WHY FBMC/OQAM?

In wireless communications the media is dispersive when there is no visual line of sight between the transmitter and the receiver. This results in a channel that induces inter-symbol interference (ISI) giving rise to frequency selectivity. This may become an obstacle to benefit from the MIMO technology developed in narrowband communications, where the media is nondispersive. The strategy of transmitting the information in blocks and equalizing the channel in the frequency domain has been proven to be able to deal with ISI [10–12]. The alternative that consists in equalizing the channel in the time domain may require a digital signal processing speed that is prohibitively high, which makes the solution impractical and unattractive. The block processing described in [10,12] can be implemented in single carrier and multicarrier modulated systems. The idea in both cases hinges on receiving a signal that is expressed as the circular convolution of the channel with the transmitted block. This property is satisfied thanks to the transmission of a cyclic prefix (CP), which should be larger than the most delayed echo of the channel. If don’t, there is inter-block interference (IBI) and the system performance degrades significantly. In the literature, the single carrier and the multicarrier solutions based on the CP transmission are called single carrier frequency domain equalization (SC-FDE) and orthogonal frequency division multiplexing (OFDM), respectively. Both schemes have similar complexity because the same blocks are used. The difference of SC-FDE with respect to OFDM is that the inverse fast Fourier transform (IFFT) is moved from the transmitter to the receiver. As a consequence, in the OFDM case the symbols are detected in the frequency domain. Conversely, the decisions are carried out in the time domain when the SC-FDE scheme is implemented. Hence, the energy of a given symbol is distributed over all the frequency band when the single carrier system is considered. Hence, SC-FDE presents an increased robustness to deep spectral notches, a reduced sensitivity to carrier frequency offsets and a reduced peak to average power ratio (PAPR) when compared to OFDM. Based on this, the SC-FDE scheme seems to be the most attractive solution. However, the system performance can be substantially improved in OFDM if the modulation order and the power allocated on each subcarrier are based on the channel gains. With adaptive modulation and power allocation, the block processing based on the multicarrier concept outperforms the single carrier alternative [13]. It is worth mentioning that the PAPR problem that arise in OFDM can be circumvented by spreading the symbols over all the frequency range by using the discrete Fourier transform (DFT) [14]. As a result, SC-FDE is only suggested by IEEE 802.16. while OFDM has been included in the physical layer specifications of several standards such as: the digital video broadcasting (DVB), the digital audio broadcasting (DAB), IEEE 802.16 and IEEE.802.11. Actually, OFDM is nowadays the most prominent multicarrier modulation. Aside from the ability to mitigate the dispersion of the media, the beauty of OFDM comes from the fact that the end-to-end communication system, which accounts for the transmitter, the channel and the receiver, can be represented as a set of parallel flat fading channels. It must be mentioned that this is the key aspect that enables combining straightforwardly OFDM with MIMO techniques. In this sense, OFDM can benefit from the theory developed in MIMO narrowband systems. Nevertheless, the orthogonality conditions, which enable independently processing each subcarrier, hinge on shaping the subcarrier signals with the rectangular window along with transmitting redundancy in the form of a CP. This highlights that OFDM presents several limitations, which are listed below:

- The CP transmission implies a reduction of the spectral efficiency as well as wastage of power.
- Any time and frequency misalignment between the transmitter and the receiver destroys the orthogonality between subcarriers and, therefore, subcarrier signals leak to unintended subcarriers. Since the rectangular window is characterized to have a sinc-like shape spectrum, the leakage severely degrades the quality of the demodulated data. As a result, it is deemed necessary to achieve a tight synchronization between nodes. The stringent synchronization requirements limit the use of OFDM in dynamic spectrum access networks where nodes are unlikely to be perfectly aligned [15].
• The poor stopband attenuation exhibited by the rectangular pulse obliges the designer to leave empty several subcarriers at the boundaries of the band. Otherwise, the OFDM signal may degrade other services transmitted on adjacent bands.

• The large side lobes that characterize the sinc pulse implies that narrowband interferences will affect several subcarrier signals.

