Ecole Polytechnique Fédérale de Lausanne

Wireless receivers: algorithms and architectures

EE-442

Orthogonal Frequency Division Multiplexing

Authors:

Vincent Roduit

Filippo Santiago Quadri

December 27, 2023

Abstract

Orthogonal Frequency Division Multiplexing (OFDM), widely employed in wireless receivers, is a prominent method for multi-carrier transmission. Specifically, OFDM stands out as a specialized approach within the broader category of multi-carrier transmission methods [OA07]. This report documents the construction of an acoustic OFDM system. Initially, a concise introduction to OFDM systems is provided, laying the foundation for understanding the subject matter. Subsequently, the report presents the results obtained from the implementation and experimentation with such a system in a coherent and informative manner.

Keywords— OFDM, Wireless receivers, Fading Channel, Multipath, Efficiency, BPSK, QPSK

Contents

1 Introduction

The course "EE-442 Wireless Receivers: Algorithms and Architectures" offers a comprehensive introduction to wireless receivers. In the latter part of the course, there is an in-depth exploration of Orthogonal Frequency-Division Multiplexing (OFDM). Alongside the theoretical aspects, a hands-on project is assigned. The primary goal of this project is to thoroughly investigate the structure of OFDM receivers, with a specific emphasis on implementing an acoustic OFDM structure using MATLAB.

This document is organized into distinct sections. Initially, a concise introduction to the OFDM structure will be provided, establishing the foundation for a more profound understanding. Subsequently, the document will delve into the design intricacies of both the receiver and transmitter structures. Following this, the results obtained from the implemented system will be presented and subjected to analysis. In the concluding stage, the document will address potential issues and propose pathways for enhancing the acoustic OFDM structure.

Instead of single-carrier modulation, where one symbol is sent at a time, in an OFDM structure, the frequency spectrum is shared among a specific number of subcarriers. Research has shown that the OFDM structure is an efficient way to counteract the multipath fading that occurs in single-carrier transmission [LS06]. Instead of sending one symbol for a short period of time, N subcarrier symbols are sent for a longer duration. A more theoretical view is presented in Section 2.

At the end of the report, the limitations of the implemented system are presented. Additionally, solutions that can be further developed are discussed.

2 Theoretical Aspects

In this section, theoretical aspect of a OFDM is presented by first focusing on general structure of the data. Secondly, both transmitter and receiver is presented.

2.1 Constellations

This section presents the different symbol constellations necessary to build our version of an OFDM frame. The first one is the binary phase shift keying (BPSK). This digital modulation maps a bit 0 to '-1 + 0j' and a bit '1' to '1 + 0j'. The resulting constellation is presented in Figure 1a. This constellation is used for the preamble and training and are explained in 2.2. The second constellation is Quadrature Phase Shift Keying (QPSK). Such modulation maps pair of bits according to the Table 1. This mapping is known as gray mapping. In this mapping, only one bit changes between two near symbols. This reduces the bit error rate [DIZ15]. Furthermore, in order to obtain a signal power of 1, there is a need to normalize the symbols. The power of a M-QAM is given by:

$$\bar{P}_{M-QAM} = \frac{2}{3}(M^2 - 1) \tag{2.1}$$

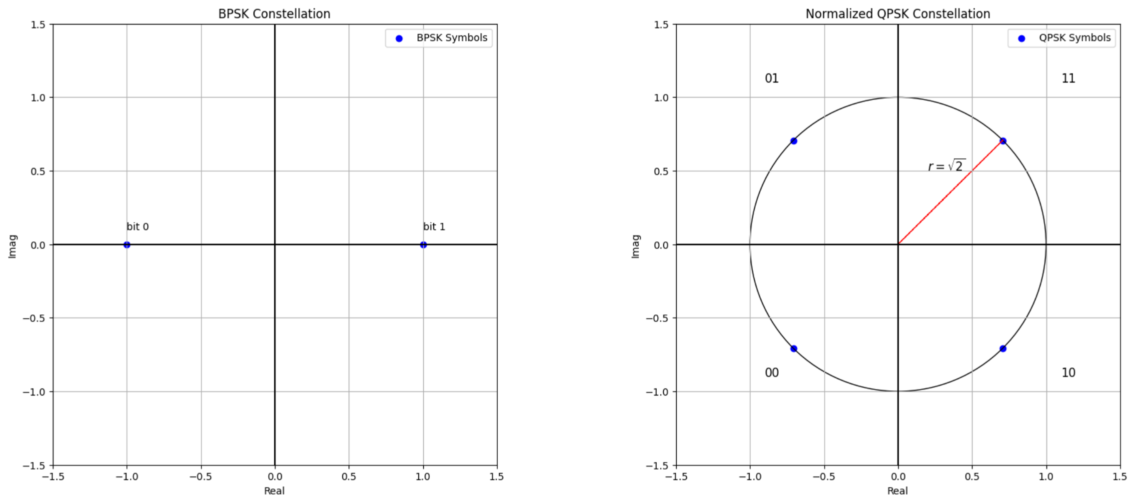
$$\bar{P}_{QPSK} = \frac{2}{3}(2^2 - 1) = 2 \tag{2.2}$$

Therefore, the normalized symbols are given by:

$$S_{norm} = \frac{S}{\sqrt{\bar{P}_{QPSK}}} = \frac{S}{\sqrt{2}} \tag{2.3}$$

Bits	Symbol	Normalized symbol
00	$-1-j$	$\frac{1}{\sqrt{2}}(-1-j)$
01	$-1+j$	$\frac{1}{\sqrt{2}}(-1+j)$
10	$1-j$	$\frac{1}{\sqrt{2}}(1-j)$
11	$1+j$	$\frac{1}{\sqrt{2}}(1+j)$

Table 1: QPSK gray mapping



(a) BPSK constellation (b) QPSK constellation

Figure 1: Different constellations

2.2 Structure of a Frame

A typical structure of a frame in a OFDM is presented in Figure 3. The frame starts with a preamble sequence, mapped into BPSK symbols. The preamble is a pseudo-random sequence, known from both transmitter and receiver. The purpose of this sequence is to detect the beginning of data in order to synchronize the receiver. There is several ways to generate pseudo random sequence. A common practice is to implement a linear phase shift register (abr. LFSR), shown in Figure 2.

