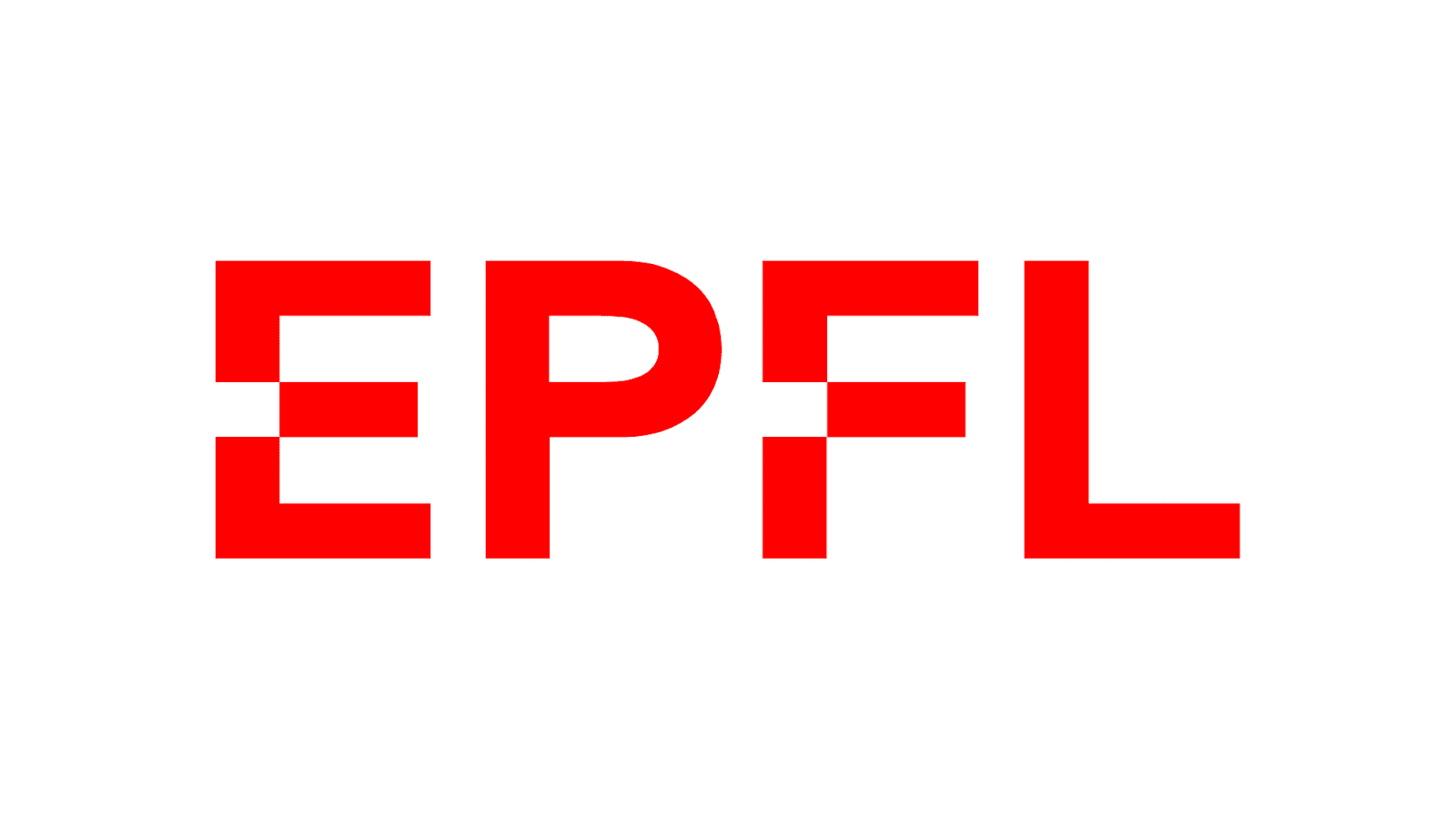
**École Polytechnique Fédérale de Lausanne**



Wireless receivers: algorithms and architectures

**OFDM Project**

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# Introduction

Insingle-carrier modulation, all data is transmitted using one carrier frequency, making it simple but highly sensitive to channel impairments like multipath fading and interference.

