ESCUELA TÉCNICA SUPERIOR DE INGENIEROS
INDUSTRIALES Y DE TELECOMUNICACIÓN

UNIVERSIDAD DE CANTABRIA

Trabajo Fin de Máster

Técnicas de Reducción de PAPR para un Data Link OFDM

(PAPR Techniques for an OFDM Data Link)

Para acceder al Título de

Máster Universitario en Ingeniería de Telecomunicación

Autor: Ana Ruiz Oviedo

Septiembre - 2018

E.T.S. DE INGENIEROS INDUSTRIALES Y DE TELECOMUNICACION

MASTER UNIVERSITARIO EN INGENIERÍA DE TELECOMUNICACIÓN

CALIFICACIÓN DEL TRABAJO FIN DE MÁSTER

Realizado por: Ana Ruiz Oviedo
Director del TFM: José Diez Secadas
Título: “Técnicas de Reducción de PAPR para un Data Link OFDM”
Title: “PAPR Techniques for an OFDM Data Link “

Presentado a examen el día: 26 de septiembre de 2018

para acceder al Título de

MASTER UNIVERSITARIO EN INGENIERÍA DE TELECOMUNICACIÓN

<u>Composición del Tribunal:</u>
Presidente (Apellidos, Nombre): Santamaría Caballero, Ignacio
Secretario (Apellidos, Nombre): Ibáñez Díaz, Jesús
Vocal (Apellidos, Nombre): Cobo García, Adolfo

Este Tribunal ha resuelto otorgar la calificación de: ....

Fdo.: El Presidente | Fdo.: El Secretario

Fdo.: El Vocal | Fdo.: El Director del TFM

Vº Bº del Subdirector | Trabajo Fin de Máster Nº

Dedicado a
mi padre

Agradecimientos

Quiero agradecer a todas esas personas que me han ayudado con este Trabajo Fin de Máster que supone el fin de una etapa en la que he crecido tanto intelectual como personalmente.

En primer lugar, quiero dar las gracias a José y Laura de Berten DSP por haberme dado la oportunidad de trabajar con ellos y realizar este proyecto. Agradecerles su ayuda, paciencia y dedicación así como el tiempo invertido en enseñarme y en contribuir a que todo saliese adelante. Ha sido un placer trabajar con vosotros.

A mi compañero en Berten, Manuel Merino, quiero agradecerle todo el tiempo, el esfuerzo, la ayuda y, sobre todo, la paciencia que ha tenido.

También quiero dar las gracias a Ignacio Santamaría el interés mostrado y la ayuda y soporte que me ha proporcionado en los momentos críticos. Gracias por invertir tu tiempo contribuyendo en este proyecto.

Finalmente, agradecer a mi madre por todo lo que me ha enseñado a lo largo de mi vida. Por ser la que siempre ha confiado en mi, incluso cuando ni yo misma lo hacía. Gracias por tu incondicional apoyo, tu paciencia y tu cariño. Este proyecto es en gran parte tuyo.

Contents

List of Figures

List of Tables

Palabras Clave

OFDM, procesado de señal, PAPR, DFT-Spread OFDM, símbolos piloto, Simulink.

Keywords

OFDM, signal processing, PAPR, DFT-Spread OFDM, pilot tones, Simulink.

Chapter 1

Introduction

Wireless communications are one of the most growing sectors in the telecommunications field. The rising develop of the Internet of Things (IoT) and the expansion of the wireless systems are some examples.

In the past, wireless communications were based on narrow band single carrier systems. However, the arrival of new technologies required new wireless transmission systems and wide band multicarrier schemas are now the solution to the technology demands.

The main idea of multicarrier communications is to divide the communication wide band channel into narrow band subchannels and transmit the data stream split through them.

Orthogonal Frequency-Division Multiplexing (OFDM) is one of the multicarrier transmission modulation format more used nowadays [1]. The main advantages of OFDM communication is its robustness. OFDM communications are barely affected by narrow band interference and multipath. Moreover, they are able to fight against frequency selective wide band channels. In addition, it uses the transmission spectrum efficiently so its utilization is extended in many communications standards such as DVB-T, IEEE 802.11a, IEEE 802.16 and LTE.

1.1 Objectives

The objective of this project is to study Peak-to-Average Power Ratio (PAPR) reduction techniques for an OFDM Data Link for airborne wireless systems. The implementation of this PAPR reduction techniques allows a more efficient use of the power amplifiers dynamic range. This means that the power back-off is reduced and the amplifiers can work closer to its P_{1dB} point.

The project will take into account the integration of the technique into the Data Link processing chain design by Berten DSP. For the evaluation of the system, simulations have been carried out to analyse the improvement of the PAPR and the transmitted signal characteristics.

Chapter 2

OFDM Communications

2.1 Introduction

OFDM (Orthogonal Frequency Division Multiplexing) is a particular type of multicarrier transmission. It is one of the most common transmission schemes in multicarrier-wideband communications due to its robustness and flexibility.

In OFDM, all the subcarriers are orthogonal, resulting in a higher spectral efficiency when compared with traditional FDM (Frequency Division Multiplexing) systems. This means that the total transmission rate is close to the Shannon capacity of the frequency-selective channel. In addition, because of the subcarrier orthogonality, cross-talk is eliminated, band guards are not required, and subcarriers can be overlapped for its transmission, reducing the occupied bandwidth, as shown in Figure 2.1.

In the OFDM systems, the frequency selective channel is divided into N narrow band parallel subchannels, each of them affected by flat fading. In the same way, the data stream is divided into N substreams. For each subchannel the data is modulated over a subcarrier using standard digital modulation such as PSK (Phase-Shift Keying) or QAM. Then, by adding all the modulated subcarriers, the OFDM symbol is formed before sending it through the communications channel.

Frequency selective channels produce a distortion on the signals, spreading them over time. If this temporal spread is larger than the symbol period it produces intersymbol interference (ISI). In order to eliminate ISI the OFDM symbol length is increased. This means that when the data stream

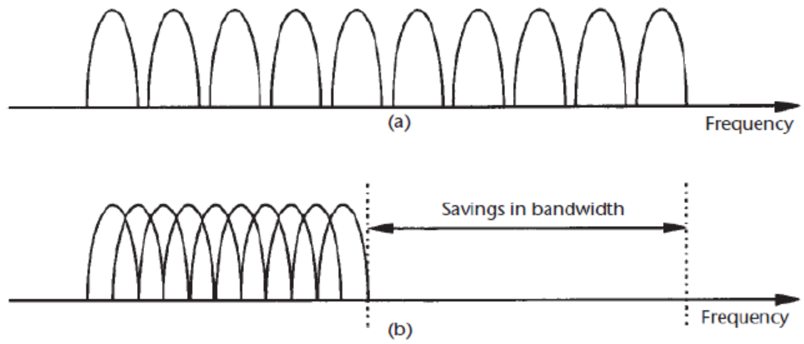


Figure 2.1: Spectral comparison of FDM (a) and OFDM (b) techniques

is split into smaller data substreams, the transmission rate is lower and so the temporal spread. As a result, the channel estimation and equalization complexity at the receiver is drastically reduced.

2.2 OFDM Architecture

The OFDM modulator uses the IFFT algorithm at the transmitter side and the FFT one at the receiver side. Although the benefits of this technique have been known for long time, its use was not spread until the cost of the digital signal processing components lowered and their performance increased. Figure 2.2 shows a simplified OFDM block diagram.

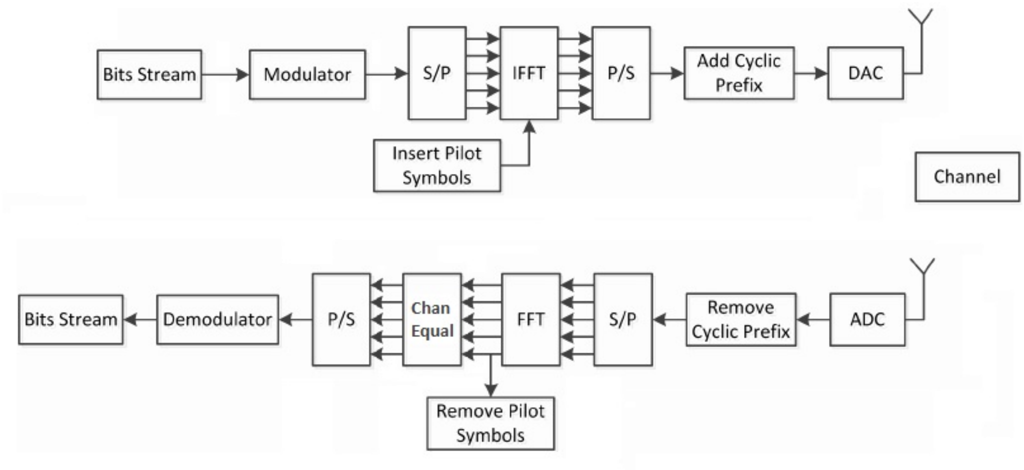


Figure 2.2: OFDM block diagram

The binary serial data is modulated in the transmitter and mapped into the constellation of the chosen modulation. The data stream is multiplexed into N substreams and the pilot symbols are inserted between the subcarriers. The frequency-domain data and pilot subcarriers are transformed into the time-domain by the IFFT. Then, the data is serialized again and cyclic prefix is inserted before the Digital-to-Analog conversion (DAC) and further RF modulation, upconversion, and transmission of the signal.