It is obvious that the OFDM disadvantages associated to the rectangular window can be overcome to a significant extent if the subcarrier signals are shaped with well-frequency localized waveforms. The idea of shaping the subcarrier signals with a pulse different from the rectangular window has its origins at sixties. Chang was the first who devised a multichannel transmission system in which amplitude modulated (AM) data is transmitted in parallel by band-limited pulses, [16]. Therein Chang met the orthogonal conditions that resulted in a new set of pulses that enable achieving the maximum data rate in the absence of ISI and inter-carrier interference (ICI). Soon after, Saltzberg in [17] extended the scheme envisaged in [16] and proposed a parallel quadrature amplitude modulation (QAM) transmission. The modification consisted in staggering in-phase and quadrature components of symbols drawn from a QAM constellation. It must be mentioned that both schemes achieve the same bandwidth efficiency since a partially spectrum overlapping between adjacent channels is permitted. However, neither Chang’s nor Saltzberg’s transmultiplexer (TMUX) was regarded as a candidate in transmission data systems. Single channel transmission schemes were more appealing since they needed far less circuitry. Aiming at reducing the hardware requirements many researchers investigated the possibility of designing an equivalent digital system. In this regard, Bellanger proposed a special structure that combines a polyphase network (PPN) and a digital Fourier processor, [18]. The idea of overcoming the circuit complexity by using the digital Fourier transform (DFT) was further studied by Hirosaki giving rise to a new digital signal processing method, [19]. Therein the Saltzberg’s data transmission scheme was efficiently reformulated in the digital domain. It must be mentioned that Hirosaki’s scheme works with real samples. Even though the digital Fourier processor as well as the PPN process complex data, only the real part of the incoming signal to be fed to the digital to analog converter is extracted. This processing is suitable for baseband applications. However, Coriolaro et al. demonstrated that the sampling rate can be reduced by a factor of two for bandpass transmissions, [20]. To do so, Saltzberg’s scheme is rearranged into a digital virtual complex model. At this point little attention was paid to the inherent discretization of the pulses. The orthogonal conditions originally formulated for continuous-time signals do not hold when the digital model is considered. In this regard Siohan et al. and Bolcskei addressed different approaches to establish the discrete orthogonality in [21] and [22], respectively. It is worth mentioning that Vetterli [23], Vaidyanathan [24] and Karp and Fliege [25], among other authors, have also carried out studies to efficiently implement filter bank-structures.

In the literature the multicarrier schemes that resort to pulse shaping techniques are called filter bank multicarrier (FBMC) systems. These systems are divided into two categories depending on the real or complex nature of symbols. In the complex case the multicarrier signal can be generated according to the filtered multitone (FMT) scheme [26,27], or the generalized frequency division multiplexing (GFDM) scheme [28]. The FMT technique uses frequency confined pulses but the subcarrier signals are not allowed to overlap in the frequency domain. As a consequence, FMT systems fail to achieve the maximum bandwidth efficiency. The spectral efficiency loss is related with the roll-off factor of the pulses in the sense that the higher is the roll-off factor, the higher is the transition band of the pulses and consequently the higher has to be the subcarrier spacing. The GFDM system can be understood as a parallel transmission in several SC-FDE links, which are separated in frequency. Hence, each subcarrier performs a block transmission with a CP. In addition, subcarrier signals can be shaped with the desired waveform independently. Since subcarriers overlap in the frequency domain and waveforms are not orthogonal, the received signals are degraded by ICI. This highlights that the bandwidth of each subcarrier together with the design of the pulses are of paramount importance to control the energy that leaks through non-intended
Despite of this, the GFDM scheme in [29] is considered as a candidate to address the requirements that cognitive radio and machine-to-machine communications introduce to 5th generation cellular networks.