This was not a reliable modulation for modern technologies where we seek reliability and security. So that’s why we avert to multi-carrier modulation techniques. The idea is to divide the data across multiple carrier frequencies and send them with N parallel streams, improving resilience to impairments.

Orthogonal Frequency Division Multiplexing (OFDM) is a cornerstone modulation technique in modern digital communications, celebrated for its capacity to efficiently utilize bandwidth while mitigating intersymbol interference (ISI) and combating the challenges of multipath fading. As communication systems demand greater data rates and robustness, OFDM has emerged as an optimal solution, striking a balance between spectral efficiency and system reliability.

OFDM divides the available channel bandwidth into numerous subcarriers, each transmitting data independently. These subcarriers, spaced at precise intervals based on the symbol rate, maintain orthogonality in the frequency domain. This orthogonality ensures that signals transmitted over one subcarrier do not interfere with those on adjacent subcarriers, thereby upholding the principles of interference-free transmission while enabling simultaneous data streams.

One of the most compelling advantages of OFDM lies in its simplified channel equalization. The narrowband nature of each subcarrier ensures that the channel response remains nearly constant within its scope, reducing the complexity of combating multipath effects. This trait, combined with OFDM's inherent resilience to noise and interference, renders it particularly effective in challenging environments with significant distortion or reflection.

This report delves into the theoretical foundation of OFDM, tracing its evolution from single-carrier modulation to its current form as a multicarrier paradigm. Through an exploration of system design and implementation, the interplay between critical design parameters and performance metrics such as Bit Error Rate (BER) and channel spectrum are analysed. The discussion also includes various tracking methods to address channel variability, ensuring a comprehensive understanding of the principles and practicalities of OFDM communication systems.

A diagram of different colors

Description automatically generated

Figure 1 Single vs. Multi carrier comparison

The signal after the modulation will have the following format:

Where X(k) is the data stream transmitted on the k-th subcarrier, T is the duration of the OFDM signal, is the frequency of the k-th subcarrier, where is the subcarrier spacing with .

With a sampling interval , we will get to the sampled version of the OFDM signal, given by:

The last equation shows the expression of the Inverse Discrete Fourier Transform (IDFT), showing that IFFT modulation can be used.

# Transmitting the signal

We have some raw bits that need to be transmitted. For this to be done we need a clear plan of the steps we need to take to process the bits into a signal suitable for transmission through the physical channel. For that we built the following block diagram and followed it up with a suitable Matlab code.

A diagram of a computer program

Description automatically generated with medium confidence

Figure 2 Block diagram of transmitter

1. **Mapping**

The first step that need to be taken is finding a way to map them into symbols.

In digital communication systems, information is represented in bits (binary data). However, transmission over a physical channel is achieved using modulated waveforms, not raw binary sequences. Mapping bits into symbols is an essential step to bridge the digital world (bits) with the analog domain (waveforms). Symbols represent groups of bits as distinct values or points in a constellation diagram, each corresponding to a unique waveform. In this project Gray QPSK mapping will be used. QPSK is a digital modulation scheme where two bits are mapped onto a single symbol, resulting in four unique symbols. Each symbol corresponds to a phase shift in the carrier signal, typically 0, 90, 180 or 270 degrees. Each constellation point is equidistant from the origin to represent equal energy, and the angle of each point corresponds to a specific phase of the carrier. The Gray part comes into play so that we ensure the symbols differ by 1 bit from one another.

1. **Forming the TX symbols**

The next step is to combine the bits we are transmitting with the training symbols sequence. The training symbols are predefined sequences of bits known to both the transmitter and receiver. They play a crucial role in channel estimation and equalization, enabling the system to mitigate the distortion effects caused by the real channel.  
Two different ways of generating the training symbols were used:   
**block-based** and **comb-based** training methods.

* 1. **Block-based training**

In the block-based approach, training symbols are transmitted periodically in an OFDM system, with each training symbol spanning across all the subcarriers in the system. These periodic training symbols enable the receiver to perform channel estimation at regular intervals, allowing it to adapt to slowly varying channel conditions effectively.

