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Abstract:

This report summarizes the investigations on the use of FBMC for RRM in both ad-hoc and cell-based PMR networks and compare it with alternative CP-OFDM technology. The authors analyze how filter based multicarrier waveforms can reduce the interference between nodes when orthogonality over the whole bandwidth is not provided and the sub bands are not the same. The process to assess the advantages of network and resource management is given. Moreover, to provide solutions to optimize RRM performance in PMR networks using FBMC, some cross-layer approaches are investigated in detail.

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Table of Contents

1. Introduction

This report describes the work carried out within T5.1 "Advantages of filter bank-based multi-carrier (FBMC) for Radio resource management (RRM)" of the EMPhAtiC (Enhanced Multi-carrier Techniques for Professional Ad-Hoc and Cell-Based Communications) project. The focus of the work is therefore on the use of FBMC and its benefits in radio resource management (RRM) in the context of Professional Mobile Radio (PMR) communications with cell-based and Ad hoc based infrastructure.

This report first represents an overview of the proposed PMR concept, including the motivation and the reason why FBMC is a more favorable scheme against OFDM multi-carrier technology. A qualitative analysis of the benefits of FBMC RRM is then conducted. In the literature review, the theoretical analysis and numerical results in the evaluation of the performance of FBMC/OQAM in asynchronous uplink MIMO scenario are represented. On the other hand, the report introduces quantitative analysis of the benefits of FBMC in RRM by using one example in CR networks (it is known that PMR transmissions can be regarded as secondary user services), the mathematical expressions of the interference are then presented. By constructing and solving a power minimization problem, via numerical results it is shown that FBMC has superiority over CP-OFDM in terms of robustness against interferences.

It is described in detail how the proposed PMR concept can be realized with a focus on PMR communications under cellular networks. Basically two approaches are discussed, i.e., relying on the cognitive radio technology and the integration of PMR communications with cellular systems, such as LTE. For each case, potential benefits and possible challenges are elaborated. The state-of-the-art is also introduced and reviewed. Moreover, the difference between the RRM in PMR communications and that in cellular networks, e.g., LTE and LTE-A, is analyzed, where a review of fundamental algorithms for resource allocation problems is provided. It is also pointed out that the more sophisticated RRM mechanism of cellular systems may bring benefits to PMR communications. On the other hand, potential challenges of the corresponding design of RRM algorithms are also highlighted. Furthermore, the advantages of employing FBMC in PMR communications, such as relaxation on synchronization, interference management, spectrum sensing, are also discussed. Previous works on RRM schemes in FBMC-based systems are reviewed, which lays foundation for developing RRM algorithms in the future.

Concentrating on an ad hoc scenario, specific characteristics different from those of a cellular network are first introduced. The challenges, such as the lack of inter-cell interference management and also the asynchronism in the transmissions, are discussed. In order to model the inter-cell interference with multi-carrier techniques, the power spectral density (PSD) is reported as a useful tool for analysis the interference between primary user (PU) and secondary user (SU). However, asynchronous interference between the primary and secondary systems is not considered in the PSD model. In order to address this problem, the use of "Inter-cell interference table" is suggested and the detailed power tables with OFDM and FBMC techniques are given in detail. State-of-the-art resource allocation algorithms in an uplink multiuser scenario with both OFDM and FBMC techniques are also discussed. The numerical results in these works imply that FBMC leads to a higher spectral efficiency in asynchronous cognitive radio networks. In addition, it is also pointed out how these previous works that focus on a cognitive scenario with two cells can be extended to ad hoc networks.

2. Use of FBMC in PMR networks

2.1 Proposed future PMR concept

Radio communications systems are deployed by public safety organizations for usages known as PPDR (Public Protection in day to day mode as well as in exceptional planned events and Disaster Relief in exceptional unplanned events). They correspond to Professional Mobile Radio (PMR) services. Currently deployed PMR networks, such as TETRA, TETRAPOL, and APCO25, only use a small bandwidth, and thus the achievable throughput is quite limited. Hence, they mainly support voice communications and other low data-rate communications. However, there are also very crucial services that require much higher data rates but cannot be supported by current PMR networks. This fact gives rise to the need of upgrading these PMR/PPDR systems such that broadband data communications services can be deployed, enabling the data applications that demand high data rates.

Instead of obtaining new frequency bands and reserving them specifically for PMR services, in this project, we focus on fitting a novel FBMC broadband service within the scarcely available spectrum devoted to PMR systems. In the considered coexistence scenario, the broadband data services are deployed in a channel band that is already occupied by several narrowband PMR channels. As illustrated in Fig. 2-1, to reach a good spectral efficiency without introducing interference between services, the data services with well-contained spectrum are preferred in order to avoid adjacent channel interference. In addition, an even more intriguing approach of upgrading the current PMR systems is to enable the coexistence of PMR communications and modern cellular networks, e.g., LTE. To achieve this, PMR communications can be treated as a secondary service of cellular networks, exploiting the cognitive radio technology. An alternative way that has received a mount of interest recently is to integrate PMR services into cellular networks. All these proposals of upgrading PMR communications call for a multi-carrier scheme that contributes to good spectral efficiency and robustness against timing and frequency misalignments.

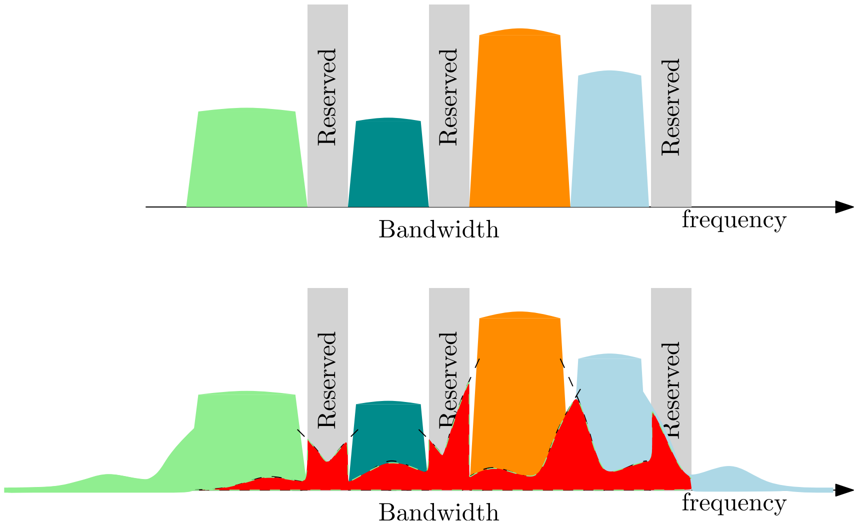

Figure 2-1: Proposed PMR broadband in coexistence and cohabitation with several reserved narrowband services.

