Implementation of OFDM and MC-CDMA Systems

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Introduction

Orthogonal Frequency Division Multiplexing is a digital modulation technique that divides a high-data-rate signal into multiple lower-rate subcarriers, which are orthogonal to each other. OFDM is renowned for its ability to combat multipath fading, mitigate interference, and achieve high spectral efficiency. Orthogonal Frequency Division Multiplexing (OFDM) is a robust and widely adopted modulation technique, yet it is not without limitations. One of the significant challenges faced by OFDM is its sensitivity to frequency-selective fading channels, which can lead to Inter-Carrier Interference (ICI) and performance degradation in the presence of multipath propagation. This limitation is effectively addressed by the introduction of Multicarrier Code Division Multiple Access (MC-CDMA). MC-CDMA combines the advantages of both OFDM and Code Division Multiple Access (CDMA), offering improved performance in scenarios where OFDM alone might struggle. Multicarrier Code Division Multiple Access (MC-CDMA) is a wireless communication technology that combines the principles of both multicarrier modulation and code division multiple access. This innovative approach aims to improve spectral efficiency, enhance data rates, and provide robust communication in the presence of fading channels and interference.

Fundamentals of OFDM

OFDM utilizes the concept of orthogonal subcarriers, allowing them to be spaced closely without causing interference. The subcarriers are modulated with data symbols, and the entire spectrum is efficiently utilized. The Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) algorithms play a crucial role in the modulation and demodulation processes.

Advantages of OFDM

- **High Spectral Efficiency:** OFDM enables efficient use of available spectrum by closely packing orthogonal subcarriers.
- **Resistance to Frequency Selective Fading:** OFDM's inherent multicarrier nature helps combat frequency-selective fading, a common challenge in wireless communication.
- **Improved Data Rates:** OFDM allows for higher data rates by simultaneously transmitting multiple data streams.

Applications of OFDM

- **Wireless Communication:** OFDM is widely used in wireless communication standards such as Wi-Fi, LTE, and 5G due to its ability to handle multipath fading and provide high data rates.
- **Digital Audio and Video Broadcasting:** OFDM is employed in digital television (DTV) and radio broadcasting to enhance signal quality and coverage.
- **Powerline Communication:** OFDM is used for data transmission over power lines, providing a robust communication solution for smart grids and home networking.

Challenges

- **Peak-to-Average Power Ratio (PAPR):** OFDM signals often have a high PAPR, leading to power inefficiency and reduced amplifier efficiency. Various techniques such as clipping and filtering can be employed to mitigate this issue.
- **Carrier Frequency Offset (CFO):** CFO can degrade the performance of OFDM systems. Techniques like pilot symbols and advanced synchronization algorithms are used to address this challenge.

OFDM Implementation Flow

Start:

- Initialization and setup.

Input Parameters:

- Define system parameters such as the number of subcarriers N, symbol duration T, and guard interval T_g.

Generate Data Symbols:

- Let d_k represent the data symbols, where k is the index of the subcarrier. Let $\wedge$ represent the set of constellation points in the given modulation technique.

$$d_k \in \wedge$$

Mapping to Subcarriers:

- Map the data symbols onto individual subcarriers using a mapping function $X_k(f)$, where f is the frequency.

$$X_k(f) = \{d_k\}$$

IFFT (Inverse Fast Fourier Transform):

- Apply IFFT to convert the data from the frequency domain to the time domain.

$$x(t) = \text{IFFT}\{X_k(f)\}$$

Cyclic Prefix Addition:

- Add a cyclic prefix to the time-domain signal to mitigate the effects of channel delay spread.

$$x_{\text{CP}}(t) = \text{AddCyclicPrefix}\{x(t)\}$$

Transmit Signal:

- Transmit the OFDM signal through the communication channel.

$$y(t) = x_{\text{CP}}(t) * h(t)$$

Channel Effects:

- Simulate or account for the effects of the channel, such as noise and fading.

$$y(t) = x_{\text{CP}}(t) * h(t) + w(t)$$

  where $w(t)$ represents the channel noise.

Receive Signal:

- Receive the distorted signal at the receiver.

$$y_{\text{Rx}}(t) = y(t) * h_{\text{Rx}}(t)$$

  where $h_{\text{Rx}}(t)$ is the channel response at the receiver.

