MOBILE COMMUNICATIONS

LAB REPORT

A MATLAB SIMULATION REPORT ON MOBILE COMMUNICATION- OFDM

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INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation technique widely used in modern communication systems due to its ability to overcome the effects of **multipath propagation**, **increase spectral efficiency**, and mitigate **inter-symbol interference** (ISI)

Many applications require high data rates, but as the data rate increases, the symbol duration decreases, leading to more pronounced ISI in single-carrier modulation due to dispersive fading in wireless channels.

On the other hand, OFDM modulation divides the frequency-selective fading channel into numerous multiple orthogonal subcarriers/narrowband flat fading subchannels or Non-frequency-selective channels. This enables the transmission of high-bit-rate data in parallel without experiencing ISI due to the longer symbol duration, meaning multiple users can share the bandwidth and every carrier can deploy a modulation technique.

These subcarriers are spaced apart at precise frequencies to ensure orthogonality, meaning they do not interfere with each other, even when they overlap in the frequency domain which reduces large delay spreads.

The objective of this lab is to implement OFDM modulation and study the properties and impact of complex envelope, subcarrier, effects of Cyclic Prefix and the equalizer process.

- Properties of the complex envelope of the OFDM signal (without CP)
- Channel Impact on the Power Spectral Density and subcarrier constellations,
- Effects of Cyclic Prefix and the one-tap equalizer
- Study of Impact of timing error in OFDM signal

In digital communication, a one-tap equalizer is often used in situations where the channel distortion causes inter-symbol interference (ISI), where adjacent symbols interfere with each other due to channel characteristics, a one-tap equalizer may be sufficient to adjust the phase or magnitude of the received signal to mitigate the interference.

Sequence 1 : Properties of the complex envelope of the OFDM signal (without CP)

Complex Envelope: The complex envelope is the modulated signal or carrier signal in the complex plane. In simple terms, a carrier signal is typically a real-valued signal /a sinusoidal wave with both amplitude and phase components.

Carrying out the analysis of the program of OFDM transmitter by choosing the number of subcarriers as 64(Length of OFDM block) and the number of useful carriers as 1 in BPSK modulation.

Pl follow the MATLAB file: PSD_OFDM_final for the program

psd_OFDM_final.m

OBSERVATION OF POWER SPECTRAL DENSITY PLOT

CASE 1: Nu=1 – BPSK

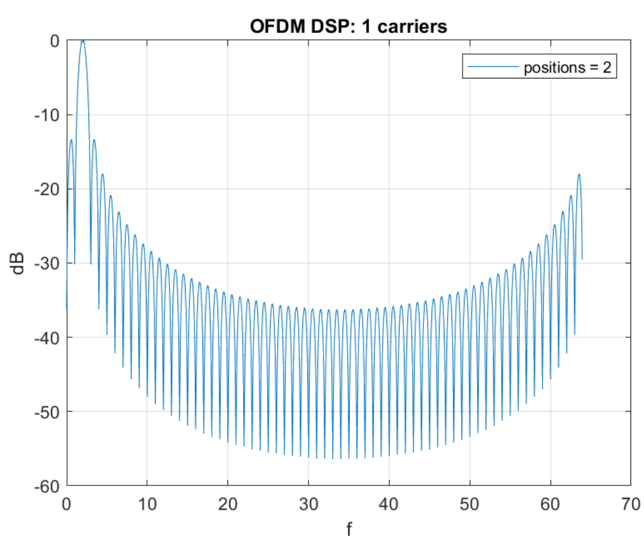


Fig: Power spectral Density plot of OFDM-1 CARRIER

Analyzing the PSD plot, the PSD is correct for a single carrier at position [2:2]. The program uses Welch method for estimating the PSD by dividing the signal into overlapping segments, computing the periodogram for each segment using the FFT, and then averaging the resulting periodograms to obtain a smoother estimate of the PSD. As per the image, of 1 subcarrier in the range 0 to 1, the subcarrier peak is found in the plot which verifies that orthogonality is maintained. Hence, PSD is correct.

OBSERVATION OF PDFs FOR REAL & IMAGINARY PARTS OF THE SIGNAL

According to the central limit theorem, the real and imaginary parts of the complex envelope of an OFDM signal should follow Gaussian distributions if the number of sub-carriers is sufficiently large and there is no specific structure in the signal that deviates from Gaussian behavior. The program uses histograms to estimate the PDFs of the real and imaginary parts of the OFDM signal which are then compared to Gaussian distributions for visual analysis.

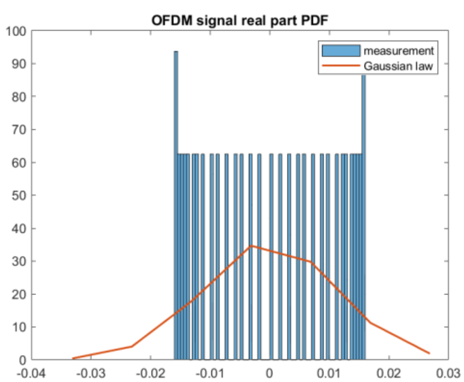


Fig:Probability Density Function Real part

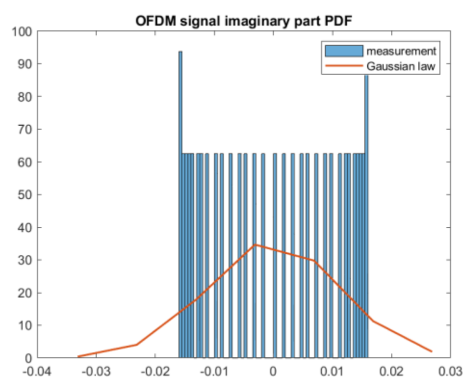


Fig:Probability Density Function Imaginary part

In this case of useful carriers Nu=1, the signal does not exhibit a Gaussian distribution due to an insufficient number of sub-carriers, indicating that the central limit theorem is not fully satisfied as the Central Limit Theorem provides an approximation rather than an exact result. The larger the sample size, the better the approximation, and the modulus of the envelope of the signal follows a Rayleigh distribution.

ANALYSIS OF REAL PART OF SUBCARRIER CENTERED AT f=0 & f=1/T.

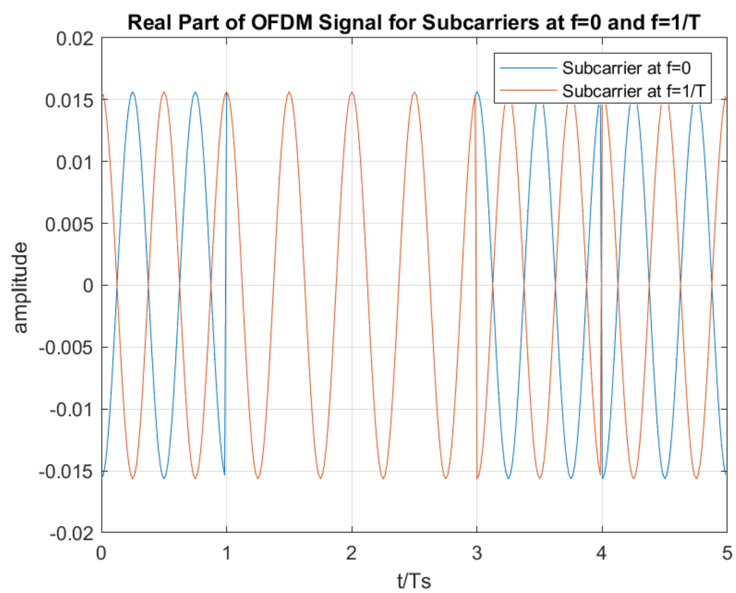


Fig: Real part subcarrier signal center at f=0 & f=1/T

In general case, Subcarrier at f=0: The real part of this subcarrier should show a constant value over time, corresponding to the DC component of the OFDM signal, and for a BPSK modulation, in the image, the real part takes two amplitude values -0.015 & +0.015.

