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BACHELOR THESIS

TITLE: Study of different waveform performance for enhanced communications in 5G and beyond networks

DEGREE: Bachelor's Degree in Telecommunications Systems Engineering

AUTHOR: Andrea Crespo Caballero

DIRECTOR: Luis Alonso Zárate

SUBMISSION DATE: 06/09/2024

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Abstract

This work aims to evaluate FBMC modulation in comparison to OFDM for 5G networks, considering the need to explore technological alternatives for 5G and beyond. Although OFDM is maintained in 5G due to its compatibility with 4G systems, FBMC is presented as a promising option to improve spectral efficiency and reduce latency.

The methodology employed consists of MATLAB simulations in three different scenarios: indoor, rural and urban. In each scenario, key parameters such as BER versus SNR, latency, spectral efficiency and throughput are compared. These simulations allow us to determine which modulation is best suited to the different conditions.

The results indicate that, in terms of BER vs. SNR, both FBMC and OFDM show similar performance in rural and urban environments, while in indoor environments, FBMC requires a high sampling rate and larger inter-subcarrier spacing to assume adequate BER values. On the other hand, FBMC excels in all scenarios in latency, thanks to having no cyclic prefix, as it reduces latency and makes it more suitable for applications requiring URLLC communications in 5G. FBMC also offers better spectral efficiency in all cases analyzed, which makes it an attractive alternative in environments with high user density, such as urban areas.

However, it should be emphasized that FBMC involves higher complexity and higher SNR to achieve optimal performance, this is a disadvantage in terms of cost and implementation compared to OFDM. In conclusion, while OFDM remains a robust and cost-effective option for 5G deployments, FBMC excels in scenarios where latency and spectral efficiency are critical. In future work, system optimization using equalizers could be implemented to decrease the number of errors and be able to use higher order modulations. In this way we could fully explore the capabilities of FBMC in environments with high data demands.

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Glossary

AFB	Analysis Filter Bank
AMPS	Advanced Mobile Phone System
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
DAB	Digital Audio Broadcasting
DFT	Discrete Fourier Transform
DVB-T	Digital Video Broadcasting – Terrestrial
EDGE	Enhanced Data Rates for GSM Evolution
EMBB	Enhanced Mobile Broadband
FDMA	Frequency Division Multiple Access
FBMC	Filter Bank based Multi-Carrier
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Service
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IoT	Internet of Things
ISI	Inter-Symbol Interference
LDPC	Low-Density Parity-Check
LOS	Line-of-Sight
LTE	Long-Term Evolution
MIMO	Multiple-Input Multiple-Output
MMTC	Massive Machine-Type Communications
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
OOB	Out-of-Band
OQAM	Offset Quadrature Amplitude Modulation
PPN-FFT	Polyphase Network-FFT
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SFB	Synthesis Filter Bank
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
URLLC	Ultra-High Reliability & Low Latency
V2X	Vehicle-to-everything
T	Period of time
N	Number of subcarriers
T_s	Symbol period
Δf	Spacing of subcarriers
BW	Bandwidth
N_{CP}	Samples of CP

1. Introduction

1.1 Context and Motivation

Over the past few decades, mobile connectivity has undergone an astonishing evolution as technological advancements in the world of wireless communications have grown exponentially. From a few years ago until now, communications have become essential and necessary for everyday life.

It all started in 1970 with the first generation (1G) technology, which brought us the first analogue signal and the first phones with limited functions, such as phone calls. Since the analog systems had limitations such as they were not suitable for long distance communication, the distorted signals due to noise were impossible to recover, and there was no data encryption or privacy protection over the network, So the communication systems soon moved on to digital standards. A decade later, the second generation (2G) came along, introducing text messaging. Second generation mobile communication used digital multiple access technologies such as Time division multiple access (TDMA) and Code division multiple access (CDMA). However, it was not until 2000 that the first mobile data transmission began with 2.5G technology. It was with the arrival of the third generation (3G) that transmission speeds really started to become high.

Since then, we have seen mobile data rates increase calls and internet access expand with fourth generation (4G) technology. Today, with 5G, we enjoy much faster speeds and lower latency. But the technology doesn't stop there, the sixth generation (6G) is already in development. This next generation will focus on even higher data rates and low latency along with ultra reliable communication with use of technologies such as artificial intelligence applications and advanced connectivity [1].

Figure 1.1 shows the evolution of mobile networks over time.

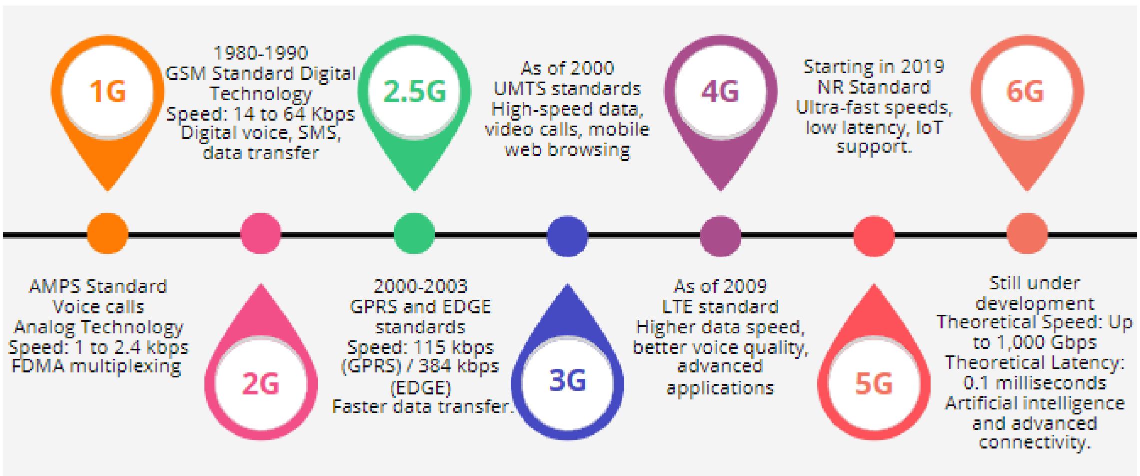


Fig. 1.1 Evolution of Mobile Networks

This project focuses on 5G technologies, specifically 5G proposed waveforms performance comparison ,which aims to offer a wide range of services by significantly improving the performance, flexibility, scalability and efficiency of today's mobile networks. To achieve this, 5G NR (New Radio) takes full advantage of available spectrum, whether in licensed, shared or unlicensed bands, spanning over a variety of spectrum bands.

The future of mobile systems will be characterized by a wide range of possible use cases, ranging from Enhanced Mobile Broadband (eMBB) to Massive Machine Type Communications (mMTC) and Low Latency High Reliability Communications (URLLC) in vehicular communications.

Depending on the intended use, we will use one technology or another. For example, in data-intensive applications, such as video streaming or immersive gaming, high bandwidth is required; therefore, eMBB is used.

When it comes to latency-sensitive services that require extremely high reliability, availability and security, uRLLC is used. An example of this would be autonomous driving and touch internet applications.

Finally, low-cost, low-power devices with small volumes of large-scale data, such as in smart cities, use mMTC [2].

An overview of the different types of communications and their respective services can be seen in Figure 1.2.

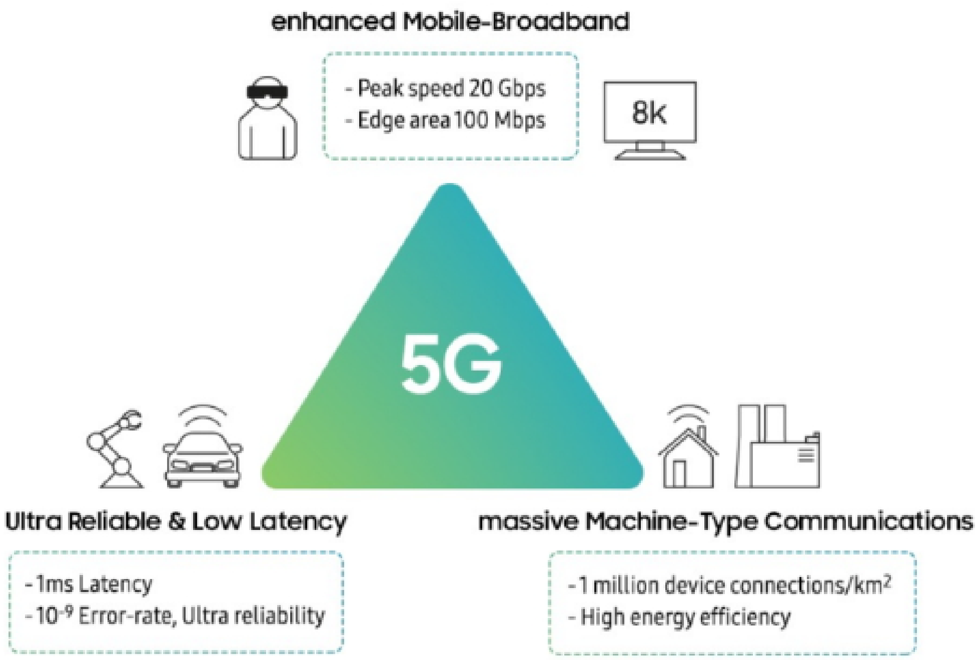


Fig. 1.2 5G communications [3]

To efficiently support these various use cases, a flexible allocation of available resources in time and frequency is required. However, this is difficult to achieve with conventional Orthogonal Frequency Division Multiplexing (OFDM), which is the most commonly used modulation scheme. For this reason, it is interesting to make various modifications to OFDM, such as the use of windowing or filtering. Alternatively, a different modulation scheme can be used, such as Filter Bank Multi-Carrier Modulation (FBMC) [15].

The modulation waveform in a system is one of the characteristics that can most influence the quality of data transmission and reception. For this reason, it is an interesting subject to study and evaluate from the different circumstances of the channel in which we find ourselves.

This is an area of research which needs to be investigated more and is important to study, as it is necessary to optimize as much as possible to offer high performance at low complexity, support various spectrum bands, spectrum types and deployment models. In order to define which modulation waveform is best in each situation it is important to evaluate different parameters such as BER with respect to SNR, latency, spectral efficiency and throughput.

1.2 Project Objectives

Although it was decided to continue using OFDM for 5G due to its compatibility with 4G systems, it is essential to explore alternatives such as FBMC as the research continues towards 5G beyond and 6G. Some studies have shown that FBMC is a very promising option. For this reason, the project aims to do a comprehensive study to determine whether its implementation in 5G would be efficient and beneficial.

The aim of this project is to compare, by means of different Matlab simulations, FBMC and OFDM modulations. For this purpose, different scenarios with various delays and interferences will be applied in order to define which waveform offers the best channel performance. In this way, the aim is to determine which modulation is best suited for different circumstances.

The main difference between the two systems is the replacement of the cyclic prefix in OFDM by the filter banks in both transmitter and receiver in FBMC. Because of these filters, the transmitted symbols can overlap in time, leading to the need for slightly more complex adaptations than OFDM uses for signal processing.

Therefore, it is crucial to clearly and concisely define the architecture, characteristics, advantages and disadvantages, implementation and adaptability in 5G of the different modulation waveforms.

Once this is defined, the next step will be the practical phase, where three different scenarios will be simulated in Matlab. The results obtained will be used to compare the different waveforms and determine which one is more viable in terms of BER, SNR, throughput, and spectral efficiency.

Additionally, a system will be implemented that can autonomously determine the best performance by varying parameters such as subcarrier spacing and the number of subcarriers.

Therefore, the main objective is to be able to verify whether FBMC modulation coupled with OQAM (Offset Quadrature Amplitude Modulation) is capable of being a good competitor to OFDM in order to meet the objectives set by 5G technology.

1.3 Simulation Environment and Tools

Matlab, a robust and versatile simulation software widely used in the engineering field, was used in this project to carry out the required simulations.

Matlab allows the representation of various scenarios, such as indoor, rural and urban environments, offering a flexible platform to adjust and customize the conditions of the different transmitters and receivers in each simulation.

At the beginning of each simulation, the type of scenario to be run is selected. Each scenario includes two transmitters, one using FBMC and the other OFDM. The program itself will make comparisons with different values that affect the quality of the system and choose the best performance for each modulation.

Once the system has selected the best parameters for the simulation, it will be possible to determine the optimal waveform for each channel. This will effectively evaluate the advantages and disadvantages of FBMC compared to OFDM under various conditions.

To carry out these simulations in Matlab, it is essential to have the Communications System Toolbox package, which provides the necessary functions and tools to design, simulate and analyze communications systems [4].

2. Fundamentals of OFDM

Orthogonal frequency division multiplexing (OFDM) is a transmission technique using multiple carriers spaced orthogonally in the frequency domain. This technique allows a large data stream to be transformed into several smaller streams, which are transmitted in parallel using different frequency subcarriers.

Each OFDM subcarrier carries information modulated by QAM (Quadrature Amplitude Modulation) or QPSK (Quadrature Phase Shift Keying) constellations. QPSK modulation is used in applications where noise resistance is crucial, such as in satellite communications and certain cell phone systems. In contrast, QAM modulation is used in systems that require high spectral efficiency, such as digital television, Wi-Fi and LTE networks.

OFDM is used in a variety of systems, including DAB (Digital Audio Broadcasting), DVB-T (Digital Video Broadcasting - Terrestrial) and the IEEE 802.11a and 802.11g Wi-Fi standards.

OFDM is also a key technology in 4G and 5G networks, although with some differences. In 4G, it is used exclusively for the downlink (from the base station to the mobile device), with a fixed subcarrier spacing of 15 kHz and subcarrier modulations that can be BPSK, 16-QAM or 64-QAM.

In 5G, OFDM offers greater flexibility by allowing adjustment of the subcarrier spacing and number of subcarriers according to channel conditions and data rate requirements. OFDM is used in both uplink and downlink, with variable subcarrier spacings (15 kHz, 30 kHz, 60 kHz, 60 kHz, 120 kHz and 240 kHz) and up to 3300 subcarriers. Subcarrier modulations can be QPSK, 16-QAM, 64-QAM or 256-QAM. This flexibility and the use of multiple subcarriers allow very high data rates to be achieved.

2.1 Operation

The main feature of OFDM is orthogonality, which is achieved through “optimal spacing” between carriers. This is achieved by ensuring that the spectral separation between consecutive carriers is always constant and equal to the inverse of the symbol period.

Initially, symbols are sent in series, one after the other, within a symbol period (Ts). However, these symbols then become a block of symbols in parallel that are transmitted simultaneously over a period of time (T). This time is the product of the number of subcarriers (N) and the symbol period (Ts), as shown in equation 2.1 [9].

$$T = N \cdot Ts \tag{2.1}$$

Figure 2.1 shows the scheme of the different signals converted into parallel symbols, transmitted in the same period of time.

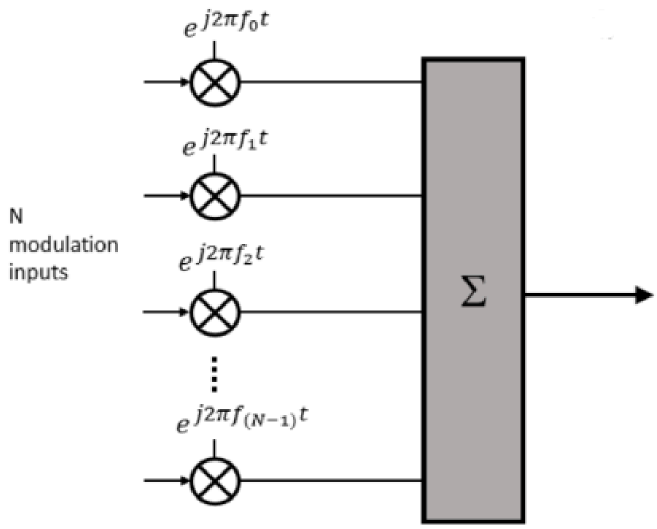


Fig. 2.1 An OFDM modulator adds signals of different frequencies [15]

For optimal spacing, the spectral separation between consecutive carriers should be Δf, which is the minimum necessary for them to be orthogonal. This improves spectral utilization and reduces inter-symbol interference (ISI) [10].

Optimum separation is defined as:

$$\Delta f = \frac{1}{T_s} \tag{2.2}$$

N subcarriers are combined, all with the same spacing to form a matrix of parallel signals [4].

Each subcarrier is modulated with a QAM/QPSK modulation and once modulated they are combined to provide maximum data throughput.

It is important to note that the number of subcarriers must ensure that the symbol period of each subcarrier is much larger than the channel delay spread. That is, the bandwidth of each subcarrier must be less than the channel coherence bandwidth (Bc), to avoid excessive inter-symbol interference (ISI) [11].

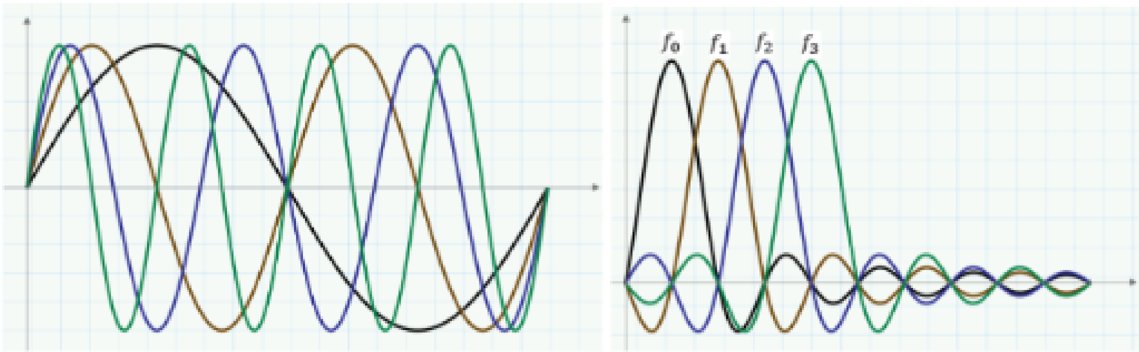
$$\Delta f = \frac{BW}{N} \tag{2.3}$$

In Equation 2.3 BW refers to the system bandwidth and N to the number of subcarriers.

At the output of the summation in Figure 2.1 we will find the subcarriers in the time domain as seen in Figure 2.2 (a). The narrowest subcarriers correspond to the highest frequencies, and all are spaced at multiples of Δf. The black trace represents the frequency f_0, i.e., the lowest frequency subcarrier.

In the frequency domain, what is noticeable is that the amplitude of each subcarrier crosses zero at the center of other subcarriers, which guarantees orthogonality. Each subcarrier has a specific frequency, as I discussed above, and they overlap in the time domain.

To transform from the frequency domain to the time domain, the Inverse Fast Fourier Transform (IFFT) is used, and the Fast Fourier Transform (FFT) is used for the inverse process. This allows to efficiently transform these subcarriers into a single wireless signal.



a.Temporal representation b. Spectral representation

Fig. 2.2 OFDM signal [5]

To sum all the subcarriers, all separated by the same spacing, the mathematical process of Equation 2.4 must be followed.