Once the signal is transmitted over the communication channel the receiver has to undo all the transformations in order to recover the transmitted signal. Firstly, the received data is downconverted and then an ADC (Analog-to-Digital converter) is used to transform it from analog to digital. Then, in order to recover the transmitted streams, it is necessary to make both temporal and frequency synchronization so the start of the OFDM symbols can be detected. This synchronization corrects the frequency offset that the channel has added to the signal.

The next module is in charge of removing the cyclic prefix added in the transmitter before transforming the signal to the frequency domain. Then, the data is multiplexed and the FFT (Fast Fourier Transform) is performed to change the signal domain. Once this is done, the channel estimation and equalization are carried out using the pilot tones.

Finally, the signal is serialized and the demodulator is able to detect the transmitted symbols and recover the data bits.

In the following sections, the transmitter and receiver modules will be explained in more detail.

2.3 Transmitter

2.3.1 Modulator

The modulator block is in charge of mapping each subcarrier individually. The process consists in grouping the input bits and transforming them to a complex number, X_k, which is mapped over a constellation given by the chosen modulation. In this way, X_k is a constellation symbol. The most common digital modulations used in OFDM transceivers are *M-PSK* and *M-QAM*, where M is the number of points of the constellation.

M-PSK modulations transmit information by varying the phase of a constant amplitude subcarrier. This technique uses a finite number of phases in order to represent a complex symbol i.e. a set of bits. M-PSK schemes represent the phase (I) and quadrature (Q) of the points of the constellation as complex numbers. BPSK (Binary Phase-Shift Keying) and QPSK (Quadrature Phase-Shift Keying) are the less efficient and more robust PSK modulations.

In the BPSK modulations the information is transmitted by changing the phase of the subcarrier between 0 and 180 degrees. Since coding is binary, only 1 bit per symbol is required and the constellation is as shown in Figure 2.3.

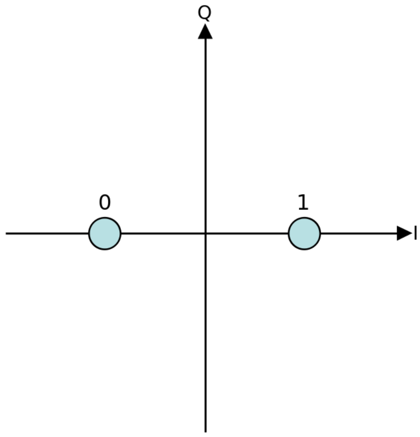


Figure 2.3: BPSK constellation

For QPSK, the subcarrier phase can take four values, resulting in a 2 bits per symbol coding as shown in Figure 2.4.

Although BPSK is the simplest and robustest modulation within the PSK schemes, QPSK is widely used in wireless communications. This is because QPSK takes benefit of I-Q channels and does not affect the BER (Bit Error Rate) for the same Eb/No.

M-QAM modulations combine both amplitude and phase modulation. The constellations are usually represented as a regular lattice. Because the square lattice used to represent the constellation, the number of points, M, is a power of two. Increasing the number of points in the constellation leads to an increase in the bits per symbol and the spectral efficiency. However, more points in a constellation means that these symbols are closer one to another, increasing the Bit Error Rate (BER) for the same energy per bit to noise power spectral density ratio (Eb/No).

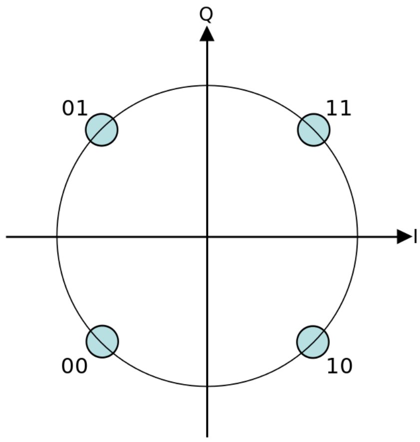


Figure 2.4: QPSK constellation

Figure 2.5 shows a 16-QAM constellation as an example of M-QAM constellation.

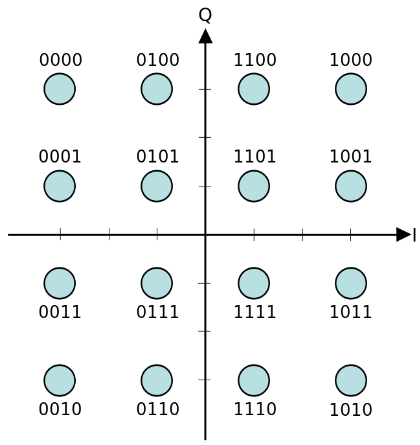


Figure 2.5: 16-QAM constellation

In Figures 2.3, 2.4 and 2.5, the constellation and the binary encoding of each point is shown. The example uses Gray coding, whose main characteristic is the one-bit different between adjacent symbols. This helps the decoder block in the receiver to reduce the system BER.

2.3.2 Pilot Tones Insertion

In OFDM, channel estimation and equalization at the receiver is key to recover the transmitted signal. The technique used in OFDM systems is called PSAM (Pilot Symbol Aided Modulation). PSAM sends a set of pilot subcarriers known at the transmitter and the receiver. These pilot subcarriers are interlaced with the information subcarriers in order to allow the receiver to perform an estimation and equalisation of the channel by the knowledge of the pilot subcarriers.

The pilot symbols can be distributed in different ways. Usually, the optimal location for the pilot tones depends on the characteristics of the communication channel. There are two typical pilot symbols arrangements: block-type and comb-type.

The block-type arrangement has been designed for slow fading channels. In this schema, OFDM symbols for channel estimation are transmitted periodically and are used as pilots, as shown in Figure 2.6. So, if the channel is constant during the block, there will be no errors in the estimation that can be performed by using LS (Least Squares) or MMSE (Minimum Mean Square Error) [3]. The calculated results can be used for the following OFDM symbols in the same block or be updated using equalization with feedback decision.

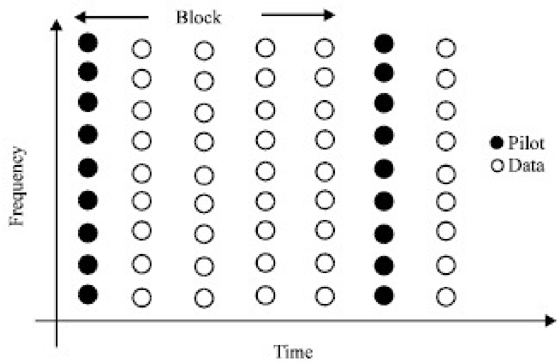


Figure 2.6: Block-type pilot arrangement.

When using block-type arrangement, the transmission period of the pilot symbols has to be less than the channel coherence time (T_c), which is defined as the time-scale variation. The coherence time is related to the Doppler spread (D_s) which depends of the maximum relative velocity (moving scatters or relative shift between Tx and Rx) as:

$$D_s = \frac{v_{max} f_c}{c}, \tag{2.1}$$

where

- v_{max} (in m/s) is the relative velocity,

- f_c is the carrier frequency,
- c = $3{\cdot}10^8$ (m/s) is the speed of light.

Hence, the coherence time is defined as:

$$T_c = \frac{1}{D_s}. \tag{2.2}$$

In fast fading channels, the channel gains can significantly vary between consecutive OFDM symbols, causing errors in the estimation and equalization when using the block-type pilot arrangement. That is why the comb-type schema has been introduced, to avoid these failures when the channel changes during the same OFDM block. The comb-type methodology works using algorithms for estimating the channel at pilot frequencies and interpolating the results.

In order to track the channel changes, pilot subcarriers are inserted periodically between data subcarriers in each OFDM symbol, as shown in Figure 2.7.

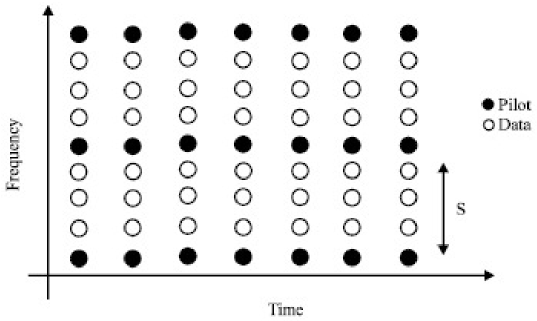


Figure 2.7: Comb-type pilot arrangement.

In the comb-type arrangement the channel is considered to be frequency-selective invariant over each received block, but is allowed to vary form one to another.

The design of a channel estimator is based on two main facts:

- The amount of pilot symbols to be transmitted.
- The complexity of the estimator.

The MMSE estimator has good performance but high complexity whereas the LS one is simpler but less efficient. However, LS and MMSE show similar results under high SNR. For this reason, for channel estimation it is used first a LS estimator on the pilot subcarriers. Then, this information is employed to perform a frequency domain interpolation in order to estimate the channel in the data subcarriers. To achieve a precise calculation, the separation between the pilot subcarriers in the OFDM symbol has to be less than the channel coherence bandwidth (B_c).