In Subcarrier at f=1/T: The real part of this subcarrier should exhibit a sinusoidal shape with a frequency of 1/T , and for a BPSK modulation, the real part will undergo a simple sinusoidal oscillation according to binary data.

CASE 2: Nu=2 – BPSK

Adjacent:

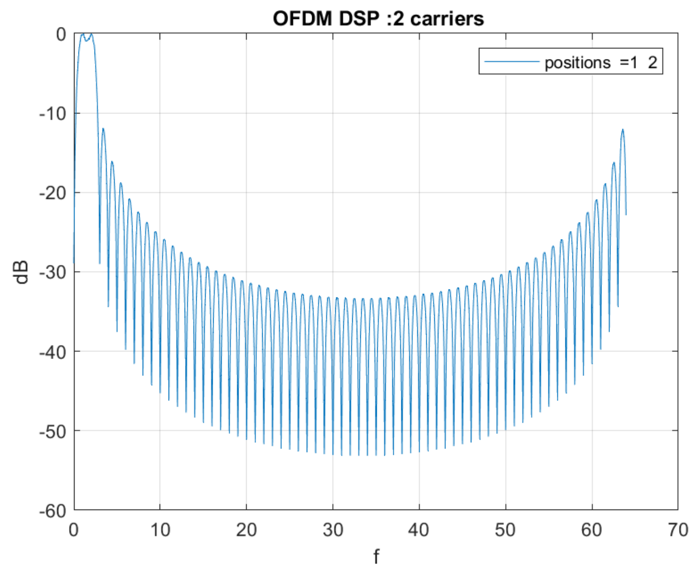


Fig: Power Density Plot of OFDM signal-2 carriers

In the adjacent case, it can be observed from the power spectral density plot, that the main lobe of 2 subcarrier signal is overlapping due to the adjacent position of the subcarrier. Hence the Power Spectral Density plot is correct.

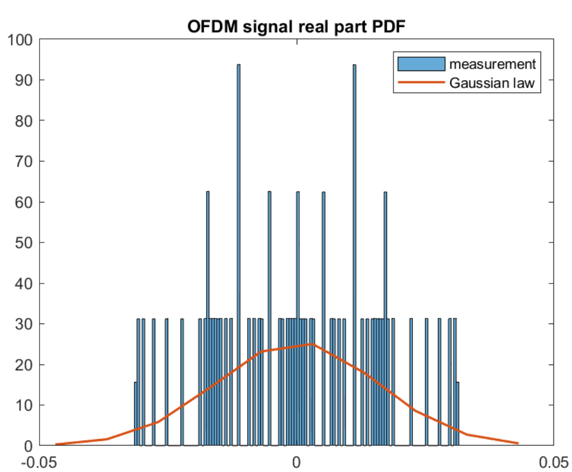


Fig: Probability Density Function Real part

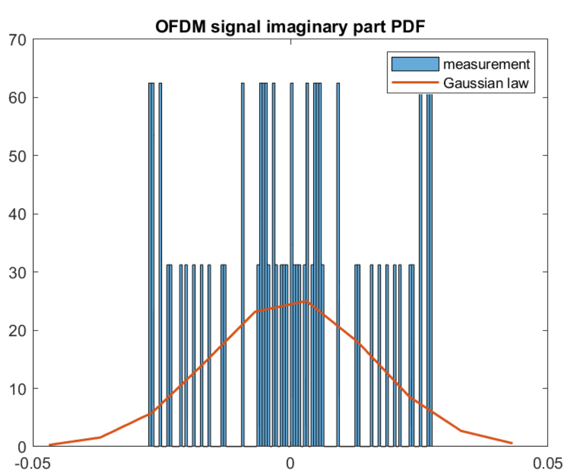


Fig: Probability Density Function Imaginary part

Analyzing the real and imaginary parts of the Density Function plot, it can be concluded that the measured signal does not exhibit Gaussian distribution due to the deficient number of subcarriers which makes the distribution deviate from a Gaussian curve distribution.

In BPSK, each symbol represents a bit, and the phase of the carrier signal is shifted by 180 degrees depending on the bit value. The real and imaginary parts of the signal can only take on two distinct values, resulting in a discrete distribution. While the sum of a large number of BPSK symbols might approximate a Gaussian distribution due to the Central Limit Theorem, but individual symbols do not follow Gaussian distributions.

- <u>Non-Adjacent</u>

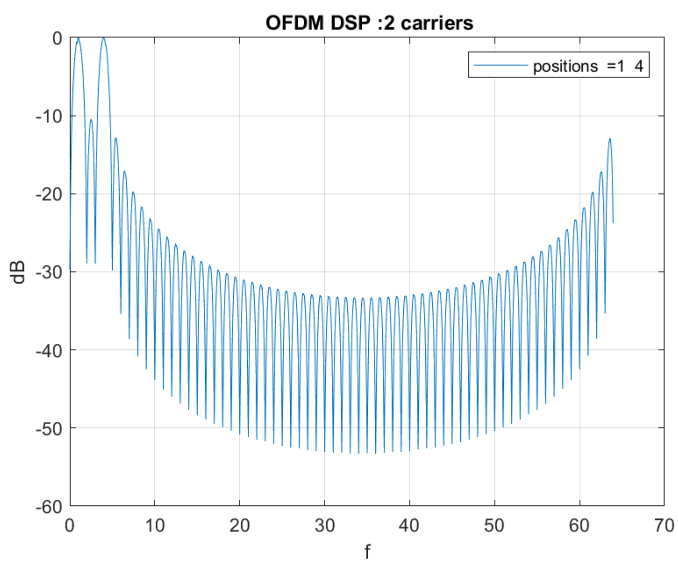


Fig: Power Spectral Density Plot-2 Carriers

In the scenario of 2 non-adjacent subcarriers, it can be observed that the Power Spectral Density is correct as the main lobes of 2 carriers are separated at a gap of 3 positions.