In Equation 2.5 the different frequencies are calculated, considering f_o as the lowest frequency and Δf the spacing between subcarriers.

$$x(t) = \sum_{n=0}^{N-1} e^{j2\pi f_n t} \tag{2.4}$$

$$f_n = f_o + (n \cdot \Delta f) \qquad n \in \{0, 1, ..., N - 1\} \tag{2.5}$$

2.2 Architecture

The generic OFDM model used will be implemented in a time-discrete manner with a cyclic prefix (CP). Cyclic prefix (CP) is nothing but the last N_{cp} samples appended at the beginning of the OFDM symbol and assuming that all processing is in baseband.

OFDM with cyclic prefix is the most commonly used multicarrier scheme in wireless LANs (Wi-Fi) and LTE. In this system, the signals on each subcarrier are generated by rectangular pulses in the time domain, which is equivalent to a modulation with pure sinusoidal signals in the frequency domain. This structure allows an efficient use of the Fourier Transform (DFT/IDFT), significantly reducing the computational complexity of the modulation and demodulation process.

Figure 2.3 shows a generic view of all the steps that make up an OFDM system.

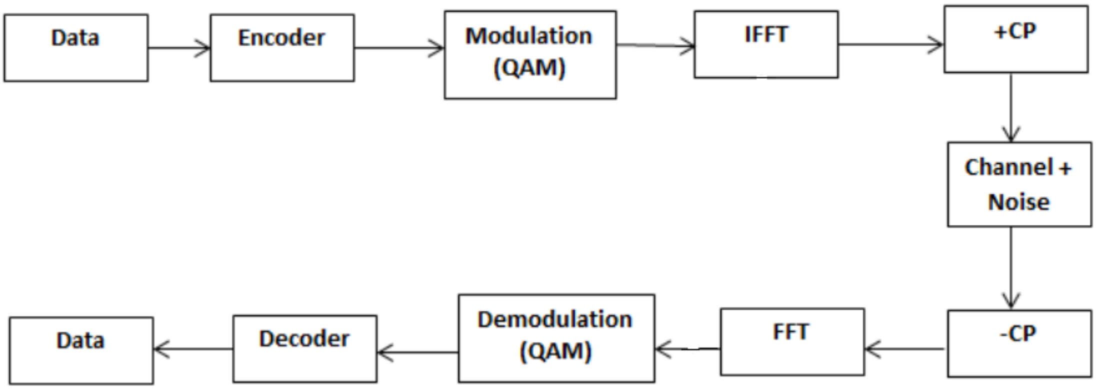


Fig. 2.3 Digital implementation of a baseband OFDM system

As in all current systems, OFDM consists of two main parts: the transmitter and the receiver.

At the transmitter, the data bit stream is first modulated by assigning appropriate symbols to them. Then, an Inverse Fast Fourier Transform (IFFT), is performed to transform the signal to the time domain. Once the signal is converted to serial format, a cyclic prefix is added before transmission to protect against inter-symbol interference and improve robustness against channel time dispersion.

In the receiver, the signal must be synchronized in time and frequency. Then, the reverse process of the transmitter is performed. This includes the removal of the cyclic prefix, the conversion from serial to parallel, the Fast Fourier Transform (FFT), to convert the signal from time domain to frequency domain, and finally, the demodulation of the symbols to recover the original data bit stream.

For an overview of what an OFDM signal looks like in the two domains, see Fig. 2.4.

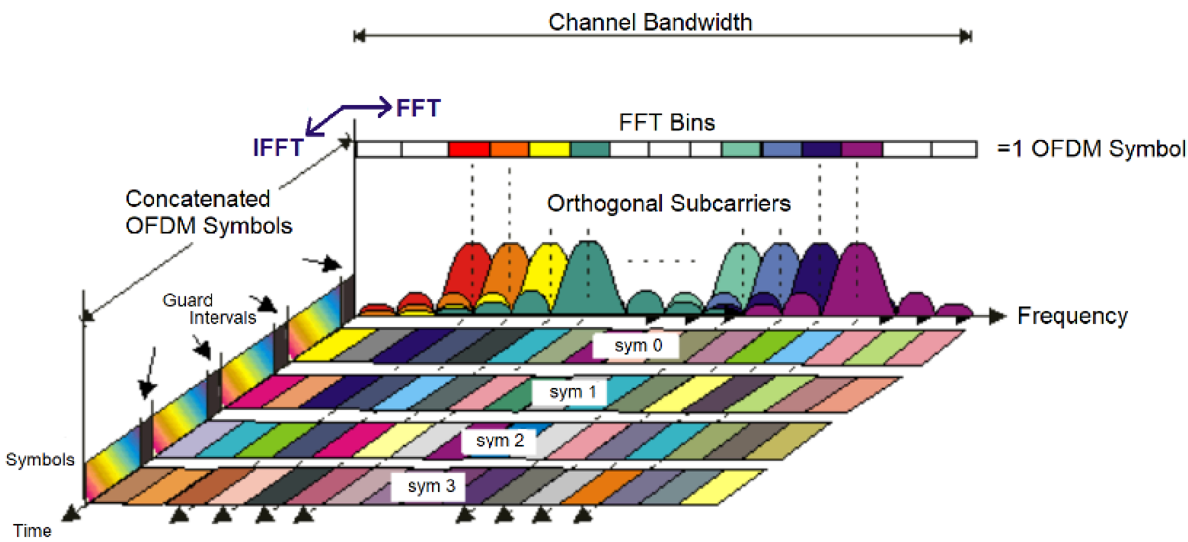


Fig. 2.4 Combined time/frequency domain view of the OFDM signal [5]

In the graph, the horizontal axis represents the frequency domain, spanning the entire bandwidth of the OFDM signal. This axis shows how different subcarriers occupy different parts of the frequency spectrum, each modulated with specific data. On the vertical axis, the amplitude of each subcarrier is shown, reflecting the power with which each is transmitting at any given time.

The third axis, which is projected perpendicularly off the page, represents time. This axis allows one to visualize the time evolution of the OFDM signal, showing how the different symbols are transmitted continuously. As one 'advances' on this axis, one follows the progression of the signal from the beginning to the end of the transmission process.

Each point or symbol in this three-dimensional graph corresponds to a set of OFDM subcarriers that are simultaneously transmitted through the channel at a specific time instant. This set of subcarriers carries different parts of the total data stream, which allows OFDM to transmit large amounts of information efficiently. The graphical representation provides a clear view of how the OFDM signal is distributed in the frequency domain and how it propagates over time, highlighting the structure and dynamics of the transmission process.

2.2.1 OFDM Transmitter

The process for a message to be correctly sent through a channel begins with the transmitter, which, as its name indicates, is responsible for generating and transmitting the signal.

It all starts with the generation of data in the form of a binary sequence. This data is sent to the first block of the system, which is a QAM or QPSK modulator. In this block, the data bits are transformed into symbols, each associated with a specific amplitude and phase in the frequency domain. This assignment of amplitude and phase to each subcarrier allows the data to be represented efficiently and robustly.

The QAM/QPSK modulator maps binary information to symbols in a constellation diagram (see Figure 2.5), where each symbol represents a point with a particular combination of amplitude and phase. This modulation allows multiple bits to be transmitted simultaneously over different subcarriers.

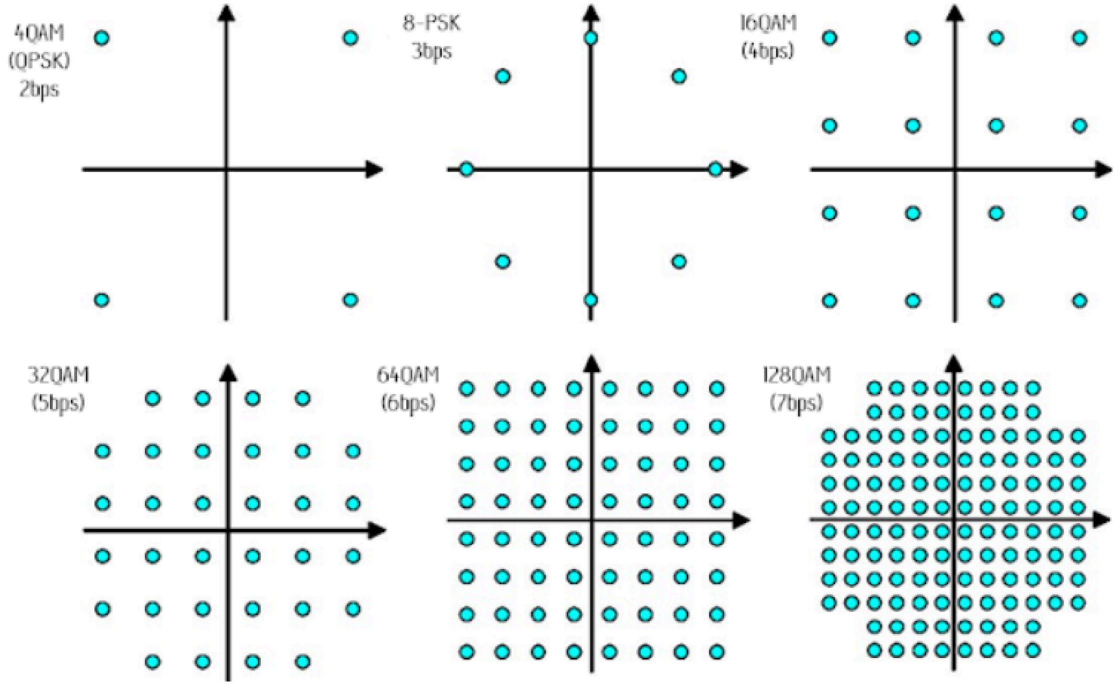


Fig. 2.5 Examples of common modulation constellations [22]

The choice of modulation technique depends on the specific applications and the desired transmission rate. In my case, as will be discussed in the practical section, 4-QAM will be chosen. This choice is due to the fact that more advanced modulations, although they may offer higher transmission rates, tend to introduce more noise in the signal.

In contrast, 4-QAM offers an appropriate balance between complexity and robustness for the specific test environment.

Once the symbols have been modulated, the signal is converted from serial to parallel format by a serial-to-parallel (S/P) conversion process. In this step, the modulated symbols are distributed in parallel blocks, assigning them to different subcarriers. Each subcarrier has a bandwidth much smaller than the coherence bandwidth of the channel.

Once the subcarriers are in parallel format, this finite number of samples will be defined as N. These samples represent the discrete frequency components of the OFDM transmitter. Then, these samples go through the next block of the system, known as IDFT (Inverse Discrete Fourier Transform), in charge of frequency multiplexing, converting the samples from the frequency domain to the time domain. The mathematical process is shown in Equation 2.6.

$$x[n] = \frac{1}{N}\sum_{k=0}^{N-1} X[k]e^{j\frac{2\pi}{N}\cdot kn}, \qquad n = 0,\ 1,\ 2,\ldots,\ N-1 \tag{2.6}$$

The IDFT takes a signal in the frequency domain ($X[k]$) and converts it into a signal in the time domain (represented by $x[n]$). This is done by summing the contributions of all frequencies (from $k = 0$ to $k = N - 1$) weighted by the complex exponentials, which act as sinusoidal oscillations with different frequencies.

The time samples pass through the next block (P/S), where they go from parallel to serial and, finally, the cyclic prefix (CP) and guard bands are added to form the OFDM symbol.

The CP is generated by copying the final part of the OFDM symbol, obtained through the IDFT, to the beginning of it. In this way, the CP functions as a guard interval.

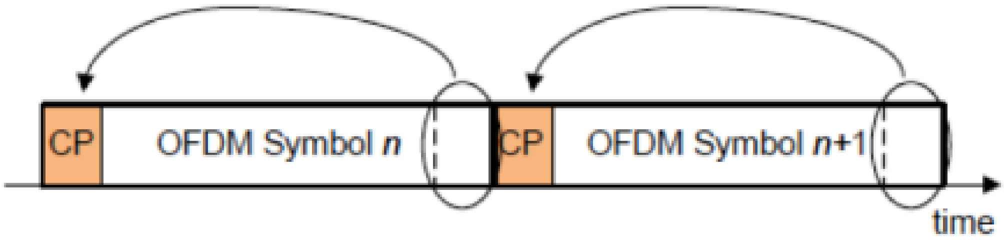


Fig. 2.6 Cyclic Prefix [13]

The CP is highly necessary, since a small deviation between the transmitter and receiver can misalign the carriers, causing signal rotation in the time domain, i.e., inter-carrier interference (ICI). In the frequency domain, on the other hand, inter-symbol interference (ISI) occurs [11]. The graphical representation can be seen in Figure 2.7.

By adding a CP and guard band between adjacent OFDM symbols we can solve these problems, as it prevents the tail of one symbol from overlapping with the next and any replication arriving at the receiver, whether direct or delayed, becomes periodic, ensuring orthogonality. Although this introduces redundancy in terms of information, affecting bandwidth efficiency and increasing transmission power, it is crucial to avoid ISI and ICI [6].

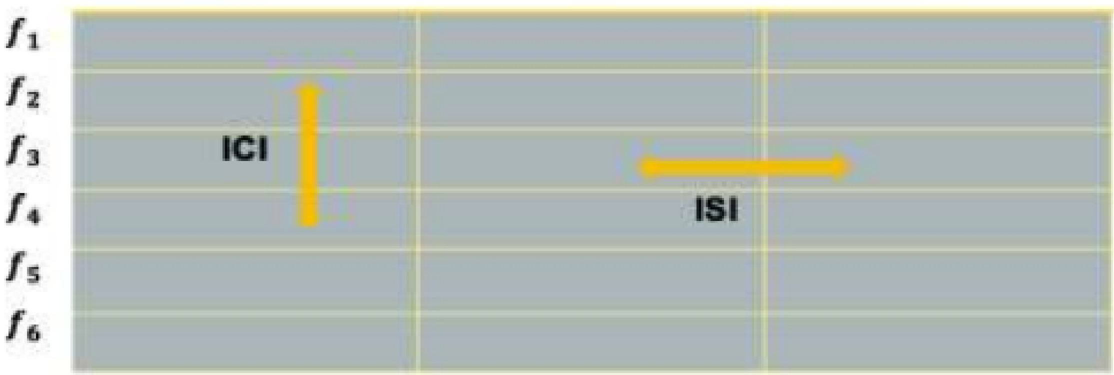


Fig. 2.7 Problems with ISI and ICI [11]

The guard band is implemented using the Zero Padding technique, where during the guard interval, the transmitter sends a series of zeros (null subcarriers), achieving a more defined signal in the frequency domain.

The size of the cyclic prefix depends on the specific application. In this case study, a value of $\frac{1}{14}$ will be used, as it offers a suitable compromise between ensuring robustness against multipath interference and minimizing the loss of spectral efficiency.

A longer CP could provide better protection against ISI, but it would also reduce spectral efficiency because less time would be devoted to transmitting useful data, so it is essential to choose the CP duration as the minimum possible value to resist channel dispersion.

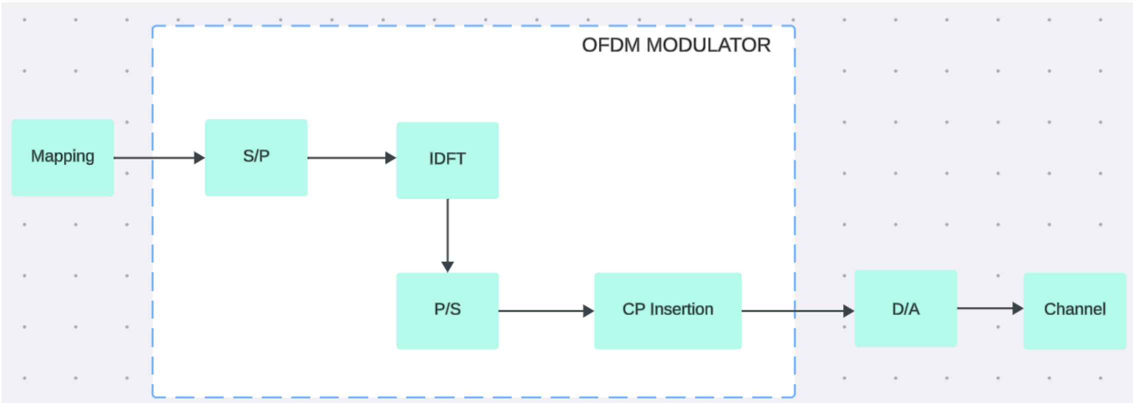


Fig. 2.8 OFDM Transmitter

After the OFDM modulator, the signal generated as a digital signal needs to be converted into an analog signal in order to be transmitted over a physical medium such as air. The DAC (Digital-to-Analog Converter) performs this conversion, allowing the digital information to travel as an analog signal through the channel.

2.2.2 OFDM Receiver

In the OFDM receiver, the blocks work inversely to those of the transmitter.

First, we receive the analog signal from the channel, which is converted to digital format by the analog-to-digital (A/D) converter.

Once we have the data in digital format, the next step is to remove the cyclic prefix and guard bands added during transmission. This stage cleans the data packet, eliminating the redundant parts that were added to manage channel dispersion.

Once the CP and guard bands have been removed, the data is reorganized into a parallel (S/P) format. This conversion is necessary because the Discrete Fourier Transform (DFT), which is then applied, works with data in parallel format to separate the different subcarriers.

The DFT converts the time domain data back to the frequency domain. The mathematical process is shown in Equation 2.7.

$$X[k] = \sum_{n=0}^{N-1} x[n]e^{-j\frac{2\pi}{N}kn}, \qquad k = 0, 1, 2,..., N-1 \qquad (2.7)$$

DFT takes a time domain signal $x[n]$ and decomposes it into a series of frequency components $X[k]$. Each $X[k]$ value represents the amplitude and phase of a specific frequency contributing to the original signal.

Finally, to recover the data originally generated at the transmitter, it is necessary to go through the demapping block, which performs the reverse of the modulation. This process involves decoding the modulated symbols that have been transmitted through the channel, converting them back into the original bits that were sent.

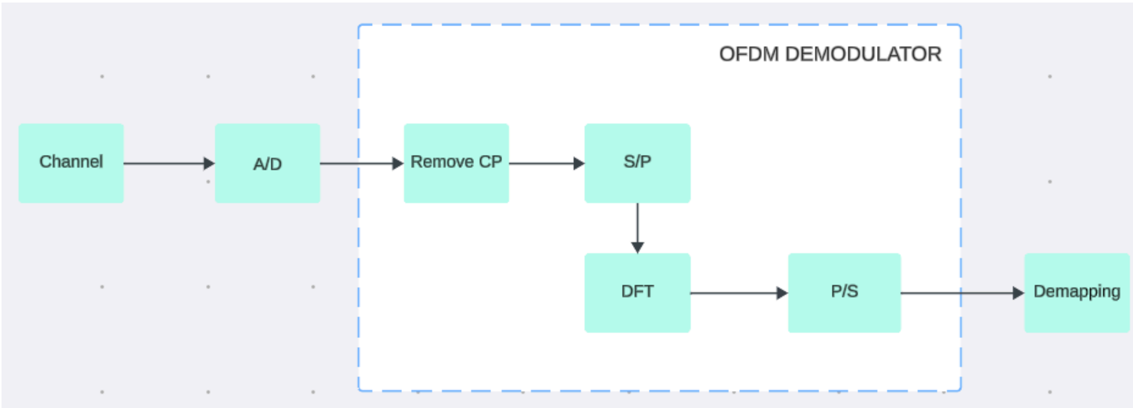


Fig. 2.9 OFDM Receiver

2.3 Solutions Provided by OFDM

OFDM is capable of solving the dispersion and multipath problems that often occur in wireless channels or optical fibers.