The coherence bandwidth is defined as:

$$B_c = \frac{1}{\tau_{rms}}, \tag{2.3}$$

where τ_{rms} is the rms delay spread.

Although block-type and comb-type arrangement are the most commonly used they are not the only schemas. There are other communication systems where the pilot subcarriers distribution is different. As an example, the DVB-T standard combines both block-type and comb-type pilot, as shown in Figure 2.8

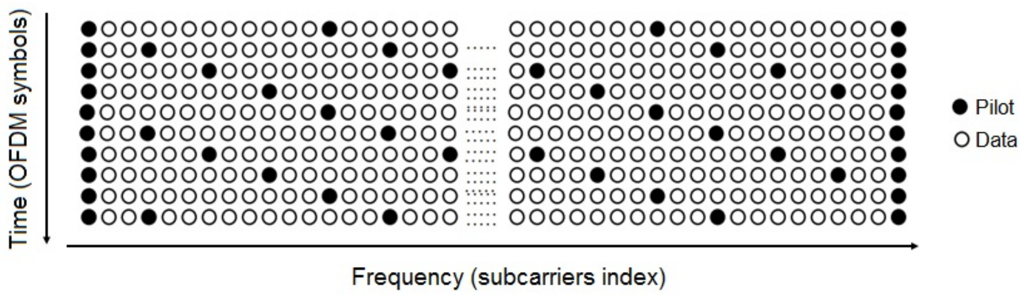


Figure 2.8: Pilot subcarriers arrangement for DVB-T.

More power is transmitted at pilot tones to improve channel estimation under low SNR conditions. As discussed in Section 3, this difference contributes to the reduction of the PAPR.

2.3.3 IFFT - Inverse Fast Fourier Transform

OFDM communications systems use an IFFT at the transmitter and a FFT at the receiver. However, in the beginning of this type of communications, the IFFT and FFT had not been discovered. Instead, they uses multipliers banks and analog oscillators. It was not until 1971 when Weinstein and Ebert [4] used the Discrete Fourier Transform (DFT) and the

Inverse Discrete Fourier Transform (IDFT) to modulate and demodulate the baseband signal in each communication channel. The utilization of DFT and IDFT transformed the implementation from a mixed analog/digital domain to a full digital one. Nevertheless, the high complexity of processing DFT and IDFT made them unable to be employed in commercial products. It was with the implementation of the FFT (Fast Fourier Transform) and the IFFT (Inverse Fast Fourier Transform) by Cooley and Tukey [5] when the usage of Fourier transform in OFDM systems became extended.

The FFT is a mathematical method that computes the DFT in an efficient and fast way. Generally, calculate the DFT over N subcarriers will take N^2 complex multiplications and *N(N-1)* complex additions. However, when using the FFT and its most common algorithm, known as Radix-2, the number of operations needed is reduced to $\frac{N}{2}(\log_2 N - 1)$ complex multiplications and $N \log_2 N$ complex additions. The same relationship exists between the IFFT and the IDFT.

This section is meant to be focused on the transmitter of an OFDM system, so now on, the properties and details of the IFFT will be explained. In Section 2.4 the receiver will be describe in detail and with it, the FFT. In the following, the number of subcarriers used by the transmitter IFFT and the receiver FFT are denoted as N_{FFT}.

The IFFT is intended to convert the frequency domain input data to the time domain at its output. After the mapping block and the pilot tones insertion, the IFFT has N_{FFT} input complex numbers. This N_{FFT} data are the OFDM modulation subcarriers. Each one has a complex number that represent one point of the chosen constellation (e.g. PSK or QAM) and specifies the subcarrier amplitude and phase. So, the IFFT can be seen as an simpler form of data modulation over orthogonal subcarriers.

The output of the IFFT is the addition of all N_{FFT} sinusoids and is commonly known as OFDM symbol. Usually, the IFFT size, N_{FFT}, is a power of 2 and results in a more efficient algorithm implementation.

After performing the IFFT over the data, the OFDM complex discrete time baseband signal can be express as:

$$x_n = \frac{1}{\sqrt{N_{FFT}}} \sum_{k=0}^{N_{FFT}-1} X_k \cdot e^{j2\pi nk/N_{FFT}}, \qquad \text{n} = 0, 1, \cdots, N_{FFT} - 1 \tag{2.4}$$

where X_k is the complex symbol of the k-th subcarrier.

Figure 2.9 shows the ideal spectrum of the output OFDM signal before transmitting it through the communication channel.

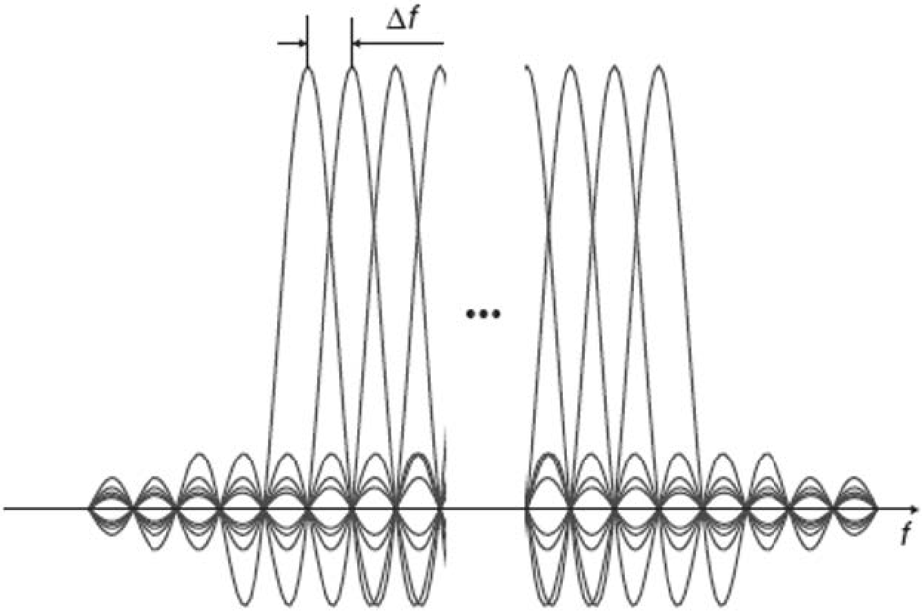


Figure 2.9: OFDM subcarriers spectrum.

Due to the usage of rectangular pulses as filters, subcarriers are orthogonal *sincs* in the frequency domain. In this way, as seen in Figure 2.9, the spectrum of the OFDM symbol is a set of N_{FFT} overlapped *sincs* that have nulls that match the others central frequency so Inter-Carrier Interference (ICI) is avoided. The central frequency of each subcarrier is given by:

$$f_k = f_0 + k \cdot \Delta f, \tag{2.5}$$

where f_0 is the transmission central frequency, k is the k-th subcarrier index, and Δf is the frequency spacing between subcarriers.

Finally, the occupied bandwidth of an OFDM symbol can be calculated as:

$$BW = N_{FFT} \cdot \Delta f. \tag{2.6}$$

2.3.4 Cyclic Prefix Insertion

The cyclic prefix improve the signal robustness in frequency selective channels. This type of channel provokes ISI (Inter-Symbol Interference) and ICI (Inter-Carrier Interference), which are critical problems of broadband wireless systems.

The first technique used to avoid ISI was adding a temporal interval, called cyclic prefix, between consecutive OFDM symbols. In this way, all the replicas arrived at the receiver before the new symbol did it, counteracting the temporal dispersion introduced by the frequency selective channel. The receiver discards the guard interval before data demodulation.

However, this technique did not avoid dispersion between the N_{FFT} subcarriers sent in one OFDM symbol, i.e. did not avoid ICI. The orthogonality is a key point in this communications because if the subcarriers are not orthogonal the performance is drastically degraded. So in order to battle ICI and avoid loss of orthogonality between data, Peled and Ruiz [6] proposed in 1980 the usage of the cyclic prefix (CP).

The use of CP consist of transmitting a copy of the final samples of the OFDM symbol before the useful part of it, as shown in Figure 2.10. In this way, if the CP length (temporal length) is greater than the maximum temporal delay caused by the transmission channel, ISI is avoided and orthogonality between subcarriers is not degraded, i.e. there is no ICI [7].

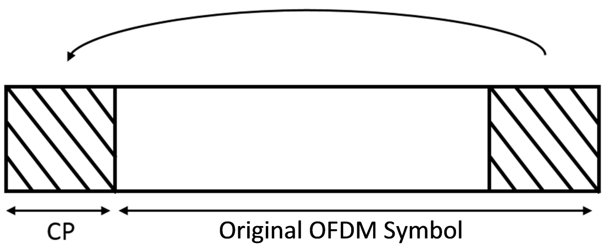


Figure 2.10: Cyclic prefix insertion.

Therefore, an OFDM symbol consists of user data and redundant data (CP). The structure is shown in Figure 2.11, where T_u is the useful time interval, T_{cp} is the cyclic prefix, and T_S is the OFDM symbol length.

