwanted signals that would cause interference and impair the orthogonality of the transmission.

In terms of the equipment to be used the high peak to average ratio of multi-carrier systems such as OFDM requires the RF final amplifier on the output of the transmitter to be able to handle the peaks whilst the average power is much lower and this leads to inefficiency. In some systems the peaks are limited. Although this introduces distortion that results in a higher level of data errors, the system can rely on the error correction to remove them.

KEY FEATURES OF OFDM

The OFDM scheme differs from traditional FDM in the following interrelated ways:

1. Multiple carriers (called subcarriers) carry the information stream
2. The subcarriers are orthogonal to each other.
3. A guard interval is added to each symbol to minimize the channel delay spread and intersymbol interference.

OFDM ADVANTAGES

OFDM has been used in many high data rate wireless systems because of the many advantages it provides.

- ***Immunity to selective fading:*** One of the main advantages of OFDM is that is more resistant to frequency selective fading than single carrier systems because it divides the overall channel into multiple narrowband signals that are affected individually as flat fading sub-channels.
- ***Resilience to interference:*** Interference appearing on a channel may be bandwidth limited and in this way will not affect all the sub-channels. This means that not all the data is lost.
- ***Spectrum efficiency:*** Using close-spaced overlapping sub-carriers, a significant OFDM advantage is that it makes efficient use of the available spectrum.
- ***Resilient to ISI:*** Another advantage of OFDM is that it is very resilient to inter-symbol and inter-frame interference. This results from the low data rate on each of the sub-channels.
- ***Resilient to narrow-band effects:*** Using adequate channel coding and interleaving it is possible to recover symbols lost due to the frequency selectivity of the channel and narrow band interference. Not all the data is lost.
- ***Simpler channel equalisation:*** One of the issues with CDMA systems was the complexity of the channel equalisation which had to be applied across the whole channel. An advantage of OFDM is that using multiple sub-channels, the channel equalization becomes much simpler.

OFDM DISADVANTAGES

Whilst OFDM has been widely used, there are still a few disadvantages to its use which need to be addressed when considering its use.

- ***High peak to average power ratio:*** An OFDM signal has a noise like amplitude variation and has a relatively high large dynamic range, or peak to average power ratio. This impacts the RF amplifier efficiency as the amplifiers need to be linear and accommodate the large amplitude variations and these factors mean the amplifier cannot operate with a high efficiency level.
- ***Sensitive to carrier offset and drift:*** Another disadvantage of OFDM is that is sensitive to carrier frequency offset and drift. Single carrier systems are less sensitive.

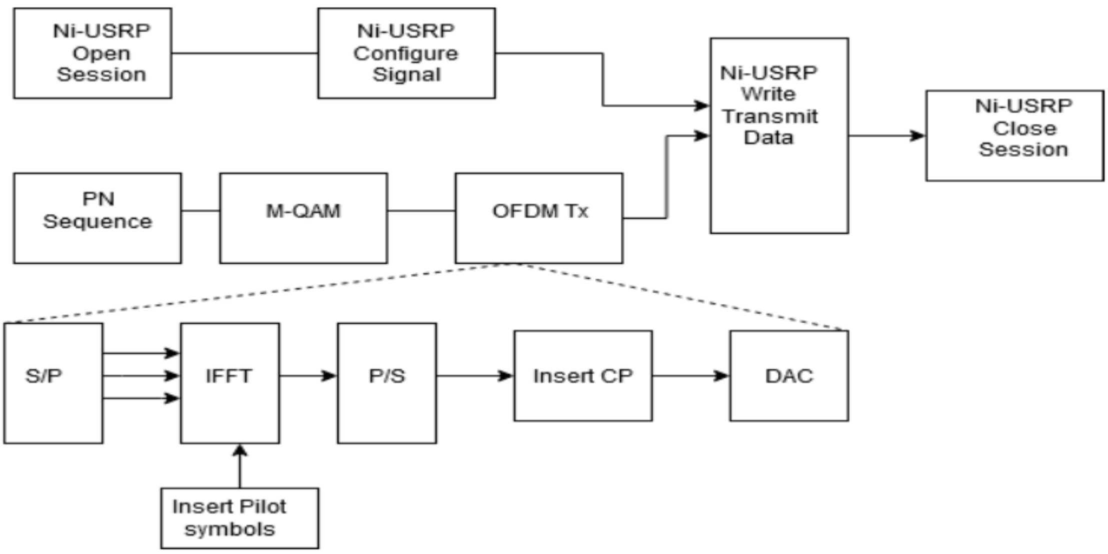


Figure 1: Block schematic of Ni-USRP Transmitter to transmit OFDM signal.

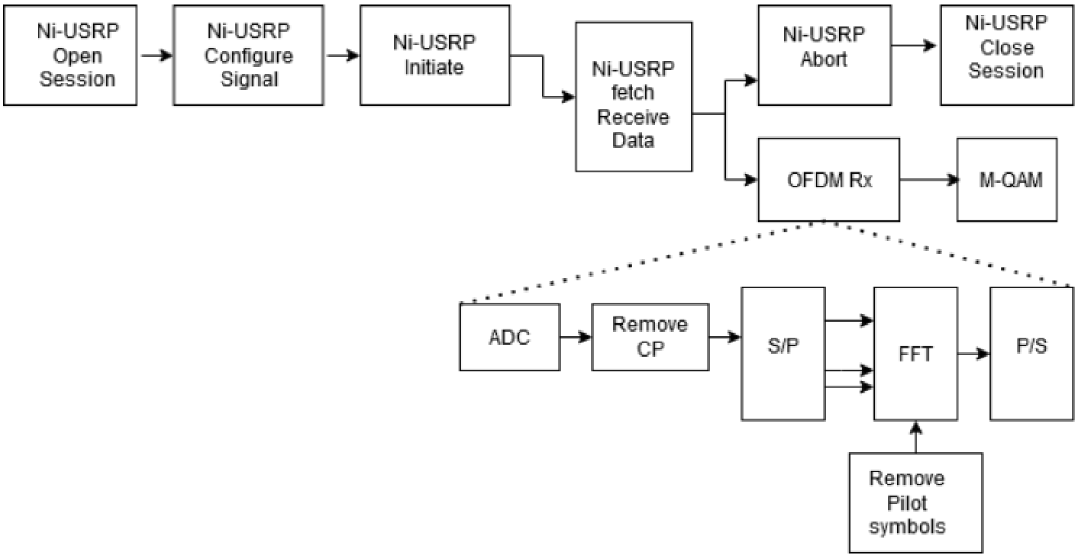


Figure 2: Block schematic of Ni-USRP Receiver to receive the OFDM signal.

1. SYMBOL PERIOD

The symbol period is the duration of time for which each subcarrier carries its assigned data.

The specification of the symbol period in OFDM is determined by the total duration of the transmitted signal and the number of subcarriers used. The symbol period should be chosen such that the subcarriers are orthogonal to each other, which means they should be separated by integer multiples of the reciprocal of the symbol period.

- A longer symbol period results in more efficient use of the available frequency spectrum, but it also reduces the number of subcarriers that can be transmitted within a given bandwidth which reduces the data rate.
- On the other hand, a shorter symbol period allows for a higher data rate but also requires more precise frequency synchronization and more complex hardware. This is because the subcarriers are spaced more closely together, making them more susceptible to interference and frequency offsets.

In general, the symbol period is a trade off between spectral efficiency and implementation complexity. It is typically chosen based on the specific application requirements, such as the available bandwidth, required data rate, and the complexity of the hardware used for transmission and reception.

TASK 1: The bandwidth of one OFDM symbol is determined by the sample rate and the number of subcarriers used, while the OFDM symbol period affects the time-domain characteristics of the signal and, therefore, the bandwidth in the time-domain. A longer symbol period results in a narrower bandwidth in the time-domain, while a shorter symbol period results in a wider bandwidth in the time-domain.

TASK 2: Sample rate/bandwidth of one OFDM symbol = Total number of samples / Duration of one OFDM symbol

In this case, the total number of samples is 80 and the duration of one OFDM symbol is x seconds. Therefore, the sample rate/bandwidth of one OFDM symbol is:

Sample rate/bandwidth of one OFDM symbol = 80 / x

2. FFT LENGTH

In OFDM (Orthogonal Frequency Division Multiplexing), FFT (Fast Fourier Transform) is used to convert time-domain OFDM signal into the frequency domain. The length of the FFT determines the number of subcarriers that can be used in the OFDM system.