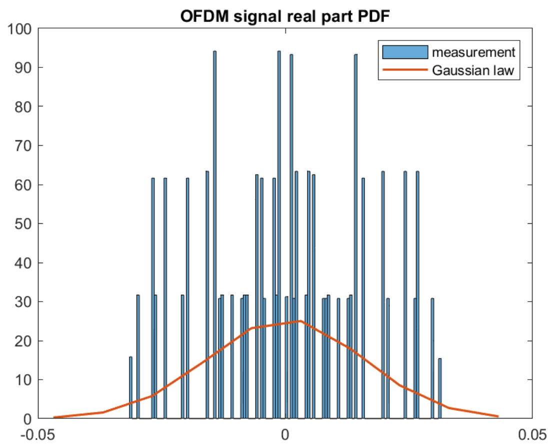


Fig: Probability Density Function Real part

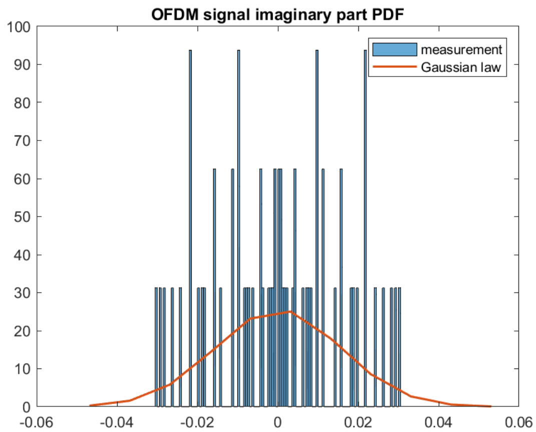


Fig: Probability Density Function Imaginary part

Further analyzing the power density function of 2 non-adjacent subcarriers, also does not exhibit Gaussian distribution due to the deficient number of subcarriers which makes the distribution deviate from a Gaussian curve and not entirely according to Central Limit Theorem.

CASE 3: Nu=10 – BPSK

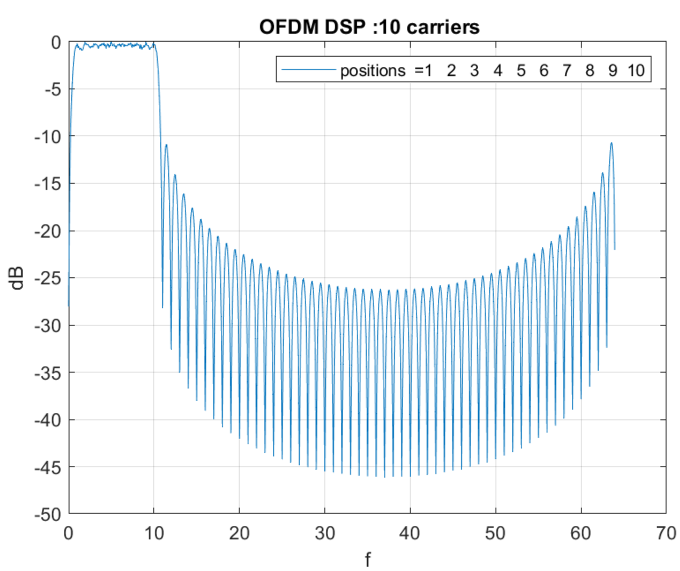
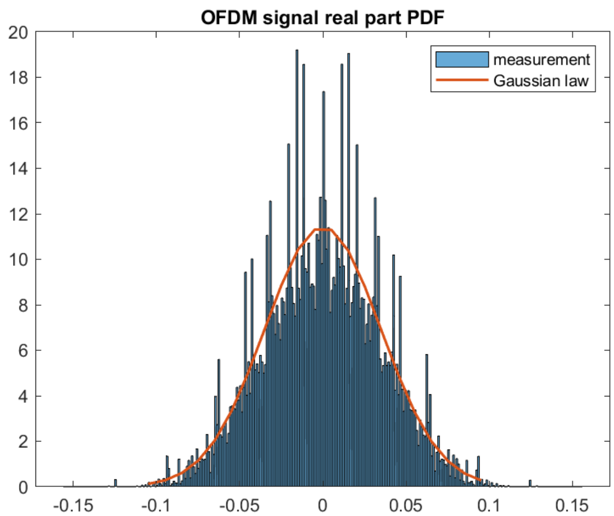
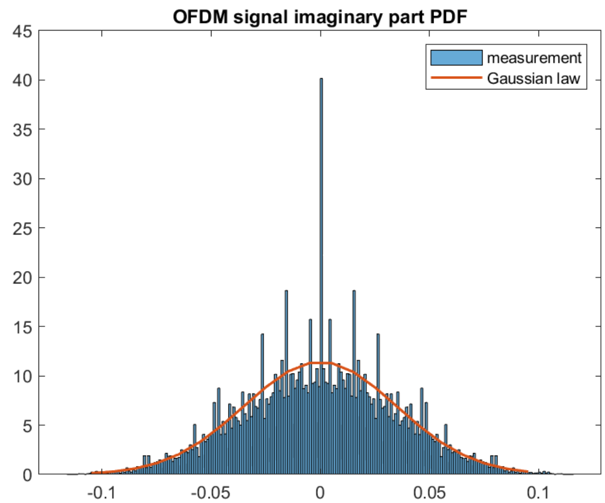


Fig: Power Spectral Density Plot-10 Carriers

In this part, the Spectral Density of 10 subcarriers in adjacent positions is analyzed and it can be observed from the plot, that the main lobe of 10 subcarrier signals is overlapping in the X-axis range 1 to 10 frequency which verifies the orthogonality property. Hence the plot is correct.





Compared with the previous cases of a lower number of subcarriers, the subcarrier count contains a major contribution in proving the Central Limit Theorem. Using **10 useful subcarriers** yields a Gaussian distribution Power Density Function plot with a negligible deviation.

OBSERVATION OF PDFs FOR N=64 SUBCARRIERS

Envelope Fluctuation: Envelope fluctuation refers to the variation in the amplitude or magnitude of a modulated signal over time and depends on the modulation scheme, the more **complex modulation schemes exhibit greater envelope fluctuations** compared to simpler schemes. These fluctuations can impact the ability of the receiver to accurately detect and demodulate the transmitted symbols leading to potential challenges in signal detection and demodulation.

During the case of **N=64-BPSK modulation & QPSK modulation**:

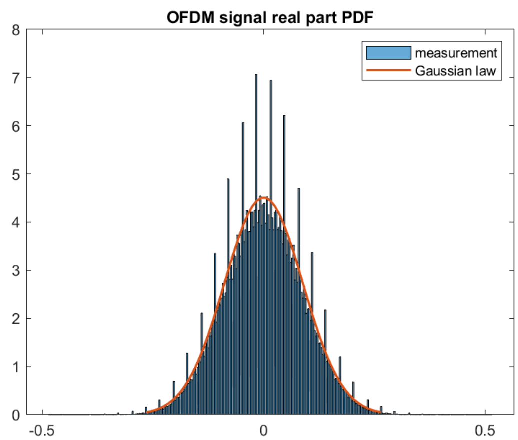


Fig: PDF of BPSK

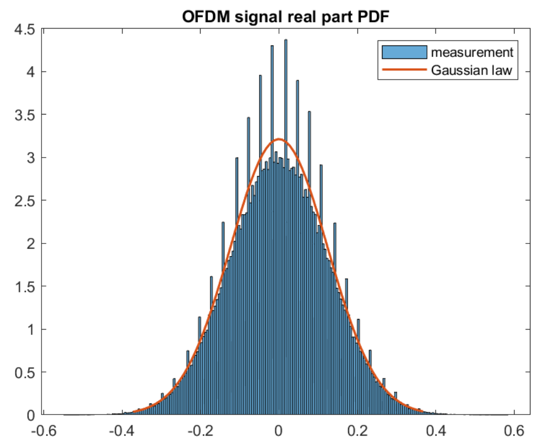


Fig: PDF of QPSK

BPSK uses two phase shifts and QPSK uses four different phase shifts (0, 90, 180, and 270 degrees), allowing for one bit and two bits to be transmitted per symbol respectively. Again, the real and imaginary parts of the signal can only take on a limited set of values, resulting in a discrete distribution. Similar to BPSK, the distribution of individual symbols is not Gaussian hence it deviates from following the Gaussian law.