From the T_u parameter, frequency spacing between subcarriers can be calculated as:

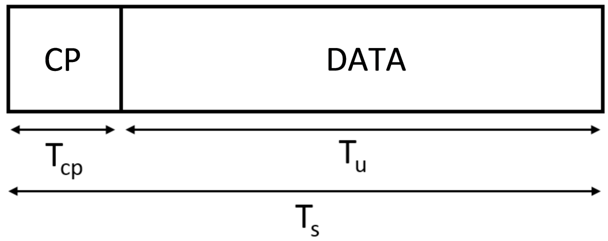


Figure 2.11: OFDM Symbol structure.

$$\Delta f = \frac{1}{T_u}. \tag{2.7}$$

The CP insertion reduces Eb/No at the receiver. Even if the information carried by the cyclic prefix is not useful, the transmitter spends some energy for sending it through the communication channel. This energy waste can be seen as a degradation of the SNR and can be expressed as:

$$SNR_{loss_{CP}} = -10\log_{10}\left(1 - \frac{T_{cp}}{T_s}\right). \tag{2.8}$$

2.4 Receiver

In this section, the basic modules and their functions in the OFDM receiver chain will be explained.

2.4.1 Cyclic Prefix Removal

As it was explained in Section 2.3.4 the cyclic prefix keeps the orthogonality between subcarriers and allows a correct signal demodulation in the OFDM receiver.

The insertion of the cyclic prefix into the OFDM symbol makes possible to express the received signal as al circular convolution, which results in an easier demodulation by using a FFT. If the channel is assumed to be invariant during a symbol, then the received data can be expressed as:

$$y[m] = x[m] \otimes h[m] + w[m], 0 \leq m \leq N_{FFT} - 1, \tag{2.9}$$

where,
$x[m]$ is the transmitted signal,
$h[m]$ is the channel impulse response, and
$w[m]$ is the complex, white, additive and Gaussian noise.

However, in order to recover the original stream, the cyclic prefix has to be removed before processing the signal at the receiver. As a consequence, ISI caused by multipath distortion is mitigated.

2.4.2 Fast Fourier Transform - FFT

Once the cyclic prefix has been removed, the received signal is converted from serial to parallel. After this, the FFT is performed over the N_{FFT} subcarriers (see Figure 2.2).

As explained in Subsection 2.3.3, the use of the FFT is a fast and efficient mathematical method of calculating the DFT. This technique, in combination with the new digital circuits technologies, made it possible to integrate this calculation in ICs (Integrated Circuits), which is the key of the widespread use of OFDM communications.

The FFT transforms the received signal from the time to the frequency domain. In this way, using equation (2.9) and assuming a perfect temporal and frequency synchronisation between the transmitter and the receiver, the output data of the FFT module can be expressed as:

$$Y_k = X_k \cdot H_k + W_k, 0 \leq k \leq N_{FFT} - 1, \tag{2.10}$$

where W_k still being white, additive and Gaussian noise.

Analysing equation (2.10) it can be seen that performing the FFT over the received signal splits the wideband channel into N_{FFT} narrowband ones. In a noiseless channel, the result obtained is that the received symbol in each subcarrier (Y_k) is the transmitted symbol (X_k) multiplied by the channel impulse response at the subcarrier frequency (H_k). This effect is shown in Figure 2.12.

Assuming an ideal situation where $H_k = 1$, the output of the FFT module will be the original OFDM symbol transmitted before performing the IFFT.

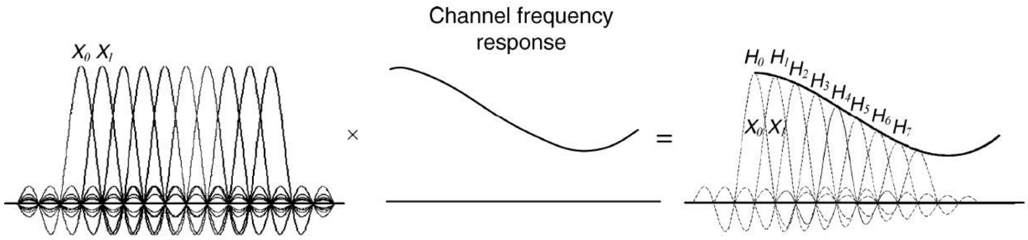


Figure 2.12: Channel frequency response effect over OFDM subcarriers.

Therefore, if the received data was represented on the complex domain the result will be the constellation used by the mapper (see Section 2.3.1).

From this FFT block on, all the data is processed as a single stream. That is why the N_{FFT} symbols obtained at the output of the FFT module are serialized using a parallel-to-serial converter.

2.4.3 Detection

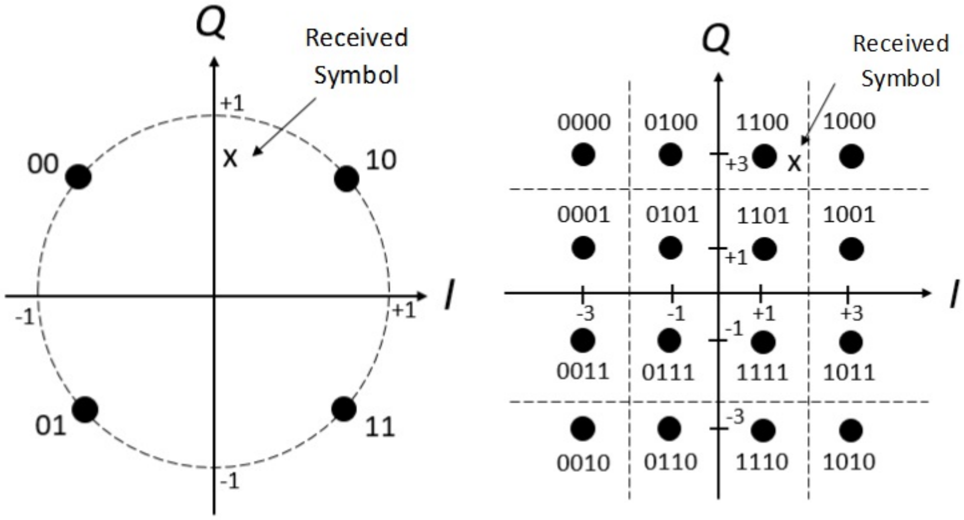
Once the signal is in the frequency domain, the detection process starts. The objective of this step is to determine which symbols were transmitted in each subcarrier. The module used for this task is the demodulator (see Figure 2.2), who is in charge of making the decision and demapping the received symbols into the corresponding bits of the transmitted constellation.

There are two types of detection depending on how much information is generated from the received symbol. They are called *hard-decision* and *soft-decision* [8].

On the one hand, the ***hard-decisor*** detection determines the received symbol by comparing it with different thresholds. More concretely, for making a decision, the complex plane of the constellation is divided into regions. These decision regions set up the bits that match each demapped symbol. In general, due to the channel effect over the subcarriers, some errors may appear when deciding the position of the received data in the original constellation. The maximum likelihood decision is the one that matches each received symbol with its closest point in the constellation. Two examples of *hard-decision* for QPSK and 16-QAM modulations are shown in Figure 2.13.

For QPSK constellation (Figure 2.13a), the decision thresholds are the complex plane axis. In this example, the received symbol is closest to the first quadrant point so the output bits for this data will be 10.

For 16-QAM constellation (Figure 2.13b), the decision thresholds are delimited by the dashed lines and the complex plane axis. The received symbol is closest to the $1 + 3j$ point so the output bits will be 1100.



(a) QPSK

(b) 16-QAM

Figure 2.13: *Hard-decision* detection

The *hard-decision* based choices are suboptimal because they do not take into account, during the process, potentially useful information.

On the other hand, the ***soft-decision*** detector output is made up of the bits corresponding to the chosen symbol plus some information bits containing the reliability of the given output. For example, in Figure 2.13a, the received symbol is close to one of the thresholds. In these situations, a *hard-decision* determines the output without taking into account the uncertainty of the choice. However, a *soft-decision* adds these information to the data. One typical way of providing this additional bits about the reliability of the choice is to add a "weight" between the received symbol and the I/Q thresholds. In this way, using the example in Figure 2.13a, the "weight" of the first (left) bit will be smaller than that given to the second (right) because the possibility of changing from 10 to 00 is greater than 10 to 01 or 00 to 11.

The main objective of *soft-decision* is to provide this information to the channel decoder, improving error correction.

The complexity of the *soft-decision* is higher compared to the *hard-decision* but it improves up to 2 dB the coding gain [9].

Finally, it is important to underline that the codification algorithm used in the constellation points is, usually, Gray coding. This type of encode makes that the shift of a symbol to an adjacent region caused by the noise only results in a wrong bit. This helps to improve overall system performance.

Chapter 3

PAPR Reduction Techniques

3.1 Introduction

OFDM is a modulation format for wireless transmissions with high-rate information requirements that deals well with this type of systems challenges. By breaking wideband channel into several narrow-band subchannels and transferring parallel information, OFDM obtains an appropriate performance in frequency selective fading channels. However, the main drawback of multi-carrier systems such as OFDM is that they show a non-constant envelope in the time domain.

Since an OFDM signal consists of several independently modulated sub-carriers, when the signals are combined, high amplitude peaks appears. This results in the need of power amplifiers back-off to avoid saturation.