The two techniques that lie into the second category, where transmitted signals belong to the real field, are named staggered modulated multitone (SMT) and cosine modulated multitone (CMT), [30,31]. The CMT and SMT schemes are respectively related to the Chang’s method [16] and the Saltzberg’s method [17]. In this dissertation we focus on SMT, which is also identified with the terminology FBMC/offset quadrature amplitude modulation (FBMC/OQAM) or OFDM/offset quadrature amplitude modulation (OFDM/OQAM). The reason lies in the fact that the low-rate signals multiplexed over each subband belong to the QAM constellation, which is obtained by staggering in-phase and quadrature components of QAM symbols. The approach based on the QAM scheme is gaining momentum because in contrast to FMT, GFDM and OFDM it achieves maximum bandwidth efficiency. That is because no redundancy is transmitted and subcarrier signals can overlap in the frequency domain as described in [17]. This allows reducing the subcarrier spacing when compared to FMT and, therefore, we can increase the number of streams that are frequency multiplexed. In view of this discussion, we have favored the FBMC/OQAM modulation over the others filter bank multicarrier schemes.

It is important to remark that we may improve the system performance of OFDM systems by choosing a signal basis different than that built upon the rectangular pulse. To this end, several techniques to suppress the side lobes can be found in [32–37]. Even though these techniques succeed in reducing the out of band emission, the implementation complexity may increase and the capacity loss in the prefix is not solved. It must be mentioned that if subcarrier signals convey complex valued symbols as it happens in the OFDM context, then there exists a theoretical limit that restricts the factor with which the pulses of the orthogonal basis decay. The authors in [38] show that these limits can be exceeded, thus a faster decay can be achieved, if the symbols are drawn from the QAM constellation, which confirms that FBMC/OQAM is an attractive multicarrier modulation.

In summary, FBMC/OQAM exhibits a low out of band emission while the spectral efficiency is not degraded. Therefore, the FBMC/OQAM has the key features that are needed to transmit in a fragmented spectrum or in networks where tight synchronization cannot be attained. This may tip the balance towards FBMC/OQAM when designing the air-interface in networks where different systems coexist in the same bandwidth. With that being said, the FBMC/OQAM-based air interface can be considered as a possible candidate for future wireless communications. Therefore, it is of paramount importance to demonstrate that the FBMC/OQAM scheme can benefit from the additional degrees of freedom provided by the spatial dimension. It is well-know that if the channel frequency selectivity is not appreciable in the frequency range of at least one subchannel, then some of the pre- and post-processing techniques originally devised for OFDM can be applied to FBMC/OQAM without destroying the orthogonality. However, the applicability of FBMC/OQAM to MIMO communication systems is a non-trivial task when the channel is frequency selective at the subcarrier level. Under this assumption the orthogonality between subcarriers is destroyed and the data symbols leak to unintended slots and subcarriers. As a consequence, the demodulated signals are affected by ISI, ICI and inter-antenna interference (IAI). In the light of the above discussion along with the characteristics of the QAM, we can assert that in general the optimal MIMO precoding and decoding matrices originally devised for OFDM systems are not optimal for FBMC/OQAM. Therefore, the reasons that motivate us to devise signal processing techniques specifically thought for the FBMC/OQAM modulation are twofold:

• The channel may induce interference and, therefore, aside from the noise the received signal may be degraded by ICI, ISI and IAI.

• The QAM symbols only convey information in a single dimension.
The first point reveals that the loss of orthogonality has to be considered. The second point indicates that the real and imaginary parts of the received samples have to be independently processed so that all the second order statistics come into play. This way of performing can be viewed as a special case of widely linear processing (WLP) when the variables to be estimated are real-valued [39]. In general, WLP is used to exploit the improperness of data sequences, [40]. In this sense, applications of WLP include: prediction [41], multiuser detection with improper multiple access interference [42], suppression of rotationally variant residual multiuser interference [43], equalization [44], equalization for STBC transmission [45, 46], single antenna interference cancellation for global system for mobile communications [47,48], transceiver structure employing widely linear filters [49,50], multiple antenna interference cancellation [51] and improper signaling on the interference channel [52].

Since the aim of this thesis is to provide insight into the design of filter bank multicarrier and multiantenna systems based on OQAM, it is deemed necessary to take into account the issues that have been previously raised. In the European Union’s 7th Framework Project PHYDYAS [53] some light has been casted into the design of FBMC/OQAM systems. However, some areas are not fully explored yet and there is room for improvement. In this sense, next section briefly introduces the research areas that have been studied in this thesis.
BIBLIOGRAPHY