TASK 1: The sample rate per bandwidth of an OFDM symbol can be derived mathematically as follows:

Let N be the number of subcarriers in the OFDM system, including the DC subcarrier. Let Ts be the OFDM symbol period, which is equal to the IFFT length. Let Tc be the duration of one cycle of the subcarrier spacing, which is given by $Tc = 1/(N * \Delta f)$, where Δf is the subcarrier spacing.

The total bandwidth of one OFDM symbol is given by $B = N * \Delta f$.

The sample rate of the OFDM symbol is given by $Rs = 1/Ts$.

Therefore, the sample rate per bandwidth can be expressed as:

$Rs/B = (1/Ts)/(N * \Delta f)$

$= 1/(N * \Delta f * Ts)$

$= Tc/Ts$

So, the sample rate per bandwidth of one OFDM symbol is equal to the ratio of the duration of one cycle of the subcarrier spacing to the OFDM symbol period.

TASK 2: The specification of the FFT length in OFDM is determined by the available bandwidth, the desired data rate, and the number of subcarriers required.FFT length must be a power of two for efficient implementation. It is typically chosen such that the subcarriers are spaced equally apart in frequency, and the spectral efficiency is maximized.

- A longer FFT length allows for more subcarriers to be used, results in higher spectral efficiency and higher data rates. However, a longer FFT length also increases the complexity of the OFDM system, which can increase hardware cost and implementation complexity. It also increases the latency of the system, which can be undesirable in real-time applications.
- A shorter FFT length reduces the complexity of the system and reduces latency, but at cost of lower spectral efficiency and lower data rates. It can also result in higher out-of-band radiation and inter-carrier interference due to the wider subcarrier spacing.

If we add more data subcarriers to an OFDM system while keeping the total bandwidth constant, the subcarrier spacing will decrease which is more susceptible to interference and noise

3. CYCLIC PREFIX

The basic concept behind the OFDM cyclic prefix is quite straightforward. The cyclic prefix performs two main functions.

- The cyclic prefix provides a guard interval to eliminate intersymbol interference from previous symbol.
- It repeats the end of the symbol so the linear convolution of a frequency-selective multipath channel can be modeled as circular convolution, which in turn may transform to the frequency domain via a

discrete Fourier transform. This approach accommodates simple frequency domain processing, such as channel estimation and equalization.

The cyclic prefix is created so that each OFDM symbol is preceded by a copy of the end part of that same symbol.

Different OFDM cyclic prefix lengths are available in various systems. For example within LTE a normal length and an extended length are available and after Release 8 a third extended length is also included, although not normally used.

TASK 1: The bandwidth of one OFDM symbol is determined by the number of subcarriers and the subcarrier spacing, which are typically fixed parameters in an OFDM. Therfore the length of the cyclic prefix does not affect the bandwidth of the OFDM symbol

4. GUARD BAND

In OFDM (Orthogonal Frequency Division Multiplexing), a guard band is a frequency gap inserted between adjacent subcarriers. The guard band is a portion of the available bandwidth that is not used for data transmission but is reserved for protection against interference from adjacent subcarriers.

- The specification of the guard band in OFDM is determined by the frequency selectivity of communication channel and the amount of interference between adjacent subcarriers.
- By inserting a guard band, the subcarriers are separated in frequency, which reduces the likelihood of ICI and other forms of interference.

However, the use of a guard band also reduces the overall spectral efficiency of OFDM, as a portion of the available bandwidth is not used for data transmission. This can limit the achievable data rate of the system.

In practice, the guard band is a tradeoff between spectral efficiency and interference protection. The guard band is typically chosen based on the characteristics of the communication channel and the requirements of the application, such as the allowable bit error rate (BER) and the required data rate.

- A larger guard band provides better interference protection but reduces the overall spectral efficiency, while a smaller guard band provides better spectral efficiency but may result in increased interference and errors.

TASK 1: Doubling the number of guard bands in an OFDM system does not affect the channel bandwidth. The guard bands are inserted to avoid inter-carrier interference caused by frequency offset and Doppler shift, and maintain orthogonality between subcarriers. The length of guard bands is typically chosen to be larger than the maximum frequency offset and Doppler shift in the channel. By doing this, the OFDM system can effectively mitigate the effect of frequency offset and Doppler shift and improve system performance.

5. AWGN

AWGN is a random signal that is added to the transmitted signal, which can degrade quality of the received signal. In OFDM, AWGN can have a significant impact on the system's performance.

The effect of AWGN on OFDM depends on its PSD and variance, as well as signal-to-noise ratio of the system.SNR is ratio of the signal power to the noise power, and it is often used to quantify quality of the received signal.

- When SNR is high, the effect of AWGN is minimal, and received signal is of high quality. However, as the SNR decreases, the effect of AWGN becomes more significant, and the received signal becomes more degraded. This can result in a higher bit error rate (BER) and a lower data rate.

In addition to coding techniques, other methods can be used to improve the system's performance in the presence of AWGN, such as adaptive modulation, which adjusts the modulation scheme according to the SNR. Other techniques include antenna diversity, equalization, and interference cancellation.

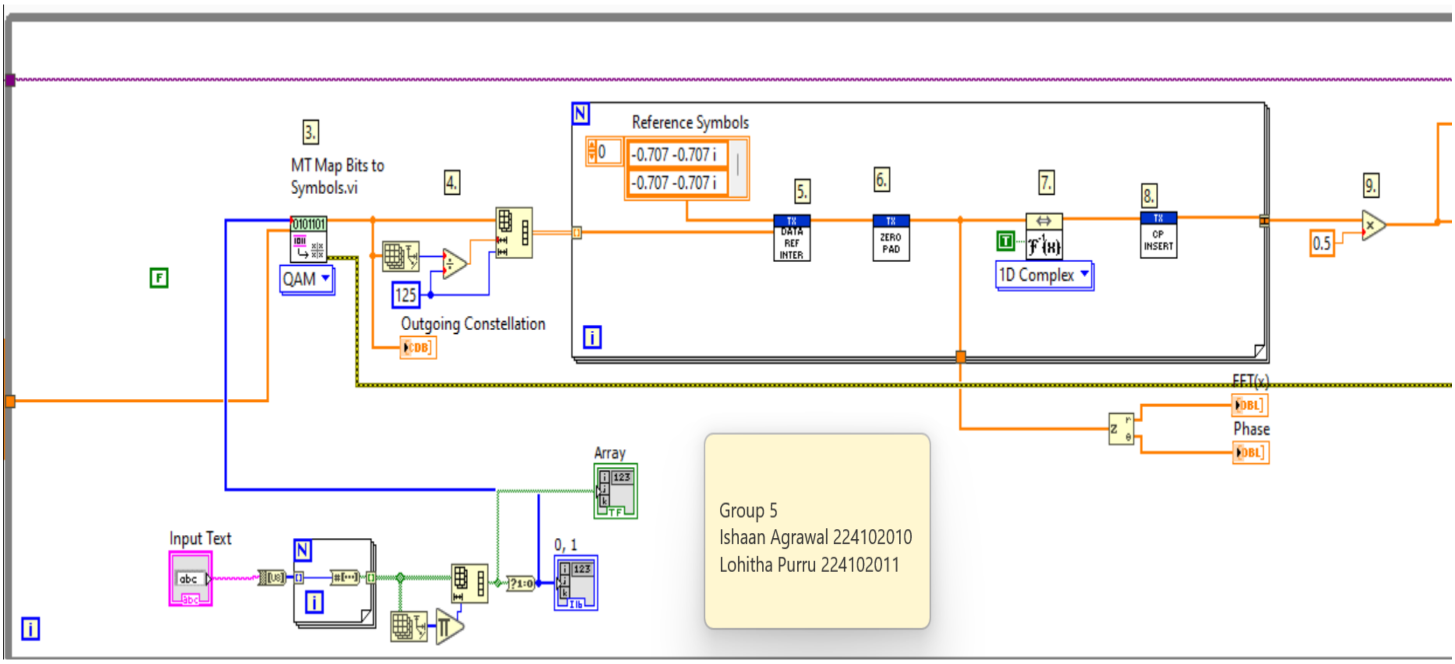
Overall, the specification and effect of AWGN on OFDM depend on several factors, including the PSD and variance of the noise, the SNR of the system, and the techniques used to mitigate the impact of the noise on the received signal.