In order to avoid saturation, high dynamic range amplifiers, whose costs are very expensive, may be used. Moreover, these peaks make digital to analog converters (D/A) and analog to digital converters (A/D) less efficient. For evaluating them, peak-to-average-power-ratio (PAPR) is used.

3.2 PAPR Definition

An OFDM signal in an interval symbol ($mT_u \leq t \leq (m+1)T_u$) can be expressed as:

$$x(t) = \sum_{k=0}^{N_c-1} a_k^m e^{jk2\pi\Delta ft}, \tag{3.1}$$

where

- N_c is the number of subcarriers,
- a_k is the modulated signal to kth subcarrier,
- Δf is the frequency spacing between adjacent subcarriers, and
- T_u represents the interval of one OFDM symbol.

If the number of subcarriers is large enough, based on the central limit theorem, the resulting signal $x(t)$ can be approximated as a complex Gaussian process. Therefore, the real and imaginary parts of an OFDM symbol are Gaussian distributed, and its envelope and power follow Rayleigh and exponential distributions, respectively. Besides, the PAPR for continuous time signal, $x(t)$ is defined as the maximum power to its average ratio. For the mth OFDM symbol:

$$PAPR = \frac{\max\limits_{mT_u \le t \le (m+1)T_u} |x(t)|^2}{\frac{1}{T_u}\int_{mT_u}^{(m+1)T_u} |x(t)|^2 dx}. \tag{3.2}$$

It is found that PAPR for the oversampled discrete-time signal offers an accurate approximation of the PAPR of the continuous-time one , if the oversampling factor is at least 4. With this information, the PAPR of the discrete-time OFDM signal is expressed as:

$$PAPR = \frac{\max\limits_{0 \le n \le N-1} |x(n)|^2}{E\{|x(n)|^2\}}, \qquad N = LN_c \tag{3.3}$$

where, N_c is the number of OFDM subcarriers and L is the oversampling factor.

It can also be expressed in dB as

$$PAPR(dB) = 10\log_{10} \frac{\max\limits_{0 \le n \le N-1} |x(n)|^2}{E\{|x(n)|^2\}}. \tag{3.4}$$

3.3 PAPR Techniques

A great variety of PAPR reduction techniques have been developed. In this section, some of the main algorithms will be explained highlighting their pros and cons.

3.3.1 Clipping and Filtering

One of the simplest methods to reduce the PAPR is to clip the high peaks of the OFDM signal, before the power amplifier. Clipping limits the signal envelope as following:

$$T\left(x(n)\right) = \begin{cases} x(n) & \text{if } |x(n)| \leq CL \\ CL \cdot e^{j\angle x(n)} & \text{if } |x(n)| > CL \end{cases} \tag{3.5}$$

where

- $x(n)$ is the OFDM signal,
- CL is the clipping level,
- $\angle x(n)$ is the signal phase.

Clipping is a non-linear function, causing in-band an out-of-band distortions. Out-of-band distortion results in spectral spreading of the signal which can be compensated by filtering. While the in-band distortion, which degrades BER performance, cannot be corrected by filtering. However, over-sampling by taking longer IFFT can reduce the in-band distortion effect as noise is reshaped outside of the signal band, that can be removed later by filtering.

3.3.2 Peak Windowing

In this method, a predetermined threshold level is defined and if the high peaks goes beyond it, they are multiplied by a weighting function known as window function. Many window functions have been introduced for reducing high peaks of OFDM signal, e.g., Hamming, Kaiser, Hanning, and Cosine Gaussian windows are the most well-known ones [19]. Window functions should be designed in a way, so that it is aligned with the signal samples. The objective is to multiply the function valleys with the signal peaks and the crest with the lower amplitudes. The width of it in the time domain must also be as low as the signal. Since, in this method, the function is aligned with the samples, it has lower distortion and it is called soft clipping.

Peak windowing scheme does not employ hard clipping, showing less signal distortion. However, there is still distortion that can not be completely avoided.

3.3.3 Coding

This technique tries to reduce PAPR by avoiding some specific symbol combinations. As it is demonstrated in [10], among all the possible symbol combinations there are some of them that generate higher PAPR than others. Hence, an extra coding state before the mapping block is introduced, avoiding higher PAPR symbol sequences.

With this method, the final PAPR can be significantly reduced. However, the usefulness of this schema is limited because of the complexity of finding the optimal coding and the associated computational cost, even OFDM systems with low number of subcarriers.

3.3.4 Selective Mapping - SLM

Selective mapping (SLM) is a relatively simple method to reduce PAPR. A set of different OFDM symbols x_m, $0 \leq m \leq$ M-1, which represent the same information as the original symbol are generated. Then, the OFDM symbol with the minimum PAPR is transmitted. The block diagram of the SLM technique is shown in Figure 3.1.

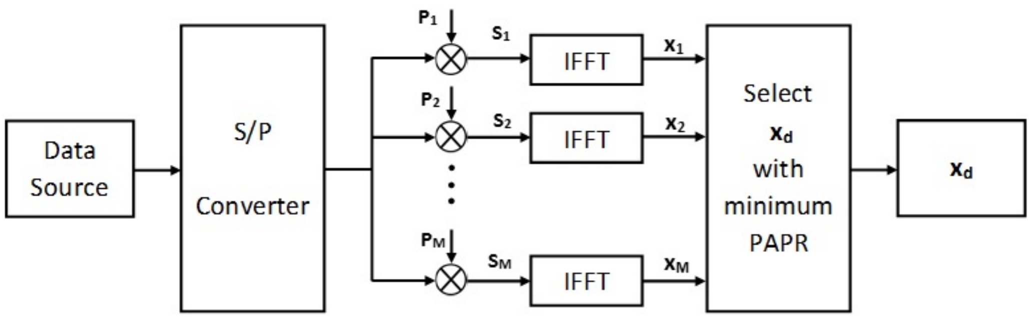


Figure 3.1: Selective Mapping (SLM) block diagram

To generate different symbols set, original data block $X = [X_1, X_2, \cdots, X_N]$ can be multiplied by M different phase sequences, P_m, element-by-element. This is performed before the IFFT. These phase sequences can be described as

$$P_m = \left[e^{j\varphi_{m,1}}, e^{j\varphi_{m,2},\cdots,e^{j\varphi_{m,N}}}\right], \tag{3.6}$$

where $\varphi_{m,k} \in [0, 2\pi)$, for $k = 1, 2, \cdots, N$. Therefore, the modified OFDM symbol is the IFFT of the element-by-element multiplication of X and P_m:

$$x_m = IFFT\left[X_1 e^{j\varphi_{m,2}}, X_2 e^{j\varphi_{m,1}}, \cdots, X_N e^{j\varphi_{m,N}}\right]. \tag{3.7}$$

The transmitted OFDM symbol can be written as:

$$\tilde{x} = \underset{0\leq m\leq M-1}{\text{argmin}} \left[PAPR\left(x_m\right)\right]. \tag{3.8}$$

The amount of PAPR reduction achieved by the SLM method depends on the number of generated phase sequences and the design of them. In order to detect the transmitted signal, information from the selected phase series must be transmitted to the receiver as side information. If the size of the OFDM blocks is large and the number of phase sequences (M) is increased, optimizing the process of selecting the best OFDM signal will be cumbersome.

3.3.5 Partial Transmit Sequence - PTS

In partial transmit sequence (PTS) method, data block of length N is divided into several disjoint sub-blocks. Then each of them are padded with zeros and weighted by a phase factor. The block diagram of PTS is shown in Figure 3.2.

The IFFT is performed for every single sub-block separately, and they are then weighted by a phase factor. The phase factor is chosen in a way that the combined signal of all the sub-blocks gets the minimum PAPR.

The data block of $X = [X_1, X_2, \cdots, X_N]$ is partitioned into M disjoint sub-blocks of $X_m = [X_{m,1}, X_{m,2}, \cdots, X_{m,N}]$, 1$\leq m \leq M$, and X is the combination of all the M sub-blocks:

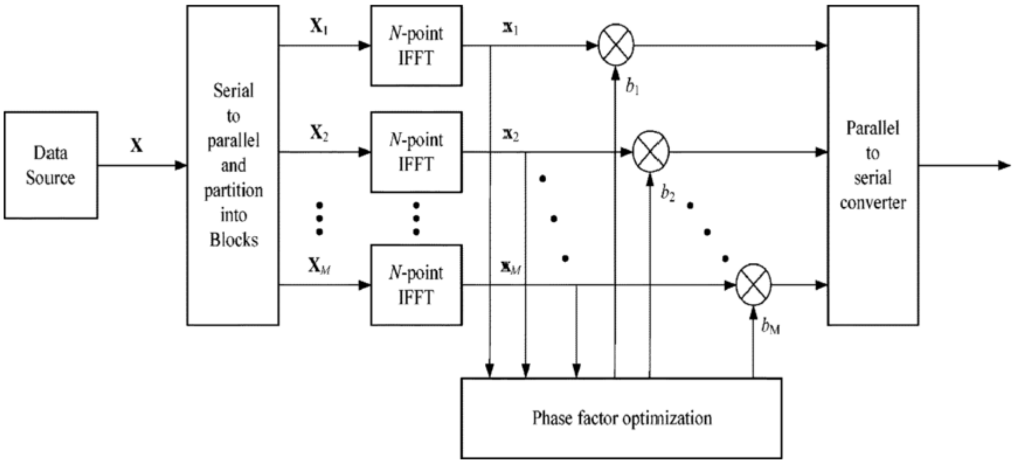


Figure 3.2: Partial Transmit Sequence (PTS) block diagram

$$X = \sum_{m=1}^{M} X_m. \tag{3.9}$$

The IFFT of each sub-block X_m, $1 \leq m \leq M$, is then calculated. In the process of selecting the optimum phase factors, searching is usually limited to a few ones to reduce the complexity, which rises as M increases exponentially.