Dispersion occurs when signals propagate through a medium with different propagation speeds. To address this problem, OFDM separates the signal into multiple subcarriers, each of which behaves as an independent channel that only undergoes attenuation and not dispersion in each subchannel.

Multipath occurs in the channel when multiple replicas of the signal arrive with different amplitudes and delays due to reflections and refractions in the environment. This can lead to overlaps between adjacent symbols, causing ISI. To avoid this, OFDM uses the cyclic prefix at the beginning of each symbol.

OFDM methods offer several advantages, but also have some disadvantages.

2.3.1 Advantages

The dispersion, as I mentioned before, is solved with one of the main features of OFDM, the orthogonality between the subcarriers, which allows an efficient use of the spectrum. The subcarriers can overlap without interfering with each other thanks to this orthogonality.

By modulating the subcarriers, a nearly flat frequency response is obtained, thus mitigating problems in frequency selective environments.

On the other hand, multipath is solved with the CP, which extends the symbol time, ensuring that any fading or interference affects only a small part of the received symbol, thus reducing the probability that the entire symbol is affected. This improves the robustness of the system against selective fading over time.

In addition to these advantages, OFDM stands out for its simplicity in terms of implementation. Its main components, such as IFFT and FFT, do not require large computational power. These mathematical operations can be performed efficiently by small, low-cost processors, making OFDM an attractive option for many communication applications.

2.3.2 Disadvantages

Like any system, apart from its advantages, it has its disadvantages.

One of the main disadvantages of OFDM is that a small deviation in frequency can cause loss of orthogonality between the subcarriers. This can lead to significant signal quality problems. In addition, OFDM has a high out of band emissions, requiring wider guard bands to avoid interference. The use of the cyclic prefix also contributes to resource waste by reducing bandwidth efficiency. The signal spectrum can be found in section 5.1.

Therefore, although OFDM is popularly used in broadband wireless communication systems, it has several limitations, such as high spectral leakage, stringent synchronization requirements, and a greater need for information redundancy. In addition, OFDM is particularly sensitive to frequency dispersion, which makes phase noise a critical problem in millimeter waves used in 5G networks [13].

3. Fundamentals of FBMC

Filter bank multicarrier modulation (FBMC) is an alternative technique to OFDM multicarrier modulation that has been very successful and can be a good alternative for OFDM to use in 5G.

As its name indicates, it involves applying a filter bank that filters each subcarrier separately. This allows for reduced secondary lobes of each subcarrier and more optimal spectral efficiency, giving us the possibility of less strict synchronization compared to OFDM. This, in turn, makes the system more resistant to time and frequency shifts and allows us to dispense with the cyclic prefix that OFDM uses to combat ISI. Therefore, resources are conserved; however, the filtering requires more complex processing [14].

The modulation I am going to use for this waveform is OQAM (Offset Quadrature Amplitude Modulation). This modulation, when combined with a filter bank, optimizes the filtering of the subcarriers by attenuating the side lobes of the prototype filter. These features support applications requiring different bandwidths and facilitate spectrum fragmentation [8].

The filtering process almost completely eliminates the out-of-band components of each subcarrier, thus reducing the need for guard bands. This filtering can be performed in two ways: by frequency processing or by using a PolyPhase Network-FFT (PPN-FFT), which is performed in the time domain [11].

Both methods produce a similar response, differing mainly in the location of the filtering stage relative to the IDFT. The choice of which method was used is indicated in section 3.2.

Although the filter structure and the way the signal is extended in FBMC for each symbol might give the impression of longer signal duration, the elimination of the cyclic prefix, which is necessary in OFDM, generally results in lower overall latency. This makes FBMC more suitable for applications requiring low latency and higher spectral efficiency [10].

In FBMC the interference that can arise is between adjacent subcarriers; for example, subcarrier k can interfere with subcarriers k-1 and k+1, but not with the others. For this reason, orthogonality is crucial only for adjacent channels.

On the other hand, thanks to the PHYDYAS project, the design of filter prototypes has been published, which has significantly contributed to the development and optimization of this technology in advanced communication environments [12].

In summary, the use of FBMC in 5G is still in the research phase. Although it offers flexibility comparable to OFDM, it stands out for its ability to better handle interference between subcarriers and reduce redundancy. It therefore presents itself as a promising option for optimizing spectral efficiency in future communication networks.

3.1 Operation

In an FBMC system, any type of modulation can be used, as long as it is ensured that the subchannels are not mixed. This means that data must be transmitted exclusively on odd or even subchannels to avoid overlapping. This constraint can limit the optimal use of all available resources, therefore, specialized modulation that can effectively manage overlap between adjacent subcarriers is necessary.

The most efficient FBMC variant is the Offset Quadrature Amplitude Modulation (OQAM), which is the offset QAM modulation. This scheme allows better spectrum utilization [8].

In this modulation, the odd subcarriers are modulated at different intervals than the even subcarriers. Consequently, to transmit N symbols, 2N subcarriers will be necessary [13].

In this way, we divide our symbols into real and imaginary components and shift them one symbol period apart, so that they are interleaved in both time and frequency. Thus, since a real number is orthogonal to an imaginary one, even if the symbols overlap, the orthogonality is maintained, as shown in Figure 3.1 [14].

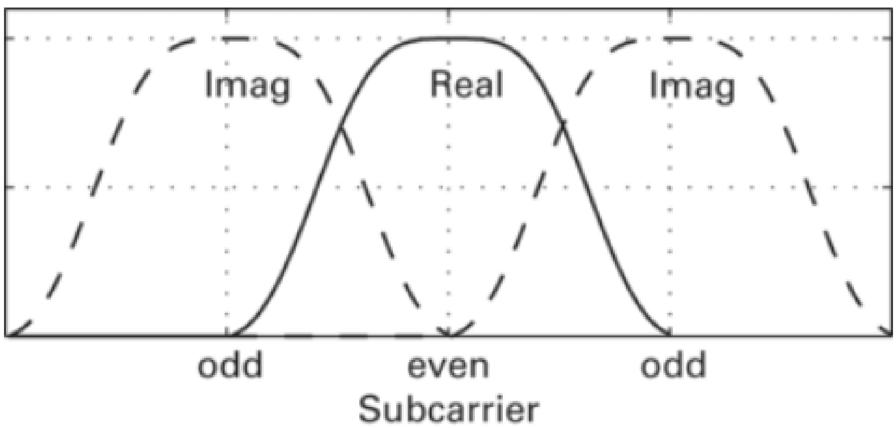


Fig. 3.1 OQAM Subcarrier [14]

The input signal $c_k(l)$ is decomposed into its real and imaginary part, and both components are interpolated by a factor of 2, which implies the insertion of zeros between samples to double the sampling rate. In the even case (upper part of the diagram), the interpolated signal corresponding to the imaginary part is delayed by one sample. Subsequently, the real and imaginary parts are summed.

In the odd case (lower part of the diagram), the order is slightly different, since it is the interpolated real part that is delayed by one sampling. Then, the delayed real part and the interpolated imaginary part are added together.

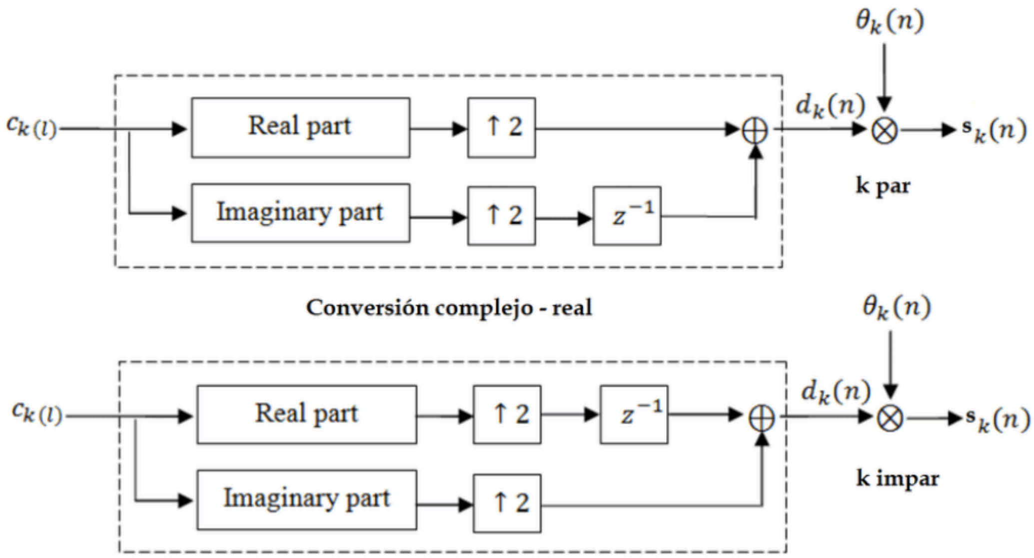


Fig. 3.2 OQAM Modulation [26]

Therefore, once it is understood how the real and imaginary symbols are generated, we can analyze their representation in Figure 3.3. In this figure, it is observed that, unlike the traditional OFDM scheme, here two symbols are generated in each period T. This means that each symbol in the time domain is separated by an interval of $\frac{T}{2}$, allowing a higher density of symbols per unit of time.

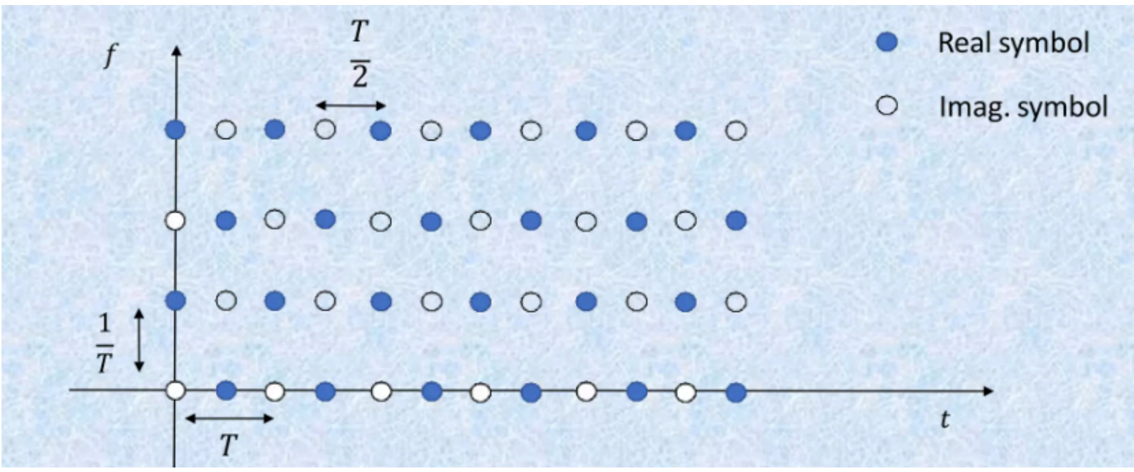


Fig. 3.3 Representation of real and imaginary symbols in an OQAM modulation [23]

As I mentioned earlier, for each of the subcarriers, FBMC employs a filter bank in order to minimize the spectrum on each subcarrier.

The choice of an appropriate filter is crucial to ensure the quality of the system, since it is essential that the selected filter has good properties in both the time and frequency domains.

3.1.1 PHYDYAS Filter

In 5G, the prototype filter known as PHYDYAS is preferred by the scientific community. Its design and features make it an ideal choice for optimizing system performance, especially in terms of out-of-band attenuation and bandwidth efficiency [16].

The choice of this filter is due to its ability to maintain the orthogonality of the symbols and minimize the interference between them, critical aspects for the efficient operation of new generation communication networks. Therefore, it will be the one I will use for my simulations.

The filter is characterized by the value of the overlap factor (K), which is the ratio of the filter impulse response duration to the unfiltered multicarrier symbol period (T_s). The values of the overlap factor are generally $K = 2, 3\ and\ 4$.

The overlap factor has different functions depending on the domain in which it is considered. In the time domain, it indicates how many multicarrier symbols overlap. In the frequency domain, it reflects how many frequency coefficients are inserted between the FFT filter coefficients. As the value of K increases, the out-of-band attenuation also increases [17].

The filter values have been obtained from the study presented in the paper [13] and can be seen in Table 3.1.

K	H_0	H_1	H_2	H_3	$\sigma^2(dB)$
2	1	$\sqrt{2}/2$	-	-	-35
3	1	0.911438	0.411438	-	-44
4	1	0.971960	$\sqrt{2}/2$	0.235147	-65

Table 3.1 PHYDYAS filter frequency coefficients

The different values of H are amplitude coefficients for different filter components. As K increases, the number of coefficients used can also increase, providing a more precise definition of the filter response.

Parameter $\sigma^2(dB)$ is a value indicating how much the signal is reduced outside the desired frequency range. More negative values mean better attenuation and therefore better filtering.

The prototype filter is designed so that adjacent subcarriers overlap but remain orthogonal, and interference on non-adjacent subcarriers is negligible.

With this design and using OQAM modulation, inter-symbol interference (ISI) is eliminated. The modulations are implemented using DFT, placing the polyphase components of the filter after each DFT output instead of filtering each subchannel, which allows an efficient implementation [13].

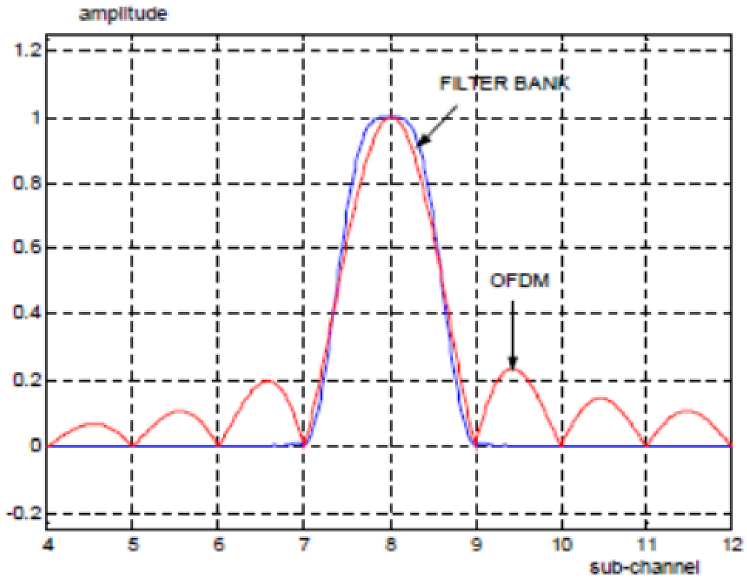


Fig. 3.4 FBMC and OFDM frequency response [13]

Later, in section 5.1, I will perform a Matlab simulation to compare the FBMC and OFDM spectra, providing a more realistic analysis of their spectral behaviors.

3.2 Architecture

As I discussed earlier, the FBMC architecture is very similar to OFDM, but there are three fundamental differences between the systems. FBMC does not include a cyclic prefix, the complex input symbols have their real and imaginary parts interleaved, resulting in an OQAM modulation, and after the complex modulation of each subchannel, a filtering step is performed [13]. The filtering step, i.e. the use of filter banks, can be carried out in two different ways.

The first one performs frequency processing by means of FS (Frequency Spreading).

The second one, performs a processing in time, by means of a PPN-FFT. In my case, this second processing method is chosen due to the high computational cost associated with increasing the IDFT value in the frequency domain (FS). It should be noted that by applying either method a similar response is obtained, the difference between each method is the location of the filtering stage with respect to the IDFT [11].

The process for generating an FBMC signal is detailed below, following the block diagram schematic shown in Figure 3.5.

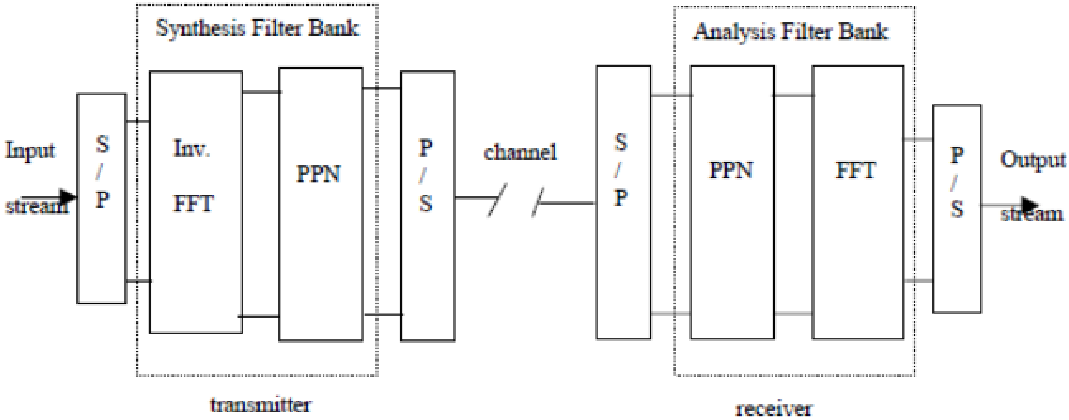


Fig. 3.5 Implementation of a FBMC system [24]

The transmitter and receiver use specific filter banks to handle the signals.

The synthesis filter bank (SFB) in the transmitter decomposes the original signal into several components, each corresponding to a specific subchannel. This is done by a series of digital filters that separate the signal into different frequencies.

On the other hand, in the receiver, an analysis filter bank (AFB) is used to process the received signal. These filters analyze the input signal and decompose the composite signal into its individual components corresponding to each subchannel.

3.2.1 FBMC Transmitter

As in the OFDM process, to start transmitting a message, as is logical, we will start with the transmitter, which we can see the different blocks in Figure 3.6.

In FBMC, two blocks (OQAM and PPN) are incorporated, which distinguish OFDM from FBMC. In addition, we note that the CP has disappeared.

To start the process, the bits are first generated and enter the first block (Mapping) to be modulated by QAM modulation.

This modulation (M-QAM) follows the same procedure as used in OFDM, resulting in the output of this block being a complex number corresponding to a QPSK, 16-QAM, 64-QAM or 256-QAM constellation, depending on the selected modulation scheme.

After passing through the QAM modulator, a sequence of complex symbols is generated in series. This sequence is then converted into a set of N complex symbols in parallel (S/P) to facilitate the input of these symbols into the OQAM block [11].

In the OQAM block, the symbols are separated into two components: the real part and the imaginary part. Each of these parts is treated separately and then sent directly to the IDFT, where it converts this data from the frequency domain to the time domain, allowing the generation of the appropriate time signal.

OQAM modulation is described in detail in section 3.1.

The system maintains the size of the IDFT, but incorporates additional digital filters to improve performance (PPN). Therefore, at the output of the IDFT we will obtain the replicated signal K times, and the filter length will be L , calculated in Equation 3.1. Where K is the overlap factor mentioned above and N the number of samples.

$$L = K{\cdot}N \tag{3.1}$$

The mathematical process of the IDFT can be found in section 2.2.1.

