OFDM MODULATION TECHNIQUE1.1. Development history  
The Orthogonal Frequency Division Multiplexing (OFDM) channelization technique is a multi-carrier modulation method in which subcarriers are orthogonal to each other, allowing the receiver to recover the signal even though the spectra of these subcarriers overlap. This spectral overlap enhances the Spectrum Efficiency of OFDM modulation significantly compared to other modulation techniques. It was first introduced in the United States in 1966 by R.W. Chang, and over the past decades, various research works have been deployed. One of these works is the research by Weinstein and Ebert, which demonstrated that OFDM modulation is implemented using the Inverse Discrete Fourier Transform (IDFT) for modulation and the Discrete Fourier Transform (DFT) for demodulation. Since then, digital signals have been modulated using the OFDM modulation technique and have become the widely standardized modulation method for digital audio broadcasting (DAB) and digital radio mondiale (DRM), terrestrial digital television (DVB-T), mobile communication systems 4G, and more. One of the broadband networks upgraded through the use of OFDM technology is Asymmetric Digital Subscriber Line (ADSL). OFDM is also a modulation method in WiMax broadband wireless access networks according to the IEEE 802.16a standard and fourth-generation mobile networks. Particularly, in these 4G mobile information systems, OFDM is utilized with Multiple Input Multiple Output (MIMO) technology for enhanced wireless channel capacity and Orthogonal Frequency Division Multiple Access (OFDMA) for efficient mobile network multiple access. OFDM technology is combined with spatial channel coding methods used in wireless communication, such as Space-Time Block Coding (STBC) and Space-Frequency Block Coding (SFBC), forming the Coded OFDM (COFDM) system. By using these channel codes, the signal is divided into different blocks based on the transmission channel's quality to combat errors and noise occurring on the transmission path. Thus, the Adaptive Modulation Technique OFDM (Adaptive Modulation OFDM) emerged, enabling the estimation of channel conditions based on signal power to determine suitable encoding or modulation levels. The adaptive modulation technique has been used in the HiperLAN/2 European broadband information system.

1.2. Characteristics of OFDM Modulation technique

Upgrading and optimizing algorithms, OFDM systems provide highly advantageous features for wireless transmission and transceiver system design:

* **Complete Elimination of ISI (InterSymbol Interference):** OFDM systems can entirely eliminate ISI by employing an appropriate Guard Interval, thus mitigating multipath distortion.
* **Suitable for High-Speed Transmission Systems:** OFDM is well-suited for high-speed transmission systems due to the significant reduction in Frequency Selectivity compared to single-carrier transmission. This reduction minimizes the impact of frequency-selective fading.
* **Simple Receiver Structure:** OFDM systems boast a simple receiver structure, contributing to ease of implementation.

However, OFDM technology also has its drawbacks that need careful consideration and practical research for designing a system suitable for specific purposes:

* **Uneven Amplitude Envelope:** The amplitude envelope of the signal is uneven, causing nonlinear distortion in power amplifiers at the transmitter and receiver.
* **Guard Interval Impact on Transmission Efficiency:** While the guard interval is used to eliminate ISI, it also reduces transmission efficiency due to wasting power on transmitting useless signals.
* **Impact of Orthogonality Conditions between Subcarriers:** The requirement for orthogonality between subcarriers makes the system susceptible to the effects of Doppler, frequency offset, and time offset due to synchronization errors.

These challenges require careful consideration and research to optimize the performance of the OFDM system under real-world conditions and ensure that the drawbacks do not significantly affect transmission quality

1.3. OFDM Modulation method and transceiver architechure  
Orthogonal Frequency Division Multiplexing (OFDM) modulation is based on the Frequency Division Multiplexing (FDM) technique, with the key distinction that the subcarrier waves are placed orthogonally to each other. Thanks to this orthogonality, their signal spectra overlap without affecting the demodulation process at the receiver. The signal spectrum of a system of subcarrier waves is illustrated in the figure.

A black and white diagram of a wave

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*Figure 1. a) Spectrum of a single subcarrier; b) Spectrum of 5 subcarriers [6]*

In this figure, the signal spectrum of each subcarrier channel has the form of sin(x)/x. The subcarriers are distributed evenly across the frequency range, ensuring that the peak points of one channel coincide with the null points of adjacent subcarrier channels. In the OFDM system, the signals, after passing through the digital modulator, undergo an Inverse Fast Fourier Transform (IFFT) to form OFDM symbols. The use of IFFT allows the OFDM modulator to simultaneously modulate multiple channels, a task that is challenging with FDM modulators.A diagram of a data processing process

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*Figure 2. Block diagram of the OFDM system*

Principles of operation for each block:

* **S/P (Serial to Parallel):** Converts serial data into parallel data, splitting high-speed bit streams into K lower-speed bit streams, where K is the number of subcarrier waves in the system.
* **M-QAM Modulation:** Utilizes QAM modulation to map pairs of bits into complex signals in the QAM signal constellation. The modulation level M is chosen based on different transmission systems.
* **Zero Insertion:** Inserts virtual subcarriers to ensure the DC component's average value is zero and creates a frequency guard band between information systems to avoid Intercarrier Interference (ICI).
* **IFFT (Inverse Fast Fourier Transform):** Performs a fast implementation of the Inverse Discrete Fourier Transform, transforming signals from the time domain to the frequency domain, creating orthogonal subcarrier waves.