The main limitation of the CP-OFDM is the poor spectral containment due to the large side lobes of the OFDM signals. A number of enhancement techniques based on the traditional CP-

OFDM multicarrier scheme have been investigated. The most intuitive solution is to isolate the new services and legacy services with relatively wide guard bands. However, the introduction of guardbands is not preferred due to the waste of valuable bandwidth. In recent years, an extensive number of research activities encourage the use of FBMC scheme as a candidate solutions to isolate the services without compromising system spectral efficiency.

In order avoid interference between frequency adjacent services, instead of using IFFT and FFT with a rectangular window, a set of spectrally well contained synthesis and analysis filter banks is considered in the FBMC/OQAM transmission systems. The in-phase and quadrature components of QAM signal have a time offset of half symbol period. The multicarrier spectral characteristics are determined by the design of prototype filter. The orthogonality can be maintained by designing pulse shapes different from a rectangular window. By introducing FBMC, the side lobes of multicarrier components can be significantly reduced [1].

2.2 Qualitative analysis of the benefits of FBMC for RRM in PMR networks

In this section an introduction of FBMC is given. FBMC features a well-contained spectrum such that by using FBMC, a good spectral efficiency is achieved and the interference between different services is minimized. The behaviors of CP-OFDM and FBMC in asynchronous scenarios in PMR systems are discussed.

In OFDMA systems, a subset of subcarriers is allocated to each transmitter, the subcarriers to be allocated to each transmitter must be scheduled by the resource allocation systems. To facilitate the resource allocation schemes in a multicarrier transmission system, a group of subcarriers is defined as a subchannel. Depending on the pattern of the subcarriers allocation pattern, the resource allocation methods can be classified as block type and interleaved type [1].

In the block type of RRM scheme in the PMR network, each subchannel consists of a set of adjacent subcarriers. The system sum throughput can be improved by allowing the transmitters to choose their preferred subchannels based on their channel conditions as well as the interference level. The benefit of using such a block type of resource allocation is the simplicity of channel estimation, because each block is constructed within the coherence bandwidth. On the other hand, in an interleaved type of resource allocation scheme, the subcarriers are interleaved throughout the whole available bandwidth. In this type of RRM scheme, a problem arise in this case is which the system throughput is subject to the interference level between adjacent subcannels allocated to different transmitters. The side-lobes introduced by CP-OFDM transmission, result in significant interference among subcarriers that originate from un-synchronized nodes. Furthermore, synchronization is not trivial in the uplink where a number of nodes are transmitting separately in PMR networks.

In the case where OFDMA is used, the orthogonality of different users' subcarriers is lost due to time/frequency offsets. The orthogonality can only be ensured if substantial guardbands are inserted. The known radio resource allocation schemes may become inefficient, since interference between nodes will become harder to predict. In order to alleviate the deleterious effects of inter-carrier interference, instead of using IFFT and FFT at CP-OFDM transmitter and receiver, a set of spectrally well contained synthesis and analysis filter banks is considered in the FBMC transmission systems. One of the common approaches is to use modulated uniform polyphase filter banks based on prototype filter design, and the system spectral characteristics are determined by the prototype filter. The orthogonality can be maintained by designing pulse shapes different from a rectangular window. By introducing FBMC, the side lobes of multicarrier components can be significantly reduced [1]. In an FBMC-based PMR network, under the assumption of a sufficiently linear transmission chain, much smaller guardband compared to the case of CP-OFDM is sufficient to isolate different groups of subcarriers and therefore mitigate the interference between different services.

2.2.1 State-of-the-art

In recent years, a growing number of literatures have been reported to analyze the benefits of using FBMC based transmissions for RRM. The authors of [2] consider the resource allocation problem in a MAC channel. The main advantage of FBMC property is explicitly exploited in order to evaluate an asynchronous network where the transmissions from different users are not aligned in time. The improvement of using FBMC is evaluated by means of the rate that can be achieved by dynamically allocating carriers to users. In a more general case, [3] formulates a contiguous dynamic resource allocation problem, a set of throughput estimation metrics are provided. The paper also proposed an algorithm that allocates in each step a contiguous collection of resources to the pending user resulting in the highest estimated throughput. In [4], the FBMC application is then extended to consider cognitive radio networks. In order to maximize the total sum rate without introducing excessive interference to the primary systems, a greedy suboptimal dual decomposition technique is proposed with acceptable complexity. [4] also highlights the advantage of using FBMC in future cognitive radio systems. As mentioned in the previous text, to realize the coexistence of PMR services with other reserved services, one way is to rely on cognitive radio principles which is able to achieve very efficient spectrum utilization. The basic idea is treat broadband PMR communications as secondary systems. Previous works on RRM in cognitive radio networks employing FBMC then provide insights into our analysis of RRM in FBMC-based PMR systems.

2.3 Quantitative analysis of the benefits of FBMC for RRM in PMR networks

In this section, we present a numerical example of RRM in a cognitive radio network considering both FBMC and OFDM, where the benefits that FBMC provides are observed. Here PMR communications are treated as a secondary service. Instead of considering system sum rate [5], the objective is to maximize the Quality of Service (QoS) of the PMR network under power and interference constraints. The subcarrier power spectrum density (PSD) is considered to calculate the interference introduced by the subcarriers to the primary users (PUs) in both OFDM and FBMC configurations, and the mathematical expression of the interference between different services is also presented.