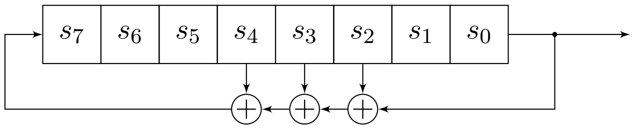


Figure 2: Linear Phase Shift Register

After this preamble, a training sequence is incorporated. This training sequence comprises a BPSK OFDM symbol. Similar to the preamble, this sequence should be known from both parties. It can be generated using various methods, as long as it is reproducible by both parties. Once again, the choice was made to generate this sequence using a LFSR. The purpose of this sequence is to give the receiver a first estimation of the channel (magnitude and phase) for each subcarrier. The reason behind the use of a pseudo-random sequence for the training is explained at the end of Section 2.3. Following the training sequence, the data are appended. The data consist of a set of OFDM symbols. The exact number of symbols has to be determined based on the requirements and the quality of the channel estimation. Between each elements, a guard interval is needed to perform a free intersymbol system. In order to achieve a free intersymbol, the guard interval has to be longer than the impulse response of the channel. There is several option to build this guard interval. A basic option could be to simply transmit nothing during this time interval, but a more elaborated and interesting practice is to use a so-called cyclic-prefix. This idea simply copies the last N_{cp} samples of the OFDM symbol in front of the signal. the final length of a OFDM symbol is therefore $N + N_{cp}$, where N represents the length of a OFDM symbol. With this addition, the convolution of the transmitted signal with the channel becomes a circular convolution, allowing for ISI-free transmission. Using circular convolution, the signal can be "recovered" through a transformation applied to the DFT of the RX signal. The final result of a single frame is presented in Figure 3. Incorporating an excessively long Cyclic Prefix (CP) can compromise the system's efficiency (see Equatione 2.4). Therefore, it is crucial to identify an optimal cyclip prefix length that ensures circular convolution while maintaining a satisfactory level of efficiency.

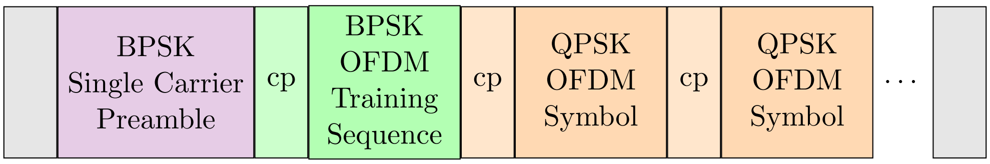


Figure 3: OFDM frame structure

2.3 Transmitter (TX)

In this section, the configuration of the OFDM transmitter is detailed, as illustrated in Figure 4. The structure is relatively straightforward. The main goal of the transmitter is to transmit a source bitstream to a receiver. This is accomplished by producing a signal that can be decoded by the receiver and is resistant to specific undesirable effects, such as noise and interference from multipath channels.

On the left side of the diagram, the "generation part" handles the creation of a pseudo-random sequence for both the preamble and the training sequence. Choosing to generate a pseudo-random bitstream for these components, rather than a simple sequence of ones or zeros, is intentional and serves a specific purpose.

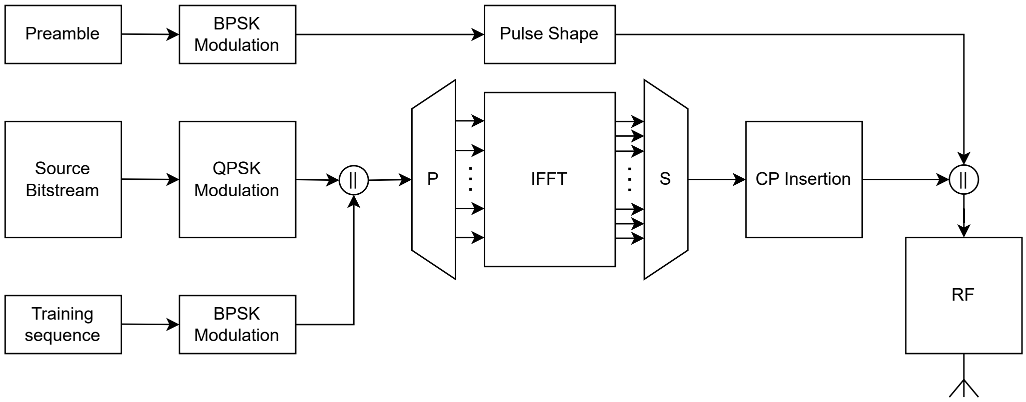


Figure 4: OFDM Trasmitter

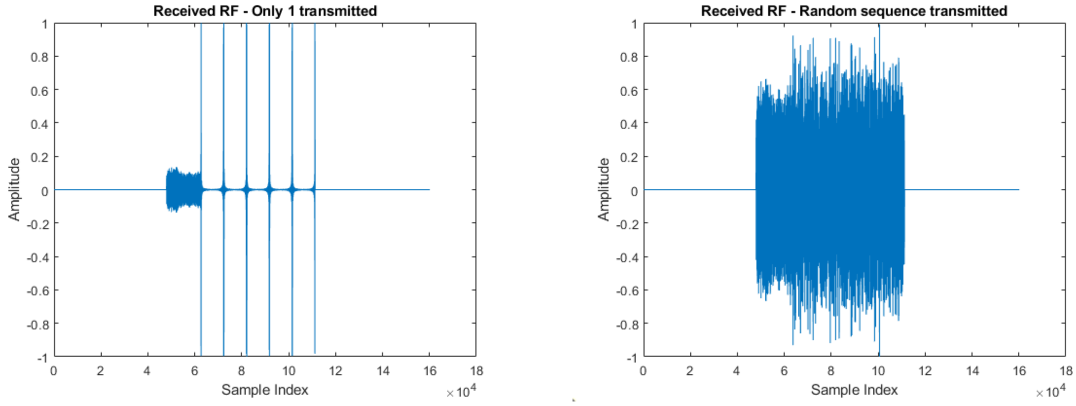
In designing the preamble, the goal is to achieve a highly effective autocorrelation function that enhances synchronization at the receiver. A desirable autocorrelation function displays a distinct peak at a specific point, corresponding to a matched sequence, while maintaining minimal values at all other points. Opting for a pseudo-random sequence is the most effective approach to achieve an autocorrelation function similar to a Dirac pulse, that is a very interesting autocorrelation function.

Regarding the training sequence, the reason to use a pseudo-random sequence is less mathematically oriented and more rooted in technical considerations. The objective is to mitigate the peak-to-average power ratio (PAPR), an inherent concern in OFDM modulation. In OFDM modulation, the transmitted signal involves the Inverse Fast Fourier Transform (IFFT), and using a constant signal (in frequency domain), such as a sequence of ones, across all frequencies would lead to a Dirac pulse in the time domain. The issue arises when the transmitted symbol concentrates all its power in a small peak, leaving the remainder of the symbol with negligible power (as shown in Figure 5a). This situation can result in clipping during transmission and may pose challenges at the receiver, especially with amplifiers that struggle to handle such a large dynamic power range. To circumvent these issues, opting for a pseudo-random training sequence proves to be a prudent choice.