This filter ensures that adjacent subcarriers are in quadrature, maintaining orthogonality in the real domain. This means that interference between adjacent symbols will be real, while adjacent symbols will be imaginary, preventing such interference from affecting the transmitted symbol.

In this method, the N samples obtained at the output of the IDFT are delayed by a number of times equal to $K - 1$ before filtering is applied. This delay allows fine tuning so that the filtering and the polyphase network structure work in a coordinated manner [11].

As the value of K increases, more out-of-band attenuation is achieved, but the complexity of the system also increases.

After the polyphase network (PPN), we proceed to the last block of processing, which includes the conversion of the data from parallel to serial (P/S), as well as the overlap and sum operation (Overlap and Sum). In this step, the data is transformed from parallel to serial format and, as in OFDM, guard bands are inserted. However, in FBMC, the size of these guard bands can be much smaller due to the better spectral confinement provided by this technique.

Finally, since the symbols have initially been separated into their real and imaginary parts, it is necessary to sum the overlapping parts to obtain the correct final signal. The summation ends up spanning $\frac{N}{2}$ samples.

To complete the process, the filtered signals need to be adjusted, and the overlapping parts must be properly aligned. To achieve this, a delay of $\frac{N}{2}$ samples is applied, ensuring that the overlapping and summation are performed accurately [11].

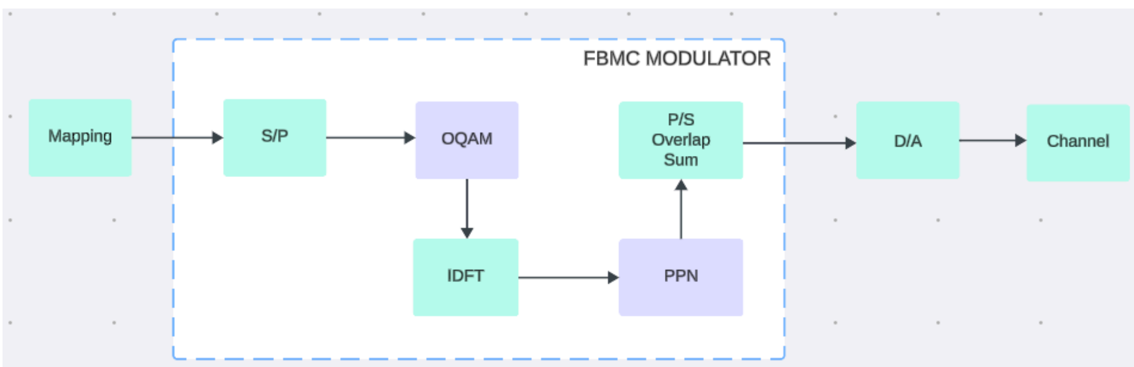


Fig. 3.6 FBMC Transmitter

3.2.2 FBMC Receiver

In the FBMC receiver, the process is the reverse of that of the transmitter, as with OFDM. The objective is to recover on one frequency what in transmission was spread over several frequencies.

The transmitted signal passes through the channel and arrives at the receiver in serial format and the first step is to convert it into parallel format (S/P).

The information in parallel format passes through the inverse polyphase network which is applied, as the name suggests, to filter the received signal. The samples are delayed by $\frac{N}{2}$ to properly coordinate the inverse filtering process and correctly sum the separate parts.

The filtered signal goes through DFT to convert the time domain data to the frequency domain and allows the original complex symbols to be recovered.

Once in the frequency domain, OQAM demodulation is applied. Here, the real and imaginary components are combined to recover the original QAM symbols. In this block, to obtain the transmitted OQAM symbols and reduce inter-symbol interference, the symbols are chosen alternately, i.e. real or imaginary, depending on the index of the received multicarrier symbol [11].

QAM symbols retrieved in parallel format are converted back to serial format to facilitate data output.

Finally, the serial symbols are demodulated using the same QAM scheme that was used in the transmitter (QPSK, 16-QAM, 64-QAM, 256-QAM, depending on the choice).

QAM demodulation converts complex symbols into bits, thus recovering the original transmitted information.

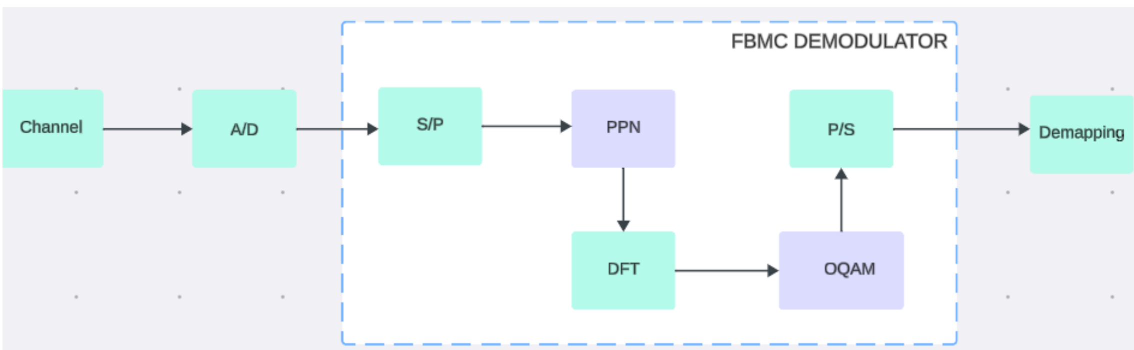


Fig. 3.7 FBMC Receiver

3.3 Solutions Provided by FBMC

OFDM addresses the problem of scattering and multipath in wireless transmission, but it also has some disadvantages that can be solved with FBMC.

Unlike OFDM, FBMC does not require guard times or cyclic prefixes, avoiding the OFDM limitations associated with its large sidelobes in the frequency domain, which impose orthogonality constraints between subcarriers.

FBMC uses OQAM modulation, which enables higher transmission capacity over the entire bandwidth. Subchannels in FBMC can be grouped into independent blocks, crucial for scalability and dynamic access. In addition, a device can simultaneously sense and receive spectrum on cognitive radios, ensuring consistency between these functions.

In FBMC, the transmission channel is divided into subchannels that overlap only with their immediate harmonics, allowing two groups of contiguous subchannels to be independent by leaving only one empty subchannel between them. This frequency response feature greatly improves the performance and operational flexibility of wireless systems.

In order to have a clearer view, Table 3.2 shows the characteristics of FBMC.

Features	FBMC
Out-of-band emission (OOB)	Low
Spectral Efficiency	High
Processing complexity	High
CP required	No
Orthogonality	Yes
ISI/Multipath dispersion	Low
Latency	Low
OFDM support	Yes

Table 3.2 FBMC characteristics [10]

3.3.1 Advantages

As we can see in Table 3.2, FBMC stands out for its frequency selectivity and latency, outperforming OFDM by dividing the channel into subchannels using filter banks. This improves throughput and reduces the need for guard bands.

OQAM modulation allows interleaving symbols, which optimizes bandwidth usage without reducing the bit rate, thus improving data transmission speed. Another important advantage of OQAM modulation is that it eliminates the need to use a cyclic prefix, which is an additional cost in terms of spectral efficiency. It should be noted that FBMC is compatible with phased OFDM systems without CP.

We can conclude that the most notable advantages of an FBMC system are increased spectral efficiency compared to OFDM and reduced latency. These characteristics make FBMC particularly suitable for advanced technologies in 5G, such as in low latency and high reliability applications, as in environments like Internet of Things (IoT) and vehicular communications (V2X).

3.3.2 Disadvantages

FBMC presents several challenges that must be taken into account. Firstly, in MIMO environments, this approach may encounter difficulties due to the complexity of the signal and the need for additional processing. This complexity arises from the use of filter banks, which generate overlap in the waveforms, leading to blocks that depend on the overlap factor at the transmitter. In this project, the use of MIMO has not been considered, so these specific challenges have not been addressed.

In addition, FBMC requires twice as many subcarriers compared to OFDM to transmit the same amount of data, which increases the processing load.

Another drawback is that spectral efficiency can be low when transmitting short bursts of data, due to the overhead associated with managing the filters in each subchannel.

Finally, from a hardware and processing point of view, FBMC is more complex and therefore more expensive than OFDM, which may limit its viability in resource-constrained systems.

4. Design and simulation configuration

In this section, the two studied waveforms will be designed and simulated to compare their BER, latency, spectral efficiency, and throughput in a practical manner using Matlab. The simulations have been performed at the link level, considering a point-to-point communication.

In order to perform the calculations correctly, it is first essential to know which parameters can be configured and their specific values, especially in the context of 5G.

4.1 5G Specifications and Configurable Simulation Parameters

5G technology, as noted above, shares similarities with 4G, although it presents some parameters with wider configuration options.

One of the objectives of the project is to develop a system capable of iterating with different values and selecting those that offer the best performance. To achieve this, it is essential to define the exact parameters that each system can support. These characteristics can be found in Table 4.1.

Parameters	OFDM / FBMC
Frequency range	450 MHz-6 GHz 24,25 GHz-52,8 GHz
Carrier separation Δf	15 KHz, 30 KHz, 60 KHz, 120 KHz, 240 KHz
Maximum number of subcarriers	3300 (up to FFT of 4096)
Guard bands	Up to 16 carriers
Number of symbols OFDM FBMC	$\frac{Block\ Length}{Subcarriers \cdot log_2(MQAM)}$ $\frac{2 \cdot Block\ Length}{Subcarriers \cdot log_2(MQAM)}$
Modulations	QPSK, 16QAM, 64QAM, 256QAM
Maximum carrier bandwidth	50 MHz (@15 Khz), 100 MHz (@30 Khz), 200 MHz (@60 Khz), 400 MHz (@120 Khz)

CP Duration (in the case of OFDM)	$\frac{1}{14\cdot\Delta f}$
Overlap factor K (in the case of FBMC)	2, 3, 4
Channel Coding	Polar Codes (control); LDPC (data)

Table 4.1 Configurable OFDM and FBMC parameters for 5G [7]

It is true that FBMC does not yet have fully defined specifications, since it is still in the research phase. Nevertheless, we will consider the characteristics in Table 4.1 to establish comparable conditions.

The Block Length value, shown in the equation for the number of symbols, is defined by the LDPC encoder described in section 5.1. On the other hand, the value of the CP duration is detailed in section 2.2.1.

4.2 Channel Scenarios

To compare both waveforms, it is essential to define different scenarios, as each one presents unique characteristics. This approach will allow for a comprehensive analysis of all possible situations.

The types of channels to be simulated have been defined in the main program, *PROGRAM.mxl*, from which the simulation is executed. A switch statement has been implemented to prompt the user to select the desired scenario before starting the simulation, with the options being 1 for Indoor, 2 for Rural, and 3 for Urban.

To simulate these channels, the *comm.RayleighChannel* object in MATLAB was used. This object is characterized by multiple signal paths, each defined by a specific delay and gain [18].

The reasoning behind the chosen sample rate will be explained in Section 4.3, as it was selected to ensure that both systems achieve a $BER < 10^{-3}$.

The value of the sample rate is Fs, which meets Nyquist as seen in Equation 4.1, with $delta\_f$ being the separation between the subcarriers and $NoSub\_Data$ being the number of subcarriers.

$$Fs = delta\_f \cdot NoSub\_Data \cdot 2 \tag{4.1}$$

Due to the larger number of subcarriers used by FBMC, it requires a higher sampling frequency to capture all signals without aliasing or loss of quality. Consequently, the channels have been simulated using the FBMC sampling frequency rather than the OFDM sampling frequency.

On the other hand, in addition to incorporating a different channel for each simulation, which already adds interference and noise, a white noise is also included in all cases, as shown in Code 4.1.

```
RX_OFDM = awgn(chanout_OFDM, adjustedSNRdB, 'measured');
RX_FBMC = awgn(chanout_FBMC, snrdB, 'measured');
```

Code 4.1 Add white noise to the signal

Before proceeding to the evaluation of each channel, it is important to know that the propagation of wireless signals faces several phenomena, among them: reflection, which occurs when a signal encounters a complex structure, and bounces off it instead of passing through it; refraction, which happens when the signal changes direction as it passes from one medium to another with different density; diffraction, which occurs when the signal encounters an obstacle that it cannot directly overcome, deviating or bending around it; and multipath fading, which occurs when the transmitted signal reaches the receiver by multiple different paths due to the aforementioned reflections, refractions and diffractions. These paths, having different lengths, cause the signals to arrive with different delays and phases.

Although these phenomena occur in all environments, the magnitude and impact of these phenomena vary significantly between indoor, urban and rural environments due to differences in the arrangement and nature of the obstacles present.

4.2.1 Indoor Environment

In indoor environments, such as offices, homes and buildings, the presence of walls, ceilings, furniture and other objects creates an environment dense with reflections and diffractions. Signals can bounce off these surfaces, generating multiple paths to the receiver.

Multipath fading is especially significant in these environments due to the proximity of obstacles and the abundance of reflective surfaces.

Table 4.2 shows the parameters of the indoor channel.

Path Delays	Average Path Gains
0 ns	0 dB
50 ns	-10 dB
100 ns	-20 dB

Table 4.2 Parameters of indoor channel

The delays can be very small due to the short distances between the transmitter and receiver. Therefore, a higher sample rate has been applied to this channel compared to the others to capture these small delays with greater precision.

The exact value of the sampling frequency is $Fs{\cdot}90$. We meet Nyquist and it is also quite high. This choice ensures compliance with the Nyquist criterion and provides a sufficiently high sampling rate. It has been selected to meet the $BER < 10^{-3}$ requirement for FBMC.

Three rays reach the receiver. The first is the line-of-sight (LOS) path, while the other two arrive with delays. The second ray has a delay of 50 ns, and the third ray has a delay of 100 ns. Considering that the rays travel at the speed of light, the second ray travels 15 meters and the third ray travels 30 meters.

$$distance = c \cdot t \tag{4.2}$$

In the Equation 4.2, we can see how the distances of each ray are calculated, where c is the speed of light in air ($3{\cdot}10^{8} m/s$) and t is the time in seconds that it takes to reach the receiver.

Depending on the path, the signal is attenuated “Average Path Gains”. Signals arriving with greater delays tend to experience more attenuation due to the longer distance traveled and potential additional obstacles along their path.

4.2.2 Rural Environment

In rural environments, although there are fewer dense structures, you can still experience phenomena that we see in the indoor scenario. Obstacles such as trees, hills, or isolated buildings can cause reflection and diffraction. However, due to the lower density of obstacles, multipath fading tends to be less severe compared to urban and indoor environments, but can be more unpredictable due to the variety in geography and vegetation.

Path Delays	Average Path Gains
0	0 dB
100 ns	-15 dB
300 ns	-25 dB

Table 4.3 Parameters of rural channel

In this channel, a sampling frequency of $FsFBMC$ (see equation 4.1) is more than enough to create an efficient system. Three signals will arrive at the receiver: one with a direct line-of-sight (LOS) path and the other two with delays.

Based on Equation 4.2 from the previous section, the distance traveled by each ray can be calculated using the delay values provided in Table 4.3. It is also important to note the attenuation of each signal. The greater the delay, the more attenuated the signal becomes upon arrival.

As I mentioned at the beginning of this section, compared to the indoor channel, there are fewer obstacles in this channel, but the distances are greater, which causes more delay and attenuation.

4.2.3 Urban Environment

In urban environments, signals can bounce off tall buildings, narrow streets, vehicles and other complex structures, creating multiple paths to the receiver due to reflections and diffractions. Multipath fading is particularly pronounced in these environments because of the abundance of reflective surfaces and obstacles. Although less severe than in an indoor environment, it is more significant than in a rural environment.

Path Delays	Average Path Gains
0 ns	0 dB
200 ns	-20 dB
500 ns	-30 dB

Table 4.4 Parameters of urban channel

As in the rural scenario, a sampling frequency of Fs (see Equation 4.1) is adequate to obtain a scenario with good performance for both systems (OFDM and FBMC).

In Table 4.4, we observe one direct line-of-sight ray from the transmitter to the receiver, along with two delayed rays: one with a distance of 60 meters and the other with a distance of 150 meters (refer to Equation 4.2 for distance calculations). The corresponding attenuations for these rays are -20 dB and -30 dB, respectively.

5. Simulation and results

In the following sections, the relationship between BER and SNR, latency, performance, and spectral efficiency will be evaluated for each scenario. Additionally, the system will assist in determining the optimal parameters for each modulation scheme (OFDM and FBMC) to ensure the best performance under various conditions. Finally, the most efficient modulation for each scenario will be identified.

It is important to note that, for sections 5.3 and 5.4, I have used the same number of subcarriers in both FBMC and OFDM, to ensure that both systems occupy the same bandwidth. This causes the number of symbols in FBMC to double due to the OQAM modulation, which allows a more efficient distribution of symbols. This occurs because each subcarrier in FBMC transmits the symbols alternately in time: first the real part, and then with a shift of $\frac{T}{2}$, the imaginary part. Despite the doubling in the number of symbols, FBMC remains competitive thanks to its higher spectral efficiency and the elimination of the cyclic prefix (CP) present in OFDM.

The configurable parameters are those defined in Table 4.1. In *PROGRAM.mlx*, a loop is implemented to iterate through the various parameters, ultimately providing the values that yield the best performance based on the metrics being measured.

For the current study, the system will exclusively use 4-QAM (QPSK) modulation across all scenarios. This choice is based on the observation that other modulation schemes introduced a significant amount of errors in the channel. However, for future research, implementing an equalizer could be beneficial, as it might enable the use of these additional modulation schemes.

For the FBMC simulation, an overlap factor of $K = 4$ was chosen. This value strikes a balance between abrupt frequency roll-off and the duration of the impulse response, as supported by the study in article [14].

It is also important to note that FBMC requires twice as many symbols as OFDM to transmit the same amount of data. This is due to OQAM modulation, which introduces a π/2 offset between the real and imaginary components of the symbols. As a result, the number of symbols required to represent the same data is doubled.

To finalize the system setup, it is important to mention that an LDPC (Low-Density Parity-Check) encoder was incorporated to ensure a robust system. Details about this encoder and its impact on the simulation will be discussed in section 5.2.

5.1 OFDM vs FBMC Spectrum

For the simulation of OFDM and FBMC I followed the article [11], being the *OFDM.m* and *FBMC.m* classes.

One of the most important features of the latest technologies, such as 5G in our case, is the efficiency in the use of the spectrum for data transmission. As frequency bands become increasingly saturated, it is essential to optimize the available spectrum to handle the same amount of information in a smaller space.

Figure 5.1 presents a comparison between the power density spectrum of a signal modulated using OFDM and another using FBMC with an overlap factor K=4. The other values can be found in Table 5.1.