2.3.1 Calculation of the interference

The power spectrum density (PSD) is used to calculate the interference introduced by the subchannels to the primary users (PUs). There are L PU bands, denoted as $B_1, B_2, ..., B_L$. The non-active bands are used by the secondary system. They are divided into N subcarriers, each with a Δf bandwidth. The interference induced to the l^{th} PU band should not exceed the predefined interference temperature limit, I_{th}.

2.3.1.1 CP-OFDM

The power spectral density $\Phi_i(f)$ of the i^{th} subcarrier with CP-OFDM is:

$$\Phi_i^{\text{OFDM}}(f) = |G_i(f)|^2 \tag{2.1}$$

where $|G_i(f)|^2$ is the Fourier transform of the used pulse shape g_T. Assuming a rectangular pulse with the symbol duration T_s is consisting of the information duration $T_U = 1/\mathit{\Delta} f$ and the cyclic prefix (CP) with the length of T_G

$$|G_i(f)|^2 = T_s + 2\sum_{r=1}^{T_s-1}(T_s - r)\cos(2\pi f r) \tag{2.2}$$

2.3.1.2 FBMC

The power spectral density with FBMC is:

$$\Phi_i^{\text{FBMC}}(f) = |H_i(f)|^2 \tag{2.3}$$

where $|H_i(f)|^2$ is the frequency response of the prototype filter. For FBMC, a filter bank created from a prototype filter and the others are generated from shift by $i\mathit{\Delta} f$. Here the insertion of CP is not required as in case of OFDM, leading to an increased spectral efficiency. The coefficients of the prototype filter $h(n) : 0 \le n \le W-1$ are symmetric around the $\left(\frac{w}{2}\right)^{th}$ coefficient, i.e., $h(W/2-i) = h(W/2+i)$, and $h(0) = 0$. Using these properties, the discrete Fourier transform (DFT) is given by

$$H(f) = h(\frac{W}{2}) + 2\sum_{i=1}^{\frac{W}{2}-1} h(\frac{W}{2} - i)\cos(2\pi f i). \tag{2.4}$$

2.3.1.3 Interference Calculation

In a multiple carrier systems such as CP-OFDM or FBMC, the PSDs of the subchannels are identical in amplitude and shifted by multiplies of frequency spacing $\mathit{\Delta} f$. $\Phi_i(f) = \Phi(f - i\mathit{\Delta} f)$. The interference power introduced by the i^{th} subchannel into the l^{th} PU band B_l with center frequency f_{cl} is

$$\begin{aligned} I_i^l &= P_i|g_i^l|^2 \int_{-\frac{B_l}{2}+f_{cl}}^{\frac{B_l}{2}+f_{cl}} \Phi(f - i\mathit{\Delta} f)df \\ &= P_i|g_i^l|^2 \int_{-\frac{B_l}{2}+f_{cl}-i\mathit{\Delta} f}^{\frac{B_l}{2}+f_{cl}-i\mathit{\Delta} f} \Phi(f)df = P_i\Omega_i^l \end{aligned} \tag{2.5}$$

where P_i is the transmit power assigned to the i^{th} subchannel, g_i^l denotes the channel gain, and $d_i = f_{cl} - i\mathit{\Delta} f$ is the spectral distance between the i^{th} and the l^{th} PU band. And Ω_i^l represents the interference factor. For power normalization we let $\int_{-\infty}^{+\infty} \Phi(f)df = 1$.

The power spectral density $\Phi_i^{\mathrm{OFDM}}(f)$ of the i^{th} subcarrier with CP-OFDM

$$\Phi_i^{\mathrm{OFDM}}(f) = T_s \left(\frac{\sin(\pi f T_s)}{\pi f T_s} \right)^2 = T_s \mathrm{sinc}(\pi f T_s)^2, \tag{2.6}$$

Considering Nyquist sampling frequency which is equal to the band width $B = N\varDelta f$, then $T_s = M/B$, where M is the number of samples of one symbol. By integrating $\Phi_i^{\mathrm{OFDM}}(f)$ over the interval $[f_1, f_2]$ inside the OFDM band, the interference as a function of the normalized frequency $\nu = \frac{f}{B}$ can be calculated as

$$\begin{aligned} \int_{f_1}^{f_2} \Phi_i^{\mathrm{OFDM}}(f) df &= \int_{f_1}^{f_2} T_s \mathrm{sinc}(\pi f \frac{M}{B})^2 df \\ &= \int_{\frac{f_1}{B}}^{\frac{f_2}{B}} \frac{T_s}{B} \mathrm{sinc}(\pi \nu M)^2 d\nu \\ &= \int_{\nu_1}^{\nu_2} M \mathrm{sinc}(\pi \nu M)^2 d\nu. \end{aligned} \tag{2.7}$$

For FBMC transmission, we use the PHYDYAS prototype filter with the length of $W = 128$. Its coefficients are defined as

$$h(n) = 1 - 1.94392 \cos(2\pi \frac{n}{128}) + \sqrt{2} \cos(4\pi \frac{n}{128}) - 0.470294 \cos(6\pi \frac{n}{128}). \tag{2.8}$$

Therefore, the normalized PSD is computed as

$$\Phi_i^{\mathrm{FBMC}}(f) = \frac{N}{W^2} |H(f)|^2, \tag{2.9}$$

where N is the number of number of sub-channels. Fig. 2-2 shows a comparison between $\Phi_i^{\mathrm{OFDM}}(f)$ and $\Phi_i^{\mathrm{FBMC}}(f)$ for $N = 32$, 6.67% CP in OFDM. The amplitude and frequency are normalized as shown.