However, analysing the complex envelope PDF plot below it is noted that there is no peak amplitude and the measured histogram closely matches the theoretical Rayleigh distribution indicating the fading characteristics. Characterized by random amplitude variations of the received signal, these variations closely follow Rayleigh distribution but not entirely, which arises when the in-phase and quadrature components of the received signal are both subject to independent, identically distributed Gaussian random variables.

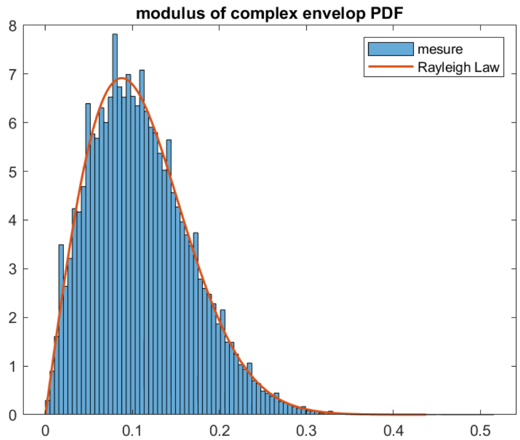


Fig: Envelope PDF of BPSK

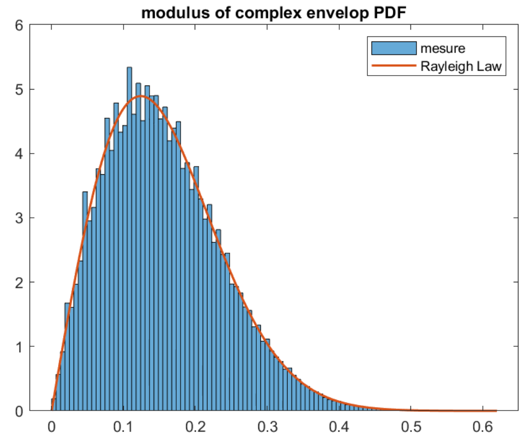


Fig: Envelope PDF of QPSK

However, in the case of **N=64-16 QAM,** each individual symbol in 16QAM does not follow a Gaussian distribution, the sum of many symbols tends towards a Gaussian distribution due to the Central Limit Theorem. 16QAM combines both amplitude and phase modulation,

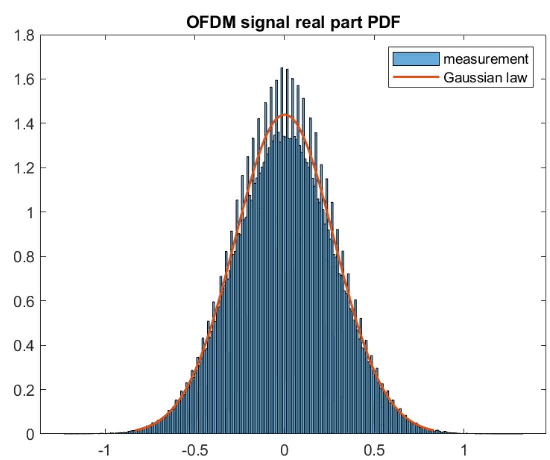


Fig: Probability Density Function for 16 QAM

allowing for four amplitude levels and four phase shifts, resulting in a total of 16 possible symbols. The distribution of the signal depends on both amplitude and phase, leading to a complex distribution that is not entirely Gaussian but closer to Gaussian distribution as in above plot of PDF.

The envelope fluctuation of 16 QAM due to variation in random amplitude in the received signal. The magnitude of the resulting complex envelope (encompassing both in-phase and quadrature components) follows a Rayleigh distribution.

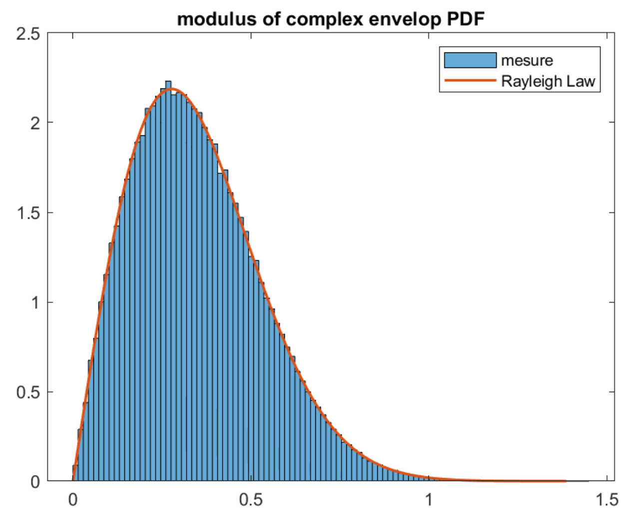


Fig: Complex envelope PDF for 16 QAM

EFFECT OF NULL OBO IN ABSENCE OF PAPR REDUCTION TECHNIQUE

A well-known problem of OFDM signals is their high Peak-to-Average Power Ratio (PAPR), as the signal with high PAPR requires large linear range of Power Amplifier. If the signal exceeds linear region,it suffers from non-linear distortion. Hence in the absence of PAPR reduction techniques, poses a significant challenge within the context of Orthogonal Frequency Division Multiplexing (OFDM) as OFDM signals introduce inherent complexities in the amplification process.

- Operating the amplifier solely in the linear region, i.e., with a large output back-off, results in an undistorted transmitted signal, but at the expense of a low SNR at the receiver.

- Driving the amplifier into saturation, on the other hand, maximizes the received SNR, but causes severe nonlinear signal distortions in the amplitude peaks of signal in the amplifier. Consequently, attaining a null OBO becomes difficult due to the nonlinearities associated with the high PAPR of OFDM signals.

To address this challenge, it is essential to implement PAPR reduction techniques such as clipping, filtering, and coding. Failure to control the issue may result in interference with adjacent channels leading to degradation in the link budget.

Sequence 2: Impact of the channel on the DSP and OFDM subcarrier constellations, CP dimensioning and role of the one tap equalizer (=channel compensation)

To mitigate the effects of ISI caused by channel delay spread, each block of N- IFFT coefficients is typically preceded by Cyclic Prefix (CP) which is simply a guard interval consisting of N samples that is the repetition of the last N IFFT coefficients, such that the length of the CP is at least equal to the channel.