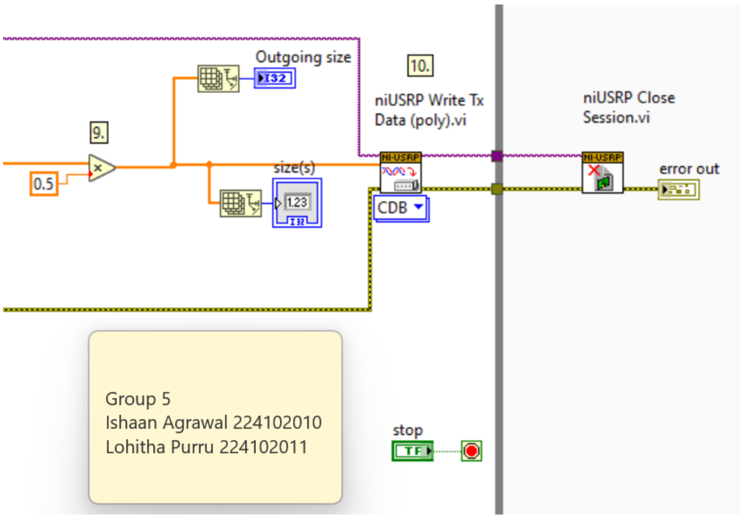
TASK 1: The number of bits per symbol setting in an AWGN OFDM system determines the modulation scheme and affects the bit error rate. Increasing the number of bits per symbol leads to higher spectral efficiency but also increases the susceptibility to noise. The symbol period setting determines the time duration of each OFDM symbol and affects the system latency. Increasing the symbol period reduces the data rate but also improves the system robustness to channel variations.

TASK 2: Increasing the value of Eb/N0 from 10 to 15, while keeping the input signal power at 10 mW, will improve the received signal constellation and reduce the bit error rate (BER). At higher Eb/N0 values, the noise power is reduced relative to the signal power, which leads to better signal-to-noise ratio (SNR) and lower BER. The improvement in signal quality and BER can be observed by analyzing the received signal constellation, which should become more distinct and less distorted as Eb/N0 increases.

OFDM USRP TRANSMITTER:

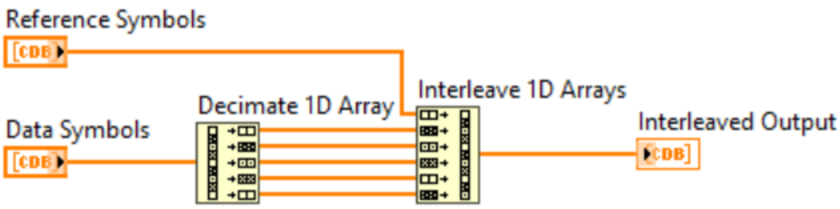
Block diagram of USRP OFDM transmitter:



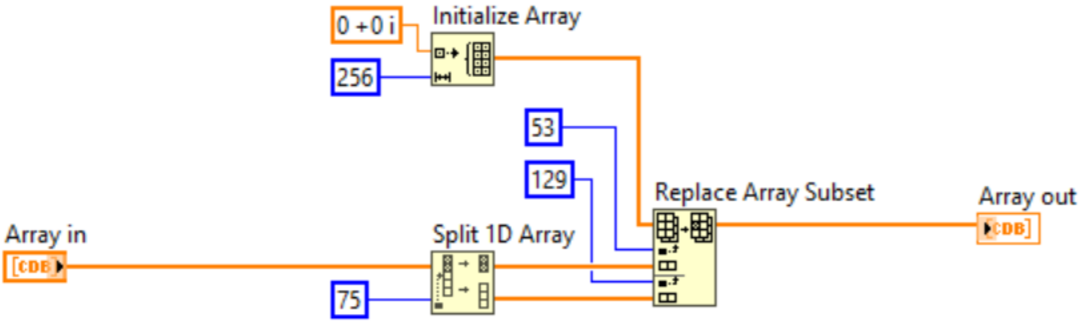


Divides the array of symbols into 5 sets of 125 point data sets and builds OFDM symbols(125 pts per OFDM symbol)

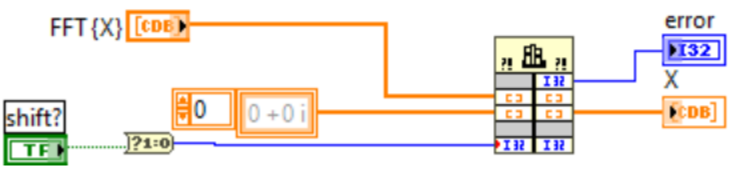
Insert one of the 25 reference symbol after every 6th data symbol(150 pts per OFDM symbol)



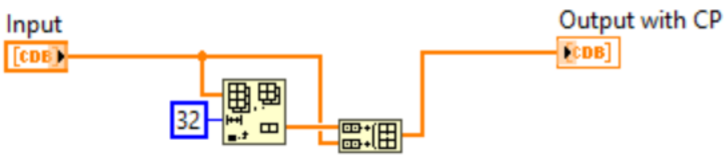
Insert 53 zeros at the edges of the passband and 1 zero at DC (256 pts per OFDM symbol)



Perform an inverse FFT to convert the frequency domain design to a time domain signal(256 point IQ time domain waveform)



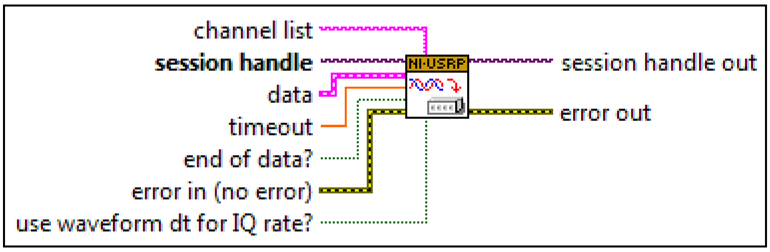
Insert a 64 point cyclic prefix by duplicating the last 64 points of the array at the beginning (320 point IQ time domain wavefom)



Scale the 5 domain OFDM waveforms to a complex magnitude below 1, typically below 0.7 for each I and Q (1600 point IQ time domain waveform)

niUSRP Write Tx Data (poly)

It Writes complex, double-precision floating-point data in a waveform data type to the specified channel.Thecontrols that we used in this experiment and their functions are as follows:

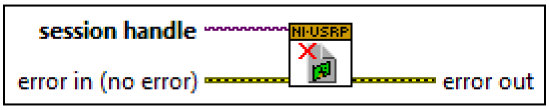


a. **Data** – it specifies the baseband samples to transmit as complex, double-precision floating-point data in waveform data type,which also includes sampling information.

With the help of the Basic Function Generator, we create the controls - sampling info, signal type andfrequency. The output of the Basic Function Generator is connected to 'data' control of **niUSRP Write Tx Data (poly)** and waveform graph. We will make the whole system to run in a loop.