2.3.2 Power minimization problem

We now consider the total available system bandwidth B is divided into N sub-channels, a primary network consisting of L active PUs working on frequency band B_l. The secondary network consists of M SUs and secondary base station CBS. In downlink transmissions, CBS can send to SUs in the active and non active sub-channels in a way such that the interference introduced to the PUs is below thresholds I_{th}^l corresponding to each PU. The target is to minimize the utilized power $P_{i,m}$ subject to required sum rate $R_{i,m}(P_{i,m} h_{i,m})$, where $P_{i,m}$ is the transmit power for the m-th SU if it is active on the i-th sub-channel. The channel gain between CBS and SUs is defined by $|h_{i,m}|^2$. One channel can be used by at most one SU. The channel indicator $v_{i,m}$ is 1 when the channel i is used by SU m. The interference by PUs is considered as additive white Gaussian noise (AWGN) and implicitly included in the noise

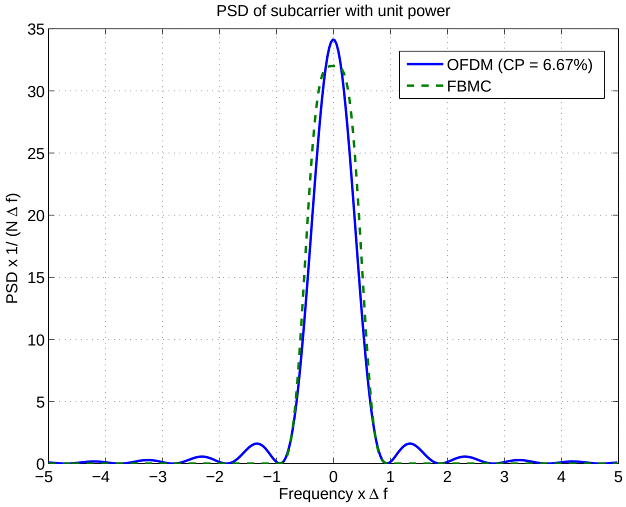

Figure 2-2: Single subchannel PSDs of the OFDM and FBMC systems vs. normalized frequency.

variance. The optimization problem can be formed as follows:

$$
\begin{aligned}
P1: \quad \min_{P_{i,m}, v_{i,m}} \quad & \sum_{m=1}^{M}\sum_{i=1}^{N} v_{i,m} P_{i,m} && (2.10)\\
\text{subject to} \quad & v_{i,m} \in \{0,1\}\\
& P_{i,m} \geq 0\\
& \sum_{i=1}^{N} v_{i,m} \leq 1\\
& \sum_{m=1}^{M}\sum_{i=1}^{N} v_{i,m} P_{i,m} \Omega_i^l \leq I_{th}^l, \forall l \in \{1, \cdots, L\}\\
& \sum_{m=1}^{M}\sum_{i=1}^{N} v_{i,m} R_{i,m}(P_{i,m}, h_{i,m}) \geq R, && (2.11)
\end{aligned}
$$

where R is the required sum rate. The rate of SU m on sub-channel i is defined as

$$
R_{i,m}(P_{i,m}, h_{i,m}) = \frac{1}{BT_s} \log_2(1 + \frac{|h_{i,m}|^2 P_{i,m}}{\sigma^2}) \quad \text{bit/s/Hz}, \tag{2.12}
$$

where σ^2 is the variance of AWGN and the approximation of the interference power introduced by PUs. Note that in case of OFDM, $BT_s = M > N$ due to the insertion of the CP, while for FBMC $BT_s = M = N$.

P1 is a mixed-integer programming (MIP) problem which is in general NP-hard. If the subchannel assignment $v_{i,m}$ is fixed, the resulting problem simplifies to

$$\begin{aligned} P2: \quad \min_{P_{i,m}} \quad & \sum_{m=1}^{M} \sum_{i=1}^{N} v_{i,m} P_{i,m} && (2.13) \\ \text{subject to} \quad & P_{i,m} \geq 0 \\ & \sum_{m=1}^{M} \sum_{i=1}^{N} v_{i,m} P_{i,m} \Omega_i^l \leq I_{th}^l, \forall l \in \{1, \cdots, L\} \\ & \sum_{m=1}^{M} \sum_{i=1}^{N} v_{i,m} R_{i,m}(P_{i,m}, h_{i,m}) \geq R, && (2.14) \end{aligned}$$

P2 is a convex problem which can be solved using the standard interior-point algorithm. Therefore, we resort to a sub-optimal problem P2 to avoid the complicated combinatorial problem. The $v_{i,m}$ is decided by assigning the ith subchannel to the mth SU which has the strongest channel gain, i.e., $m = \arg\max_{m} |h_{i,m}|^2$.

2.3.3 Simulation results

The proposed method is evaluated using Monte Carlo methods. There are $N = 32$ subchannels, $M = 3$ SUs and $L = 2$ PUs. Each PU has an active band which consists of 6 subchannels and they are centered at the frequency $f_{c1} = 8\Delta f$ and $f_{c2} = 24\Delta f$, correspondingly. The CP time of OFDM $T_G = T_U * 6.67\%$. The prototype filter in 2.8 is used for FBMC. The noise variance is set to $\sigma^2 = 10^{-6}$. The generated channel is a Rayleigh flat fading channel and all the simulation results are averaged over 500 channel realizations.

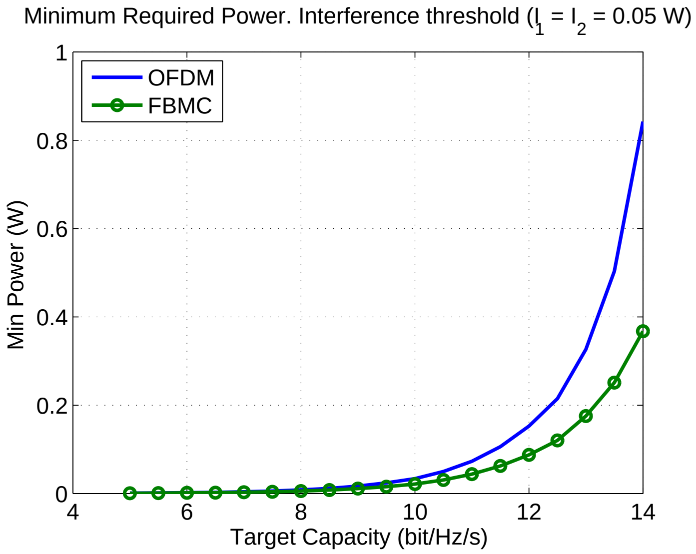

Figure 2-3: Minimum required transmit power vs. target data rate. $I_{th}^1 = I_{th}^2 = 0.05$ W.