Setting the channel coefficients as 1+1i, 0+0i, 0.5+0.5i, 0.25+0.25i and Observing the PSD and constellation for various subcarriers **without implementing Cyclic Prefix** below.

Pl follow the MATLAB file: Sequence2_noCP for the program

Sequence2_NoCP.m

In the first study, **64 useful subcarriers** are taken and analysing the output of Frequency response plot, the channel exhibits Frequency selective behaviour as the channel response is not flat

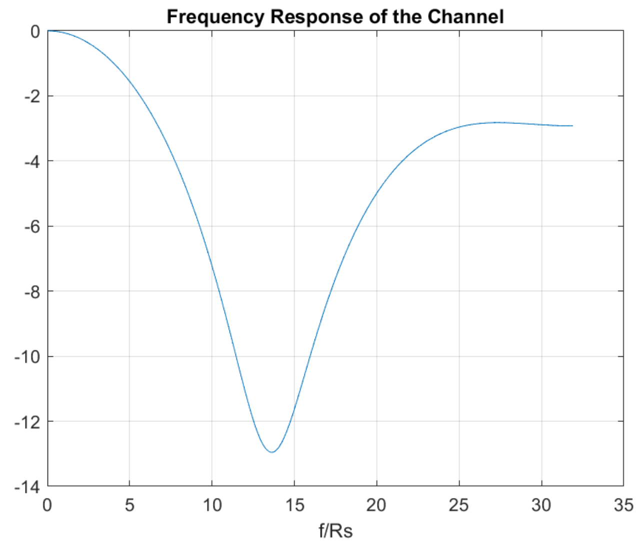


Fig: Frequency Response of Channel

Similarly, the PSD at the input and the receiver filter shows the product of Channel frequency response and the Power spectral Density of 64 subcarriers in the figure below

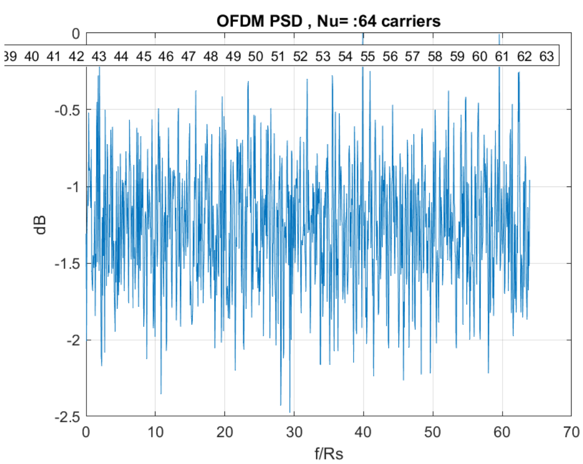


Fig: PSD at Transmitter

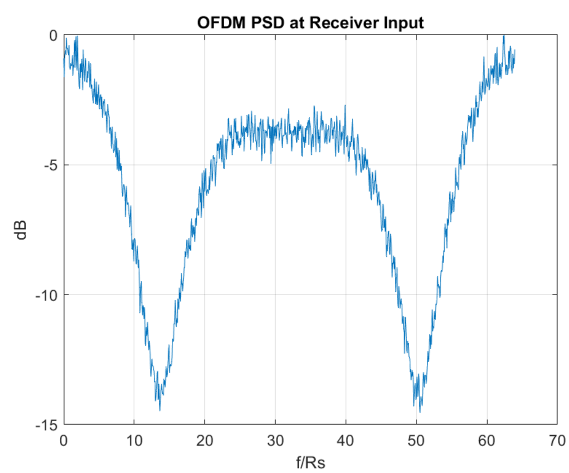


Fig: PSD at Receiver

Further observing the constellation of subcarrier 15 implementing the equalizer, the output generated below displays the role of the equalizer in compensating for the interference introduced by the channel. Although the result is minimal, it is verified by comparing the scale of two plots. However, The interference noted here is reduced but it is negligible after equalization.

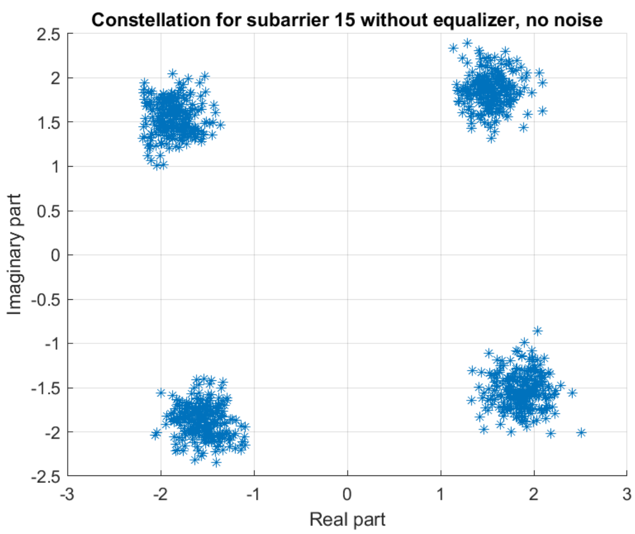


Fig: Constellation without Equalizer

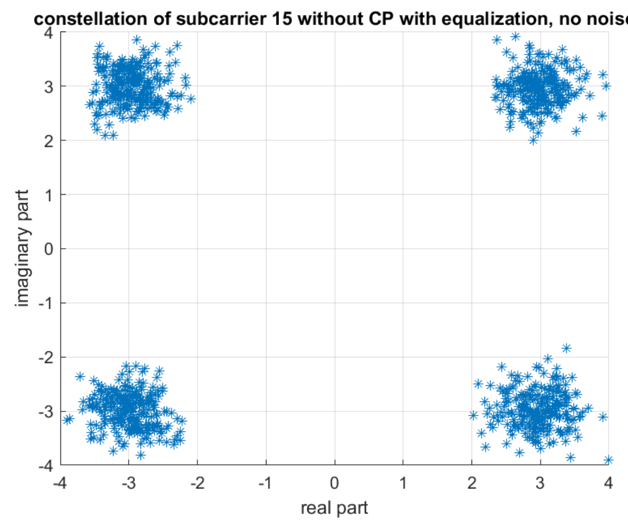


Fig: Constellation with Equalizer

In the case of 15 useful subcarriers from position 5 to 15, The Power Spectral Density plot at the Transmitter and Receiver side input for 11 carriers is below. It can be observed that the Main lobe of the PSD at the receiver side is the product of frequency response and input PSD.