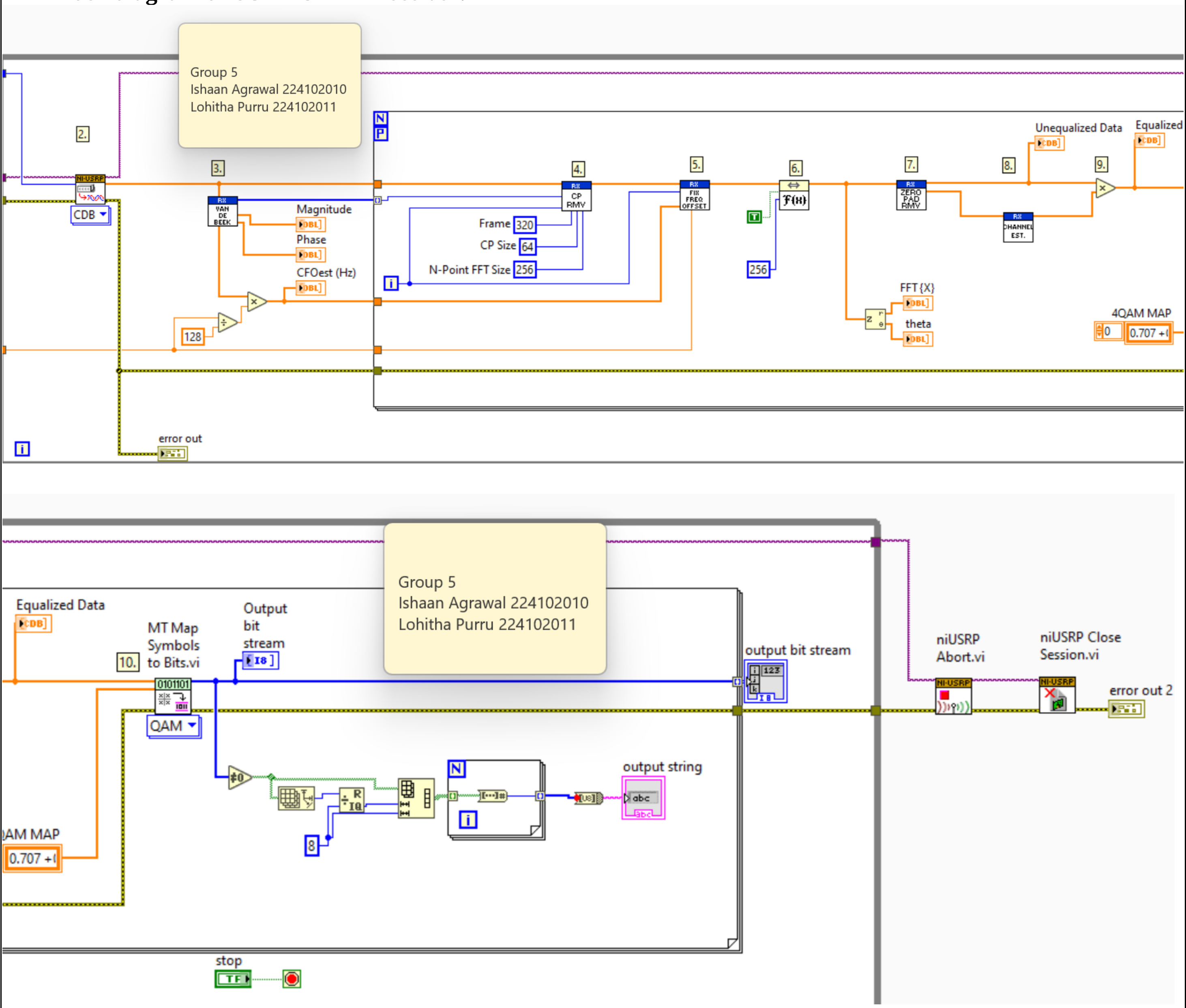
niUSRP close Session

It Closes the session handle to the device. The block diagram and some of the controls are shown below:



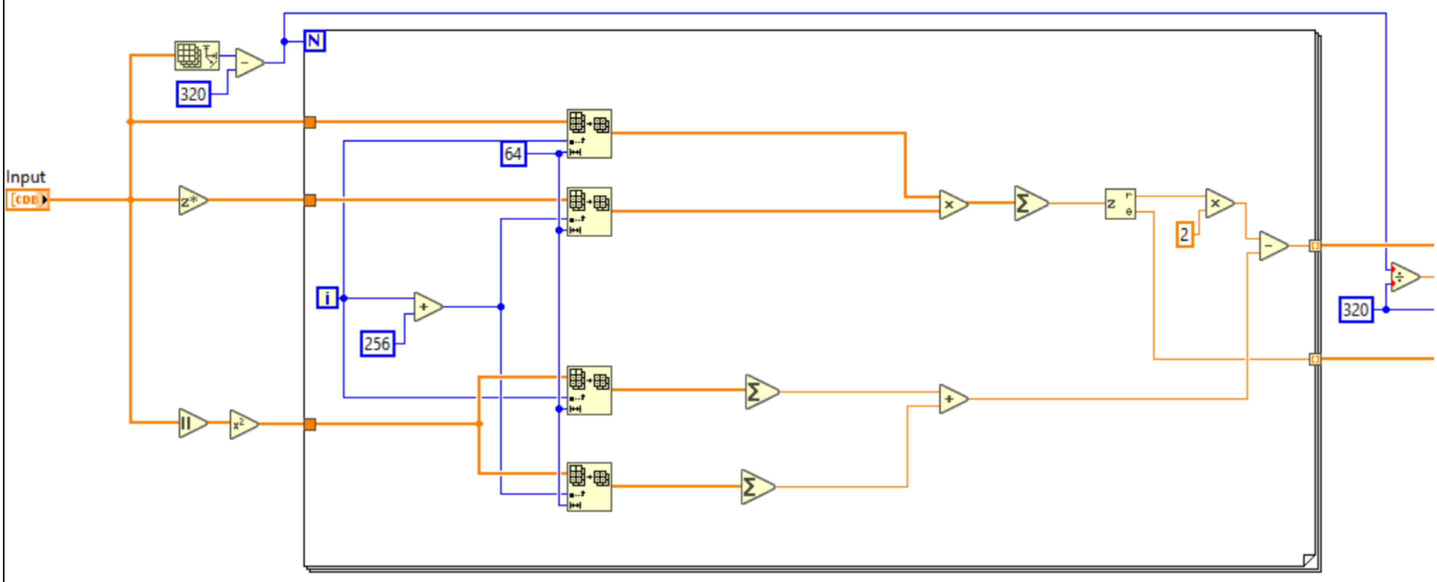
OFDM USRP RECEIVER:

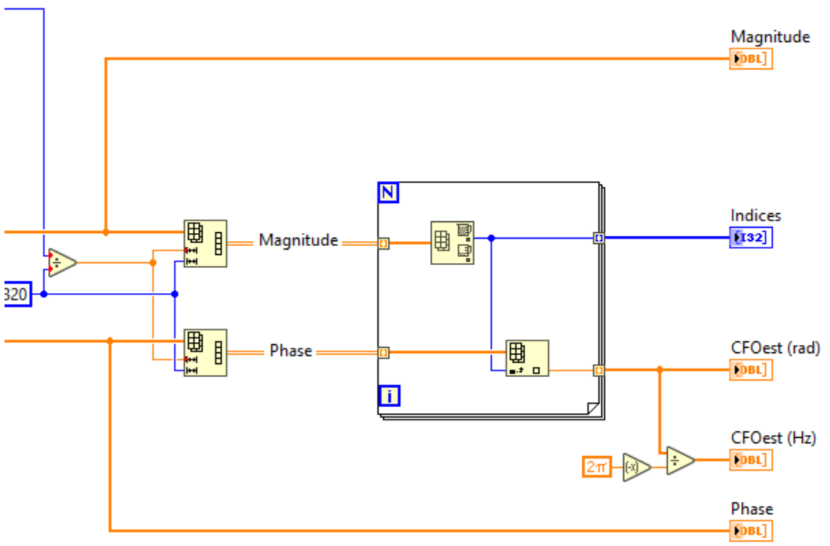
Block diagram of USRP OFDM receiver:



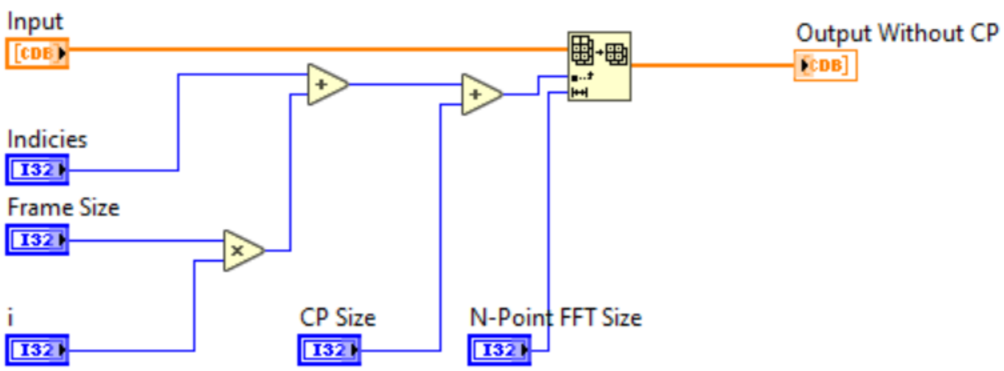
2. Generate the random data bits (PN sequence 125 bits)