3.3.6 DFT-Spread OFDM

DFT-Spread OFDM, also known as Single Carrier Frequency Division Multiplexing (SC-FDM), is another method of reducing PAPR in OFDM systems. The main characteristic of this technique is the introduction of another FFT and IFFT block into the OFDM system block diagram, as shown in Figure 3.3.

By performing the FFT over the mapped symbols these are spread over all the data subcarriers, creating a virtual single carrier scheme. As a result, less variation of the transmitted signal instant power, i.e., lower PAPR. Moreover, DFT-Spread takes advantage of the channel frequency diversity by the extension of all the symbols over all subcarriers. In this way, even if the signal suffers deep fade caused by the channel, the receiver is able to recover the information using the subcarriers with a better channel.

The main disadvantage of this technique is the noise amplification caused

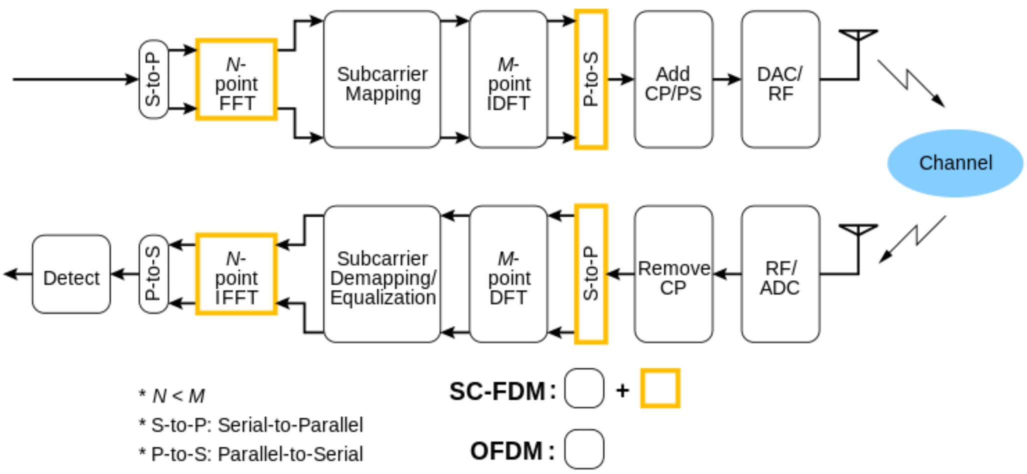


Figure 3.3: DFT-Spread OFDM block diagram

by the receiver IFFT, which means that a more complex equalization is required. However, DFT-Spread is widely used technique, for example, in LTE mobile communications. The main difference is that LTE is a multiple access scheme so a variation of the SC-FDM, known as SC-FDMA (Single Carrier Frequency Division Multiple Access), is used in the uplink.

3.3.7 Pilot Tones Optimization

The techniques described above aimed at reducing PAPR by transforming the information subcarriers. However, pilot subcarriers also affects the system PAPR. Different modulation and sequences are used in OFDM communications systems and depending on the characteristics of the sequence it can contribute to increase PAPR.

It is important to analyse the sequence characteristics, specially its autocorrelation. In [13], the used of CAZAC (Constant Amplitude Zero Auto-Correlation) sequences as a PAPR reduction technique is proposed. The main characteristic of these sequences is that they have zero autocorrelation. In [12], they cite the use of sequence with lower autocorrelation in order to reduce the PAPR. Nevertheless, the proposed methods are tedious because the selection of the sequence with lower PAPR depends on the system characteristics. Moreover, most of the algorithms for generating low autocorrelation sequences need to be performed more than once. In addition, the reduction depends on the sequence, the information symbols and the modulation used for the pilot tones.

Chapter 4

Proposed Solution

The objective of this work is to find a solution to reduce the PAPR of an OFDM transceiver developed by Berten DSP. The communication system is mainly used in aviation, concretely in UAVs (Unmanned Aerial Vehicle). It is important to take into account that the proposed technique has to be feasible for its subsequent implementation in the existing system. In other words, it should make an optimal use of the available resources of the implementation board. In addition, it should process the data fast enough to avoid producing delays in the processing chain that will lead to an incorrect functioning of the whole system.

As an optimal solution for the problem explained above, a combination of two PAPR reduction techniques has been implemented. The chosen methods are DFT-Spread OFDM and Pilot Tones Optimisation (see Sections 3.3.6 and 3.3.7). The DFT-Spread technique was selected because the trade off between performance, and complexity was the one that fitted better the problem requirements. In addition, it is being used in the uplink of LTE communications so it was considered one of the best methods. The Pilot Tones was used as a complement of the DFT-Spread, in order to gain more PAPR reduction without introducing extra complexity to the system. In this chapter, the proposed solution, the platform used for its study, and how it was introduced in the system will be explained.

4.1 Simulation Platform

The study and implementation of the proposed methodology into the existing system has been carried out by using a simulation platform of the transceiver. The chosen simulation tool has been Simulink, developed by MathWorks. Simulink is a add-on MATLAB product that provides a graphical programming environment for modelling, simulating and analysing systems.

Regarding the needs of this project, the main advantage of Simulink is its wide catalogue of DSP (Digital Signal Processing) blocks. Moreover, it is able to generate C source code for real-time implementation systems and can automatically generate synthesizable VHDL code.

4.2 Baseline System

As it was explained before, the communication system used in this project is OFDM. A general block diagram of the transmitter is shown in Figure 4.1

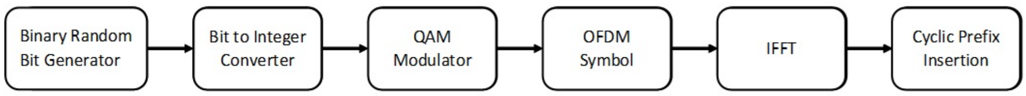


Figure 4.1: Transmitter block diagram

The information is produced by a binary random bit generator and then transformed to integer in the range of 0 to 3 for QPSK modulation. After this, the pilot tones, modulated in BPSK, and the null subcarrier are inserted, and the OFDM symbol is structured. The OFDM symbol is formed by 256 subcarriers where 32 are pilot, 1 is the null subcarrier, and the remaining 223 are information subcarriers. Because of the requirements of an OFDM system, it is convenient for the pilot tones to have more power than the information subcarriers.

Then, after the OFDM symbol is structured, the IFFT is performed over the OFDM symbol, the cyclic prefix is added and the signal is sent through the communication channel, modelled by a Simulink block. At the receiver, a downsampler is applied to lower the signal frequency and, after that, the time and frequency synchronization is performed to detect the beginning of the OFDM symbol and to remove the cyclic prefix. The FFT of the signal is then calculated in order to revert the transmitter IFFT process. Next, the equalization is performed, the pilot tones are removed and the transmitted data is recovered.

4.3 DFT-Spread OFDM

The proposed solution for reducing the PAPR of the communication system is a combination of two PAPR reduction techniques in Chapter 3. The first part of the methodology is the implementation of the DFT-Spread OFDM. This scheme introduces an extra FFT at the transmitter and an IFFT at the receiver with the main objective of extending the information in each subcarriers to all the subcarriers and so, transforming the multicarrier signal into a single carrier one.

An FFT module is applied as a precoder by the transmitter before the IFFT block. The length of the FFT needs to be a power of two. The existing communication system had 223 information subcarriers so it was not possible to perform an FFT over the subcarriers because of it.

An OFDM symbol is formed by the information subcarriers, the pilot subcarriers and the null subcarrier. The pilot subcarriers are a sequence of knowing symbols that the transmitter send periodically intertwined with the information subcarriers to give the receiver information about the channel and let it equalise the signal. Because the receiver knows the pilot tones sequence, it is able to estimate the channel and undo partially or totally, depending on the equalization technique, the effects that it would have introduced to the received signal. Sending the pilots in the correct position is the key of the information recovery at the receiver.

The null DC subcarrier of an OFDM symbol is used to avoid the undesirable effect that DC component has on the ADC conversion, taking up part of the converter dynamic range and making the automatic gain control difficult to implement [20].

To implement the DFT-Spread technique in the system it was necessary to modify it. Having in mind the functionalities of the different subcarriers of the OFDM symbol, it was decided not to introduce the null DC subcarrier and replace it with another information subcarrier. This means that now the OFDM symbol is formed by 32 pilot subcarriers and 224 information subcarriers. Although 224 is not a power of two, it can be decomposed into smaller powers of two. The final objective of this is to have a base two number of information subcarriers to perform an FFT.