Figure 5 illustrates the contrast between two distinct transmission approaches. In the initial scenario (see Figure 5a), a sequence comprised solely of ones is transmitted. In the alternate scenario (refer to Figure 5b), a pseudo-random sequence is transmitted. Notably, in the latter case, the Peak-to-Average Power Ratio (PAPR) effect is absent. It is worth mentioning that both transmissions are preceded by a preamble and contains five symbols after the training sequence (generated in the same way as the training sequence), and both are transmitted in the bypass mode.

Upon generating the different sequences, modulation is necessary. For the purpose of this project, the choice was made to modulate the preamble and the training sequence with BPSK modulation, while the source bitstream undergoes QPSK modulation.
The training sequence and source bitstream must then be "transformed" into OFDM symbols. After concatenating the two signals following the scheme presented in Figure 3 (symbol || in the TX scheme), the signals are parallelized and modulated (reconverted in time domain), thus generating OFDM symbols. It's important to note that oversampling the symbol is necessary due to the fixed sampling frequency at the DAC of the sound card of the PC used for this project. This oversampling step is done by the IFFT.

To ensure a transmission free from Intersymbol Interference (ISI) in OFDM, including a Cyclic Prefix (CP) at the onset of each OFDM symbol is imperative. This addition is crucial for achieving



(a) One's transmission

(b) Pseudo-random sequence transmission

Figure 5: Different OFDM transmissions

circular convolution, and incorporating the cyclic prefix serves as the method to accomplish this objective. The CP consists of a copy of the last samples of the OFDM symbol.

Following the insertion of the Cyclic Prefix (CP), the next step involves constructing the final signal intended for transmission. The remaining task before advancing to the radio frequency (RF) block is to incorporate the shaped preamble.

Now, entering the RF (Radio Frequency) block becomes a crucial stage for real-world transmissions. This block is essential because it facilitates the generation of an analog signal suitable for transmission through devices like a speaker. In this specific scenario, the Digital-to-Analog Conversion (DAC) process is managed by a pre-existing MATLAB function that utilizes the sound card of the device.
Specifically, there are two main tasks within the RF block. Firstly, there's the DAC conversion, and secondly, the introduction of a carrier frequency. This process involves shifting the baseband transmitter signal to a higher frequency. The frequency involved is not constant and varies considerably depending on the application. The usual order of these two operations is the one shown, although it may vary depending on the technology used (although it's generally easier to convert a baseband signal to an analog signal than its RF version).

2.4 Receiver (RX)

The receiver's structure closely resembles that of the transmitter, sharing the overarching goal of decoding the signal received by the antenna (or a microphone in the case of acoustic transmission) and converting it back into bits. Initiated by down-converting the signal from the carrier frequency, the receiver's initial task is to return the signal to its original form. Subsequently, the receiver engages in frame detection, a critical step outlined in 2.3. Each frame commences with a preamble sequence characterized by auto-correlation closely resembling a Dirac pulse.

The Frame Synchronizer, tasked with this detection, aims to identify a peak through auto-correlation computation between the received signal and the known preamble sequence. Once the beginning of the frame is found, the data undergo a transformation from series to parallel to facilitate the Fast Fourier Transform (FFT). Following the FFT, the data are equalized and revert from parallel to series. In the final stage, symbols undergo demodulation from QPSK to a bitstream.

In an ideal scenario, these straightforward steps prove effective; however, real-world transmissions encounter diverse challenges. The predominant obstacles for such systems involve fading, multipath, and phase shifting. To counteract the effects of these non-ideal conditions, a training sequence is incorporated ahead of the actual data. The addition of this sequence plays a crucial role in offering channel estimation for both magnitude and phase.

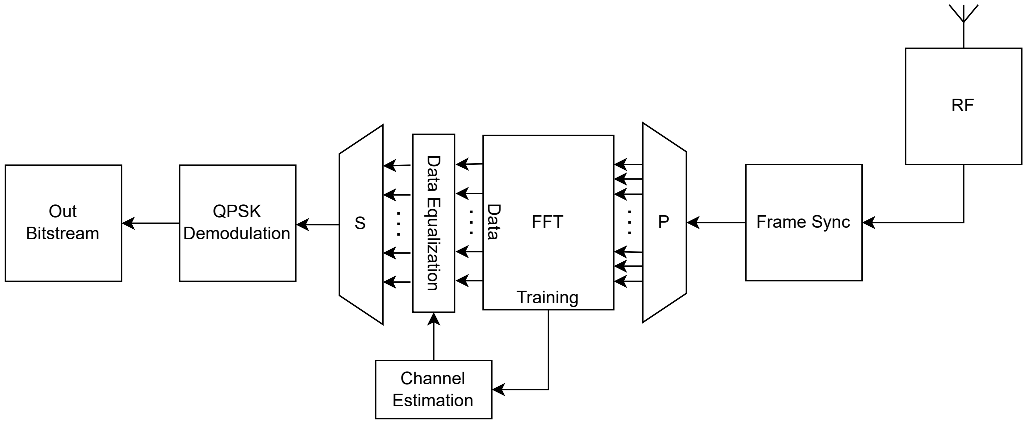


Figure 6: OFDM Receiver

The channel's magnitude is presumed to be nearly constant, a reasonably accurate approximation based on our conducted experiments. By incorporating additional training sequences, we can recalibrate the channel magnitude before significant variations occur. With this assumption, our focus shifts primarily to phase tracking, managed through the Viterbi-Viterbi algorithm.
The training sequence facilitates the acquisition of an initial phase estimation for each subcarrier, serving as a starting point reference for the subsequent phase tracking. To enhance the precision of phase tracking, especially in response to the characteristics of the random walk, a lowpass filter is integrated.

The corresponding MATLAB implementation of the Viterbi-Viterbi algorithm is presented in Listing 1.

Listing 1: Viterbi-Viterbi implementation

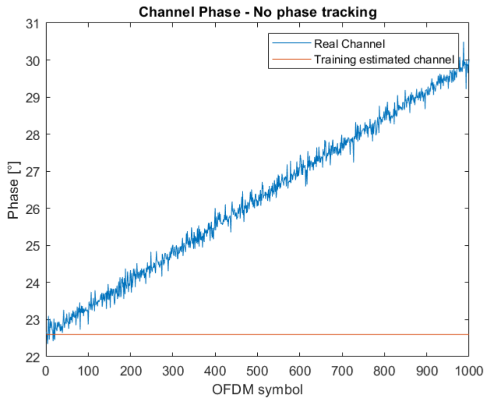
```
for k = 1:conf.ofdm_sym_per_frame
    deltaTheta = 1/4 * angle(-rx_data(:, k).^4) + pi/2 * (-1:4);
    [~, ind] = min(abs(deltaTheta - channel_phase_est(:, k)), [], 2);
    linearInd = sub2ind(size(deltaTheta), (1:size(deltaTheta, 1))', ind);
    theta = deltaTheta(linearInd);
    channel_phase_est(:, k+1) = mod(0.01 * theta + 0.99 * channel_phase_est(:, k)
        , 2*pi);
```

The impact of phase tracking is visually demonstrated in Figure 7. It is evident that it plays a pivotal role in achieving favorable results. This figure shows the phase variation of the channel of the first subcarrier over time. In both scenarios 1000 OFDM symbols was transmitted but with only one training sequence (OFDM symbol 0).