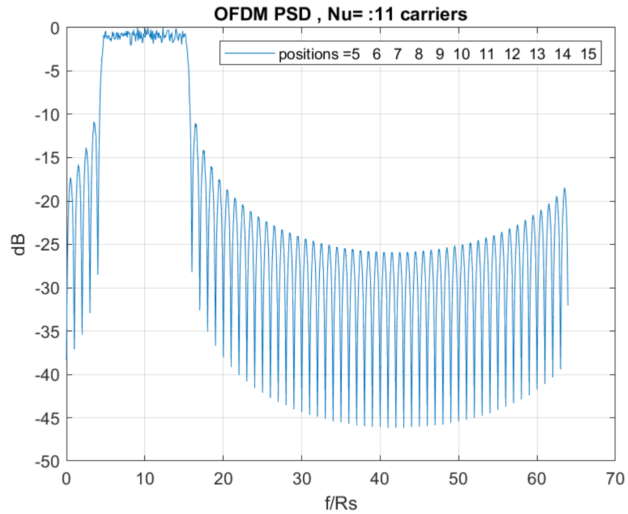


Fig: PSD at Transmitter

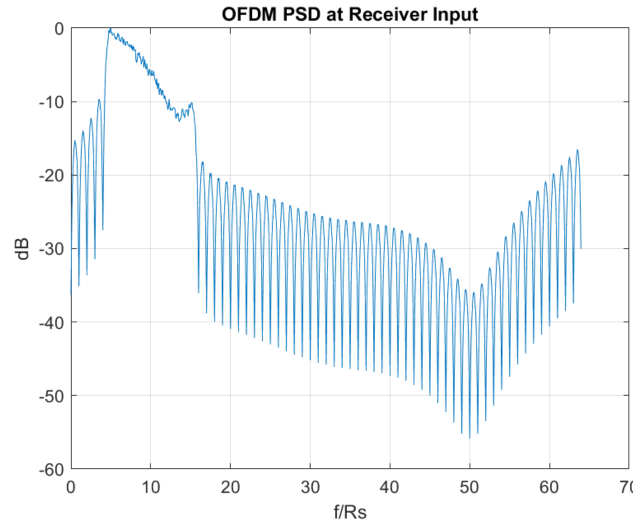


Fig: PSD at Receiver

The constellation of 11 Subcarriers varies in comparison to the previous case, the interference is less in subcarriers 5:15 and the equalizer is implemented.

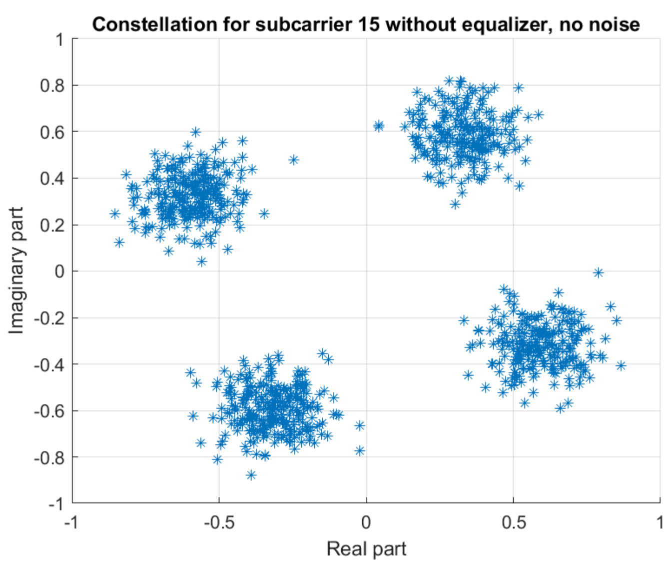


Fig: Constellation of 15th subcarrier without Equalizer

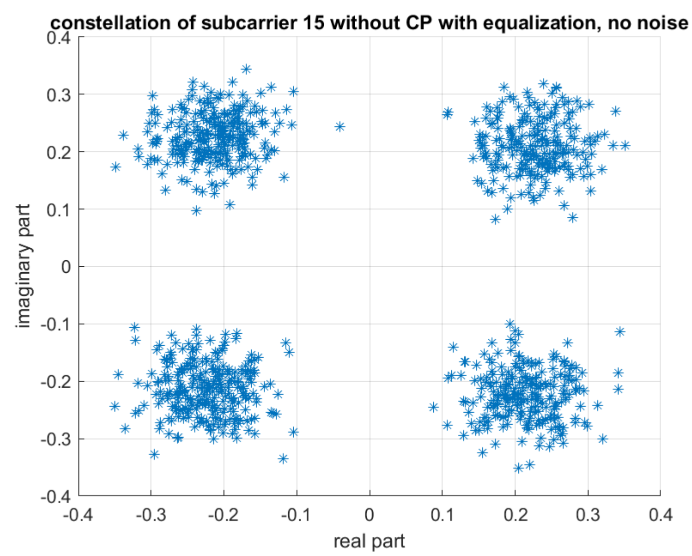


Fig: Constellation of 15th subcarrier with Equalizer

STUDY OF CHANNEL IMPACT WITH CYCLIC PREFIX

Setting the channel coefficients as 1+1i, 0+0i, 0.5+0.5i, 0.25+0.25i and Observing the PSD and constellation for various subcarriers **implementing Cyclic Prefix** below.

Pl follow the MATLAB file: Sequence2_CP for the program

Sequence2_CP.m

The Frequency Response of the channel remains the same as it is the same channel implemented without Cyclic Prefix. However, the Power spectral density for 11 carriers varies across the Cyclic Prefix length. The given CP lengths are 1,2,3,4,5 & 10. When the program is run, it generates the output for PSD and constellation plot for all the 6 Cyclic prefix for subcarriers positions from 5 to 15.

It can be observed that interruptions for each CP varies as below

- For a length of 1 cyclic prefix (CP), the interruption is 9.2302.
- If the length of CP is 2, the cutoff reduces to 8.1029.
- Further increasing the CP length to 3 reduces the cutoff to 7.0169.
- When CP length is 4, the cut-off further decreases to 5.9896.
- Increasing the CP length to 5 further reduces the cutoff to 5.0358.
- Finally, when the length of CP is 10, the cutoff decreases sharply to 1.5671.

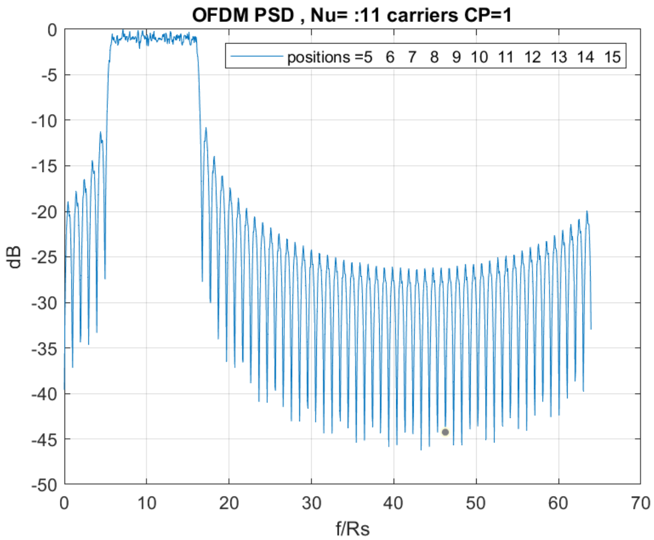


Fig: PSD at Transmitter Input for CP=1

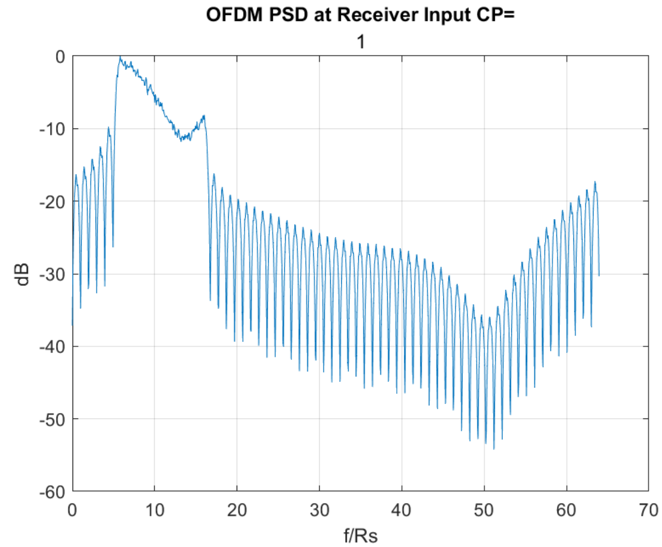


Fig: PSD at Receiver side for CP=1

Henceforth from these results, as the length of CP increases, the interference decreases. This is because longer CPs provide better protection against cross-signal interference caused by different mechanisms. In addition, the longer CP length allows for better estimation of the paths and equalization performance, reducing interference.