Cyclic Prefix Removal:

- Remove the cyclic prefix from the received signal.

$$y_{\text{NoCP}}(t) = \text{RemoveCyclicPrefix}\{y_{\text{Rx}}(t)\}$$

FFT (Fast Fourier Transform):

- Apply FFT to convert the received signal from the time domain back to the frequency domain.

$$Y_k(f) = \text{FFT}\{y_{\text{NoCP}}(t)\}$$

Demapping from Subcarriers:

- Demap the symbols from individual subcarriers.

$$\hat{d}_k = \arg\min_{b \in \wedge} |Y(f) - bH(f)|^2$$

End:

- End of the OFDM implementation flow.

Simulation of OFDM

The transmission of a QPSK signal was simulated over an Additive White Gaussian Noise (AWGN) channel. The symbols are sent according to the constellation in figure 1.

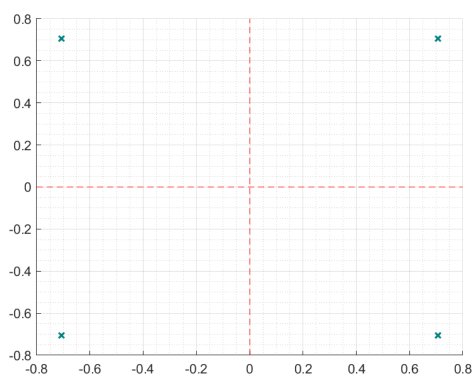

Fig 1: QPSK Constellation Plot

Stream of bits are first modulated to symbols under QPSK modulation technique. The stream is then sent in blocks parallelly. For the time domain signal for OFDM, inverse fourier transform is calculated, since every symbol is associated with a subcarrier. Inorder to remove the effect of leaking beacuse of truncation, a cyclic prefix is introduced. Figure 2 shows a such waveform to be transmitted. When this signal is sent over a channel, phenomenon called fading occurs and also the AWGN noise gets added to the waveform. FIgure 3 shows the received signal over a flat fading channel with channel coefficient of 0.7+0.7j.

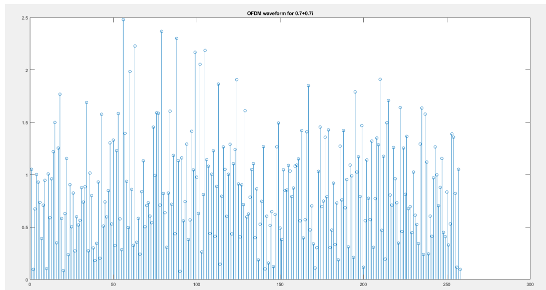

Fig 2: x(t)

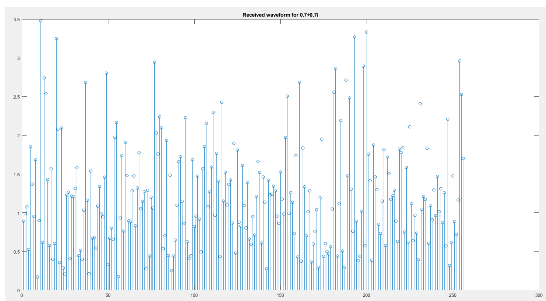

Fig 3: y(t)

At receiver FFT of the received signal is taken. Given we have the channel information (Figure 4, this would be constant as we have considered flat fading channel) then for demodulation we use a coherent detector given by,

$$\hat{X}(k) = \arg\min_{b \in B} |Y(k) - bH(k)|^2$$
$$k \in -\frac{N}{2} \text{ to } \frac{N}{2}$$

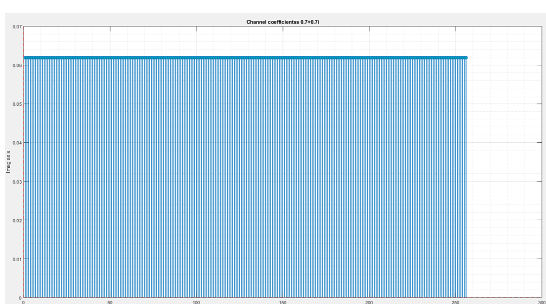

Fig 4: H(k)

Figure 5 shows constellation of received symbols.

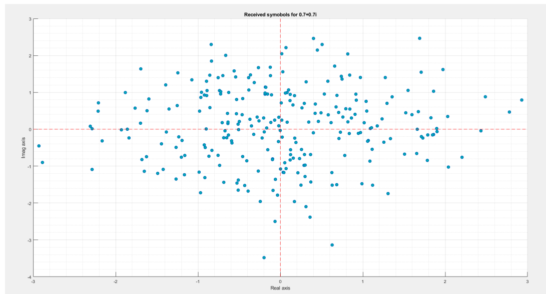

Fig 5: Y(k)

Next set of figures we show the same set of graphs for a frequency selective channel of 5 taps.