3. Use the Van De Beek algorithm to detect the cyclic prefix locations for synchronization and estimate frequency offset

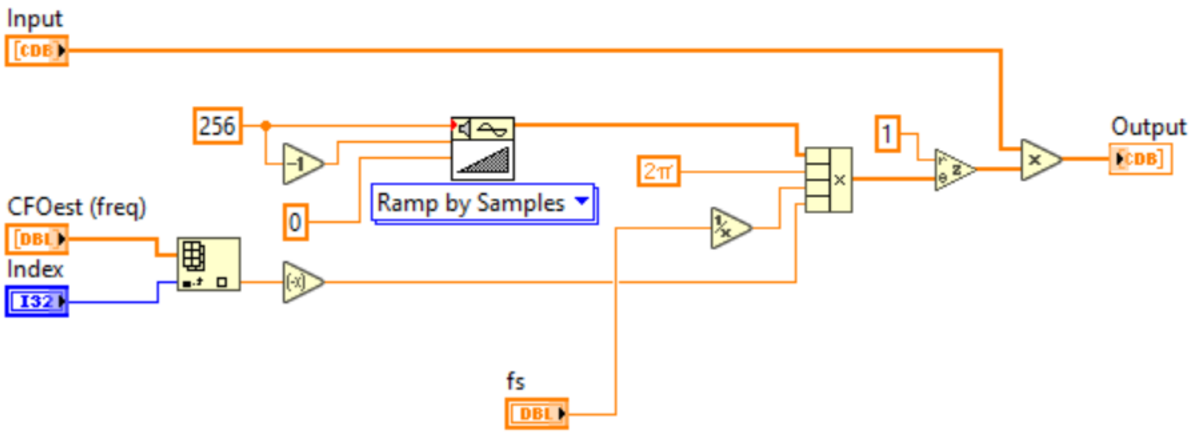




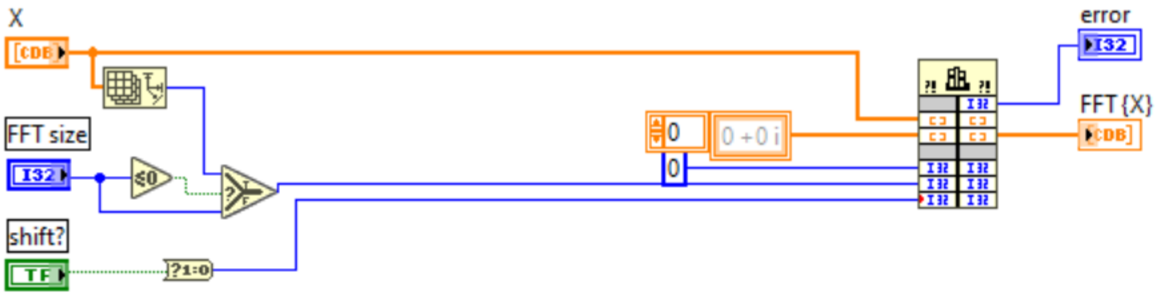
4. Remove the Cyclic Prefix



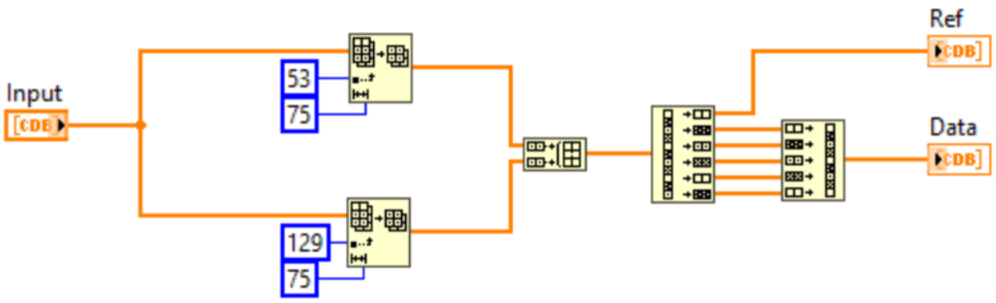
5. Remove the frequency offset from the incoming signal



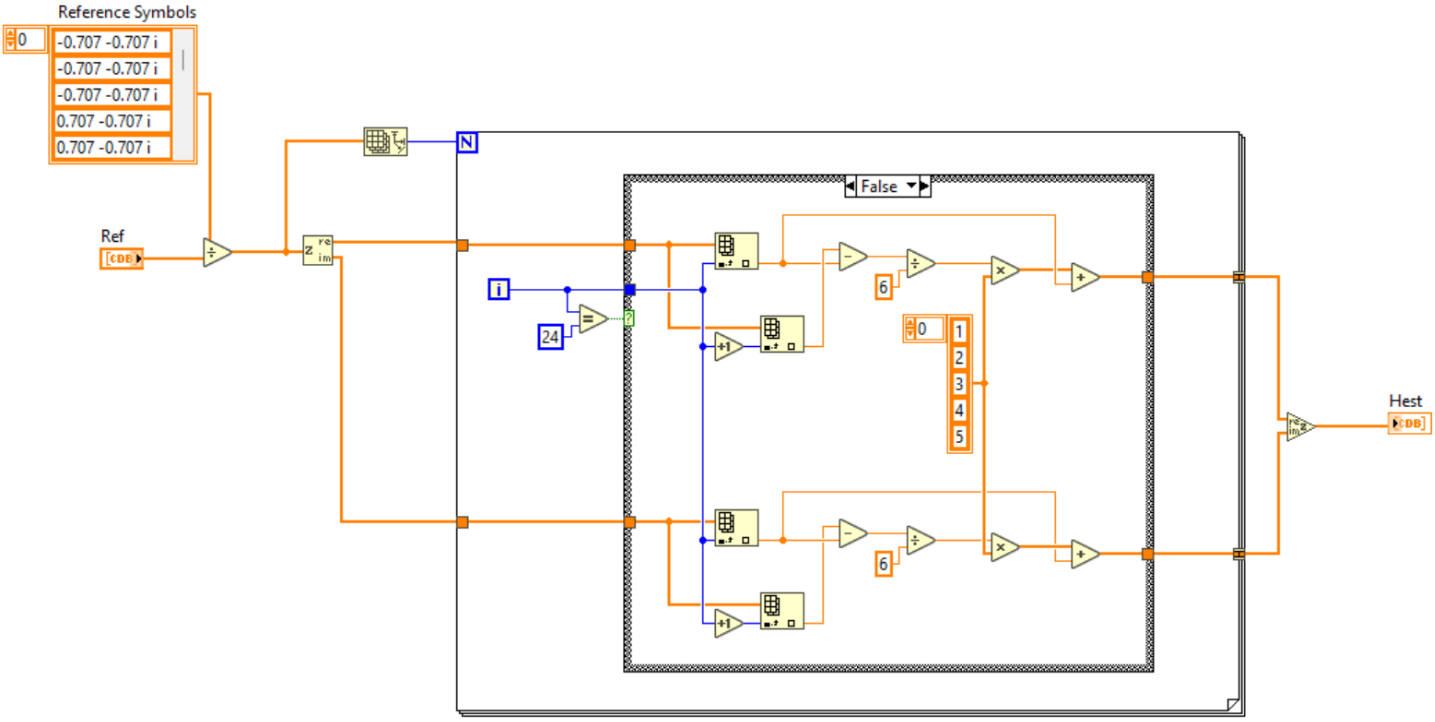
6. Compute the FFT converting the time domain OFDM symbol to the frequency domain



7. Separate the data bits, reference bits and remove zero padding



8. Compute Equalization coefficients using a linear fit for I and Q based on reference symbols.



9. Apply the equalization to the data symbols

10. Convert data symbol mapping back to data bits. Over here we decode the bits transmitted over the channel and convert it into String to decode the original text which was transmitted.

Connection with USRP:

1. Make sure the USRP is connected to the laptop having transmitter and receiver block diagrams and turned on.
2. Run the NI-USRP Configuration Utility software by clicking Windows Start -> NI-USRP Configuration Utility.
3. Find the device ID and the connection type. Name device transmitter and receiver as TX_G5.
4. Open a blank Vi and name as TX_G5.vi and RX_G5.vi for transmitter and receiver.
5. After connection, right click on the front panel -> waveform -> waveform graph. Connect this waveform Fetch Rx data in USRP receiver. Repeat the same procedure for transmitter.

Theoretical Calculations:

In OFDM with MQAM (Quadrature Amplitude Modulation), the bit error rate (BER) is affected by the ratio of energy per bit (Eb) to the power spectral density of the noise (No), also known as the signal-to-noise ratio (SNR) or Eb/No.