Fig. demonstrates the minimum required transmit power as a function of the interference threshold, which is fixed to $I_{th}^1 = I_{th}^2 = 0.05W$. Clearly, FBMC outperforms OFDM as the required data rate increases. Moreover, the number of infeasibility runs for OFDM will increase dramatically when R is high. This become more obvious in Fig. 2-4. By varying the interference threshold while fixing R, a strong infeasibility is demonstrated as the interference constraint is stringent.

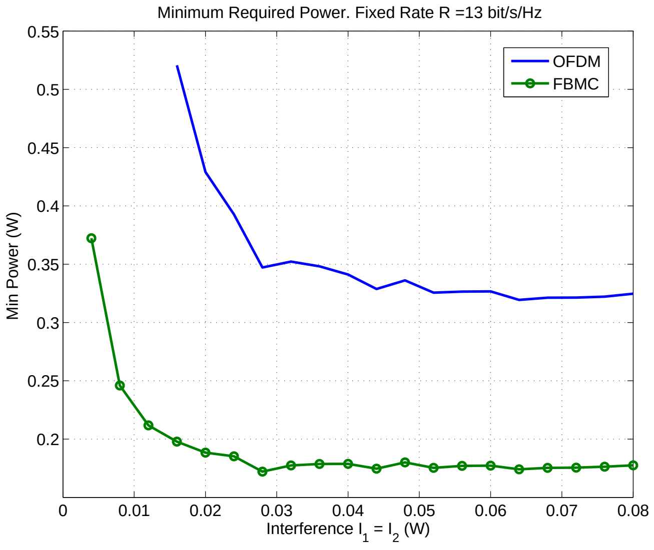

Figure 2-4: Minimum required transmit power vs. interference threshold. $R = 13$ bits/s/Hz.

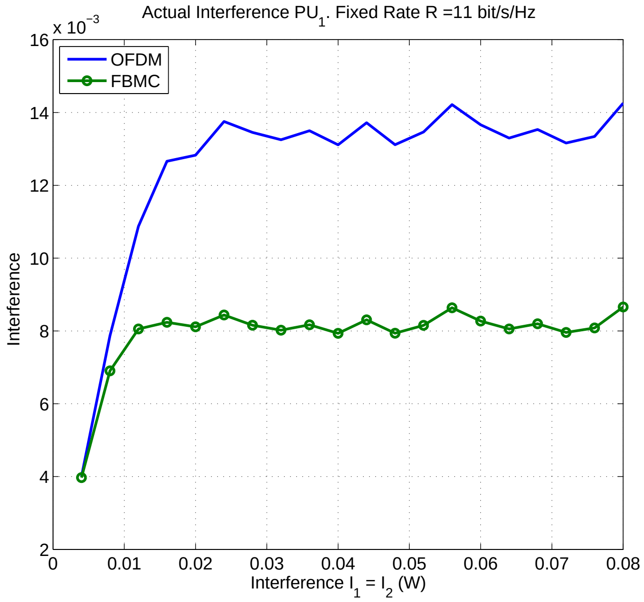

Figure 2-5: Total interference introduced to the PU1 vs. interference threshold. $R = 11$ bits/s/Hz.

Fig. 2-5 and Fig. 2-6 illustrate the total interference introduced to PU1 and PU2 as a function of the interference threshold. The interference which is imposed onto the active band of the PU grows logarithmically with respect to the interference threshold. Moreover, FBMC causes less interference than OFDM regardless of the interference threshold.

We have evaluated the performance of OFDM and FBMC in a cognitive radio network. The evaluation in term of the power required to achieve predefined rate. We find that FBMC outperforms OFDM in the amount of power requirement and the level of interference. The PSD of FBMC while it has almost no side lobes behind this performance. Another factor is

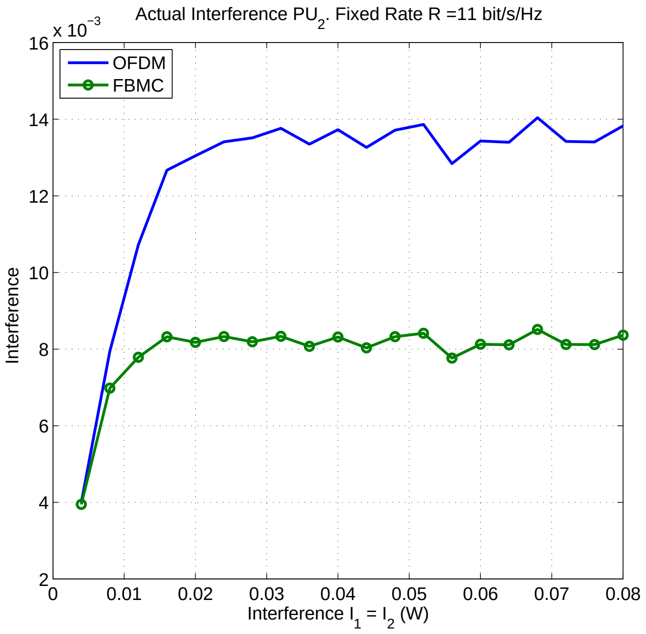

Figure 2-6: Total interference introduced to the PU2 vs. interference threshold. $R = 11$ bits/s/Hz.

that FBMC dose not require CP which reduce the capacity of OFDM systems.

3. Cell-based RRM for PMR using FBMC

3.1 Overview

The next generation of the PMR communications imposes enhancements for the support of QoS and video data transmission, interconnection with other systems, and use of advanced radio technologies. The exploitation of the cognitive radio (CR) technology and the integration with modern cellular networks, such as the LTE, are two promising options. The key factor for a successful shift from the conventional PMR communications to future PMR solutions will be the radio resource management (RRM), as the efficient spectrum utilization, packet scheduling, and interference management can guarantee the reliable operation under different infrastructures or spectrum resources. In this direction, the use of the FBMC technique is the most suitable, considering the benefits that it provides against its main competitor, the OFDM.