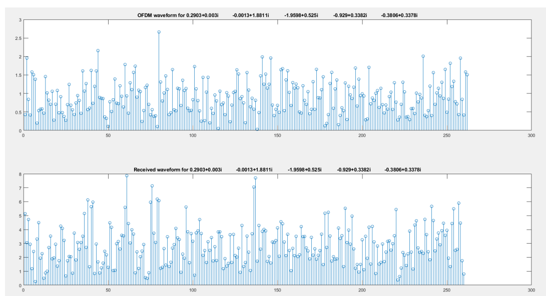

Fig 6,7: x(t),y(t)

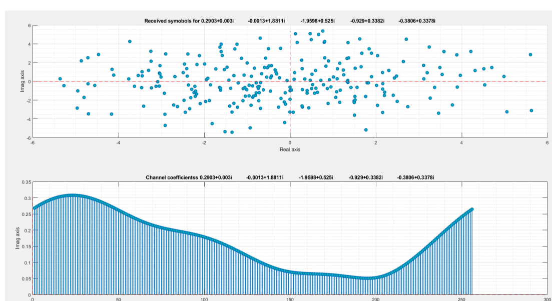

Fig 8,9: Y(k),H(k)

Such simulation is carried out 100,000 times and the bitstream obtained after demodulation is compared with original bitstream and error is noted to find the Bit Error Rate (BER) as a function of E_b/N_0.

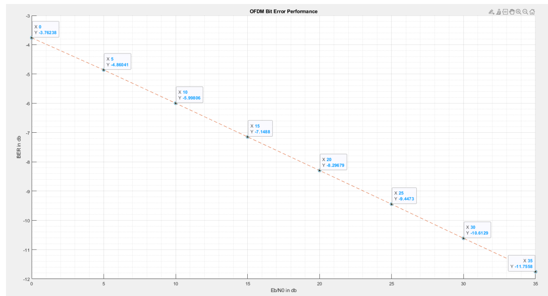

Fig 10: BER

Fundamentals of MC-CDMA

Multicarrier Modulation: MC-CDMA employs multiple narrowband subcarriers to transmit data simultaneously. This technique leverages Orthogonal Frequency Division Multiplexing (OFDM), allowing for efficient use of the available bandwidth.CDMA utilizes unique codes to distinguish different users' signals, enabling multiple users to share the same frequency spectrum simultaneously. This provides improved capacity and reduces the impact of interference.MC-CDMA systems consist of multiple subcarriers, each modulated with data symbols.Users are assigned unique spreading codes, enabling their signals to coexist on the same frequency band without mutual interference.The combination of multicarrier modulation and CDMA enhances the system's robustness against multipath fading and narrowband interference.

MC-CDMA Implementation Flow

Start:

- Initialization and setup.

Input Parameters:

- Define system parameters such as the number of subcarriers N, symbol duration T, and guard interval T_g.

Generate Data Symbols:

- Let d_k represent the data symbols, where k is the index of the subcarrier. Let $\wedge$ represent the set of constellation points in the given modulation technique.

$$d_k \in \wedge$$

Spread Spectrum Modulation and Mapping to Subcarriers:

- Spread the symbols using the assigned spreading code matrix C to obtain CDMA sequence and then map this new sequence to $X_k(f)$

$$X_k(f) = C\{d_k\}$$

IFFT (Inverse Fast Fourier Transform):

- Apply IFFT to convert the data from the frequency domain to the time domain.

$$x(t) = \text{IFFT}\{X_k(f)\}$$

Cyclic Prefix Addition:

- Add a cyclic prefix to the time-domain signal to mitigate the effects of channel delay spread.

$$x_{\text{CP}}(t) = \text{AddCyclicPrefix}\{x(t)\}$$

Transmit Signal:

- Transmit the OFDM signal through the communication channel.

$$y(t) = x_{\text{CP}}(t) * h(t)$$

Channel Effects:

- Simulate or account for the effects of the channel, such as noise and fading.

$$y(t) = x_{\text{CP}}(t) * h(t) + w(t)$$

  where *description* represents the channel noise.