With the modification of the OFDM symbol structure, the DFT-Spread method can be implemented as follows: the input data subcarriers are divided into 7 groups of 32 subcarriers each. The FFT is performed concurrently over the joints of subcarriers, taking advantage of the Simulink characteristics. Once the FFTs are computed, the data is regrouped in a vector, the pilot tones are added to the OFDM symbol, the IFFT is computed, and the cyclic prefix is added.

Then the signal is passed through the channel block and sent to the receiver. There, a downsample is performed to the signal to lower the frequency. After that, the time and frequency synchronisation stages are applied using the cyclic prefix as reference to determine where the OFDM symbol starts. The cyclic prefix is removed once the synchronism is achieved and the process of undoing the transmitter transformations starts. Firstly, an FFT is calculated over the symbols with the aim of reverting the IFFT computed at the transmitter. Next, the equalisation of the received signal is carried out by using the pilot subcarriers as the reference to estimate the channel. Once it is done, the pilot tones are removed and the data are rearranged as it was performed at the transmitter, regrouping the subcarriers in groups of 32. Then, the IFFT is computed to undo the transformations of the transmitter FFT. At the IFFT output the transmitted subcarriers are recovered and so the information they carried and the symbols can be represented on the corresponding constellation.

4.4 Pilot Sequence Optimisation

The PAPR of a communication system is caused by all the subcarriers transmitted. In the way of improving the whole performance of the system it has been decided to optimise the transmitted pilot sequence. In the previous chapter, the fact that pilot tones sequence can affect negatively to the PAPR was exposed and some different solutions can be found in the references. The common point that almost all the PAPR reduction techniques based on pilot tones sequences have, was the use of low autocorrelation series.

During the development of the solution, different pilot sequences were tried in order to reduce the PAPR of the system without modifying it. However, changing the existing pilot subcarriers for low autocorrelated ones did not provide any reduction of the PAPR.

The solution proposed in this work is the use of a low autocorrelation binary sequence as a pilot tones in combination with the DFT-Spread implementation. For selecting the best pilot series, some of the solutions proposed in [12] and [13] were implemented. The main problem found by the use of these sequences is the fact that extra computations needs to be done to obtain the optimal data series, which increases the system complexity. As the system is for a boarded device, the optimisation of the resources in a future implementation of the design is critical.

Another approach explored in order to find an optimal sequence without increasing the system complexity was to design a low autocorrelation binary sequence. In [11] they proposed different length low autocorrelated binary sequences. As the system has 32 pilot tones and this part of the OFDM symbol structure can not be modify, the sequence of length 32 is: **71112111133221221**. This sequence is written using Run Length Encoding (RLE). This encoding technique represent the sequence by counting the repetition of the same consecutive symbol, i.e. the first 7 means that the first 7 characters are the same. The decoded sequence is:

{1 1 1 1 1 1 1 -1 1 -1 1 1 -1 1 -1 1 -1 -1 -1 1 1 1 -1 -1 1 1 -1 1 1 -1 -1 1}.

Because it is a precomputed sequence, there is no need of extra calculations in order to obtain it. The previous pilot sequence was substituted by this one. It is important to notice that both the transmitter and the receiver need to know the sequence so this change in the design affects both sides. If the pilot sequence is not updated at the receiver, it will not be able to estimate the channel properly and thus the transmitted signal will not be recovered.

Chapter 5

Results

In this chapter, the results obtained by the technique proposed in this project will be analysed and discussed. Firstly, the measured parameters of the baseline system will be explained. Then, the improvement obtain by the chosen solution will be exposed and compared with the baseline system.

5.1 Baseline System

The baseline system of this project is an OFDM communication system transmitting 256 subcarriers per OFDM symbol. Among the transmitted subcarriers, 223 corresponds to the information subcarriers, 32 to the pilot subcarriers, and 1 to the null DC subcarrier.

Before analysing the solution, this system needs to be characterised in order to evaluate the feasibility and improvement of the implemented technique. Because the objective of the solution is to reduce the system PAPR, the measures are focused on the transmitter of the system although the proposed method is simulated also for the receiver.

First, the system PAPR and the characteristics of this parameter was measured. To obtain them a Simulink block for calculating the PAPR of the system was developed. The block calculate the PAPR of each OFDM symbol in dB using the equation (3.4).

All the simulations have been carried out during 50 ms which corresponds approximately to 500 samples. Each measured parameter is the mean value of the simulated samples.

Table 5.1 shows the characteristics of the baseline transmitter.

Pilot/Data Amplitude Ratio (PDAR)	4/3
Avg. PAPR, dB	8.247
Standard Deviation, dB	0.098

Table 5.1: Baseline system PAPR mean and standard deviation.

The first approach tried for reducing PAPR was to increase the pilot tones power. The draw-back of this is that the power that the information subcarriers transmit is less so it is the same as reducing the efficiency of the system. However, a comparison between the PAPR, the Pilot/Data Amplitude Ratio (PDAR) and the Data-to-Pilot Power Ratio (DPPR) was made.

$$DPPR(dB) = 10\log_{10}\left(\frac{\#\text{info. subcarriers}}{\#\text{pilot subcarriers}\cdot PDAR^2}\right). \tag{5.1}$$

The results of these measures are shown in Table 5.2.

Pilot/Data Amplitude Ratio (PDAR)	Data-to-Pilot Power Ratio (DPPR), dB	ΔDPPR	Avg. PAPR, dB	ΔPAPR, dB
1	8.432	0.000	8.275	0.000
4/3	5.933	-2.499	8.247	-0.028
5/3	3.995	-4.437	8.198	-0.077
6/3	2.411	-6.021	8.141	-0.134
7/3	1.072	-7.360	8.057	-0.218
8/3	-0.088	-8.519	7.956	-0.291
9/3	-1.111	-9.542	7.846	-0.429

Table 5.2: PAPR, PDAR and DPPR comparison.

Analysing the PAPR reduction and the DPPR reduction, it is clear that ΔDPPR is greater than ΔPAPR. This means that the loss in the power of the data subcarriers is considerably greater than the achieved reduction of PAPR. That is the reason why this increased in the pilot tones power was not a feasible solution.

5.2 DFT-Spread & Pilot Tones Optimisation

The previous analysis of the baseline system transmitted signal parameters were used to evaluate the improvement of introducing the proposed solution.

The measured parameters for the final and baseline systems are the same. However, two different FFT sizes were tested for comparing the results.

5.2.1 DFT-Spread with FFT size 223 & Pilot Tones Optimisation

One of the schemas has an FFT length of 223, i.e. the transmitter schema was not modified. The null DC subcarrier was being transmitted and the information subcarriers were not regrouped. This was the ideal scenario to solve the problem. However, this methodology is only feasible in a simulation environment because, as it was explained in the previous chapter, the FFT length must be a power of two. But, in order to have more information and to compare the results, it was useful to try it. In Table 5.3 the measures of this schema are exposed. The obtained PAPR is reduced 1.255 dB, and its standard deviation is also lower.

Pilot/Data Amplitude Ratio (PDAR)	4/3
Avg. PAPR, dB	6.992
Standard Deviation, dB	0.087

Table 5.3: Proposed solution system PAPR mean and standard deviation with FFT size 223.

The same strategy of increasing the pilot tones power has been tried in this configuration. The results of the obtained PAPR and DPPR reduction are shown in Table 5.4. The conclusion is the same as for the baseline system. It is not worth it to increase the pilot tones power because the PAPR reduction is much lower than the loss of the data subcarriers power. However, comparing these results with the previous, it can be seen that the PAPR improvement is greater with the increase of the pilot tones amplitude for in the baseline system.

Pilot/Data Amplitude Ratio (PDAR)	Data-to-Pilot Power Ratio (DPR), dB	ΔDPPR	Avg. PAPR, dB	ΔPAPR, dB
1	8.432	0.000	7.167	0.000
4/3	5.933	-2.499	6.992	-0.175
5/3	3.995	-4.437	6.730	-0.437
6/3	2.411	-6.021	6.459	-0.708
7/3	1.072	-7.360	6.209	-0.958
8/3	-0.088	-8.519	6.044	-1.123
9/3	-1.111	-9.542	5.829	-1.338

Table 5.4: PAPR, PDAR and DPPR comparison of proposed solution with FFT size 223.

5.2.2 DFT-Spread with FFT size 32 & Pilot Tones Optimisation

The design proposed above performing an FFT of size 223 is possible when using Simulink, and the results obtained are positive. However, to implement it in a real platform, an adaptation of the technique needed to be done.

The symbol structure of this technique changed by eliminating the null DC subcarrier. Moreover, as a way of achieving a power of 2 FFT size, the data subcarriers were regrouped in 32 subcarriers block and then the FFT was computed over the 7 data blocks. The resulting PAPR and standard deviation are shown in Table 5.5. It can be seen that the PAPR reduction compared to the baseline system is about 1 dB.

Pilot/Data Amplitude Ratio (PDAR)	4/3
Avg. PAPR, dB	7.255
Standard Deviation, dB	0.084

Table 5.5: Final solution system PAPR mean and standard deviation with FFT size 32.

The approach of increasing pilot tones power for gaining PAPR reduction was measure and evaluated. As in the other cases, the disadvantage caused by this power increase is more significant than the PAPR improvement. The measures results are shown in Table 5.6.