3.2 PMR communications under cellular networks

The coexistence of PMR communications with cellular communications is a very challenging task. In the literature, there are two basic approaches to this direction: i) the use of cognitive radios (CR), and ii) the integration with cellular systems. The first approach focuses on exploiting prior work on the emerging topic of cognitive radio communications. In this case, PMR communications can be seen as a secondary system that utilizes any unused spectrum portion of licensed or unlicensed spectrum that is primary used by the cellular system. The centralized node of the PMR system operates as coordinator dealing with spectrum sharing and synchronization issues. The main advantage is that the PMR communications become flexible in terms of spectrum needs. However, the RRM for the CR-based PMR devices is an open challenge. The second choice focuses on enhancing the modern cellular systems towards enabling PMR communications. The reuse of the cellular infrastructure poses a cost-effective and reliable approach. However, the spectrum reuse introduces interference issues. In the following, the main characteristics and the state-of-the-art of the aforementioned approaches are provided.

3.2.1 PMR communications as secondary networks

3.2.1.1 CR-based PMR communications

Cognitive radio (CR) technology is the key technology that enables the use of the spectrum in dynamic manner. Practically CR enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space [6]. CRs require real time interaction with its environment to determine appropriate communication parameters and adapt to the dynamic radio environment. The tasks required for adaptive operation in open spectrum are referred to as the cognitive cycle which consists of three main steps of the cognitive cycle (figure 3-2): spectrum sensing, spectrum analysis, and spectrum decision.

In Spectrum sensing a CR monitors the available spectrum bands, captures their information, and then detects the spectrum holes. Sequentially, in spectrum analysis the characteristics of the spectrum holes that are detected through spectrum sensing are estimated, while in Spectrum decision: A cognitive radio determines the data rate, the transmission mode, and the bandwidth of the transmission. Then, the appropriate spectrum band is chosen according to the spectrum characteristics and user requirements. The main issues that arises in the CR networks are: the synchronization among transmissions/receptions, an efficient spectrum sensing (sensing technique and sensing strategy), and the use of dedicated control channel. Thus, CR-based

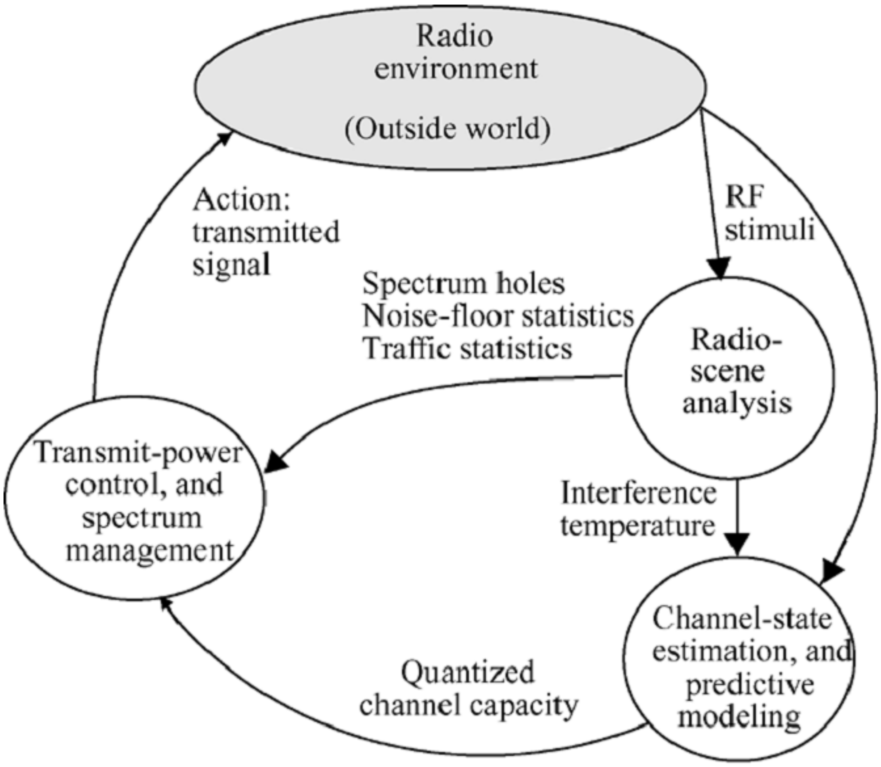

Figure 3-1: The basic cognitive cycle [6]

PMR terminals must adopt functions for assessing the spectral environment as well as sharing the spectrum, and transmit in an opportunistic way. Moreover, when CR is applied to PMR there is also the issue of guaranteeing the requested QoS for critical services (like call preemption, or emergency alarms), imposing the design of RRM solutions that guarantee certain critical resources in every moment.

3.2.1.2 State-of-the-art

A promising approach for introducing PMR communications in a cellular network is the opportunistic spectrum access (OSA) under the principles of cognitive radio networks (CRNs) [7]. OSA users, also referred to as unlicensed or secondary users (SUs), identify and dynamically use local and instantaneous unused spectrum portions, while keeping the interference to primary users (PUs), below a predefined threshold [8]. We must notice here that PMR communications for PPDR have also to support critical services, for which the resource must be available at every moment. Thus, the opportunistic PMR scheme can be better applied in non-critical services. OSA involves two basic operations: i) detection of opportunities (i.e., available spectrum portions), and ii) exploitation of opportunities. Commonly, opportunities detection is addressed by a spectrum sensing procedure and/or modeling of PU's behavior. Spectrum sensing includes the sensing method and the sensing strategy adopted by the SUs at the Physical (PHY) and Medium Access Control (MAC) layers, respectively. An interesting survey on spectrum sensing for OSA is provided in [9]. In the case of modeling PUs behavior, the theory of partially observable markov decision processes is a popular approach [10]. On the other hand, exploitation of opportunities includes the spectrum access and spectrum sharing operations for the SUs, i.e., the MAC protocol for OSA. Most of the proposed in the literature solutions use a