With n,k = 0 / N - 1A black text on a white background

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* **Guard Insertion**: Inserts a guard interval to counteract Inter-Symbol Interference (ISI). ISI arises from the influence of multipath effects when symbols arriving later interfere with symbols arriving earlier. The guard interval length depends on the transmission channel and follows the principle of copying a portion of the signal sequence that needs to be transmitted and appending it to the beginning of the signal*.*A close-up of a box

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*Figure 3. Structure of OFDM signals*

**P/S (Parallel to Serial)**: Converts parallel data back to serial, returning the signal stream to its original continuous form for transmission.

**Mixer**: Combines the signal with carrier waves before sending it to the antenna. OFDM modulation uses two different Mixers for two streams of real and complex signals from the P/S block. These two signal streams are multiplied successively with carrier waves and then added at the Mixer's output.

**LPF (Low Pass Filter)**: Low-pass filter that brings the signal back to baseband.

**D/A, A/D**: Converts signals from digital to analog and analog to digital for long-distance transmission. The signal after D/A conversion is an analog baseband signal with a bandwidth depending on the sampling frequency in the D/A converter. At the receiver, an A/D converter is used to obtain digital signals for decoding.

**Pilot Extraction, Channel Estimation**: Based on pilot signals, the receiver estimates the transmission channel using estimation algorithms.

**64-QAM Modulation/Demodulation**: Maps binary sequences to complex signals characteristic of points in the QAM signal constellation. As illustrated in Figure 6, each bit sequence corresponds to one point on the complex plane. Quadrature Amplitude Modulation (QAM) is a modulation technique that combines amplitude modulation and phase modulation. Compared to other modulation types, QAM signals can resist noise effectively because the receiver can differentiate based on both amplitude and phase. The symbol constellation of QAM signals has larger amplitude and phase differences than other modulation types with the same number of levels M, making it less susceptible to interference when symbols overlap.

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*Figure 4. 64-QAM Constellation*

Linear Minimum Squared Error (LMSE) algorithm is often applied in communication systems, including OFDM (Orthogonal Frequency Division Multiplexing), for channel estimation and equalization. LMSE is utilized to minimize the mean squared error between the estimated and true channel responses. Here is a general outline of how the LMSE algorithm can be applied in an OFDM system:

**1. Channel Estimation:**

Pilot Symbols: In an OFDM system, known pilot symbols are inserted periodically in the transmitted signal. These pilot symbols serve as reference points for channel estimation.

Received Signal: At the receiver, the received OFDM symbols, including pilot symbols, are collected.

Pilot Extraction: The receiver extracts the pilot symbols from the received signal. These symbols are known, and any discrepancies between the transmitted and received pilot symbols are attributed to channel effects.

LMSE Algorithm: The LMSE algorithm is employed to estimate the channel response. It minimizes the mean squared error between the received pilot symbols and the corresponding estimates obtained using the channel model.

Channel Coefficients: The estimated channel coefficients are then used to characterize the channel response.

**2. Equalization:**

Received Data Symbols: Once the channel coefficients are estimated, they are applied to the received data symbols to compensate for the channel effects.

LMSE Equalization: The LMSE algorithm is again employed, but this time for equalization purposes. It minimizes the mean squared error between the estimated data symbols and the true transmitted symbols.

Equalized Data Symbols: The equalized data symbols are obtained by applying the inverse of the estimated channel response to the received data symbols.

**3. Adaptation:**

Adaptive LMSE: In some scenarios, an adaptive approach is employed where the LMSE algorithm continuously updates the channel estimates based on the received data and feedback.

Iterative Process: The process of channel estimation, equalization, and adaptation may be iterative, continuously refining the channel estimates and equalization parameters.

**4. Performance Evaluation:**

BER/SER Measurement: The Bit Error Rate (BER) or Symbol Error Rate (SER) is commonly used to evaluate the performance of the system. The system performance is analyzed by comparing the transmitted and received symbols.

Feedback Loop: Based on the performance metrics, adjustments may be made to the LMSE algorithm parameters or other system parameters in a feedback loop.

**5. Implementation Considerations:**

Computational Complexity: The computational complexity of the LMSE algorithm should be considered, especially in real-time systems.

Signal-to-Noise Ratio (SNR): The algorithm's performance is influenced by the Signal-to-Noise Ratio (SNR) and other environmental factors.

By incorporating the LMSE algorithm in the channel estimation and equalization processes, an OFDM system can enhance its robustness against channel impairments, leading to improved overall performance.