Parameters	OFDM	FBMC
Subcarriers	3240	3240
Guard Band	0	0
Number of symbols	10	20
Modulation	4QAM	4QAM

Table 5.1 Fixed Parameters for spectrum simulation

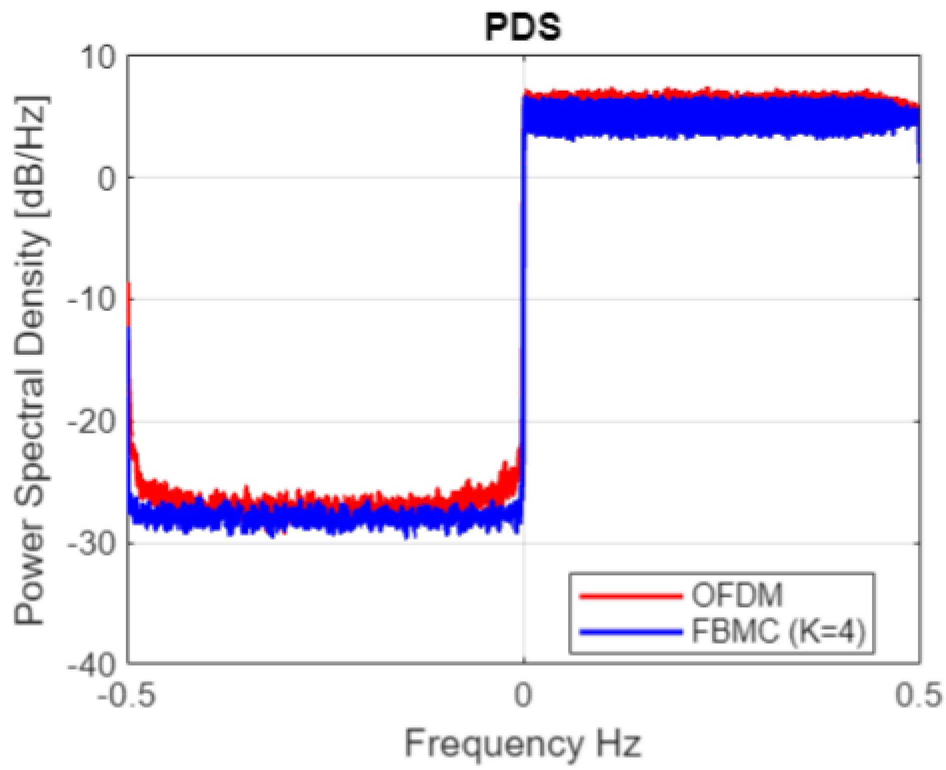


Fig 5.1 Spectrum Comparison between OFDM and FBMC

It is observed that the spectrum of the FBMC signal is more frequency-selective compared to the OFDM spectrum. This occurs because the filtering used by FBMC allows each subcarrier to disperse less energy outside its main band, thereby achieving greater spectral efficiency. In this way, FBMC can use the available bandwidth more efficiently.

In the central band, both modulation schemes exhibit a similar power spectral density, indicating that they can transmit information with comparable power levels.

This frequency selectivity is one of the main advantages of FBMC over OFDM.

5.2 BER vs SNR

The first value to evaluate was the BER as a function of SNR, as this metric is crucial for determining the quality of a system. A system is considered acceptable in terms of quality if its $BER < 10^{-3}$.

It is worth noting that I began the simulations without using any encoder or error correction in the channel. I observed that in any of the three channels, the reception exhibited a high error rate, resulting in a non-viable system (see Figure 5.2).

To address the high error rates observed initially, an LDPC (Low-Density Parity-Check) code [19] was incorporated into the system.

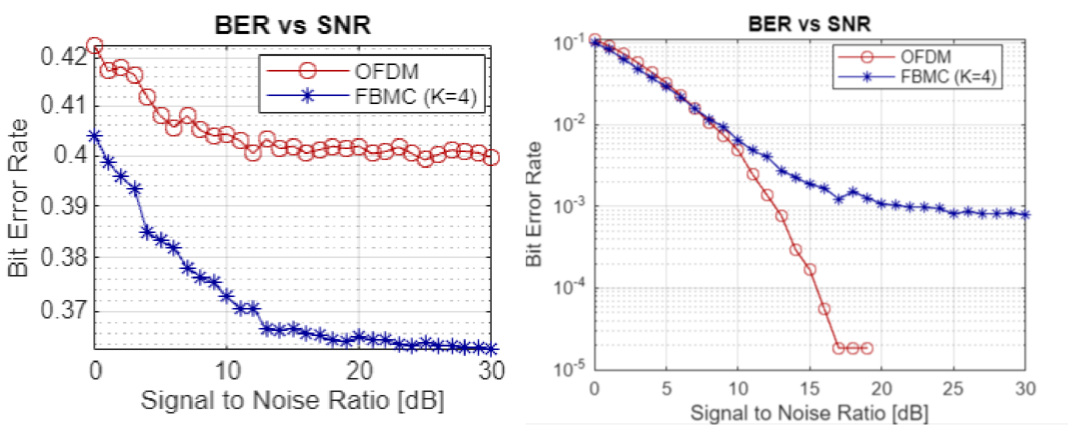


Fig. 5.2 System without LDPC vs. System with LDPC
(with the same values)

LDPC codes use a low-density parity-check matrix, characterized by having fewer ones compared to zeros. This structure reduces redundancy in data transmission, thus improving efficiency. The matrix is generated using algorithms designed to maintain this low density and enable error correction.

During transmission, data is sent along with parity information. This redundancy helps the receiver detect and correct errors. Therefore, upon receiving the data, the receiver uses the parity matrix and decoding algorithms to ensure the integrity of the information [20].

The inclusion of this encoder had a significant impact on the system's quality. The results showed a considerable improvement in the BER, indicating that the system became much more robust against noise and other distortions.

For my system, an LDPC encoder with a code rate of $\frac{5}{6} = 0.8333$ was chosen using the MATLAB function *dvbs2ldpc* to generate the parity-check matrix.

```
ldpcRate = 5/6;
H = dvbs2ldpc(ldpcRate) ;
cfgLDPCEnc = ldpcEncoderConfig(H);
cfgLDPCDec = ldpcDecoderConfig(H);
numCodewordsPerFrame = 1;
codewordLen = cfgLDPCEnc.BlockLength;
msgLen = cfgLDPCEnc.NumInformationBits;
```

Code 5.1 LDPC Implementation in Matlab

This code rate provides an effective balance between efficiency and error correction capability across my different scenarios.

I chose to implement this code rate because using a lower code rate introduced excessive redundancy into the system, which inadvertently increased errors rather than reducing them. The addition of a large number of parity bits resulted in excessive redundant information, which, instead of improving error correction, degraded transmission efficiency. Consequently, a lower code rate proved to be counterproductive to the performance of my system.

The final step before proceeding with the BER versus SNR evaluation for each scenario is to ensure that the same number of bits is generated for both OFDM and FBMC. This number is calculated by multiplying the number of codewords per frame by the message length (See Code 5.2).

```
Data_OFDM = randi([0 1], msgLen*numCodewordsPerFrame, 1);
Data_FBMC = randi([0 1], msgLen*numCodewordsPerFrame, 1);
```

Code 5.2 Generation of bits

Next, I will present the optimal values required for each system in each scenario to achieve the best BER as a function of SNR. Finally, a comparative analysis will be provided to determine which system is the most suitable for each case.

As mentioned earlier, QPSK modulation will always be used, and the study will primarily focus on subcarrier spacing. Therefore, the values shown in Table 5.1 will be fixed for all three scenarios.

The number of guard bands in both cases is zero, as they are not needed in OFDM due to its strong performance in managing inter-carrier interference, and in FBMC, the need for guard bands is eliminated thanks to its advanced filtering design.

For this section, I have chosen to use 20 symbols for FBMC and 10 for OFDM, as this value facilitates the use of a larger number of subcarriers, which in turn helps to improve BER. The benefit arises from the fact that with a greater number of subcarriers, each subcarrier is assigned a narrower bandwidth, which extends the duration of each symbol in time. This extended duration helps to reduce inter-symbol interference (ISI).

However, in the following sections they will be evaluated with different numbers of subcarriers.

In addition, this study will examine how increasing the spacing between subcarriers can reduce inter-carrier interference (ICI). However, this increase in spacing also results in a higher total system bandwidth, which may be disadvantageous if the available spectrum is limited. An increased spacing means that each subcarrier occupies a wider bandwidth, thereby reducing the symbol duration.

In my system, the encoder defines the number of required bits, which totals 64,800. Using Equation 5.1 for OFDM and Equation 5.2 for FBMC, we determine the number of subcarriers, the number of symbols, and the modulation necessary to achieve the required number of bits.

$$Bits\ = Subcarriers \cdot SymbolsOFDM \cdot log_2(MQAM) \tag{5.1}$$

$$Bits\ = \frac{Subcarriers \cdot SymbolsFBMC \cdot log_2(MQAM)}{2} \tag{5.2}$$

Once the parameters in Table 5.1 are defined, the calculation of BER as a function of SNR can proceed (see Code 5.3).

```
[NumErrors, BEROFDM] = biterr(Data_OFDM, decodedBitso);
[NumErrorsFBMC, BERFBMC] = biterr(Data_FBMC, decodedBitsf);
```

Code 5.3 Calculation of BER as a function of SNR

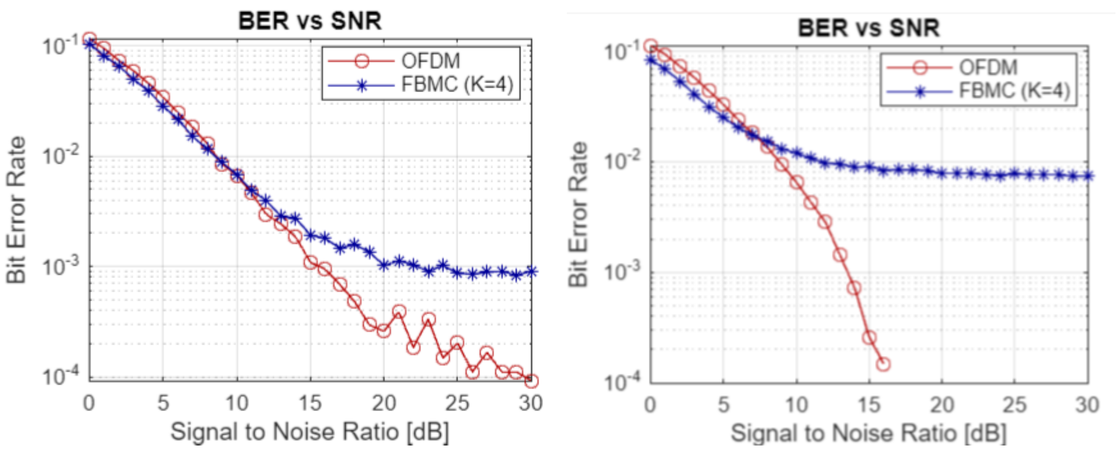
The $biterr$ function is used to count the number of erroneous bits between two data sequences. In this context, $Data\_OFDM$ and $Data\_FBMC$ represent the transmitted data sequences, while $decodedBitso$ and $decodedBitsf$ are the received bit sequences. The function compares these sequences and calculates the BER for each iteration.

5.2.1 Indoor

In this channel, using FBMC requires a very high sampling rate to achieve optimal performance (see section 4.2.1). In contrast, OFDM with a sampling rate of Fs is sufficient to achieve a satisfactory system performance.

This happens because OFDM uses a cyclic prefix, which is more effective at managing channel dispersion without requiring a significant increase in the sampling rate. This increase in the sampling rate for FBMC leads to higher complexity and cost of the system.

In Figure 5.3, the simulation of an indoor channel with the same specifications is shown, varying only the sampling frequency. It can be observed that for a high value, FBMC achieves the necessary performance to be considered a good channel, while for a sampling frequency of Fs, it never reaches the required values ($BER < 10^{-3}$).

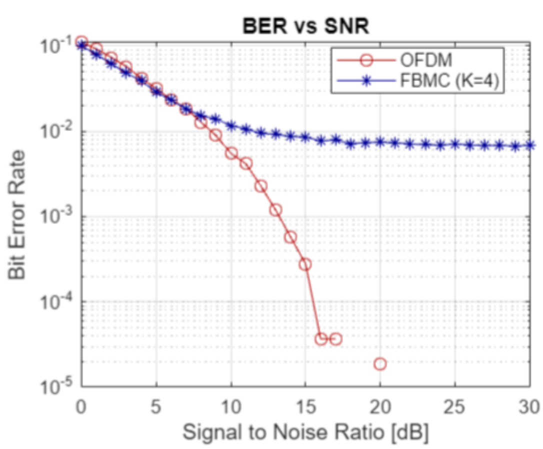
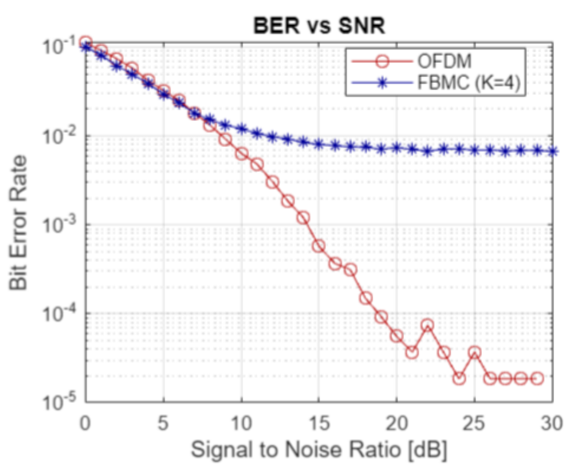


a. Sample rate = Fs·90

b. Sample rate = Fs

Fig. 5.3 BER vs SNR in indoor channel

Once the sampling frequency was defined, several simulations were conducted to test various subcarrier spacing options (15 kHz, 30 kHz, 60 kHz, 120 kHz, and 240 kHz). These simulations were performed to compare the results (see Table 5.2) and thereby determine an accurate BER value for the next sections.

15 KHz	30 KHz
	

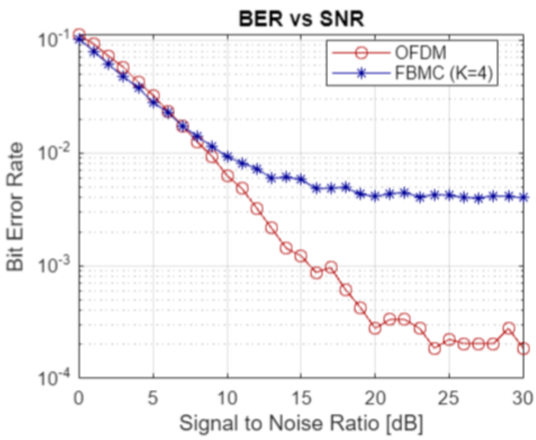
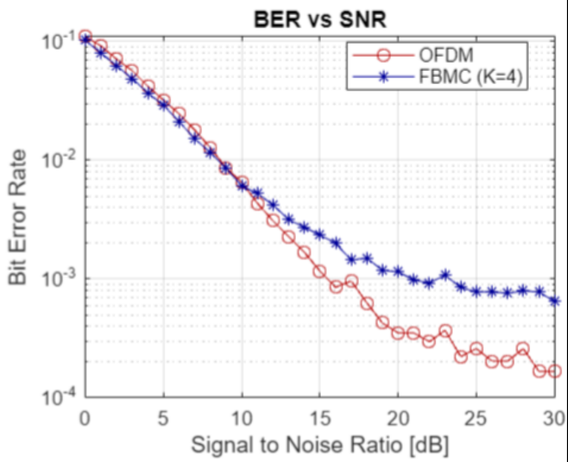
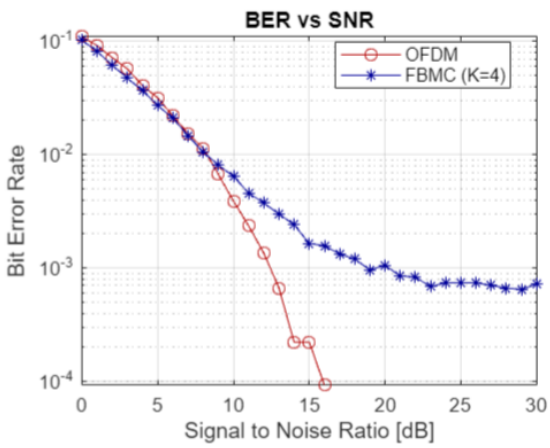
<table>
<tr><th>60 KHz</th><th>120 KHz</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><th colspan="2">240 KHz</th></tr>
<tr><td colspan="2">
</td></tr>
</table>

Table 5.2 Comparison of BER vs. SNR for different subcarrier spacing values in an indoor channel

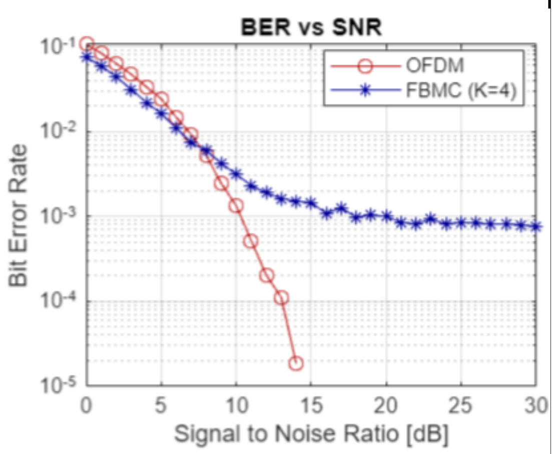
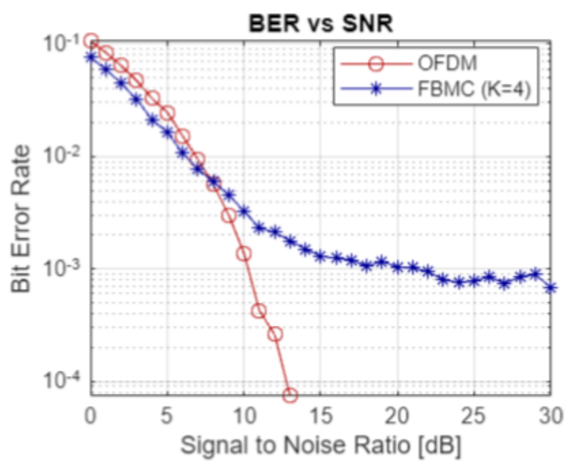
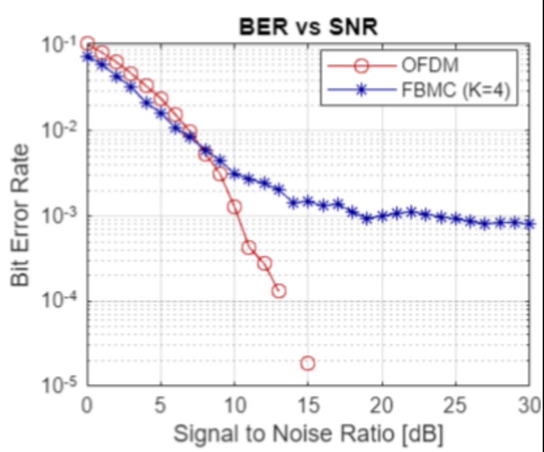
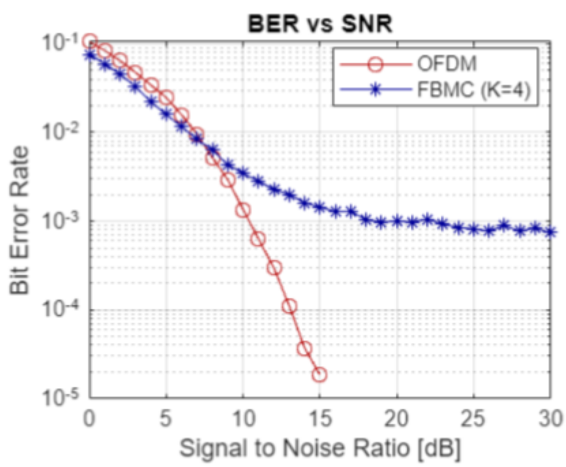
From the graphs in Table 5.2, I concluded that with $\Delta f = 15\, KHz$ and $SNR = 14\, dB$ in OFDM, it is sufficient to achieve good channel conditions in terms of BER. However, FBMC requires up to $\Delta f = 120\, KHz$ and $SNR = 20\, dB$ to achieve a $BER < 10^{-3}$. We can conclude that, when analyzing the BER as a function of SNR and the required sampling rate in an indoor channel, OFDM outperforms FBMC in terms of performance.