Common Control Channel (CCC), as an easy way to broadcast information to the secondary network, and transfer negotiation messages between secondary transmitters and receivers [11] [12] [13]. Other proposals, which do not require a CCC, impose strict synchronization mechanisms for the SUs [14]. Generally, the majority of OSA approaches in the literature focuses on ad-hoc solutions trying to manage the very dynamic environment. However, conventional PMR communications are subject to centralized control. Adopting this architecture, CR-based PMR communications can utilize the cellular base station towards coordinating the spectrum sensing procedure, deciding the sensing strategy (selection of which carriers to sense and for how much time) and resolving the spectrum sharing problem guaranteeing more reliable and fair communications (very difficult in decentralized approaches). PMR terminals can exploit the synchronization to the base station and/or available broadcast information to avoid sensing and minimize the interferences. For example, in case that the PMR transmissions are synchronized with the transmissions of the primary terminals, PMR terminals can recognize the DL and the UL periods of the primary cellular system. Thus, they can choose to transmit in the UL period, where the only primary receiver (i.e., interference victim) in the cell area is the base station. In that way, the interference that is caused to the primary system from the PMR transmissions is defined to only one primary node. In that type of approaches crucial role can be played by the FBMC technique. FBMC-based systems can handle efficiently situations where the users are not synchronized. For example, in the uplink of a base station ruled network, it is not necessary to achieve distant frequency and time alignment before starting data transmission.

3.2.2 PMR communications integrated with cellular systems

3.2.2.1 Coexistence of PMR and cellular networks

The majority of cellular networks have been designed without a provision for supporting PMR communications, while the concept of PMR communications is quite different from that of conventional cellular communications, making the integration very challenging. The integration imposes the cellular BS to work as the central node of the PMR communications, while the PMR data are transmitted directly or through the BS to one or more PMR receivers (figure 3-2).

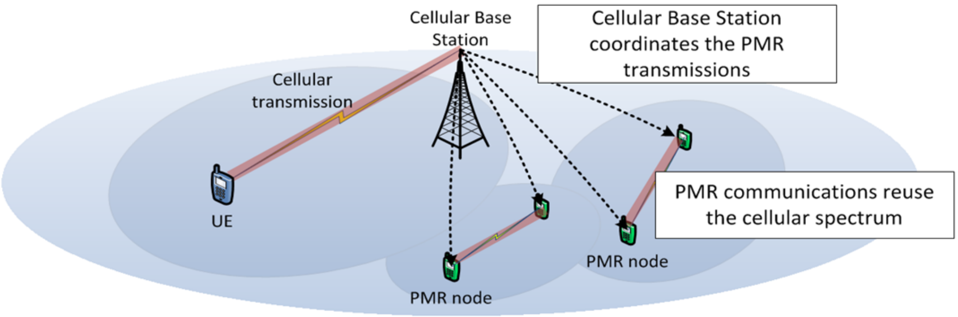

Figure 3-2: Coexistence of PMR and cellular networks

On the one hand, the main advantage of a potential integration is the enhancement of the PMR communications allowing data and media transmissions, changing radically the conventional view of the PMR communications. In case of emergency for example, the transmission of a video showing the incident is much more essential than a voice call seeking help. Additionally, the cellular systems are reliable systems and also the use of the existing infrastructure is a cost-efficient approach. Moreover, the integration will enable the integration and interoperability of PMR systems with backend data systems and external systems, a missing function from the conventional PMR systems. On the other hand, a series of new features must be adopted by a cellular system so as to enable PMR communications. The coexistence of cellular and PMR transmissions in the same spectrum raises the problem of interference management. Since the same spectrum is used, both PMR and cellular systems must avoid mutual interference. Key role to this effort can be played by the BS. Also, since PMR communication includes both Public Protection and Disaster Relief (PPDR) and commercial domain applications, the cellular system must guarantee the priority and the reliability of the crucial PPDR communications. One other characteristic of the conventional PMR communications is the group communications. Cellular systems need to develop new features to enable this kind of communications. The direct or device-to-device (D2D) communications is another challenge for the cellular networks. PMR communications take advantage of that kind of communications to improve coverage and spatial spectrum reuse. D2D transmissions are a fundamental feature of PMR communications that the cellular networks must adopt. The call setup time is also a crucial factor for the PMR communications. In cellular systems a PMR-like call, such as the Push-to-Talk over Cellular (PoC) (developed by Open Mobile Alliance (OMA)) can be established in few seconds [15], while the enabling of PMR communications requires a reduction of this time to some milliseconds.

3.2.2.2 State-of-the-art

The support of PMR communications by cellular systems is an emerging topic which is currently attracting the interest of the academia and the industry. Already, the integration of PMR communications with WLANs has been proposed in [16]. The specified solution allows TETRA terminals to interface to the TETRA Switching and Management Infrastructure (SwMI) over a broadband WLAN radio access network, instead of the conventional narrowband TETRA radio network. According to the author, the enhanced PMR terminals can support a range of brand new capabilities enabled by the WLAN, such as broadband data services, and the simultaneous reception of many group calls. The rate limitations of the TETRA system have also motivate many software vendors to consider hybrid solutions where TETRA is used for critical signaling while large data synchronization and transfer of images and video is done over 3G / LTE [17]. In the case of the integration between PMR and cellular networks, the design of Push-To-Talk (PTT) applications is currently trying to fill the design gap, introducing the concept the so-called PTT over cellular (PoC). One promising POC solutions have been developed by an industry consortium, and submitted to the Open Mobile Alliance (OMA) as a proposed standard [18]. The proposed PTT solution builds upon the 3GPP IP Multimedia Subsystem (IMS), one of the core entities in the architecture of the LTE network. The IP connectivity service is provided by the mobile network for the delivery of half-duplex, one-to-one or one-to-many voice services as well as video and data communications. The enabling of D2D communications, one of the fundamental functions of the PMR systems, has also draw the interest of the academia. On the one hand, solutions for interference-free conditions between D2D and cellular transmissions, as well as among D2D pairs have been proposed [19] [20] [21] [22]. A key challenge is the design of mechanisms that inform the BS about the channel conditions among all nodes, either directly in the form of periodic measurements of the ongoing communication quality [19] [20], or indirectly via neighborhood detection [21] [22]. An efficient design option is the exploitation of the uplink cellular period, where the cellular interference victim is the immobile BS [23].