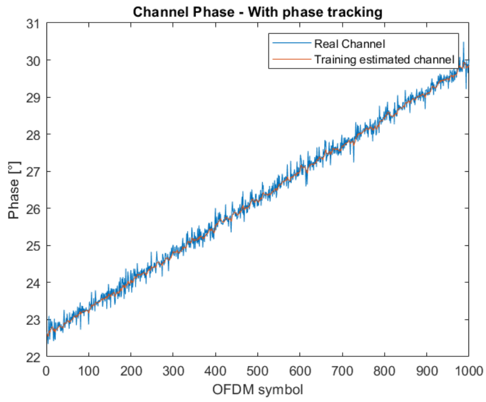
2.5 Channel

Certainly, addressing the effects of the channel is crucial in data transmission. The channel plays a pivotal role and introduces unwanted effects to the signal, some of which may be challenging to correct. Noise, for instance, can distort the points in the signal constellation. Additionally, practical channels exhibit fading and multipath phenomena, where the receiver receives multiple reflections of the signal with different delays, containing, if we have some multipath, information from previously transmitted symbols.

To overcome these challenges, it is imperative to implement effective strategies. This may involve the use of error correction techniques, adaptive modulation schemes, and advanced signal processing algorithms. Techniques such as channel equalization can help mitigate the impact of fading and



(a) Phase without phase tracking



(b) Symbols with phase tracking

Figure 7: Effect of phase tracking

multipath, ensuring more reliable signal reception. Furthermore, incorporating feedback mechanisms between the transmitter and receiver allows for dynamic adjustments to adapt to changing channel conditions. Overall, a comprehensive approach to managing channel effects is essential for optimizing data transmission performance in real-world communication scenarios. More details are presented in Section 6.2.

Finally, the efficiency of the channel can be defined with the following formula:

$$\epsilon = \frac{N}{N + N_{cp}} \tag{2.4}$$

where N represents the length of the OFDM symbol and N_{cp} the length of the cyclic prefix. Different scenarios involving various cyclic prefix length are discussed in section 4.4.

3 Implementation

This section presents the implementation for the discussed theoretical aspects. The code has been produced using MATLAB and the structure of the project can be found on Github. In this section, the strategies and decisions guiding the OFDM transmission system implementation will be explained. Following that, the upcoming sections will display results from simulations on both simulated and real channels, followed by final discussions.

3.1 Data Transmission Modalities

Various types of data have been employed for different purposes. For development and theoretical considerations, a random bitstream has been utilized. For other types of tests, the choice was made to transmit a small grayscaled image (256x256 pixels) to better assess the quality of the transmission and reception. This bitstream has the following shape:

$$\text{Bitstream} = \underbrace{\begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \dots & 0 \end{bmatrix}}_{\text{Number of frames}} \left.\vphantom{\begin{bmatrix} 1 \\ 0 \\ \vdots \\ 1 \end{bmatrix}}\right\} \text{(Bits per OFDM symbols} \times \text{OFDM symbols per frame)} \tag{3.1}$$

The sole purpose of this configuration is to streamline computations over TX and RX, and it is a deliberate design choice. As mentioned earlier, the primary advantage of this dataset lies in its adaptability, allowing for variations in length based on the mean.

3.2 Lena Image

The second dataset transmitted is the Lena image, a standard benchmark in digital image processing [Wik18]. This option provides a visual assessment of the bit error rate (BER) and channel variations, as well as a view of the transmission efficiency. A grayscale version of Lena, sized at 256×256 (`uint8`), corresponds to $256 \cdot 256 \cdot 8 = 524288$ bits. The transmission framework follows the structure detailed in Section 3.1. The number of frames required to transmit this image depends on the quantity of OFDM symbols sent per frame, a value to be discussed in the Results section.

3.3 EPFL Image

To illustrate the impact of the Peak-to-Average Power Ratio (PAPR), as discussed in Section 2.3, an additional image—EPFL Logo—has been incorporated. This image is characterized by only two distinct colors, therefore only two symbols. Consequently, the transmitted signal will predominantly comprise either ones or zeros, effectively emphasizing the observed PAPR effect. The dimensions of this image mirror those of Lena.

(a) Gray Lena (b) Gray EPFL

Figure 8: Images used for transmission

3.4 Transmitter Specifications

This section presents a concise overview of specific specifications employed in the transmitter. The first consideration is the pulse shaping of the preamble. To convert symbols into a suitable signal for transfer to the receiver, these symbols must undergo a pulse shaping. One effective approach is to employ linear modulations, such as amplitude modulation, where each pulse is defined as:

$$g_i(t) = a_i g(t) \tag{3.2}$$

To achieve spectrum efficiency, the shaping function $g(t)$ should ideally have a narrow spectrum. The ideal shape is a rectangle, and the corresponding impulse response is a cardinal sinus. Therefore, the ideal choice for this filter is an ideal lowpass filter with a spectrum given by $G(f) = \text{rect}(f/R)$. However, practical considerations render this ideal lowpass filter impractical due to its infinitely long impulse response, which converges slowly toward zero. A reasonable compromise, striking a balance between good performance and feasibility, is the so-called raised cosine filter. The specific filter used will be explained in Section 3.5.

Another crucial aspect is the cyclic prefix, employed as the guard interval. According to project guidelines, the cyclic prefix is recommended to be half the length of an OFDM symbol. As detailed in Sections 2.2 and 2.3, this implies duplicating the concluding elements of the OFDM symbol at the beginning of the symbol itself.

The second element is the up-conversion. The signal is modulated into a carrier frequency of $f =$ 8kHz. The idea is diverse. Baseband signals are centered around DC and have DC characteristics, which is not suitable for wireless comunications. In fact, designing a compact lowpass antenna is very challenging as the size of the antenna is directly related to the wavelength of the incomming signal. Assuming that the signal is comprised between 10Hz and 2kHz. The size of the antenna is given by [Bal16]:

$$d \sim \frac{\lambda}{4} = \frac{c}{4f} \tag{3.3}$$

Therefore, the antenna should ideally have dimensions ranging between 7.5×10^6 m and 3.75×10^4 m. However, this range is practically unattainable. Shifting the center of the bandwidth to a carrier frequency makes it feasible to tailor an antenna to the signal. In radio frequency, the carrier frequency typically lies in the order of magnitude of gigahertz. This way, a band spanning several megahertz around the carrier frequency exhibits approximately the same wavelength as the carrier frequency. In this project, however, since the channel is acoustic the reception is done by a microphone and the carrier frequency was set to $f =$ 8kHz.