The **minimum CP length for the cutoff to approach zero** has not been accurately determined from these results. However, we find that interference decreases significantly with increasing CP length, indicating that longer CP lengths are more effective in reducing interference so it is important to choose a sufficiently long CP length to reduce interference time considering the intricacies of trade-offs with spectral efficiency and order.

Overall, increasing the CP length has a positive effect on the system in terms of decreasing interference, improving the estimation of the paths, and increasing the equalization performance, albeit at a cost that tends to reduce the spectral efficiency due to the overhead introduced by the CP.

Altering the channel coefficients as **1+1i, 0.5+0.5i, and 0.25+0.25i** changed the frequency

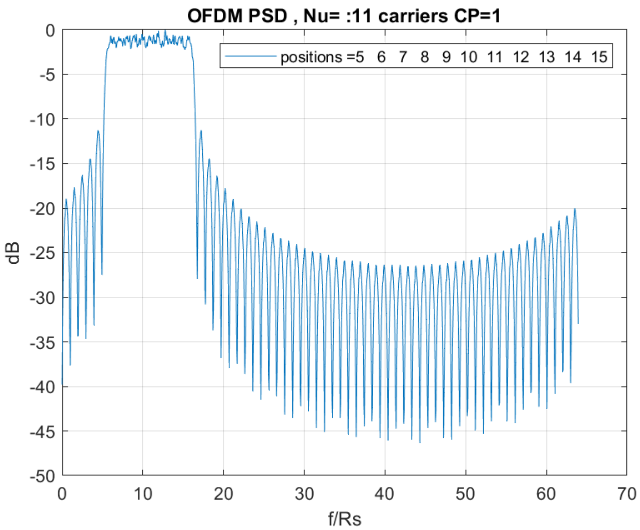


Fig: PSD at Input

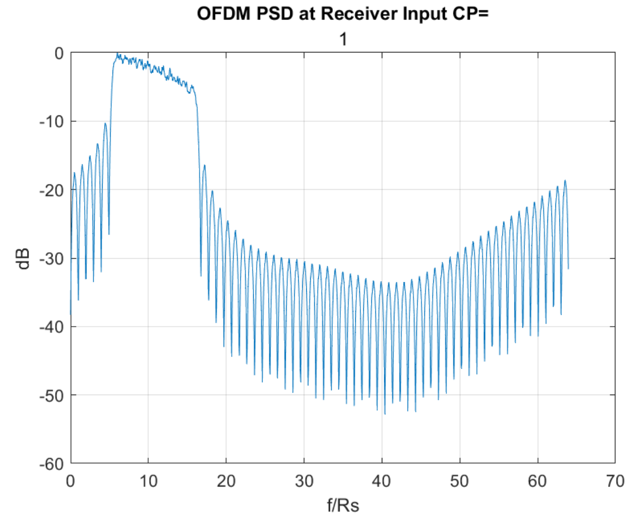


Fig: PSD at Receiver side

response of the channel in which the impact is observed in the PSD plot at the receiver side and as the length of cyclic prefix increases, the interference between adjacent subcarriers widens which can be observed in the sub lobes in below plots of **CP length=3.**

Comparing the constellation of 2 different channels, the size of the cloud is much less and more

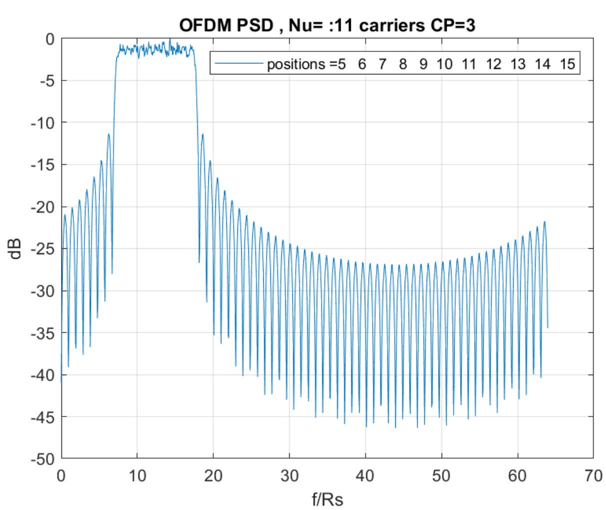


Fig: PSD at Input , CP=3

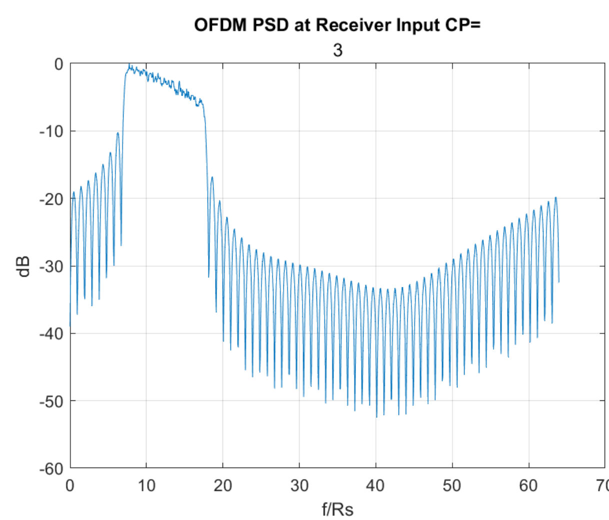


Fig: PSD at Receiver side, CP=3

equalized for the channel with 3 coefficients(case2), than the channel with 4 coefficients (Case1), below is the constellation plot for CP=1 for both cases.