The relationship between Eb/No and BER in OFDM with MQAM can be approximated by the following formula:

BER ≈ (4/3) * (1/M) * Q(sqrt((3/2)*(Eb/No)*log2(M)))

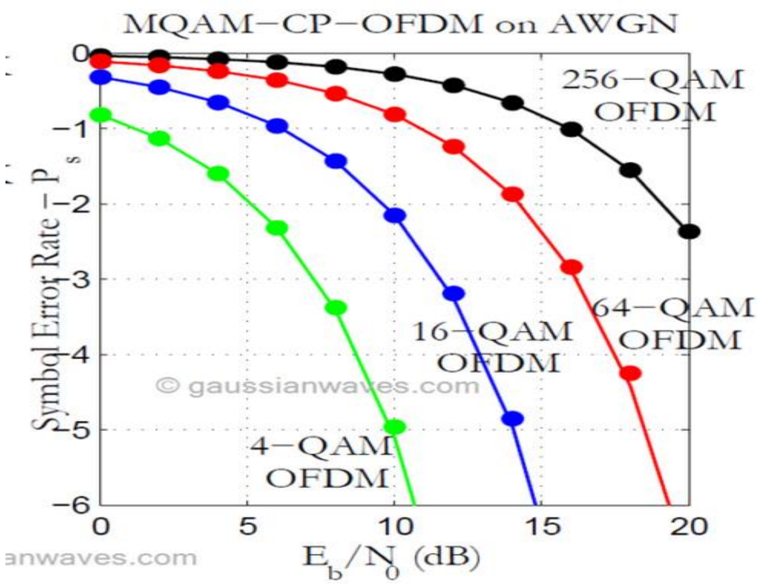
M is the number of constellation points used in the MQAM modulation

Effect of Eb/No on BER:

As can be seen from the formula, the BER decreases as the Eb/No increases. This means that higher SNR or higher energy per bit results in a lower BER. However, the relationship between Eb/No and BER is not linear. In fact, the BER decreases exponentially with increasing Eb/No.

Therefore, to achieve a desired BER, a higher Eb/No or higher SNR is required for higher-order MQAM modulations (e.g., 64-QAM) compared to lower-order MQAM modulations (e.g., 16-QAM). This is because higher-order MQAM modulations have more constellation points, which increases the likelihood of errors due to noise.

In summary, the effect of Eb/No on BER in OFDM with MQAM modulation can be described by a non-linear relationship that depends on the number of constellation points used in the MQAM modulation. A higher Eb/No or higher SNR is required for higher-order MQAM modulations to achieve a desired BER.



Performance of MQAM OFDM over AWGN noise

Effect of M on BER:

As M increases, the BER increases because the symbols are more closely placed inconstellation diagram.

Effect of FFT length on BER:

A longer FFT length can lead to a higher BER due to interference, delay spread, and non-linear distortion, but it can also offer some advantages in terms of frequency resolution and immunity to narrowband interference as longer FFT length allows for more subcarriers to be used, results in higher spectral efficiency and higher data rates which increases complexity of OFDM system.

A shorter FFT length can reduce the number of subcarriers, leading to a decrease in spectral efficiency and an increase in the likelihood of inter-carrier interference (ICI) and inter-symbol interference (ISI). This can also lead to a higher BER.

Therefore, the optimal FFT length for a specific application depends on several factors, such as the channel conditions, modulation scheme, coding rate, and system requirements. In general, there is an optimal FFT length that provides the best trade-off between spectral efficiency, delay spread, ISI, ICI, and other factors, resulting in the lowest possible BER.

Effect of Cyclic prefix length on BER:

A longer CP length in QAM OFDM can offer better protection against ISI, resulting in a lower BER and also improve synchronization and reduce the impact of phase noise, frequency offset, and time offset.

A shorter CP length in QAM OFDM can offer higher spectral efficiency but can also result in a higher BER due to reduced protection against ISI and also make the system more susceptible to phase noise, frequency offset, and timing offset, leading to synchronization errors and a higher BER.

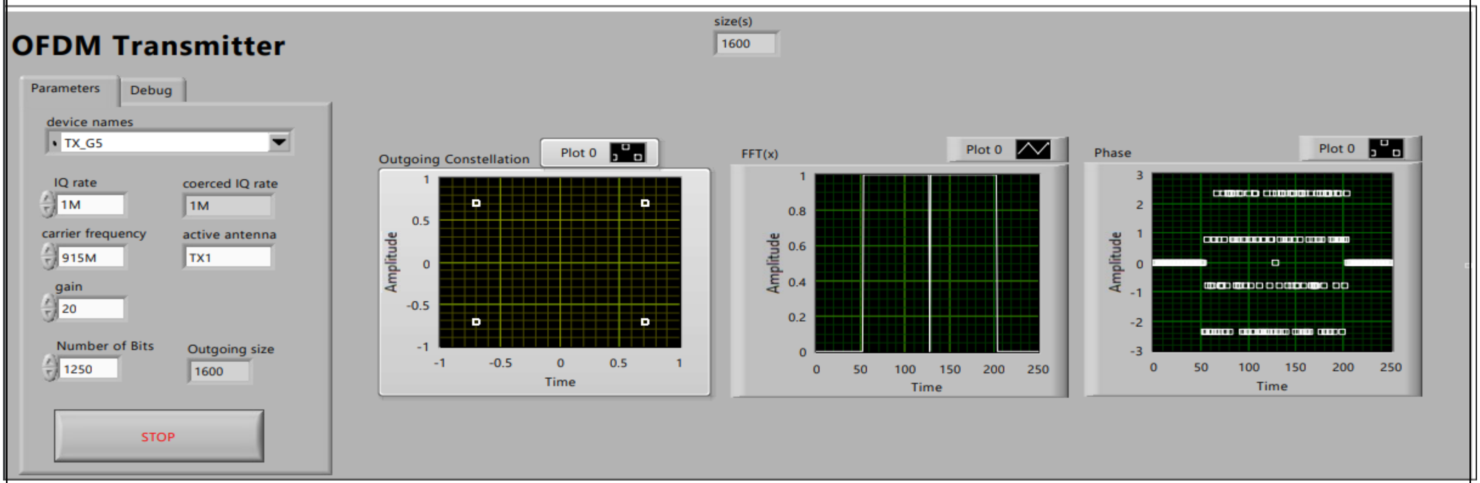
Therefore, there is an optimal CP length that provides the best trade-off between spectral efficiency and protection against ISI, resulting in the lowest possible BER. The optimal CP length depends on several factors, such as the channel conditions, modulation scheme, coding rate, and system requirements. In general, a longer CP length is preferred in QAM OFDM systems to ensure reliable communication and low BER.

RESULTS

WITHOUT TEXT

TRANSMITTER

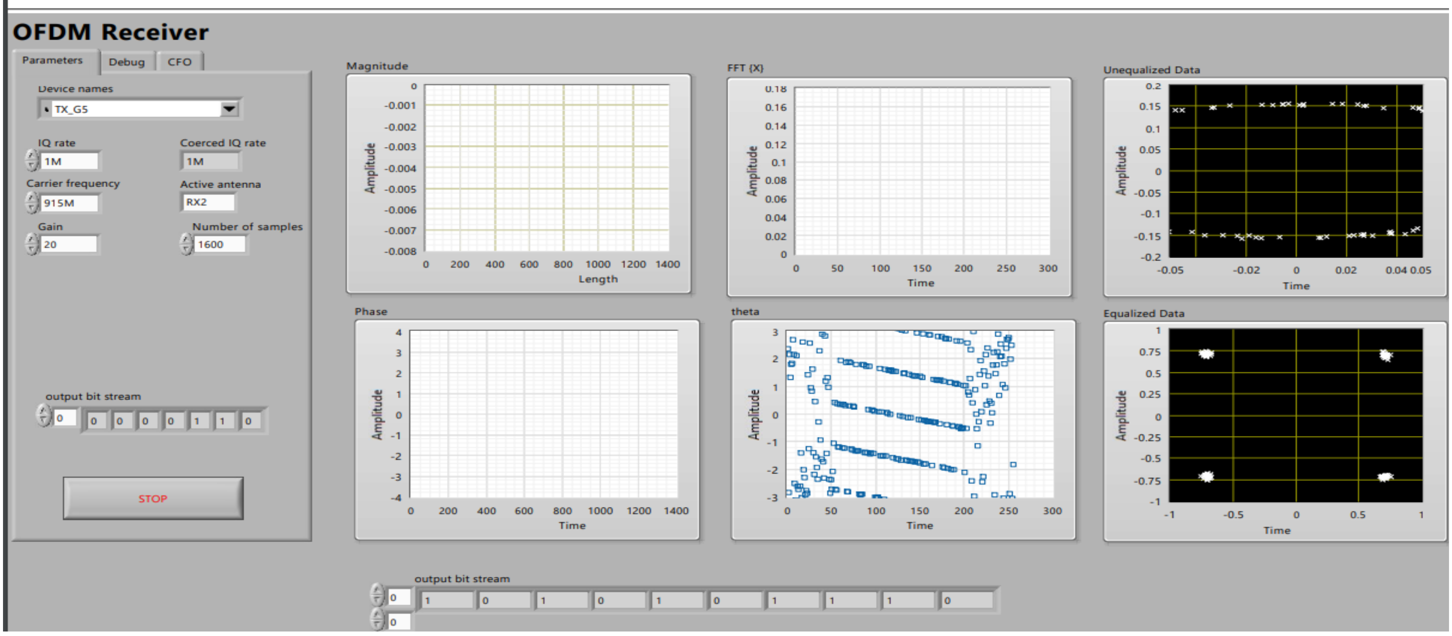
TX.vi
C:\Users\ishaa\AppData\Local\Temp\Temp1_OFDM Tx Rx.zip\OFDM Tx Rx\TX OFDM - USRP.llb\TX.vi
Last modified on 10-12-2013 at 04:19
Printed on 28-04-2023 at 11:11