In acoustic transmission, it is crucial to acknowledge that the system's performance may be influenced by alterations in the carrier frequency. This stems from the distinct frequency responses exhibited by microphones and speakers, each amplifying various frequencies with differing magnitudes and phases. Opting for an 8kHz frequency is generally a favorable compromise, ensuring nearly uniform magnitude across the entire bandwidth.

Additionally, a challenge associated with the RF block is flicker noise. This form of noise scales with frequency, posing a potential degradation in SNR at extremely low frequencies.

3.5 Receiver Specifications

From the receiver side, some elements need to be pointed out. After converting back the signal to the baseband, it is necessary to apply a lowpass filter to the signal to remove noise coming from the byproducts. The signal is:

$$\begin{aligned} r_{dc}[t] &= r_{PB}[t] \cdot e^{-j2\pi f_c t} && (3.4) \\ &= \frac{1}{2} s_{BB} + \underbrace{\frac{1}{2}(\mathscr{R}\{s_{BB}\} - \mathscr{F}\{s_{BB}\}) \cdot e^{-4\pi f_c t}}_{\text{noise term}} && (3.5) \end{aligned}$$

This noise occurs at twice the carrier frequency (f_c) and therefore needs to be filter by the mean of a lowpass filter. The resulting signal is:

$$\tilde{r}_{BB}[t] = 2 \cdot LP\{r_{dc}[t]\} \tag{3.6}$$

This lowpass filter is implementing using the MATLAB implementation of this kind of filter. The code that produces this output is presented in Listing 2.

Listing 2: Lowpass filter implementation

```
function [after] = ofdmlowpass(before, conf, f)
% LOWPASS lowpass filter
% Low pass filter for extracting the baseband signal
%
% before : Unfiltered signal
% conf : Global configuration variable
% f : Corner Frequency
%
% after : Filtered signal
% conf.sampling_freq: sampling frequency
after = lowpass(before, f, conf.sampling_freq, StopbandAttenuation = 30);
```

Another aspect requiring clarification pertains to the detection of the preamble. In order to identify the beginning of the data, the signal must undergo another round of filtering to recover the interpolated symbols. This filter is simply the complex conjugate and time-reversed version of the one used for pulse shaping on the transmitter side.

$$g_{MF} = g^*(-t) \tag{3.7}$$

Since the total filter ($g(t) * g^*(-t)$) must satisfy the Nyquist criterion, it is equivalent to state that both filters should have a transfer function equal to the square root of the raised cosine filter. This is achieved by implementing a root raised cosine (RRC) for both filters. The equation for an RRC is given by:

$$g_{\mathrm{rrc}} = \frac{\frac{4\alpha}{\pi}\cos\left(\frac{\pi(1+\alpha)t}{T}\right) + (1-\alpha)\mathrm{sinc}\left(\pi(1-\alpha)\frac{t}{T}\right)}{1-(4\alpha\frac{t}{T})^2} \tag{3.8}$$

where α is the roll-off factor. It is noteworthy that the case $\alpha = 0$ corresponds to the ideal lowpass filter. Furthermore, increasing α also expands the two-sided bandwidth, as given by:

$$B = R(1+\alpha) \tag{3.9}$$

Since the data is not transmitted as single carriers, it is crucial to employ the non-matched array for symbol recovery. The matched filter sequence, on the other hand, is exclusively utilized for frame synchronization.

4 Results

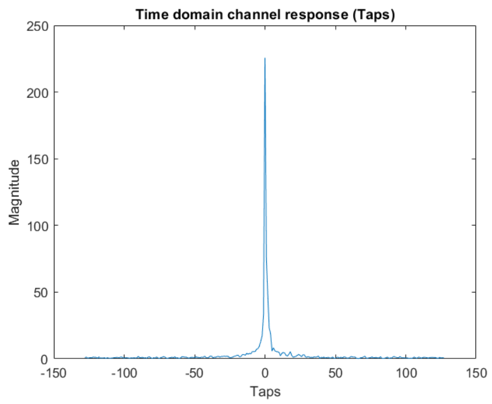
This section presents results derived from both simulation and real experiments, challenging the model under various conditions. A more in-depth discussion of the outcomes will be provided in Section 6.

In the initial stage, the project undergoes testing under favorable conditions, a term that warrants clarification. In the context of acoustic transmission, favorable conditions assume that the channel remains constant for a defined period. In practical terms, this requires the microphone's position relative to the speaker to remain stable during the channel estimation interval. This initial experiment will unveil a preliminary limitation that necessitates discussion.

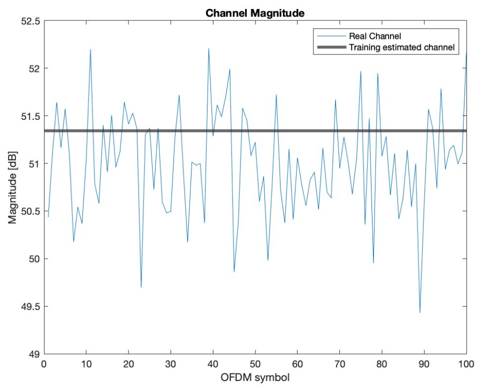
Moreover, favorable conditions also imply an absence of multipath effects. While multipath is typically unavoidable, its impact can be mitigated if the signal strength surpasses that of the multipaths. However, excessive multipath presence may lead to an increase in Bit Error Rate (BER), a topic to be addressed in Section 6.

4.1 Channel Estimation in Favorable Conditions

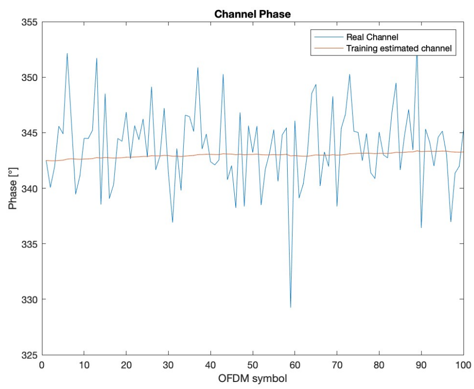
After ensuring that the system works in simulation, the first try was to put the system in real life under good conditions. The microphone was set in front of the two speakers at an approximate distance of $10[cm]$. Under these conditions, the system doesn't suffer too much from multipath effects. Results of this experiment is presented in Figure 9.