Cyclic Prefix Removal:

- Remove the cyclic prefix from the received signal.

$$y_{\text{NoCP}}(t) = \text{RemoveCyclicPrefix}\{y_{\text{Rx}}(t)\}$$

FFT (Fast Fourier Transform):

- Apply FFT to convert the received signal from the time domain back to the frequency domain.

$$Y_k(f) = \text{FFT}\{y_{\text{NoCP}}(t)\}$$

Channel Decoding:

- Apply channel decoding techniques to correct errors introduced during transmission.

$$\hat{Y}_k(f) = H^{-1}(f)Y(f)$$

Symbol Decoding:

- Apply correlation with the spreading code matrix and then apply coherent demodulation for retrieving the symbols.

$$\tilde{Y}_k(f) = C^H \hat{Y}_k(f)$$

Output Data Symbols:

- Demap the symbols from individual subcarriers

$$\hat{d}_k = \underset{b \in \wedge}{\arg\min} \left| \tilde{Y}_k(f) - b \right|^2$$

End:

- End of the OFDM implementation flow.

Simulation of MC-CDMA

Simulation of MC-CDMA is similar to OFDM apart from introduction of the spreading code. For this simulation, the symbols are associated with a Walsh code and then passed onto the OFDM block. Walsh codes are mutually orthogonal. This means that the cross-correlation between any two different Walsh codes is zero. This property is beneficial in applications like Code Division Multiple Access (CDMA), where multiple users can share the same frequency band without causing interference. C is an example 4x4 walsh matrix for spreading sequence of 4 symbols.

$$X\hat{(k)} = CX(k)$$

$$C = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & -\frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} & -\frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Figure 11,12,13,14 show waveforms obtained for MC-CDMA in same fashion it was obtained for OFDM.

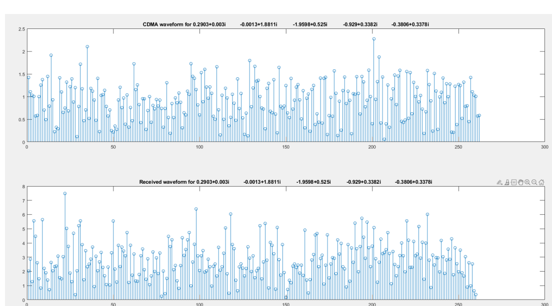

Fig 11,12: x(t),y(t)

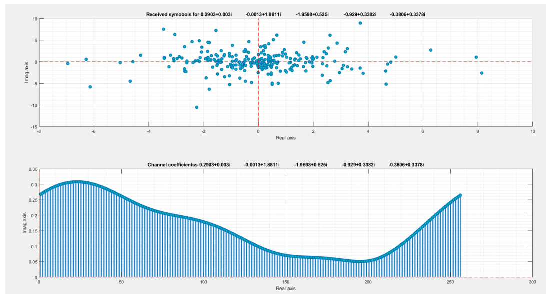

Fig 13,14: Y(k),H(k)

Such simulation is carried out 100,000 times and the bitstream obtained after demodulation is compared with original bitstream and error is noted to find the Bit Error Rate (BER) as a function of E_b/N_0.

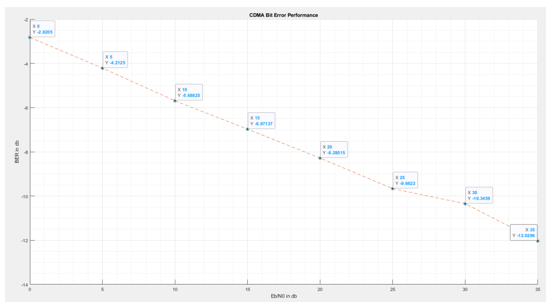

Fig 15: BER

Conclusion

In this simulation, we received similar results for implementation of both MC-CDMA and OFDM. The important thing to note in this is that while demodulating received in both cases, we are essentially multiplying the received signal with H^{-1}. Since H is not an unitary matrix and multiplying its inverse with $Y(k)$ also multiplies with noise changing its statistics.The Walsh matrix is an unitary matrix so it doesn't disturb the noise statistics.

$$OFDM$$

$$Y(k) = H(k)X(k) + W(k)$$
$$H^{-1}Y(k) = X(k) + H^{-1}W(k)$$

$$MC - CDMA$$
$$Y(k) = H(k)CX(k) + W(k)$$
$$C^H H^{-1}Y(k) = X(k) + C^H H^{-1}W(k)$$

To improve the performance we need to comeup with better equalization techniques that utilize the code introduced