IQ Rate: 1MHz
Carrier Frequency: 915MHz
Gain: 20dB
FFT length: 256
Cyclic Prefix length: 64
M= 4

RECEIVER

RX
C:\Users\ishaa\AppData\Local\Temp\Temp1_OFDM Tx Rx.zip\OFDM Tx Rx\RX OFDM - USRP.llb\RX
Last modified on 09-01-2014 at 22:17
Printed on 28-04-2023 at 11:10

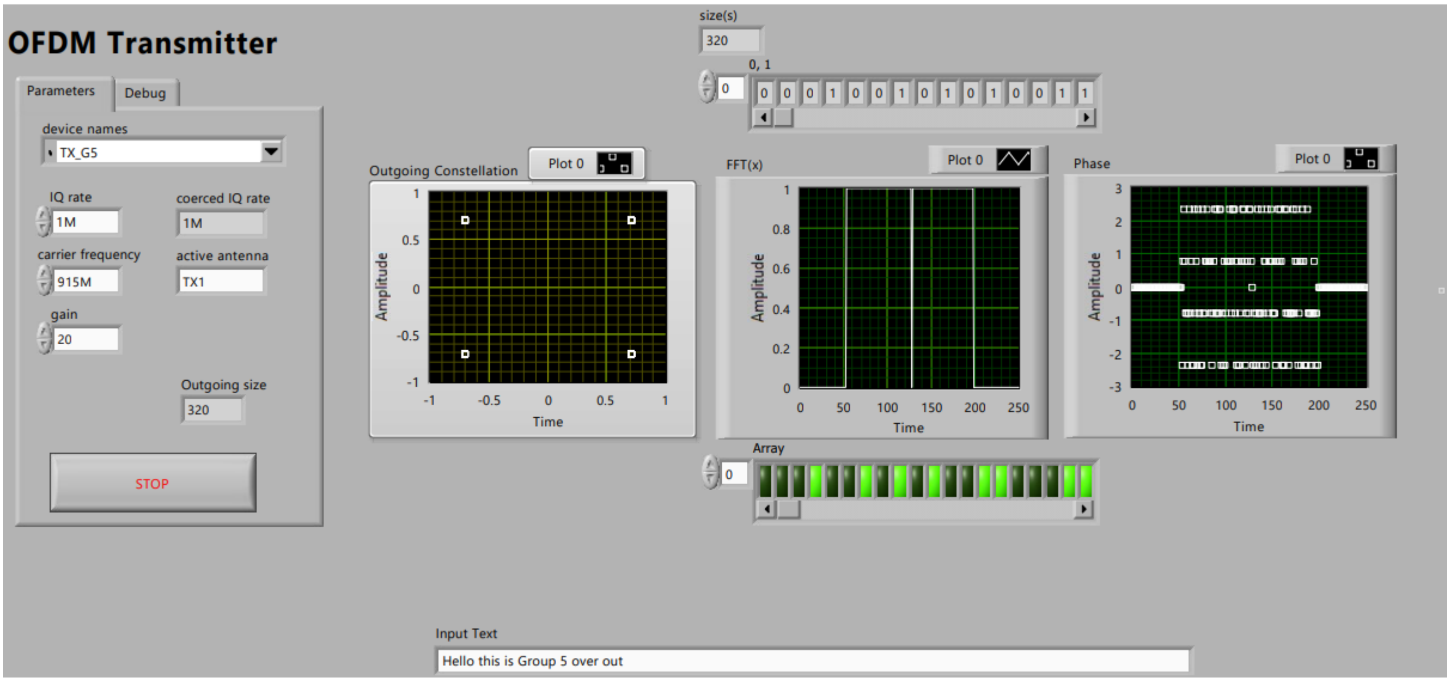


Here unequalized data represents the received data in its original form without any compensation for the channel impairments, while equalized data represents the received data that has been processed with equalization to compensate for the channel impairments and improve the accuracy and reliability of the received signal.

WITH TEXT 1

<u>TRANSMITTER</u>

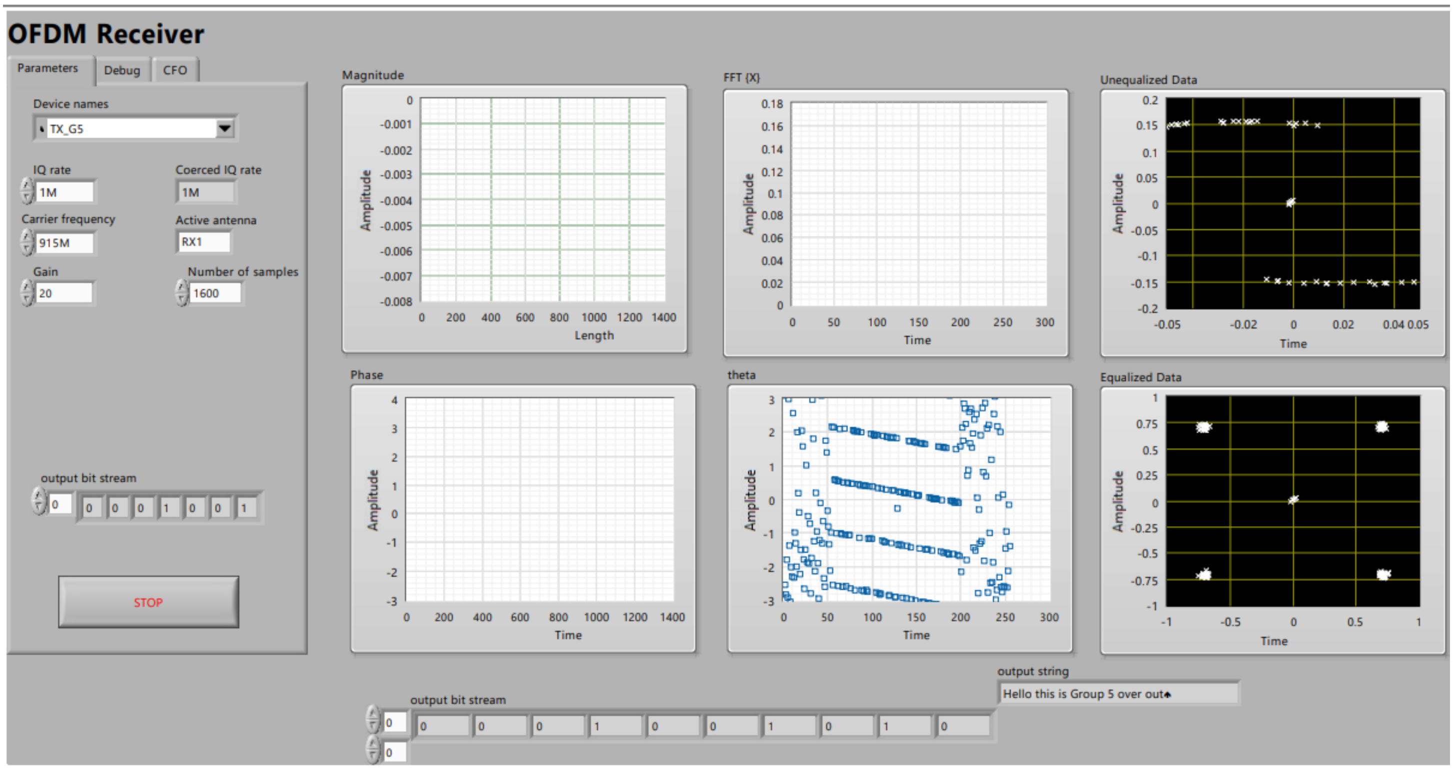
OFDMwithTextTX.vi
C:\Users\ishaa\OneDrive\Desktop\MTech Second Sem\OFDMwithTextTX.vi
Last modified on 01-05-2023 at 11:27
Printed on 01-05-2023 at 11:30