For the upcoming measurements, an SNR value of 20 dB will be set for both systems within the indoor channel. This will allow for a fair comparison between them and ensure that both meet the established requirements.

5.2.2 Rural

In the rural channel, both systems operate correctly with a sampling rate of Fs (as shown in Equation 4.1). This contrasts with the indoor channel, where FBMC required a significantly higher sampling rate than OFDM to achieve acceptable performance.

To measure the different BER values as a function of SNR, the same procedures as those used in the previous channel were followed. Various simulations were conducted for all possible subcarrier spacings (15 kHz, 30 kHz, 60 kHz, 120 kHz, and 240 kHz), with the results compared as shown in Table 5.3.

<table>
<tr><td>15 KHz</td><td>30 KHz</td></tr>
<tr><td></td><td></td></tr>
<tr><td>60 KHz</td><td>120 KHz</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">240 KHz</td></tr>
</table>

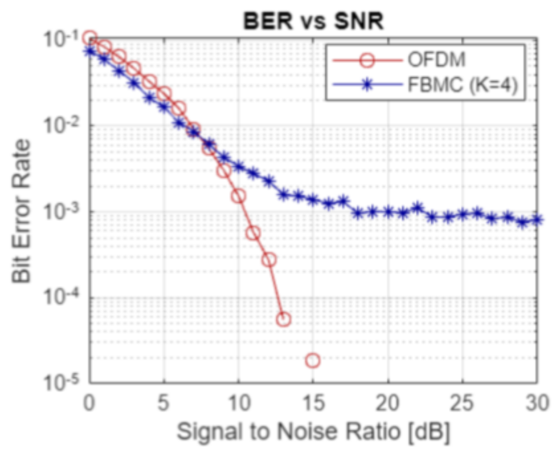


Table 5.3 Comparison of BER vs. SNR for different subcarrier spacing values in a rural channel

In this case, both systems with a $\Delta f = 15\,KHz$ and a $SNR = 19\,dB$ reach a $BER < 10^{-3}$, therefore this SNR value will be the one to be defined in the rural channel for the following steps.

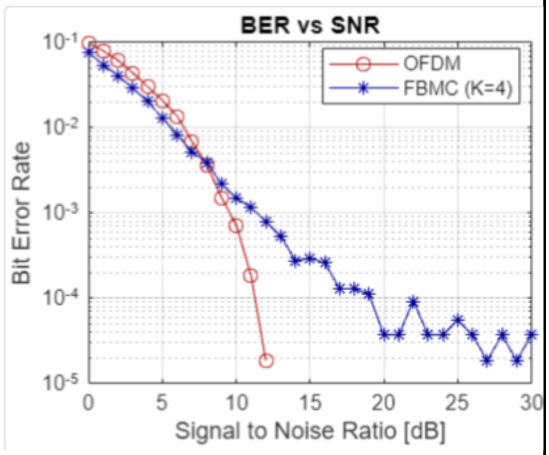
Based on the comparison of BER versus SNR, it can be concluded that OFDM exhibits a slight superiority over FBMC. Specifically, FBMC requires a higher SNR to achieve comparable performance to OFDM.

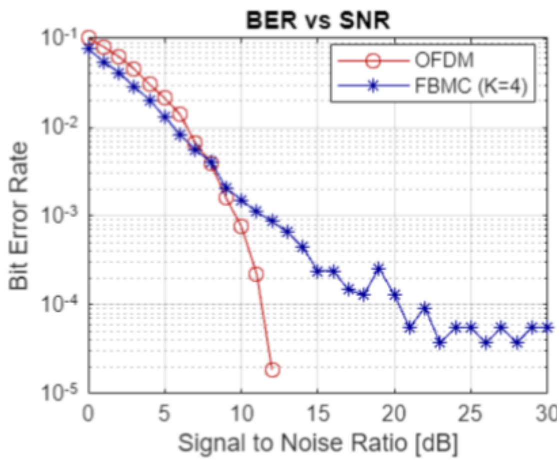
5.2.3 Urban

For the urban channel, as with the rural channel, both systems operate correctly with a sampling rate of Fs (see Equation 4.1).

Table 5.4 below compares different BER vs. SNR plots for different subcarrier spacings (15 KHz, 30 KHz, 60 KHz, 60 KHz, 120 KHz, 240 KHz) in order to define an SNR value where both systems (OFDM and FBMC) reach a $BER < 10^{-3}$ and use it in the following sections.

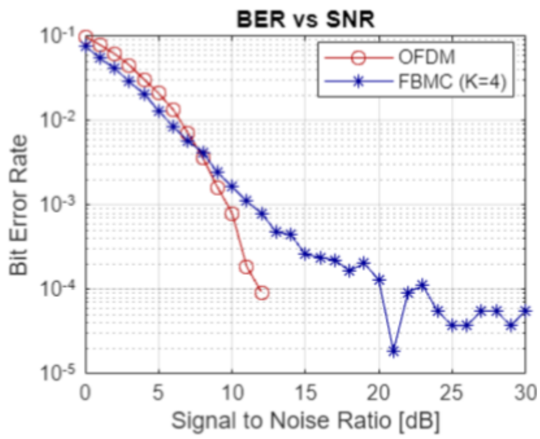
15 KHz	30 KHz

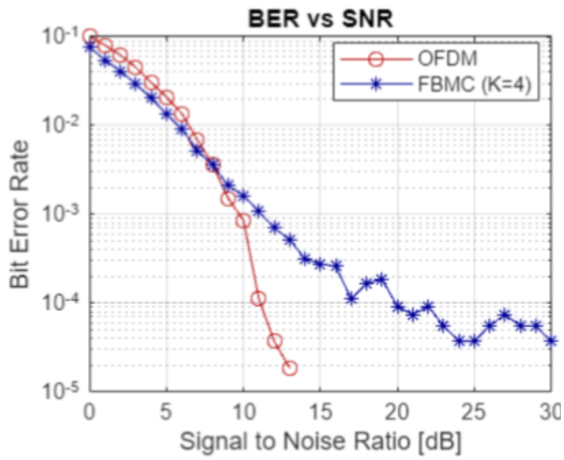




60 KHz

120 KHz





240 KHz

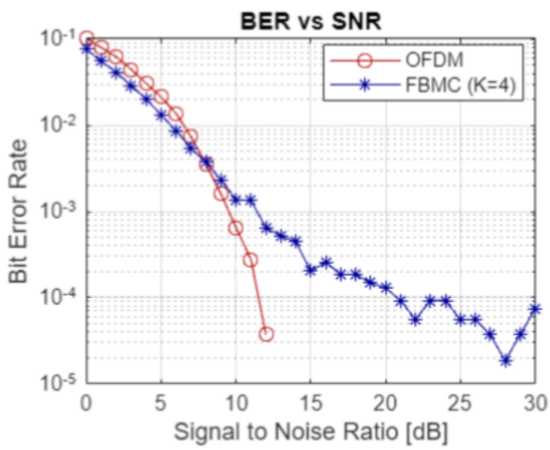


Table 5.4 Comparison of BER vs. SNR for different subcarrier spacing values in an urban channel

In this channel, both systems perform effectively with $\Delta f = 15\,KHz$ (see Table 5.4). It is observed that with an $SNR = 12\,dB$, FBMC achieves the minimum required performance to be considered a viable system. This value will be used for the urban channel in the subsequent measurements.

Comparing the three channels, the urban channel requires the lowest SNR, where FBMC and OFDM offer similar performance in terms of BER.

5.3 Latency

Comparing the latency between OFDM and FBMC helps us understand which of these systems can offer better performance in applications that require fast data transmission and rapid response. This is especially relevant in scenarios that demand real-time communications, such as the Internet of Things (IoT) and high-definition video streaming, where latency plays a crucial role in service quality. In general, latency in 5G networks for IoT applications is expected to be less than 5 ms [21].

Latency in these systems can be influenced by various factors, including processing time at both the transmitter and receiver, the propagation time of the signal through the transmission medium, and any additional delays introduced by intermediate elements such as routers or switches.

To achieve this low latency, it is essential to avoid sending excessively large amounts of data, as a higher volume of data can significantly increase latency. In my system, latency was calculated as the total transmission time for all symbols (see Equation 5.3 and 5.4).

$$latency\_OFDM = NoSymbolsOFDM \cdot t\_OFDM \tag{5.3}$$

$$latency\_OFDM = NoSymbolsFBMC \cdot t\_FBMC \tag{5.4}$$

$NoSymbolsOFDM$ and $NoSymbolsFBMC$ refers to the total number of symbols transmitted for OFDM and FBMC and, t_OFDM and t_FBMC represent the time per symbol for OFDM and FBMC, respectively.

These times are calculated as shown in Equations 5.5 and 5.6.

$$t\_OFDM = \frac{1}{FsOFDM} \cdot \left(\frac{FsOFDM}{\Delta f} + TimeCP\right) \tag{5.5}$$

$$t\_FBMC = \frac{1}{FsFBMC} \cdot \frac{FsFBMC}{2 \cdot \Delta f} \tag{5.6}$$

The term within the parentheses in Equation 5.3 ($\frac{FsOFDM}{\Delta f}$) , represents the number of samples in an OFDM symbol, where Δf is the subcarrier spacing and $FsOFDM$ refers to the sampling frequency. Thus, it can be deduced that as Δf increases, the symbol duration decreases, and consequently, the latency is reduced. However, it is important to note that the expression also includes the number of samples associated with the cyclic prefix, which is added to the total symbol time. Dividing this by the sampling frequency converts the number of samples into a time unit, representing the total duration of the OFDM symbol.

Regarding the calculation of symbol duration in FBMC (Equation 5.6), $FsFBMC$ represents the sampling frequency. The symbol duration in FBMC is determined by the ratio between the sampling frequency and the subcarrier spacing, but is adjusted by a factor of $\frac{1}{2}$. This indicates that the symbol duration in FBMC is shorter compared to OFDM for the same subcarrier spacing, which can reduce latency and improve spectral efficiency.

It is important to note that, so far, the latency calculation has only considered the transmission time of the signal, without accounting for the propagation time through the channel. Therefore, the next step is to incorporate the propagation time for each system, specifically considering the longest path taken by the signal to reach the receiver. This adjustment will be reflected in Equation 5.7 and 5.8, providing a more comprehensive and realistic calculation of the total latency in ms. It should also be noted that the processing time in FBMC systems may be longer due to their higher complexity. However, it has been assumed that the processing capacity is sufficient to handle this complexity without significantly increasing the overall latency. Therefore, the impact of the additional processing time in FBMC has not been included in the latency calculations, as it is considered that it will not affect it in a noticeable way.

$$latency\_OFDM\_total = (latency\_OFDM + Tpropagation)\cdot 1000 \tag{5.7}$$

$$latency\_FBMC\_total = (latency\_FBMC + Tpropagation)\cdot 1000 \tag{5.8}$$

For the indoor channel, the maximum propagation time is 100 ns; for the rural channel, it is 300 ns; and for the urban channel, it is 500 ns. As will be detailed later, these times are relatively insignificant to compare between the three types of channels, but it is a good implementation for future work with more advanced channels. Therefore, only a general table is presented in the report to provide a firm conclusion. However, in the main program, a detailed comparison is made for each channel individually.

The only fixed parameters that will be used are the guard bands, since, as demonstrated in section 5.2, they are not necessary to maintain a good BER vs. SNR ratio, and the modulation type (see Table 5.1). All other parameters will be adjusted to calculate the latency in each specific case. This means that the program will calculate the latency by varying the parameters of subcarrier spacing (Δf) and the number of subcarriers ($NoSubP$). The maximum value of subcarriers will be defined by the 5G specifications (see Table 4.1).

To calculate the number of symbols ($NoSymbolsOFDM/NoSymbolsFBMC$) based on the number of subcarriers, we use Equations 5.1 and 5.2.

$NoSubP$	$NoSymbolsOFDM$	$NoSymbolsFBMC$
162	200	400
324	100	200
450	72	144
540	60	120
648	50	100

810	40	80
900	36	72
1080	30	60
1350	24	48
1620	20	40
1800	18	36
2700	12	24
3240	10	20

Table 5.5 OFDM and FBMC symbols based on subcarriers

It is evident that, for the same number of subcarriers, FBMC requires twice as many symbols compared to OFDM. This occurs due to the nature of the filters and temporal overlap in FBMC. In FBMC, because the symbols are complex, each one only covers half the spectrum that an OFDM symbol would cover on a subcarrier. For example, to cover 1.620 subcarriers, 20 symbols are needed in OFDM, whereas 40 symbols are required in FBMC. This means that, to cover the same number of subcarriers and transmit the same amount of data, FBMC requires twice as many symbols in time compared to OFDM.

The subcarrier values found in Table 5.5 have been incorporated into the main program loop in order to consider a wide range of possibilities along with the different subcarrier spacing values. However, only the most representative examples will be shown below to avoid redundant information.

The comparison is made for 1620 and 900 subcarriers, along with their respective frequency separations. I have chosen these subcarrier counts because their latency values meet the requirements for 5G.

Table 5.6 presents the comparison of latencies for each system.

$NoSubP$	Δf	Latency OFDM (ms)	Latency FBMC (ms)
1620	15 KHz	1.43	1.33
	30 KHz	0.71	0.67
	60 KHz	0.36	0.33
	120 KHz	0.18	0.17
	240 KHz	0.11	0.10

900	15 KHz	2.57	2.40
	30 KHz	1.29	1.20
	60 KHz	0.64	0.60
	120 KHz	0.32	0.30
	240 KHz	0.18	0.17

Table 5.6 Latency with different subcarrier spacings and subcarrier in OFDM and FBMC

To get a more representative view and to visualize more clearly the difference in latency of each system, we have Figure 5.4.

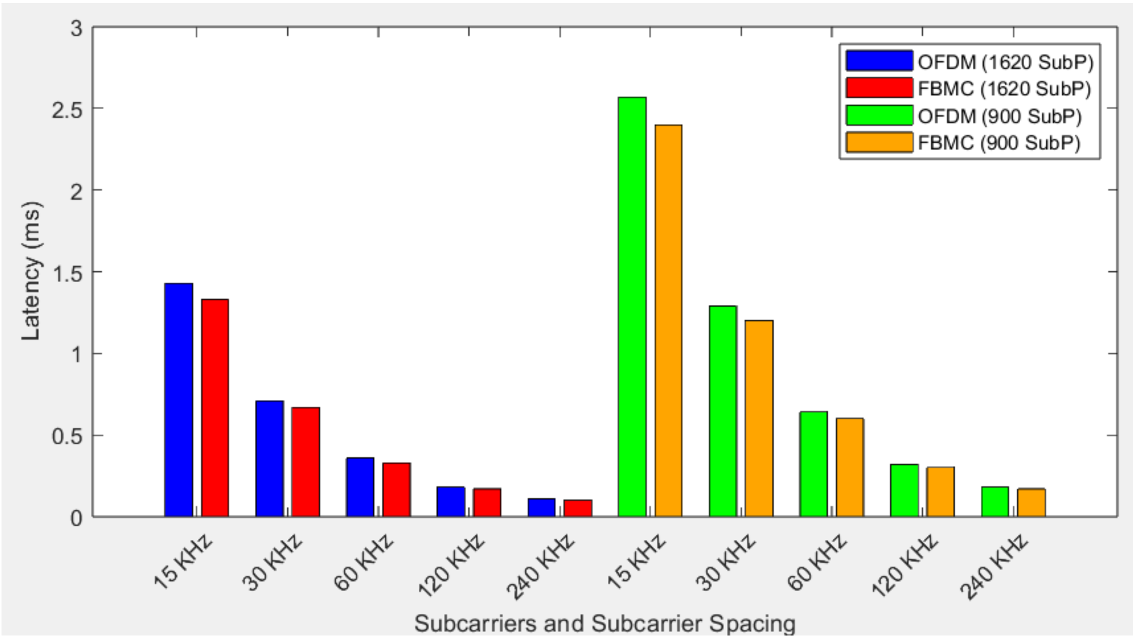


Fig. 5.4 Latency with different subcarrier spacings and subcarrier in OFDM and FBMC

As we can see, the latencies in FBMC are slightly lower compared to OFDM. This difference is more pronounced in configurations with smaller frequency spacings but becomes almost negligible at larger spacings. This suggests that FBMC may offer an advantage in terms of latency, especially in configurations requiring narrower bandwidths, such as in URLLC applications in 5G.

In addition, it is important to note that FBMC transmits twice as many symbols as OFDM, yet achieves lower latency. This reduction in latency is due to the efficiency of FBMC symbol transmission, which eliminates the need for a cyclic prefix and allows for better time-frequency overlap of symbols.

In conclusion, FBMC enables faster data transmission, making it an excellent choice for applications that require very low latency, such as real-time communication, high-definition video streaming, and critical IoT applications.

5.4 Spectral Efficiency and Throughput

In the evaluation of a communication system, two of the most crucial characteristics are spectral efficiency and throughput. These indicators are fundamental for understanding both bandwidth utilization and performance in terms of data transmission. For comparison purposes, the same number of subcarriers was simulated for OFDM and FBMC with the same spacing, as was done in section 5.3.

To calculate these two characteristics, the BER defined for each channel must be considered, as detailed in section 5.2.

Although higher-order modulations can increase spectral efficiency, this study has only utilized 4-QAM modulation. This is because more advanced modulations require additional equalizers, which could be implemented in future studies to further optimize system performance.

Spectral efficiency refers to the amount of information that can be transmitted through a communication channel within a given bandwidth and is expressed in bits per second per hertz (bps/Hz). It measures how efficiently the available frequency spectrum is utilized. Therefore, the higher the spectral efficiency, the more data can be transmitted within the same bandwidth. This is especially useful in environments with high data demand.