(a) Channel Taps



(b) Channel Magnitude



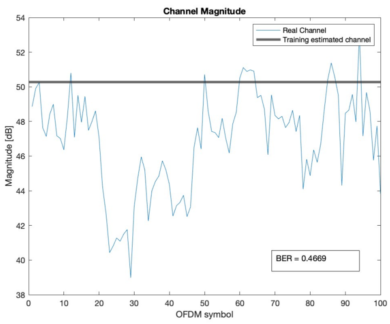
(c) Channel Phase

Figure 9: Results for a good conditions experiment

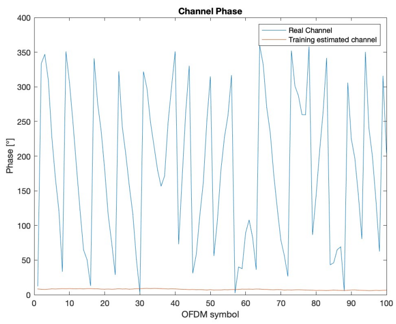
Figure 9a emphasizes the absence of significant multipath, evident in the lack of a distinct peak in magnitude. Examining Figures 9b and 9c, it becomes apparent that the estimation, facilitated by a training sequence sent ahead of 100 symbols, remains consistently accurate over time. For the magnitude there is only the training estimation, for the phase the phase tracking is activated. The corresponding Bit Error Rate (BER) is observed to be zero, underscoring the system's stability as it consistently interacts with the unchanging channel. However, it's crucial to acknowledge that this ideal scenario is not reflective of real-world conditions. It assumes a static receiver and environment throughout the symbol transmission period, a circumstance rarely encountered in practical scenarios. This unrealistic assumption is addressed in 4.2, where the detrimental effects of a dynamic channel environment are explored.

4.2 Channel Estimation under Challenging Conditions

This subsection provides an overview of the challenge outlined in Section 4.1. In this scenario, the identical bitstream is transmitted, but with a dynamic variation in the channel over time. This implies that the microphone moves and changes his orientation throughout the transmission process. The observed consequence of this dynamic channel condition is depicted in Figure 10.



(a) Magnitude



(b) Phase

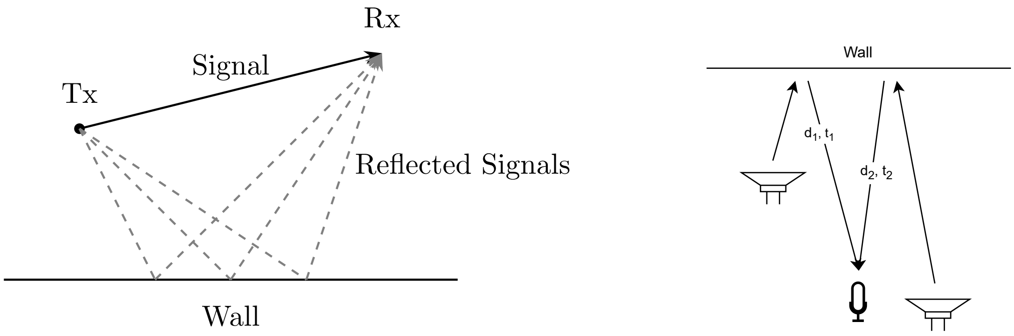
Figure 10: Results for a bad conditions experiment

These figures distinctly illustrate the impact of a channel change. For example, in Figure 10a, it is evident that starting from the 20th OFDM symbol, the microphone has shifted backward. Consequently, the magnitude of the channel has decreased. However, the estimation derived from the training sequence remains constant (at approximately 50 dB). Unfortunately, this fixed estimation is no longer accurate, leading to errors. A similar discrepancy is observed in the phase (Figure 10b), where the estimation maintains a constant value of around 0°, despite significant variations during transmission.

This experimental condition results in a high Bit Error Rate (BER) of 0.4669, which is clearly unacceptable. Resolving this issue requires the identification and implementation of appropriate solutions. Possible solutions to improve performance even in the presence of a channel that varies greatly over time can be found in the Section 6.

4.3 Multipath Fading Channel

Another aspect emphasized in Section 4 is the fading effect. As articulated in [PH06], "*Multipath fading heavily contributes to the unreliability of wireless links, causing significant deviations from link quality predictions based on path loss models*". This phenomenon cannot be overlooked and demands careful consideration. Fading occurs when reflections of the signal reach the receiver, leading to delays attributable to the increased length of reflected paths compared to the shortest path. In practical scenarios, both outdoors and indoors, reflections occur from various surfaces such as walls, buildings, or mountains.



(a) Reflection and Delay Due to a Wall

(b) Multipath Chamber Setup

Figure 11: Multipath channel

In order to observed these effects, the system is put into fading conditions that can be measured. The system has been set up as depicted in Figure 11b. Under these conditions, the length of the principal signals can be measured and therefore be simulated. This simulation can simply be done by convolving the RF signal with a multipath array :

$$TX = RF * h \tag{4.1}$$

with h defined as:

$$h = [h_1, 0, \dots, 0, h_2, 0, \dots, h_3, 0, \dots] \tag{4.2}$$

where $h_1, ..., h_n$ represent the magnitude of each channel. The number of zeros inbetween depends on the length of the path. The exact number can be found with the following formula:

$$Padding = \frac{d \cdot v_s}{f_s} \tag{4.3}$$

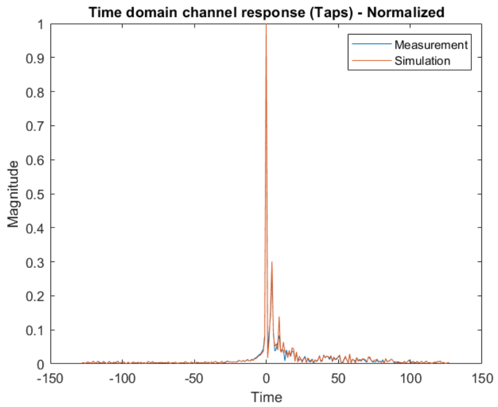
where d is the distance that the secondary path travelled, v_s is the Speed of sound ($\approx 300 m/s$) and f_s is the sampling frequency (48000Hz).

After computing the array h for the two main fading channels, simulation and experiments can be done. Results are shown in Figure 12.
In order to have a superposition in plots, the channel is normalized. By having a look in Figure 12a, it can be seen that the system suffers from two main paths. The initial one is positioned at the time index (tap) $\tau = 0$. The second one is situated at $\tau = 4$, corresponding to a path length difference of approximately 93.75 cm, consistent with the established configuration. A last one can be observed $\tau = 9$. The channel follows very well the simulation, meaning that the system is well-modelled. By looking at the magnitude plot (Figure 12b), it can also be seen that the system is in a deep fade in frequencies around 7650 and 8000Hz.