IQ Rate: 1MHz
Carrier Frequency: 915MHz
Gain: 20dB
FFT length: 256
CP length: 64
Message Transmitted: Hello this is Group 5 over out

RECEIVER

OFDMwithTextRX.vi
C:\Users\ishaa\OneDrive\Desktop\MTech Second Sem\OFDMwithTextRX.vi
Last modified on 01-05-2023 at 11:26
Printed on 01-05-2023 at 11:31

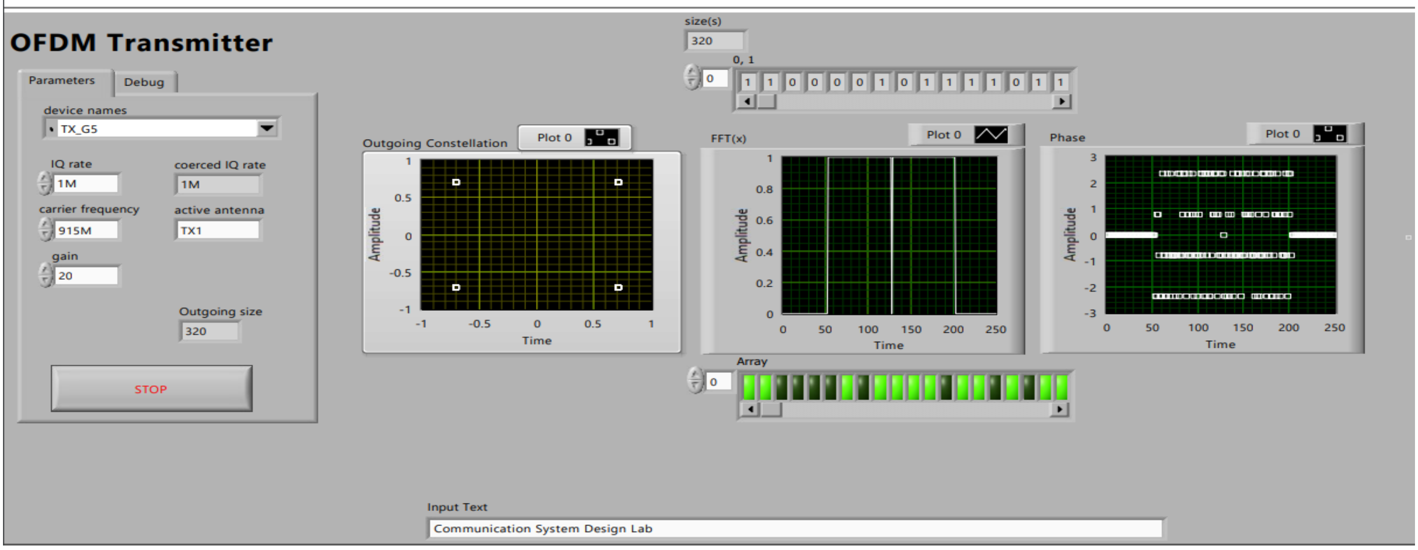


IQ Rate: 1MHz
Carrier Frequency: 915MHz
Gain: 20dB
Message Received: Hello this is Group 5 over out

WITH TEXT 2

TRANSMITTER

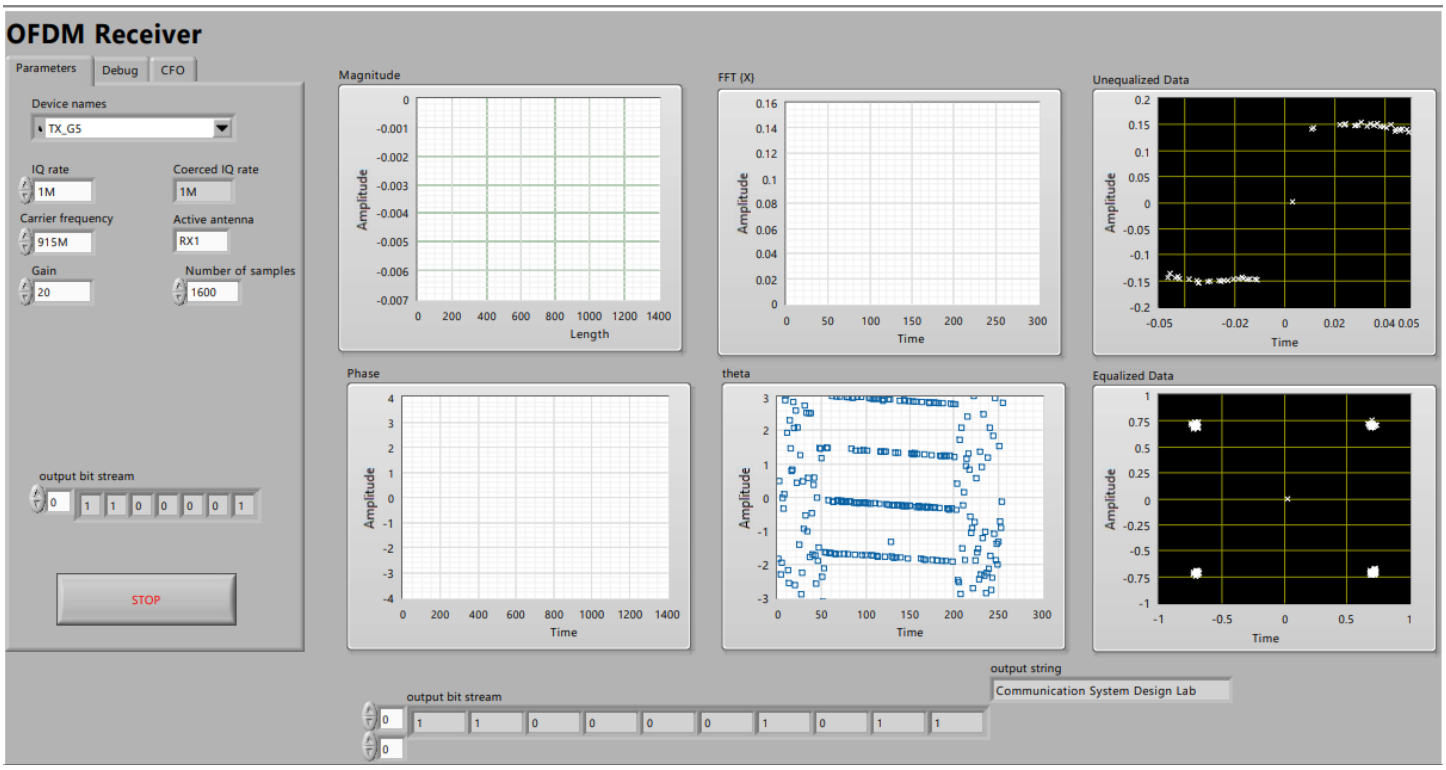
OFDMwithTextTX.vi
C:\Users\ishaa\OneDrive\Desktop\MTech Second Sem\OFDMwithTextTX.vi
Last modified on 01-05-2023 at 11:27
Printed on 01-05-2023 at 11:34



IQ Rate: 1MHz
Carrier Frequency: 915MHz
Gain: 20dB
FFT length: 126
CP length: 32
Message Transmitted: Communication System Design Lab

RECEIVER

OFDMwithTextRX.vi
C:\Users\ishaa\OneDrive\Desktop\MTech Second Sem\OFDMwithTextRX.vi
Last modified on 01-05-2023 at 11:26
Printed on 01-05-2023 at 11:34



IQ Rate: 1MHz
Carrier Frequency: 915MHz
Gain: 20dB
Message Received: Communication System Design Lab

CONCLUSION

- If Eb/No increases SNR increases and BER decreases.
- A longer symbol period reduces data rate whereas shorter symbol period increases data rate.
- A longer FFT length increase spectral efficiency, data rates and complexity which improves the BER performance of the system whereas A shorter FFT length reduces the complexity, spectral efficiency and data rates which results in high BER.
- More the Cyclic Prefix length less the BER and vice versa.