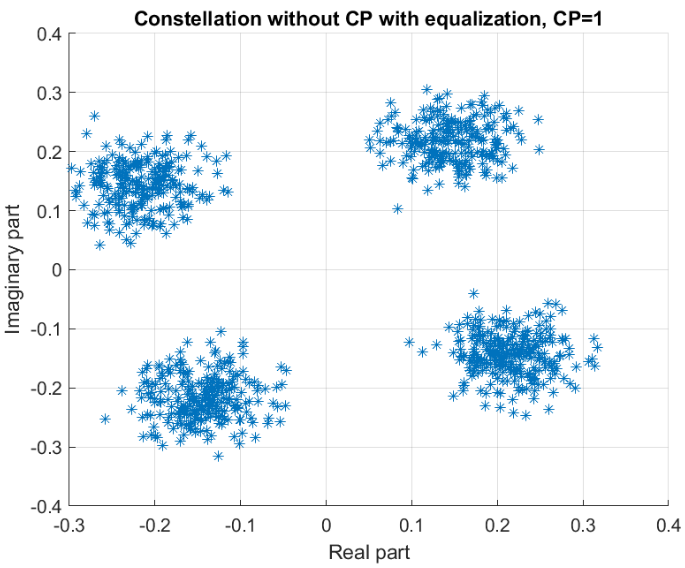


Fig: Constellation of CP=1 (Case1)

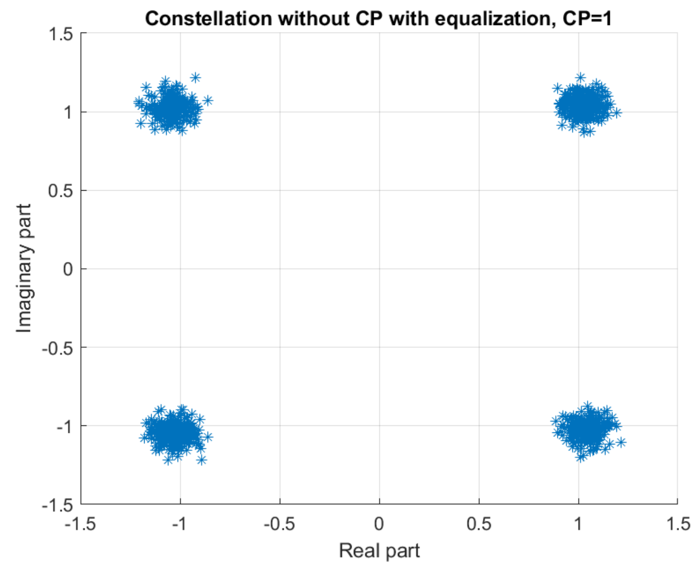


Fig: Constellation of CP=1 (Case2)

<u>Sequence 3: Impact of the timing error of OFDM signal</u>

For a channel with multipath delay spread, the received signal is a summation of the transmitted signal with different (complex) gains and delays and there are numerous factors leading to timing errors in OFDM such as multipath effects, Cyclic prefix imperfections, clock synchronization errors etc.

Pl follow the MATLAB file: Seq3_Final for the program

Seq3_Final.m

Considering 3 cases of FFT misalignment with Cyclic Prefix, the following observations are recorded

Case 1: The FFT window starts in the range [1, L-1]. This case represents a situation where the FFT window starts before the cyclic path, resulting in interference from the previous OFDM symbol. In this case, the received signal will be disturbed due to overlap with previous signal.

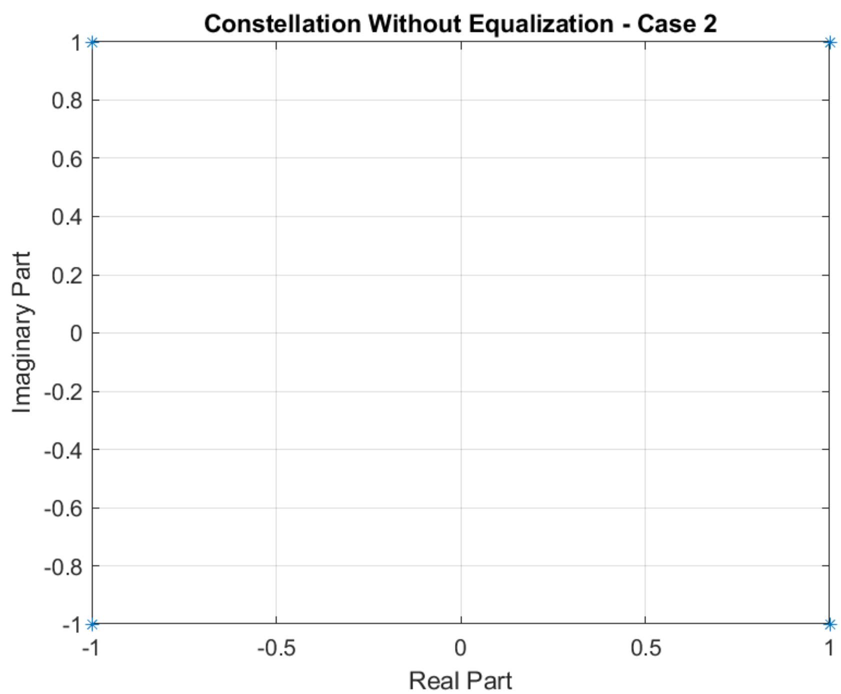


Fig: Obtained plot for Case 2

Case 2: The FFT window starts in the range [L, D+1]. This case is the ideal situation where the FFT window starts at the very end of the cyclic path, protecting against interference. In this case, there should be no interference, and the received signal should not be free of distortion caused by interference between signals.

Case 3: The FFT window starts between [D+2, D+N]. In this case, the FFT window starts after the cyclic prefix, adding a portion of the cyclic prefix to the FFT window. This ideally results in interference from the cyclic path, affecting the received signal. However, compared to Case 1, the interference should be less, as the circular path is designed to reduce the interference.

Unfortunately, the results generated did not yield the desired results. However, the obtained results has been attached.

Conclusion: Case 2 is the only interference-free case because the FFT window coincides exactly with the end of the cyclic prefix, providing protection against inter-signal interference. It should be designed to compensate for channel effects and timing errors introduced by the cyclic method of equalization. In case 2, where there is no interference, the equalizer should only focus on compensating for channel effects.

CONCLUSION

In conclusion, the complex envelope of the OFDM signal, devoid of CP, exhibits properties essential for efficient modulation and demodulation processes. Understanding the properties of orthogonality between subcarriers and spectral efficiency is fundamental to designing OFDM-based communication systems capable of achieving high data rates and spectral efficiency while eliminating the impact of channel distortions.

In Sequence 2, OFDM subcarrier constellations are susceptible to channel-induced distortions, affecting the overall signal quality and demodulation accuracy. Usage of the cyclic prefix (CP) is essential to guard against intersymbol interference, particularly in multipath environments. The one-tap equalizer serves a crucial role in compensating for channel effects, enhancing the signal's robustness, and improving overall system performance.

In Sequence 3, the impact of timing errors on OFDM signals synchronization to ensure optimal performance was studied. Total results could not be obtained but based on research, it is pointed out that timing errors can lead to intersymbol interference (ISI) and inter-carrier interference (ICI), which degrade the system's ability to recover transmitted data accurately. Additionally, the channel also introduces such as attenuation, distortion, and noise, necessitating leading to complexities.

To sum up, addressing the impact of timing errors, CP dimensioning, and employing effective channel compensation techniques are vital considerations in the operation of OFDM systems. By leveraging these techniques and optimizing system parameters, it is possible to enhance spectral efficiency, minimize error rates, and ensure reliable communication in diverse channel conditions.

THANK YOU