Pilot/Data Amplitude Ratio (PDAR)	Data-to-Pilot Power Ratio (DPR), dB	ΔDPPR	Avg. PAPR, dB	ΔPAPR, dB
1	8.432	0.000	7.609	0.000
4/3	5.933	-2.499	7.255	-0.354
5/3	3.995	-4.437	6.828	-0.781
6/3	2.411	-6.021	6.423	-1.186
7/3	1.072	-7.360	6.131	-1.478
8/3	-0.088	-8.519	5.819	-1.790
9/3	-1.111	-9.542	5.480	-2.129

Table 5.6: PAPR, PDAR and DPPR comparison of proposed solution with FFT size 32.

5.3 Final Results

For the final part of the results, some parameters of the output signal were measured with the objective of obtaining more information about how the signal characteristics changed.

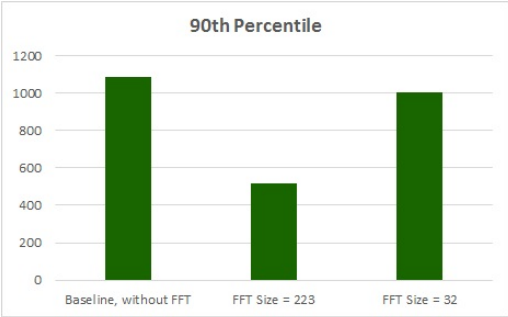
The parameters measures were the standard deviation of the output signal and then the 90th and 95th percentile. The percentile is the value below which a given percentage of observations in a group of observations lies. The comparison of the results can be seen in Table 5.7.

	Baseline, without FFT			FFT Size = 223			FFT Size = 32		
Pilot/Data Amplitude Ratio (PDAR)	Output Standard Deviation	90th Percentile	95th Percentile	Output Standard Deviation	90th Percentile	95th Percentile	Output Standard Deviation	90th Percentile	95th Percentile
4/3	717	1089	1241	349	515	567	674	1007	1125

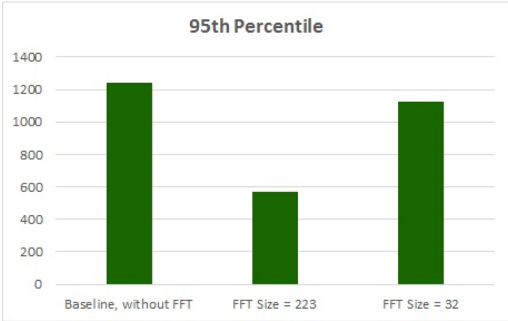
Table 5.7: Standard deviation, 90th and 95th percentile comparison.

The percentile results are shown graphically in Figure 5.1.

Finally, the comparison between the PAPR of the different techniques with the variation of the pilot tones amplitude and the evolution of the standard deviation of the PAPR measure are shown graphically in Figures 5.2.

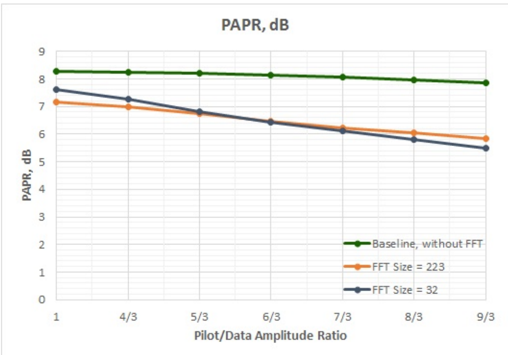


(a) 90th Percentile

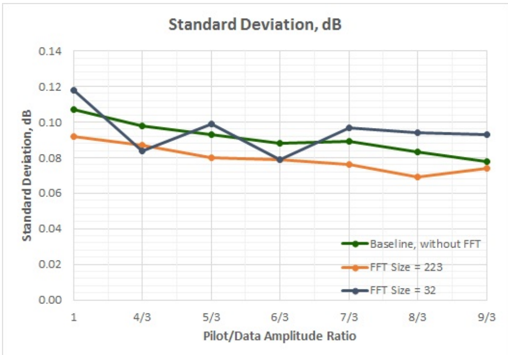


(b) 95th Percentile

Figure 5.1: Percentile comparison between techniques



(a) PAPR



(b) Standard deviation

Figure 5.2: Technique comparison of parameters evolution with the pilot tones amplitude.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Nowadays, OFDM communications are widely extended and can be found in many different applications.

The work done in this project is focussed on solving one of the critical problems of OFDM communications, the high PAPR. This has an direct impact over the power amplifiers. For this reason, improving the system PAPR will lead to an enhance on their performance usage.

More concretely, the system in which the technique was simulated is an aerospace system where the transmitted power and the amplifications are important parameters.

The proposed solution was based on studying the most common PAPR reduction techniques and choosing the one that fits better to the system. While developing the methodology, it was seen that combining more than one reduction technique has an improvement on the results. In this way, a schema based on combining DFT-Spread and a low autocorrelation pilot sequence was developed.

6.2 Future Work

As the project was developed in Berten DSP, the most immediate future work is to integrate the system design in the simulator within the commercial product. This future line is now in process and it is thought that it can result in an improvement of the system performance.

Furthermore, the optimisation of the proposed technique for obtaining more reduction of the system PAPR will be an interesting path. In the same way, combining more than one PAPR reduction methods for achieving very low PAPR on a system will be beneficial for existing system suffering from PAPR issues.

Bibliography

[1] A. R. Bahai, B. R. Saltzberg and M. Ergen, *"Multi-carrier digital communications: theory and applications of OFDM",* Springer Science & Business Media, 2004.

[2] M. Merino, "Diseño e implementación del procesado banda base de un sistema de comunicaciones OFDM embebido", Master's thesis, Universidad de Cantabria, 2016

[3] Y. M Abdelkader *et al.,* "Optimal spacing design for pilots in OFDM systems over multipath fading channels,"

[4] S. B. Weinstein and P. M. Ebert, "Data transmission by frequency-division multiplexing using the discrete Fourier transform," *Communication Technology,IEEE Transactions on*, vol.19, no.5, pp.628-634, 1971.

[5] J. W. Cooley and J. W. Tukey, "An algorithm for the machine calculation of complex Fourier series," *Mathematics of computation,* vol.19, no.90, pp.297-301, 1965.

[6] A. Peled and A .Ruiz, "Frequency domain data transmission using reduced computational complexity algorithms," in *Acoustics, Speech, and Signal Processing, IEEE International Conference on ICASSP'80.,* vol.5, pp.964-967, IEEE, 1980.

[7] N. Marchetti, M. I. Rahman, S. Kumar, and R. Prasad, "OFDM: Principles and challenges," in *New directions in wireless communications research*, pp. 29-62, Springer, 2009.

[8] J. Heiskala and J.Terry PhD, *OFDM wireless LANs: A theoretical and practical guide.* Sams, 2001.

[9] G. C. Clark Jr and J. B. Cain, *Error-correction coding for digital communications.* Springer Science & Business Media, 2013.

[10] S. H. Han and J. H. Lee, "An overview of peak-to-average power ratio reduction techniques for multicarrier transmission," *Wireless Communications, IEEE,* vol.12, no.2, pp.56-65, 2005.

[11] T. Packebusch, S. Mertens, *"Low autocorrelation binary sequences",* J. Phys. A Math. Theor., vol. 49, no. 16, pp. 165001, 2016.

[12] X. Geng, H. Hu, W. Cui, and Y. Dun, *"Optimal Pilot Design for MIMO-OFDM Channel Estimation,"* in International Conference on Signal Processing Systems, vol. 2, pp. 404–408, July 2010.

[13] L. Lei, S. Enchang, Z. Yanhua, *"A Method for PAPR Reduction Using Pilot Sequences in SC-FDMA",* 2010 6th WiCOM International Conference, Sep. 2010.

[14] Wei-Wen Hu, *"PAPR reduction for pilot-aided OFDM systems with the parametric minimum cross-entropy method,"* AEU–Int. J. Electron. Commun. 70, 367–371, 2016.

[15] C.-T. Lam, D. D. Falconer, F. Danilo-Lemoine, *"PAPR reduction using frequency domain multiplexed pilot sequences",* Proc. WCNC 2007.

[16] Oliver, J., Aravind, R., Prabhu, K.M.M. *"Pilot sequence design for improving OFDM channel estimation in the presence of CFO",* Proc. Int. Conf. on Signal Processing and Communications (SPCOM), 2010.

[17] W. O. Popoola, Z. Ghassemlooy, B. G. Stewart, *"Pilot-assisted PAPR reduction technique for optical OFDM communication systems",* J. Lightw. Technol., vol. 32, no. 7, pp. 1374-1382, Apr. 2014.

[18] M. B. N. Shirazi, A. Golestani, H. A. Yazdi, A. H. Daronkola, *"Analysis and comparison of PAPR reduction techniques in OFDM systems",* Journal of Electrical and Computer Engineering Innovations, vol3, no 1, 2015.

[19] Mamta Bisht, Alok Joshi, *"Various techniques to reduce PAPR in OFDM systems: A survey",* International Journal of signal processing image processing and pattern recognization, vol. 8, no. 11, pp. 195-206, 2015.

[20] Xiaojing Huang, *"Effect of DC offset on OFDM system with zero padded suffix",* IEEE, 2006