* Training placement – training sequence T, repeated periodically every K symbols:

, K – block interval, – data symbols

* Channel estimation – the received training symbols are related to the transmitted training symbols by the channel resposnse and the noise:
* Data equalization – for every subsequent data block we equalize with the channel response:
  1. **Comb-based training**

On the other hand, the comb-based technique distributes training symbols across the subcarriers within each symbol, with a chess-like structure. By embedding training information within every transmission, the comb-based method supports real-time channel estimation for scenarios with rapid channel variations. The subcarriers are divided into pilot subcarriers, which will be used for channel estimation, and data subcarriers, for the payload.

At a specific subcarrier Pm, where m indexes the pilot subcarriers we have the following:

Since is know, can be estimated as:

To estimate the channel response for non-pilot subcarriers we need to use interpolation techniques. In this case, linear interpolation is used, as following:

While block-based training conserves bandwidth by using fewer training symbols, comb-based training enhances the system's ability to track fast changes in the channel, offering a trade-off between spectral efficiency and the ability to combat fading and distortion.

A comparison of different types of symbols

Description automatically generated

Figure 3 Block and Comb training methods

1. **Serial to Parallel Conversion**

Next logical step is converting the serial signal to parallel N streams to mimic the nature of OFDM. A function is used that reshapes the data into 2D matrix, where the number of rows represents the number of subcarriers, and the columns represent the data for the OFDM symbols distributed across the subcarriers. Each subcarrier’s data is in a separate row, giving the parallel look.

1. **Inverse Fast Fourier Transform**

This operation is used to transform the data from frequency to the time domain, so that the signal can be physically transmitted through the channel. It’s done by combining the modulated subcarriers into a single composite time-domain signal, while ensuring the orthogonality of the subcarriers, to minimize the interference between them.

1. **Adding Cyclic Prefix**

The cyclic prefix (CP) is added to each OFDM symbol by copying the last ​ samples of the symbol and appending them to its beginning. This ensures that the transmitted signal experiences circular convolution with the channel, enabling efficient equalization in the frequency domain using FFT. The CP also acts as a guard interval to combat Inter-Symbol Interference (ISI) caused by multipath fading, preventing overlapping symbols from interfering with one another.

Mathematically, for an OFDM symbol x[n] of length N, the transmitted symbol with CP is:

Important note to add is that the cyclic prefix length ​ must be grater than the maximum channel delay spread to fully mitigate the ISI. While adding the CP reduces spectral efficiency, it is crucial for preserving subcarrier orthogonality and ensuring reliable communication in multipath environments.

1. **Parallel to serial**

We need to get the signal to the original serial form because it needs to pass through the actual physical channel which supports serial data.

1. **Preamble**

On the other hand, there are some processing steps done on the preamble as well, which is essential for synchronization. The preamble is generated like a random like bit sequence. It needs to be mapped into symbols, so in this case BPSK mapping is used. Each bit is represented by one of 2 phases: 0 or π. Bit value of 0 is mapped into +1, and a bit value of 1 is mapped into -1. Then the preamble is up sampled to match the transmission rate of the transmission signal and for better precision to be achieved when syncing. At the end the preamble is pulse shaped with the RRC filter so that the bandwidth and the ISI are limited.

1. **Normalizing signal energy**

After inserting the preamble at the start of the signal, the energy of the signal is normalized. Since QPSK mapping is used, normalizing the energy does not cause issues with ISI, as the constellation points remain well-separated. However, with higher-order modulation schemes like 16-QAM or 32-QAM, normalization can compress the constellation points, potentially increasing susceptibility to noise and ISI.

1. **Up conversion**

At the very end before transmitting the signal though the channel up conversion is done, where the baseband signal is shifted to higher frequency, in particular the carrier frequency .

A screen shot of a sound wave

Description automatically generated

Figure 4 Signal that was transmitted

A screen shot of a graph

Description automatically generated

Figure 5 Spectrum of the transmitted signal