Spectral efficiency is calculated as shown in Equation 5.9 for OFDM and Equation 5.10 for FBMC.

$$ef_{OFDM} = (1 - BER_{OFDM})\cdot NoSubP\cdot log_2(MQAM)\cdot \frac{1}{t_{OFDM}}\cdot\frac{1}{BW_{OFDM}} \tag{5.9}$$

$$ef_{FBMC} = (1 - BER_{FBMC})\cdot \frac{NoSubP}{2}\cdot log_2(MQAM)\cdot \frac{1}{t_{FBMC}}\cdot\frac{1}{BW_{FBMC}} \tag{5.10}$$

BER_{OFDM} and BER_{FBMC} refer to the bit error rate for OFDM and FBMC, respectively. Therefore, the first subtraction in the equations represents the fraction of bits that are transmitted correctly.

Next, we find the number of subcarriers for each system multiplied by the modulation. This calculates the amount of data transmitted per subcarrier, where $log_2(MQAM)$ represents the number of bits per QAM symbol. We see that in FBMC the number of subcarriers is divided by two due to the temporal overlap of the subcarriers. This occurs because the subcarriers overlap in the time domain to minimize interference between them, resulting in a reduction of the effective number of useful subcarriers compared to OFDM.

The values of t_OFDM and t_FBMC are calculated in Equations 5.5 and 5.6, respectively, and represent the duration of each symbol. Therefore, they indicate the rate of subcarrier transmission per unit of time.

Finally, the formulas divide the amount of transmitted data by the total bandwidth to obtain the spectral efficiency in bits per Hz.

The calculation of the bandwidth for each system is shown in Equation 5.11.

$$BW = delta\_f \cdot TotalSubcarriers \tag{5.11}$$

$delta\_f$ will be the value of the subcarrier spacing that the program will test at different values and the $TotalSubcarriers$ is calculated by Equation 5.12, which will also vary with the different subcarrier values (see Table 5.5).

$$TotalSubcarriers = NoSubP + 2 \cdot GuardBand \tag{5.12}$$

The final metric to be evaluated will be the amount of data successfully transmitted over a specific period, that is, the throughput in bits per second (bps).

To obtain this value, we multiply the spectral efficiency by the total bandwidth of the system (see Equation 5.13).

$$Throughput = SpectralEfficiency \cdot BW \tag{5.13}$$

The results obtained from the calculations, which include both spectral efficiency and performance, will allow us to evaluate and compare the bandwidth utilization and data transmission speed of each system.

In general, the system that exhibits higher values in these metrics will be the most suitable for applications that require fast and efficient transmission of large amounts of data. Typical examples of such applications include high-speed mobile communications and real-time video streaming.

As previously mentioned in section 5.3, when calculating latency, the main program performs calculations for all the subcarriers listed in Table 5.5. Therefore, the comparisons between the two systems will have the same bandwidth. However, in the subsequent cases, a detailed comparison will be conducted for only two numbers of subcarriers (1620 and 900) per channel to avoid extending the analysis unnecessarily.

In each channel there is a table that shows the values of spectral efficiency and throughput for different configurations of separation between subcarriers (Δf) and number of subcarriers ($NoSubP$) in OFDM and FBMC systems.

The data are organized according to two subcarrier configurations, 1620 and 900, and for each, results are presented for various subcarrier spacings: 15 kHz, 30 kHz, 60 kHz, 120 kHz, and 240 kHz.

As the number of subcarriers and the spacing between them increases, the total bandwidth occupied by the system also increases. However, the increase in throughput is not proportional to the increase in bandwidth used, resulting in a decrease in spectral efficiency. This occurs because, as the separation between subcarriers increases, they become more spread out in the spectrum. Although this may reduce interference between subcarriers, it does not increase the amount of information that can be transmitted. Although a large subcarrier spacing may result in higher bandwidth utilization, it also decreases the BER, which also affects the spectral efficiency calculation.

At the end of each simulation, the program displays on the console the number of subcarriers and the spacing between them that allow the maximum spectral efficiency to be achieved, together with the corresponding value of such efficiency. This is done by means of Code 5.7.

```
MAXeficiencyOFDM = 0;
MAXeficiencyFBMC = 0;

SpacingOFDM=0;
SpacingFBMC=0;

NoSubPortOFDM=0;
NoSubPortFBMC=0;
```

```
if ef_OFDM > MAXeficiencyOFDM
    MAXeficiencyOFDM = ef_OFDM
    SpacingOFDM = TestSpacing;
    NoSubPortOFDM = NoSubP_Data;
end
if ef_FBMC4 > MAXeficiencyFBMC
    MAXeficiencyFBMC = ef_FBMC4
    SpacingFBMC = TestSpacing;
    NoSubPortFBMC = NoSubP_Data;
end
```

Code 5.4 Initial variables and spectral efficiency comparison

We observe how the variables are initialized to zero and, as the code is executed, store the maximum values of the spectral efficiency (MAXeficiencyOFDM/MAXeficiencyFBMC), as well as the spacing between subcarriers (SpacingOFDM/SpacingFBMC) and the number of subcarriers (NoSubPortOFDM/NoSubPortFBMC) that resulted in such maximum efficiency.

5.4.1 Indoor

For the comparison of spectral efficiency and performance in an indoor scenario we have Table 5.7 and Figure 5.5.

$NoSubP$	Δf	Spectral Efficiency(bps/Hz) / Throughput (Kbps) OFDM	Spectral Efficiency(bps/Hz) / Throughput (Kbps) FBMC
1620	15 KHz	1.8669 45365.60	1.9849 48233.70
	30 KHz	1.8667 90719.44	1.9851 96478.20

	60 KHz	1.8658 181351.51	1.9904 193467.60
	120 KHz	1.8658 362716.46	1.9975 388310.40
	240 KHz	1.8669 725849.61	1.9980 776822.40
900	15 KHz	1.8660 25194.40	1.9849 26790.00
	30 KHz	1.8660 50382.27	1.9849 53593.00
	60 KHz	1.8647 100691.76	1.9889 107400.00
	120 KHz	1.8651 201428.30	1.9969 215660.00
	240 KHz	1.8663 403110.42	1.9975 431456.00

Table 5.7 Spectral efficiency and throughput with different number of subcarriers and separations between them in OFDM and FBMC for indoor scenario

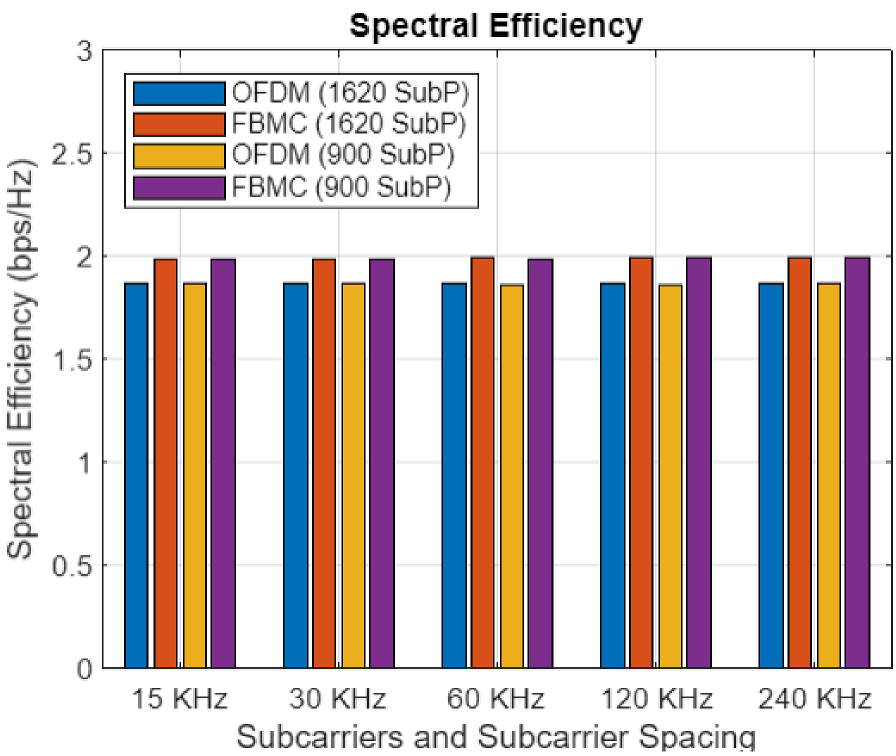


Fig 5.5 Spectral efficiency with different number of subcarriers and separations between them in OFDM and FBMC for indoor scenario

Despite transmitting the same amount of data in the two $NoSubP$ cases, FBMC still shows better performance in terms of spectral efficiency and throughput. This suggests that FBMC is more efficient in the way it uses subcarriers to transmit data, regardless of the number of subcarriers. This may occur, as I explained above, because of the use of the CP in OFDM, since it involves a waste of spectral resources.

OFDM has a constant spectral efficiency around 1,866 bps/Hz, while FBMC has a higher value around 1,984 bps/Hz. This means that FBMC achieves better spectrum utilization, since, per Hz of bandwidth, it can carry more bits compared to OFDM.

Increasing the separation between subcarriers (Δf) helps to reduce BER, as fewer subcarriers close to each other decrease the probability of interference between them and this results in higher practical spectral efficiency, as the system can recover data more accurately, without the need for packet retransmission or error correction. This may justify the increase in throughput that we observe as Δf increases.

The reason why with 900 subcarriers we have less efficiency is because having fewer subcarriers, each one must carry more data, which makes them more susceptible to errors when channel conditions are bad or when there is interference.

The results provided by the principal program are shown in Figure 5.6.

The program is indicating that the maximum spectral efficiency you can achieve with OFDM is 1.8674 bps/Hz, which is consistent with the values we saw in the table. The number of subcarriers (162) and spacing (240 kHz) chosen by the program seem to be an optimal configuration in terms of BER and throughput. Despite having a relatively low number of subcarriers the system achieves an adequate balance between efficiency and reliability.

For FBMC, the program indicates a maximum efficiency of 1,9984 bps/Hz with 3240 subcarriers and a spacing of 240 KHz.

```
RESULTS
OFDM. Máx. efficiency :
    1.8674

With number of subcarriers:
   162

With spacing between subcarriers:
      240000

FBMC. Máx. efficiency:
    1.9984

With number of subcarriers:
        3240

With spacing between subcarriers:
      240000
```

Fig. 5.6 Simulation results in indoor channel

In indoor scenarios, where available bandwidth may be limited and where interference and dispersion are high, increasing Δf has benefits in terms of robustness against interference and BER improvement. However, in a context where bandwidth is a scarce or highly shared resource, taking up more spectrum may be an unnecessary waste, especially if good performance can be achieved with a smaller Δf.

5.4.2 Rural

For the comparison of spectral efficiency and performance in a rural scenario we have Table 5.8 and Figure 5.7.

$NoSubP$	Δf	Spectral Efficiency(bps/Hz) / Throughput (Kbps) OFDM	Spectral Efficiency(bps/Hz) / Throughput (Kbps) FBMC
1620	15 KHz	0.8852 21509.18	0.9443 22947.30
	30 KHz	1.8669 90731.20	1.9981 97106.40
	60 KHz	1.8669 181462.40	1.9978 194184.00
	120 KHz	1.8669 362924.81	1.9974 388303.20
	240 KHz	1.8669 725849.61	1.9978 776750.40
900	15 KHz	0.9040 12203.42	0.9701 13097.00
	30 KHz	0.9105 24582.27	0.9969 26917.00
	60 KHz	1.8663 100777.60	1.9976 107870.00
	120 KHz	1.8663 201555.21	1.9979 215768.00
	240 KHz	1.8663 403110.42	1.9974 431440.00

Table 5.8 Spectral efficiency and throughput with different number of subcarriers and separations between them in OFDM and FBMC for rural channel

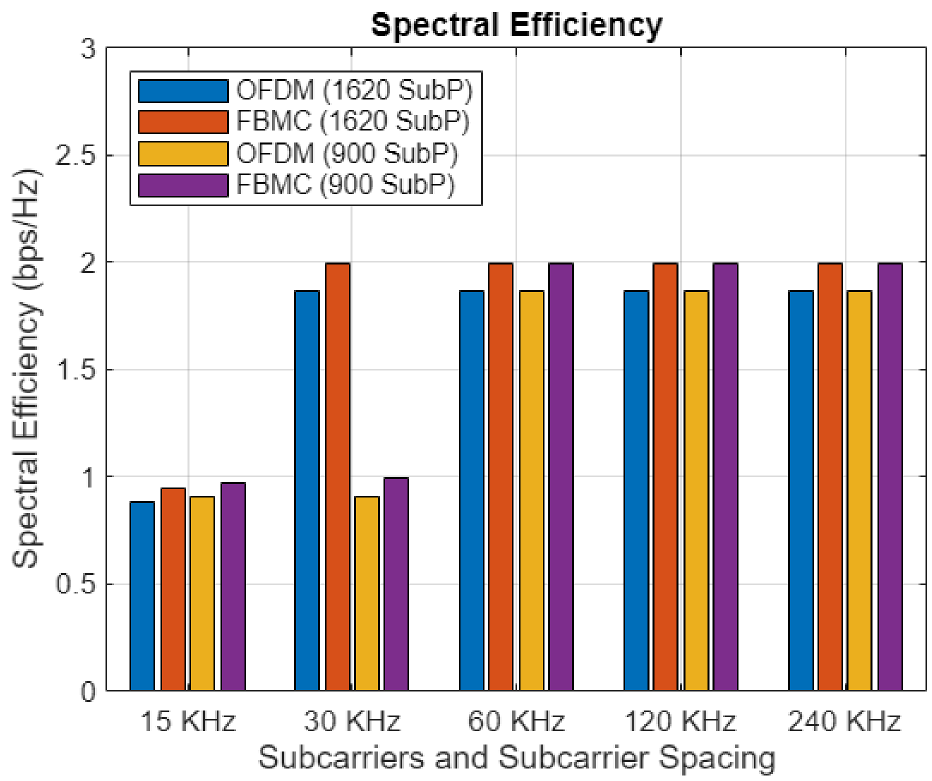


Fig. 5.7 Spectral efficiency with different number of subcarriers and separations between them in OFDM and FBMC for rural channel

From Table 5.8 and Figure 5.7, we can see how for Δf = 15 kHz, there is a clear drop in spectral efficiency, especially in OFDM. This could be a result of channel dispersion, instead, for larger separations between subcarriers ($\Delta f \geq$ 30 kHz), both schemes (OFDM and FBMC) achieve maximum spectral efficiency, but FBMC still maintains a slight advantage.

The results provided by the principal program are shown in Figure 5.8.

We note that for OFDM 162 subcarriers and a Δf of 240 KHz are chosen to achieve maximum spectral efficiency, on the other hand, for FBMC a maximum value of 1.9983 bps/Hz is achieved with 1800 subcarriers and a separation between them of 30 KHz. This shows that FBMC is still more efficient than OFDM in spectrum utilization.

With more subcarriers and a smaller separation between subcarriers FBMC can better distribute the data across the available spectrum, this occurs thanks to the filtering by subcarriers and the elimination of the CP, so you can make better use of the spectrum without having to increase excessively the separation, which also allows to have more subcarriers and therefore greater efficiency.

```
RESULTS
OFDM. Máx. efficiency :
    1.8674

With number of subcarriers:
   162

With spacing between subcarriers:
      240000

FBMC. Máx. efficiency:
    1.9983

With number of subcarriers:
        1800

With spacing between subcarriers:
       30000
```

Fig. 5.8 Simulation results in rural channel

In conclusion, FBMC with smaller subcarrier spacing and the same number of subcarriers is able to achieve better spectral efficiency, since the maximum spectral efficiency achieved by OFDM does not equal FBMC.

5.4.3 Urban

For comparison of spectral efficiency and performance in an urban scenario we have Table 5.9 and Figure 5.9.

$NoSubP$	Δf	Spectral Efficiency(bps/Hz) / Throughput (Kbps) OFDM	Spectral Efficiency(bps/Hz) / Throughput (Kbps) FBMC
1620	15 KHz	1.8666 45358.88	1.9973 48534.30
	30 KHz	1.8666 90716.08	1.9973 97068.60
	60 KHz	1.8666 181432.16	1.9970 194112.00
	120 KHz	1.8664 362830.71	1.9975 388310.40
	240 KHz	1.8667 725755.52	1.9973 776548.80

900	15 KHz	0.9237 12469.36	1 13500.00
	30 KHz	1.8659 50380.40	1.9966 53909.00
	60 KHz	1.8658 100755.21	1.9968 107828.00
	120 KHz	1.8659 201521.62	1.9964 215616.00
	240 KHz	1.8658 403020.84	1.9972 431392.00

Table 5.9 Spectral efficiency and throughput with different number of subcarriers and spacings between them in OFDM and FBMC for urban scenario

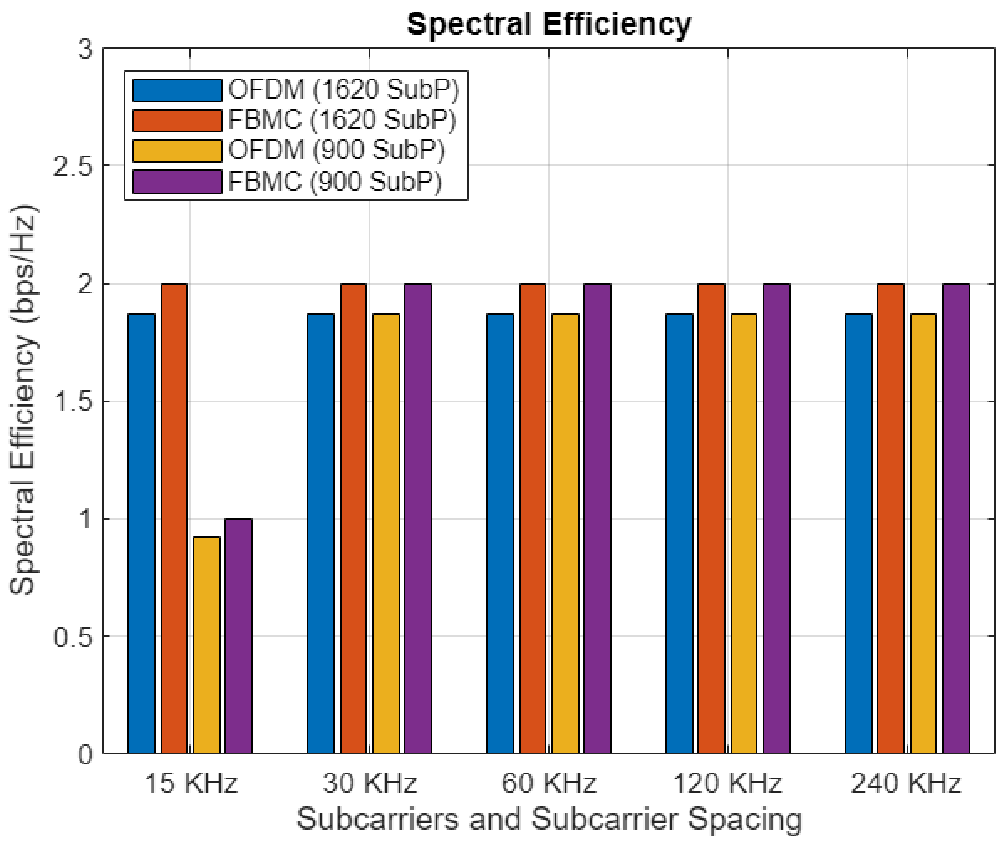


Fig. 5.9 Spectral efficiency with different number of subcarriers and spacings between them in OFDM and FBMC for urban scenario

For an urban environment, as in the case of the other two scenarios, a higher number of subcarriers (1620) tends to offer more spectral efficiency and better performance, since better use is made of the available bandwidth.