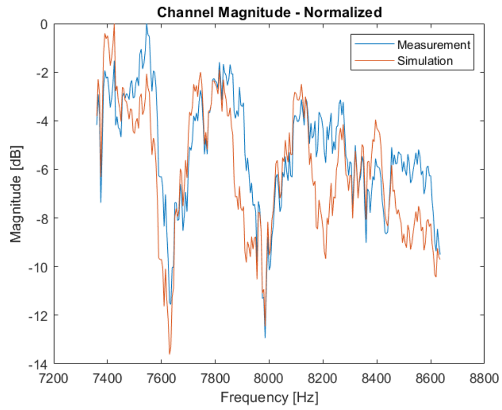
As evident from the comparison, the simulated version closely aligns with the real one. With this type of modeling, a highly accurate estimation of the channel can be attained. A more comprehensive approach to channel estimation in this environment involves collecting diverse measurements at different positions and subsequently calculating the variance across the various taps. This process enables the straightforward computation of the Power Delay Profile.

4.4 Channel Efficiency

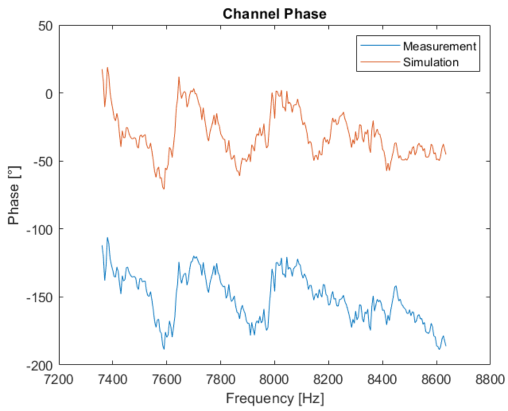
As discussed in section 2.5, the system efficiency can be computed using Equation 2.4. For efficiency calculations, the channel data extracted from measurements (Figure 12a) was employed. In this particular scenario, the channel length is approximately 280 samples. Therefore, theoretically, the minimum cyclic prefix (CP) length required for inter-symbol interference (ISI)-free transmission is 280.



(a) Channel Taps



(b) Channel Magnitude



(c) Channel Phase

Figure 12: Results for multipath experiment

Opting for a CP length equal to half the length of the Orthogonal Frequency Division Multiplexing (OFDM) symbol, the system efficiency, with 256 subcarriers and a frequency spacing of 5Hz, can be expressed as:

$$\epsilon = \frac{N}{N + N_{cp}} = \frac{256 \cdot \text{ofdm\_os\_factor}}{256 \cdot \text{ofdm\_os\_factor} + \frac{256 \cdot \text{ofdm\_os\_factor}}{2}} = \frac{2}{3} \approx 0.667 \tag{4.4}$$

Alternatively, if the minimum CP length is utilized, the resulting efficiency is:

$$\epsilon = \frac{N}{N + N_{cp}} = \frac{256 \cdot \text{ofdm\_os\_factor}}{256 \cdot \text{ofdm\_os\_factor} + 280} \approx 0.972 \tag{4.5}$$

To introduce a safety margin for potential variations in channel length (given that channel length is an estimation), a slightly longer CP length, such as 400, can be employed:

$$\epsilon = \frac{N}{N + N_{cp}} = \frac{256 \cdot \text{ofdm\_os\_factor}}{256 \cdot \text{ofdm\_os\_factor} + 400} = 0.96 \tag{4.6}$$

This demonstrates that the efficiency is minimally affected, providing a buffer for variations in channel length.

It's crucial to note that the cyclic prefix (CP) length is inherently tied to the channel length and can vary over time, even with a consistent configuration (transmitter and receiver positions). Strategies to address this issue are discussed in Section 6.2.

5 Limits of OFDM

The limitations of an OFDM system are mainly channel related. A natural question to ask is "how many symbols can I transmit before I have to add a new training sequence?

The answer, as mentioned above, depends on the type of channel the system is dealing with. If a channel is relatively stable over time, then it will have a smoother transmission without the need to add too many training sequences. On the other hand, if the channel is highly variable, the transmitter will be forced to send more training sequences to limit the BER.

Figure 13 illustrates a comparison between two transmissions. In the instance of figure 13a, the transmission employed multiple training sequences (one for every 16 symbols transmitted). Conversely, in the case of figure 13b, the transmission utilized a single initial training sequence. As observed, in the first case (despite the imperfect transmission), a relatively low Bit Error Rate (BER) is achieved (less than 2

(a) Good transmission

(b) Bad transmission

Figure 13: Different transmissions of the same Lena image

In these two cases there is therefore a different maximum number of symbols that can be sent before needing a new training sequence.

6 Discussion and Further Work

6.1 Enhancing Transmission Speed: Strategies for Optimization

Utilizing OFDM modulation enhances robustness in the presence of multipath channels. By incorporating advanced channel estimation methods, such as comb training, commendable performance can be achieved even in dynamically changing channels. However, a significant challenge has been identified in the implementation of the OFDM system—transmission speed. For instance, transmitting a standard-sized photo (256x256px) with the specified project configuration (5Hz spacing frequency and 256 carriers) takes an extended period, approximately a minute. This leads to the question: can a higher transmission speed be achieved?

Indeed, it can! To optimize transmission speed, four key factors can be manipulated:

- Adjusting spacing frequency
- Exploring different modulation types
- Changing the CP length

As is aware, the symbol duration (T_{period}) in an OFDM system is given by the reciprocal of the subcarrier spacing (f_{spacing}):

$$T_{\text{period}} = \frac{1}{f_{\text{spacing}}} \tag{6.1}$$

Increasing the spacing frequency results in a shorter symbol duration, leading to higher transmission speeds. However, it's essential to note that elevating the spacing frequency also entails an increase in bandwidth. The application's bandwidth constraints should be taken into consideration.

Modifying the number of subcarriers won't immediately impact the speed performance of our system. Instead, it will enhance the transmission efficiency, a conclusion easily drawn from Equation 2.4.

Additionally, the modulation type serves as another variable to manipulate. In the current scenario, QPSK symbols are being transmitted. By transitioning to a higher-order modulation, such as 64-QAM, the number of bits transmitted in a single symbol increases:

$$\text{Bits per symbol 64-QAM} = \log_2(64) = 6 \tag{6.2}$$

However, using constellations with a larger number of symbols heightens sensitivity to noise and other parasitic effects. Unlike QPSK, where a symbol, to become an error, must arrive in a different quadrant (bigger decision region), 64-QAM demands a much lower acceptable error for successful reconstruction of the original symbol (lower decision region). An optimal approach might involve implementing a hybrid system that provides feedback from the receiver on the channel condition. This allows dynamic adjustments of the constellation type in real time, opting for a larger modulation like 1024-QAM in stable channels and reverting to a simpler one like QPSK in highly unstable channels.

It is essential to consider that the power of OFDM modulation lies in the long symbol duration, making it robust to multipath, since the symbol duration is often greater than the multipath effect of the channel. Therefore, it is essential to avoid over-accelerating the transmission in order not to make it too sensitive to multipath.

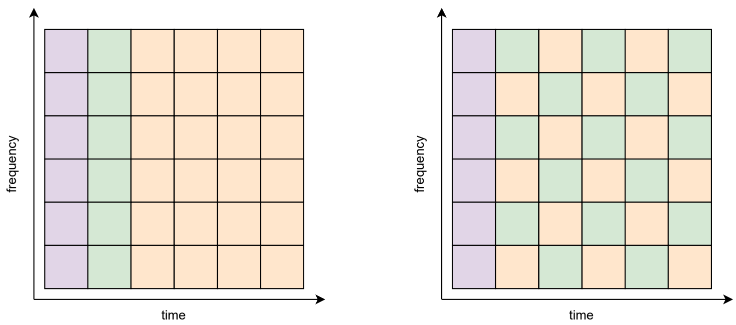
Finally, for enhancing the transmission speed, adjusting the duration of the cyclic prefix (CP) is another viable option. In the case of a "very short" channel, significant reductions in CP length can be implemented. Conversely, in the presence of a lengthy channel, especially one with substantial multipath effects, a longer CP is necessary to ensure freedom from intersymbol interference (ISI). This aspect is highly contingent on the channel characteristics, which can vary considerably over time. Thus, a potential solution involves obtaining feedback from the receiver, providing information about the current channel conditions. This feedback allows for the calibration of our transmission parameters based on the prevailing channel conditions.

6.2 Enhanced Transmission System

The implemented system is a "basic" version of an Orthogonal Frequency Division Multiplexing (OFDM) transmission system. It supports signal transmission using different carrier waves, accommodating a variable number of subcarriers with different frequency spacings. The modulation scheme employed is exclusively Quadrature Phase Shift Keying (QPSK), although it can be easily modified. The system conforms to the frame structure depicted in Figure 3. Noteworthy features include the flexibility to customize the number of symbols to be transmitted after each training sequence. Additionally, phase tracking functionality is incorporated using the Viterbi-Viterbi algorithm to enhance performance in relatively stable channels.

One advanced feature that can be incorporated is comb training, a technique that improves receiver performance by training the channel during transmission. Figure 14 illustrates two different approaches to channel training. In the current implementation, shown in Figure 14a, an entire OFDM symbol is used for channel training at the beginning before moving on to data transmission. However, this method presents challenges because only an initial estimate is available, and if the phase or magnitude of the channel undergoes significant variations beyond tracking capability, problems may arise.

To address this issue, an alternative approach is presented in Figure 14b. Here, training is distributed across the signal, allowing for more accurate channel estimation. For example, in this configuration, the channel influence on a particular subcarrier is estimated every two symbols. During non-training symbols, interpolation can be used to estimate the channel effect, providing a more robust solution for dealing with varying channel conditions.



(a) Simple training (b) Comb-training

Figure 14: Different ways to train the channel: preamble in purple, training data in green and actual data in orange

Another feature that could be implemented is that of a two-way communication between TX and RX, so as to be able to agree on various factors (e.g. modulation used, type of training, ...), as explained above. It would certainly be interesting to see how much the addition of this type of feature could improve data transmission.

To further enhance Bit Error Rate (BER) performance, incorporating error correction mechanisms such as parity bit checks is a viable option. However, it's important to note that this approach comes with a trade-off, as it introduces additional bits to the original signal, consequently reducing the overall bitrate. In scenarios where a two-way communication link is established between the transmitter (TX) and receiver (RX), the advantage becomes evident. This bidirectional communication allows dynamic adaptation based on the current "channel situation", enabling the selective use of error correction techniques when deemed necessary. This flexibility ensures an optimized trade-off between error correction and signal bitrate, depending on the prevailing conditions in the communication channel.

7 Summary

Focused on analyzing the performance and limitations of an Orthogonal Frequency Division Multiplexing (OFDM) system, the initial phase involved a comprehensive exploration of the theoretical foundations underlying OFDM technology. Subsequently, the theoretical insights were translated into practical implementation through the development of MATLAB code.

The project revealed challenges inherent in the design and operation of the OFDM system. Through MATLAB simulations, various issues and complexities were addressed, forming a basis for in-depth analysis. Key aspects such as signal synchronization, channel estimation, and the impact of noise and interference underwent thorough examination.

Furthermore, the project aimed to assess the overall performance of the OFDM system, shedding light on its strengths and weaknesses. The insights gained contribute to a better understanding of OFDM's suitability for different communication scenarios and its potential limitations.

In conclusion, this OFDM project demonstrated the system's performance under optimal conditions while highlighting its limitations in dynamic environments. The discussion proposed various improvement methods that can help build a more robust system.

References

[LS06] Ye Geoffrey Li and Gordon L Stuber. *Orthogonal frequency division multiplexing for wireless communications*. Springer Science & Business Media, 2006.

[PH06] Daniele Puccinelli and Martin Haenggi. "Multipath Fading in Wireless Sensor Networks: Measurements and Interpretation". In: *Proceedings of the 2006 International Conference on Wireless Communications and Mobile Computing*. IWCMC '06. Vancouver, British Columbia, Canada: Association for Computing Machinery, 2006, pp. 1039–1044. ISBN: 1595933069. DOI: 10.1145/1143549.1143757. URL: https://doi.org/10.1145/1143549.1143757.

[OA07] Mehmet Kemal Ozdemir and Hüseyin Arslan. "Channel estimation for wireless OFDM systems". In: *IEEE Communications Surveys and Tutorials* (2007), pp. 18–48.

[DIZ15] Younes DJEMAMAR, Saida IBNYAICH, and Abdelouhab ZEROUAL. "Performance Analysis of QPSK, 4QAM, 16QAM and 64QAM with Binary and Gray Constellation Codes over AWGN Channel". In: (2015).

[Bal16] Constantine A. Balanis. *Antenna Theory: Analysis and Design*. 4th. John Wiley & Sons, 2016. ISBN: 978-1118642061.

[Wik18] Wikipedia contributors. *Lenna*. Wikipedia, The Free Encyclopedia. Accessed: 2023-12-18. URL: https://en.wikipedia.org/wiki/Lenna.