As the separation between subcarriers increases, both modulation schemes experience an improvement in performance, being more noticeable in FBMC.

With 900 subcarriers, the spectral efficiency is naturally lower compared to 1620 subcarriers, especially with small separations such as 15 KHz. However, it is still a viable option when the infrastructure cannot support the processing of so many subcarriers or when looking to simplify the network to reduce implementation and processing complexity.

In conclusion, using 1620 subcarriers and maintaining a spacing between 15 KHz and 120 KHz seems to offer the best balance between spectral efficiency and throughput. In this context, FBMC stands out as the most efficient technology to maximize the use of the available spectrum in urban environments, where every Hz of spectrum must be optimally utilized due to high demand.

The results provided by the principal program are shown in Figure 5.10.

The maximum efficiency of FBMC (1.9980 bps/Hz) is higher than that of OFDM (1.8672 bps/Hz). This confirms that FBMC is more efficient in utilizing the available bandwidth, which is consistent with the results in the previous table. FBMC uses significantly more subcarriers (3240) than OFDM (162) to achieve its maximum efficiency. This means that FBMC can handle more subcarriers effectively, which allows it to distribute information more efficiently and improve its performance.

```
RESULTS
OFDM. Máx. efficiency :
    1.8672

With number of subcarriers:
   162

With spacing between subcarriers:
      120000

FBMC. Máx. efficiency:
    1.9980

With number of subcarriers:
        3240

With spacing between subcarriers:
      240000
```

Fig. 5.10 Simulation results in urban channel

6. Sustainability study

6.1 Environmental

The project has a minimal environmental impact, since it is based on computational simulations and does not involve the development of physical hardware. However, in terms of environmental risks and constraints, the use of computing resources may generate energy consumption associated with the execution of the simulations. Although this impact is small compared to other industrial activities, it is important to consider the efficient use of energy resources to minimize excessive consumption.

6.2 Financial

Costs associated with the project include tools such as a personal PC and MATLAB licenses, which are available to students through the university. The economic feasibility plan calls for an initial investment in MATLAB licenses, with the expectation of significant return through improved understanding and optimization of 5G communication technologies.

The project shows high feasibility due to the fact that the research results could have a considerable impact on improving communication networks. However, there are economic risks, such as possible cost overruns related to licenses or hardware, and the possibility of needing additional resources if the simulations require more time or computational power than anticipated.

6.3 Social

The project has the potential to positively impact professional and academic development by improving skills in data analysis, simulation and advanced communication technologies. This advancement may better prepare participants for future career opportunities in the telecommunications field.

From a societal perspective, the project could contribute to the advancement of 5G communications technology, offering benefits such as improved connectivity and greater efficiency in various contexts. The comparison between OFDM and FBMC can facilitate a deeper understanding and optimization of these networks, which would positively impact the application of these technologies.

The social risks associated with the project are minimal, since it does not involve direct interactions with society. However, the reliance on technology and the development of new solutions could influence technological accessibility in different areas.

7. Conclusions

Throughout this study, different key factors for new technologies such as BER, latency and spectral efficiency have been evaluated for two different schemes (OFDM and FBMC) for different scenarios: indoor, rural and urban.

Regarding BER versus SNR measurements, both in rural and urban channels, similar characteristics are observed. In these cases, both FBMC and OFDM, using the same sampling rate and the same spacing between subcarriers, achieve satisfactory BER values. However, in the indoor channel, FBMC requires a higher sampling rate and subcarrier spacing than OFDM to achieve BER values that are considered adequate. In addition, it is important to note that FBMC requires a slightly higher SNR value than OFDM in all three scenarios to obtain a $BER < 10^{-3}$. This difference may be due to the cost associated with FBMC filters, the complexity of their implementation, filter synchronization and adaptation to noisy environments.

In terms of latency, FBMC stands out as the best option in all channels analyzed. This may be because OFDM uses a cyclic prefix, which introduces additional latency resulting in higher values compared to FBMC. This difference is particularly relevant in the context of 5G URLLC communications, where low latency is a fundamental requirement to ensure reliability and performance in critical applications such as industrial networks, telemedicine and autonomous vehicles. However, it is important to note that in environments such as the rural channel, where channel conditions are generally more stable and predictable, latency may not be as critical as in urban or indoor environments.

In terms of spectral efficiency and throughput, FBMC also shows higher values in all cases analyzed. This could be due to the fact that the filters in FBMC allow a more efficient spectrum utilization compared to OFDM. In the urban environment, where user density is high and spectrum complexity demands high spectral efficiency, FBMC presents itself as a promising alternative.

It is important to emphasize that the choice between OFDM and FBMC should be based on the specific needs of the environment and its purpose, as OFDM is cheaper and less complex to implement, although there is little difference in the modulation and demodulation steps between the two systems so hardware components could be reused. Therefore, if cost is a critical factor, OFDM may be the better choice.

7.1 Future Work

From the MATLAB code provided, it is possible to reproduce the results obtained and explore various improvements to the system. Among the improvements to be considered is the implementation of equalizers, which can optimize the system conditions by compensating for distortions and fading in the channel. This optimization would allow the incorporation of higher order modulations, such as 16QAM, 64QAM or 256QAM, which could maximize the transmission rate and provide a better understanding of the capabilities and limitations of the FBMC system in high demand scenarios.

This approach will not only optimize the current system, but will also contribute to the advancement of knowledge about the applications and future potential of FBMC technology.

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ANNEX

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% MAIN PROGRAM that calls OFDM.m and FBMC.m classes for the simulation
%of 3 different scenarios to compare different waveforms.
%Author: Andrea Crespo Caballero. Universitat Politécnica de Catalunya
%Contact: andrea.crespo@estudiantat.upc.edu
%Description: This code compares BER, latency, spectral efficiency
%and throughput for OFDM and FBMC in three different scenarios
%(indoor, rural and urban). At the end of each simulation, the
%program indicates with which subcarriers and with which spacing
%between them OFDM and FBMC reach the maximum efficiency.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear;
close all;

% Channel type
disp('Select the channel type:');
disp('1. Indoor');
disp('2. Rural');
disp('3. Urban');
tipoCanal = input('Enter the channel type number: ');

%Variables initialization
minBER = 1;
minBERSP = 0;

minBERFBMC = 1;
minBERSPFBMC = 0;
```

```
MAXeficiencyOFDM = 0;
MAXeficiencyFBMC = 0;

SpacingOFDM=0;
SpacingFBMC=0;

NoSubPortOFDM=0;
NoSubPortFBMC=0;

%loop
for NoSubP_Data = [162, 324, 450, 540, 648, 810, 900, 1080, 1350, 1620,
1800, 2700, 3240]
for TestSpacing = [15e3, 30e3, 60e3, 120e3, 240e3]

  % Define LDPC parity-check matrix H using a standard matrix
  ldpcRate = 5/6;
  H = dvbs2ldpc(ldpcRate) ;
  cfgLDPCEnc = ldpcEncoderConfig(H);
  cfgLDPCDec = ldpcDecoderConfig(H);

  M_QAM = 4; % Modulation order
  NoSubP_DataFBMC =  NoSubP_Data;
  NoSimbolosOFDM = cfgLDPCEnc.BlockLength/(NoSubP_Data*log2(M_QAM));
  NoSimbolosFBMC =
2*cfgLDPCEnc.BlockLength/(NoSubP_DataFBMC*log2(M_QAM));

  No_Repeticion = 1; % Number of repetitions for the simulation
  SNR_dB = 0:1:30;
  NoSubP_x_BGOFDM = 0; % Number of guard subcarriers at the beginning
and at the end
  NoSubP_x_BFBMC = 0;
  NoSubP_Total = NoSubP_Data + 2 * NoSubP_x_BGOFDM; % Total number of
subcarriers OFDM
  NoSubP_TotalFBMC = NoSubP_DataFBMC + 2 * NoSubP_x_BFBMC; % Total
number of subcarriers FBMC
```

```
  delta_f = TestSpacing; % Subcarrier spacing
  Fs = delta_f * NoSubP_Data * 2; % Sampling frequency OFDM
  FsFBMC = delta_f * NoSubP_DataFBMC * 2; % Sampling frequency FBMC
  dtFBMC = 1 / FsFBMC; % Time between samples FBMC
  dt = 1 / Fs; % Time between samples OFDM
  FI = 0; % Frequency shift (for display purposes)
  T_IG = 1 / delta_f * 0.15; % Duration of guarding intervals (s)
  FBMC_Factor_Solapamiento = [2 3 4]; % Overlap factors
  FBMC_PPN = true; % Whether or not a polyphase network (PPN) is used is
specified
  OFDM_CP = 1 / 14 * 1 / delta_f; % Cyclic prefix length (s)


% Create the channel based on the user's selection
switch tipoCanal
  case 1 % Indoor
      rayleighChan = comm.RayleighChannel( ...
          'SampleRate', Fs * 90, ...
          'PathDelays', [0 50e-9 100e-9], ... % Road delays in seconds
          'AveragePathGains', [0 -10 -20] ... % Average dB gains
      );
      i_SNR = 20;
  case 2 % Rural
      rayleighChan = comm.RayleighChannel( ...
          'SampleRate', Fs, ...
          'PathDelays', [0 100e-9 300e-9], ...
          'AveragePathGains', [0 -15 -25] ...
      );
      i_SNR = 19;
  case 3 % Urban
      rayleighChan = comm.RayleighChannel( ...
          'SampleRate', Fs, ...
          'PathDelays', [0 200e-9 500e-9], ...
          'AveragePathGains', [0 -20 -30] ...
      );
```

```
      i_SNR = 12;
  otherwise
      error('Channel type not recognised.');
end
T_propagacion = max(rayleighChan.PathDelays);

% OFDM Object
OFDM = OFDM(...
  NoSubP_Data, ... % Number of data subcarriers
  NoSubP_x_BGOFDM, ... % Number of subcarriers per guard band
  NoSimbolosOFDM, ... % Number of OFDM symbols
  delta_f, ... % Subcarrier spacing (Hz)
  Fs, ... % Sampling frequency (Hz)
  FI, ... % Frequency shift (for visualization purposes)
  OFDM_CP, ... % Duration of cyclic prefix (s)
  T_IG ... % Duration of guard intervals (s)
);

% FBMC with K = 4
FBMC4 = FBMC(...
  NoSubP_DataFBMC,... % Number of data subcarriers
  NoSubP_x_BFBMC,... % Number of subcarriers per guard band
  NoSimbolosFBMC,... % Number of FBMC symbols
  delta_f,... % Subcarrier spacing (Hz)
  FsFBMC,... % Sampling frequency (Hz)
  FI,... % Frequency shift (for visualization purposes)
  FBMC_Factor_Solapamiento(3),... % Overlap factor; 1 = 2, 2 = 3, 3 = 4
  FBMC_PPN... % Implementation of a polyphase network (PPN)
);

N_snr = length(SNR_dB);
BER_OFDM = zeros(N_snr, No_Repeticion);
BER_FBMC4 = zeros(N_snr, No_Repeticion);
```

```
% Define LDPC
numCodewordsPerFrame = 1;
codewordLen = cfgLDPCEnc.BlockLength;
msgLen = cfgLDPCEnc.NumInformationBits;

rng(100);
% Simulation
for i_rep = 1:No_Repeticion

  % Generate the data bits
  Data_OFDM = randi([0 1], msgLen*numCodewordsPerFrame, 1);
  Data_FBMC = randi([0 1], msgLen*numCodewordsPerFrame, 1);

  % LDPC coding
  codewordo = ldpcEncode(Data_OFDM, cfgLDPCEnc);
  codewordf = ldpcEncode(Data_FBMC, cfgLDPCEnc);

  % QAM Modulation
  x_OFDM = qammod(codewordo, M_QAM, 'InputType', 'bit',
'UnitAveragePower', true);
  x_FBMC = qammod(codewordf, M_QAM, 'InputType', 'bit',
'UnitAveragePower', true);

  % OFDM/FBMC MODULATION
  TX_OFDM = OFDM.Modulacion(x_OFDM);
  TX_FBMC4 = FBMC4.Modulacion(x_FBMC);

  snrdB = SNR_dB(i_SNR);

  % Passing the signal through the Rayleigh channel
  chanout_OFDM = rayleighChan(TX_OFDM);
  chanout_FBMC = rayleighChan(TX_FBMC4);
```

```
  % Add AWGN noise to the signal
  RX_OFDM = awgn(chanout_OFDM, snrdB, 'measured');
  RX_FBMC = awgn(chanout_FBMC, snrdB, 'measured');

  % OFDM/FBMC Demodulation
  y_OFDM = OFDM.Demodulacion(RX_OFDM);
  y_FBMC4 = FBMC4.Demodulacion(RX_FBMC);

  % QAM Demodulation
  DataRX_OFDM = qamdemod(y_OFDM, M_QAM, 'UnitAveragePower', true,
'OutputType', 'bit');
  DataRX_FBMC4 = qamdemod(y_FBMC4, M_QAM, 'UnitAveragePower', true,
'OutputType', 'bit');

  % LDPC Decodification
  maxnumiter = 100;
  decodedBitso = ldpcDecode(DataRX_OFDM, cfgLDPCDec, maxnumiter);
  decodedBitsf = ldpcDecode(DataRX_FBMC4, cfgLDPCDec, maxnumiter);

  % BER CALCULATION
  [NumErrors, BEROFDM] = biterr(Data_OFDM, decodedBitso);
  [NumErrorsFBMC, BERFBMC] = biterr(Data_FBMC, decodedBitsf);

  BWOFDM = TestSpacing * OFDM.No.TotalSubport; % Total BW OFDM
  BWFBMC = TestSpacing * FBMC4.No.TotalSubport; % Total BW FBMC

  t_OFDM = OFDM.PHY.TiempoSimb; %  OFDM symbol time
  t_FBMC4 = FBMC4.PHY.TiempoSimb;% FBMC symbol time

 %% SPECTRAL EFFICIENCY
  ef_OFDM = (1 - BEROFDM)*(NoSubP_Data * log2(M_QAM) / t_OFDM) / BWOFDM;
  ef_FBMC4 =  (1 - BERFBMC)*(NoSubP_DataFBMC / 2 * log2(M_QAM) /
t_FBMC4) / BWFBMC;
```

```
  %% THROUGHPUT CALCULATION

  throughput_OFDM = ef_OFDM * BWOFDM*10^-3;

  throughput_FBMC4 = ef_FBMC4 * BWFBMC*10^-3 ;


  %% LATENCY CALCULATION

  latency_OFDM =NoSimbolosOFDM *t_OFDM;  % Total transmission time for
OFDM

  latency_FBMC4 = NoSimbolosFBMC * t_FBMC4;  % Total transmission time
for FBMC


  % Calculate total latency including propagation time

  latencia_OFDM_total = (latency_OFDM + T_propagacion)*1000;

  latencia_FBMC4_total = (latency_FBMC4 + T_propagacion)*1000;


  %% Data printed on the console at each iteration

  %fprintf('BWOFDM: %.0f Hz\n', BWOFDM);

  %fprintf('BWFBMC: %.0f Hz\n', BWFBMC);


  %fprintf('Subcarrier spacing: %.0f Hz\n', delta_f);

  %fprintf('Capacidad OFDM: %.2f bps/Hz\n', ef_OFDM);

  %fprintf('Capacidad FBMC: %.2f bps/Hz\n', ef_FBMC4);


  %fprintf('Throughput OFDM: %.2f Kbps\n', throughput_OFDM);

  %fprintf('Throughput FBMC: %.2f Kbps\n', throughput_FBMC4);


  %fprintf('Latency OFDM: %.2f ms\n', latencia_OFDM_total);

  %fprintf('Latency FBMC: %.2f ms\n', latencia_FBMC4_total);


  %if BEROFDM < minBER

      %minBER = BEROFDM;

      %minBERSP = TestSpacing;

  %end

  %if BERFBMC < minBERFBMC

      %minBERFBMC = BERFBMC;

      %minBERSPFBMC = TestSpacing;
```

```
  %end
 % Comparison to obtain the values giving the maximum spectral
efficiency
 if ef_OFDM > MAXeficiencyOFDM
     MAXeficiencyOFDM = ef_OFDM;
     SpacingOFDM = TestSpacing;
     NoSubPortOFDM = NoSubP_Data;
 end
 if ef_FBMC4 > MAXeficiencyFBMC
     MAXeficiencyFBMC = ef_FBMC4;
     SpacingFBMC = TestSpacing;
     NoSubPortFBMC = NoSubP_Data;
 end

end
clear OFDM;
clear FBMC4;
end
end

%paint the results on the console
disp("RESULTS ");
disp("OFDM. Máx. efficiency :")
disp(MAXeficiencyOFDM);
disp("With number of subcarriers:")
  disp(NoSubPortOFDM);
disp("With spacing between subcarriers:")
  disp(SpacingOFDM);
disp("FBMC. Máx. efficiency:");
disp(MAXeficiencyFBMC);
disp("With number of subcarriers:");
disp(NoSubPortFBMC);
disp("With spacing between subcarriers:");
disp(SpacingFBMC);
```

```
%colors for the chart
ColorOFDM = [1 0 0] * 0.7;
ColorFBMC4 = [0 0 1] * 0.6;
%% Plot BER vs SNR
%figure;
%semilogy(SNR_dB, mean(BER_OFDM, 2), 'o-', 'color', ColorOFDM); hold on;
%semilogy(SNR_dB, mean(BER_FBMC4, 2), '*-', 'color', ColorFBMC4);
%ylabel('Bit Error Rate');
%xlabel('Signal to Noise Ratio [dB]');
%title('BER vs SNR');
%grid on;
% legend
%legend('OFDM', 'FBMC (K=4)', 'Location', 'Best');

%% PSD Parameters
NFFT = 2048; % Number of points on the FFT
window = hamming(NFFT); % Hamming window for spectrum smoothing
noverlap = NFFT/2; % Overlap between segments
f_norm = 1; % Normalized sampling frequency

%% PSD CALCULATION
[psd_OFDM, f] = pwelch(TX_OFDM, window, noverlap, NFFT, f_norm,
'centered');
[psd_FBMC, ~] = pwelch(TX_FBMC4, window, noverlap, NFFT, f_norm,
'centered');

% Convert to dB
psd_OFDM_dB = 10*log10(psd_OFDM);
psd_FBMC_dB = 10*log10(psd_FBMC);

% PSD Graphic
figure;
plot(f, psd_OFDM_dB, 'r-', 'LineWidth', 1.5); hold on;
plot(f, psd_FBMC_dB, 'b-', 'LineWidth', 1.5);
```

```
% Axis adjustments

xlim([-0.5 0.5]);

ylim([-60 10]);

grid on;

xlabel('Frecuency [Hz]');

ylabel('Power Spectral Density [dB/Hz]');

title('Power Spectral Density');

legend('OFDM', 'FBMC (K=4)', 'Location', 'Best');
```