On the other hand, the efficient management of the D2D links is essential, including the peer discovery (D2D receiver discovery), the D2D connection establishment and maintenance, and the specific changes that must be made to the coexisting cellular network. Recognizing the importance of these tasks, the interesting idea of switching a cellular connection to a direct (D2D) one and vice versa, taking into account performance criteria, is discussed in [19] - [23]. Also, the support of QoS in D2D communications over the LTE network is proposed in [24]. However, these techniques consume operational resources of the core network, while the D2D connections are mainly used for network performance optimization and not for introducing extra communications under the same infrastructure and spectrum. The cell is inevitably loaded with extra control signaling increasing the call set-up time. This is weak aspect when thinking of D2D communication from the perspective of PMR communications. Generally, cellular networks are more and more critical and need to remain available in any cases, playing the role that is traditionally played by PMR networks. In the case of commercial PMR communications additional work has to be done for the support of PTT and D2D communications. However, in the case of PPDR the reserving of specific infrastructure and spectrum resources seems to be inevitable towards facing crisis situations when public networks are overloaded, shut down or inoperative.

3.3 RRM for cell-based PMR

3.3.1 RRM in PMR communications

Operation of PMR equipment is based on standards such as the MPT-1327, and the TETRA. TETRA system makes use of the available frequency allocations using time division multiple access (TDMA) technology with four user channels on one radio carrier with 25 kHz spacing between carriers. The used frequencies range from 300 to 450 MHz for the European countries, while both point-to-point and point-to-multipoint transfer can be used. The RRM is quite simple and the base stations normally transmit continuously and (simultaneously) receive continuously from various mobiles on different carrier frequencies; hence the TETRA system can be seen as a Frequency Division Duplex (FDD) system. Systems based on MPT-1327 only require one, but usually use two or more radio channels per site. Differing from TETRA the channel bandwidth can be 6.25, 12.5 or 25kHz. At least one of these channels is defined as the control channel (CCH) and all other channels are traffic channels (TCs) used for speech calls. A spectrum efficiency advantage over a 4-slot TDMA system like TETRA is in areas where a low-traffic network is required. The absolute minimum TETRA installation would require one carrier, carrying one CCH and three traffic channels, using up 25kHz of bandwidth. The absolute minimum MPT-1327 assignment is a single non-dedicated control channel, utilizing 12.5kHz, in most cases. Since the system composed by traffic and control channels created by dividing in time domain few frequency bands, the PMR RRM includes a simple resource allocation approach. The scheduling options are also limited and most of the time the users are served following the first come first served approach. This limitation emerges from the fact that PMR systems are designed mainly for voice communications, and, thus, there is no need to prioritize the serving calls like in data services.

3.3.2 RRM in cellular systems

In cell-based systems the central node of each cell, commonly called base station (BS) is responsible for the radio resource management. The RRM includes all the procedures that the

BS adopt in order to utilize efficiently the available spectrum resources. The commonly used duplex types are the TDD and FDD, while the multiple accessing is achieved by using time division multiple access (TDMA), frequency division multiple access (FDMA), and orthogonal frequency division multiple access (OFDMA) techniques. The most interesting approach is the OFDMA technique, which has been adopted by the modern cellular systems such as the LTE, and the LTE-A, and is based on the orthogonal frequency-division multiplexing (OFDM) method. OFDMA technique provides a much higher flexibility than the TDMA technique adopted in conventional PMR systems. OFDMA takes advantage of the multi-user diversity, i.e., the different wireless channel quality experienced by different users for the same channel, and the adaptive modulation and coding in order to improve spectrum usage and increase throughput. A plethora of algorithms that take advantage of these gains have been proposed in the literature. The main task for these algorithms is to determine which users to schedule, how to allocate spectrum resources to them, and how to determine the appropriate power levels for each transmission. The resource allocation is usually formulated as a constrained optimization problem, to either minimize the total transmit power with a constraint on the user data rate or maximize the total data rate with a constraint on total transmit power. Three fundamental algorithms refer to this problem: i) the maximum sum rate (MSR) algorithm, ii) the Maximum Fairness Algorithm, and iii) Proportional Rate Constraints Algorithm. The objective of the maximum sum rate (MSR) algorithm is to maximize the sum rate of all users, given a total transmit power constraint [25]. This algorithm is optimal if the goal is to get as much data as possible through the system. The drawback of the MSR algorithm is that it is likely that a few users close to the base station, and hence having excellent channels, will be allocated all the system resources. The maximum fairness algorithm [26] aims to allocate the subcarriers and power such that the minimum user's data rate is maximized. This essentially corresponds to equalizing the data rates of all users. A weakness of the maximum fairness algorithm is that the rate distribution among users is not flexible. Further, the total throughput is limited largely by the user with the worst SINR, as most of the resources are allocated to that user, which is clearly suboptimal. In a wireless broadband network, it is likely that different users require application-specific data rates that vary substantially. A generalization of the maximum fairness algorithm is a proportional rate constraints (PRC) algorithm, whose objective is to maximize the sum throughput, with the additional constraint that each user's data rate is proportional to a set of predetermined system parameters. Generally, the RRM in cellular based systems is more complex than in PMR systems. However, it provides high flexibility in resource allocation and scheduling, and supports the transmission of data and media flows. PMR communications can benefit from the advantages provided by the more sophisticated RRM of the cellular systems and, thus, the enabling of PMR communication in cellular systems is quite promising. From the RRM perspective the main challenges are the design of an efficient technique for spectrum sharing between PMR and cellular transmissions, the interference management, and the guarantee of priority rules in scheduling in the case of emergency PMR communications.

3.4 Utilization of FBMC for RRM

3.4.1 FBMC-based RRM

From the perspective of the RRM the use of filter banks can improve the spectrum efficiency and the flexibility of the RRM schemes. More specifically, FBMC can handle situations where the users are not synchronized and, thus, for a base station ruled network, it is not necessary to achieve distant frequency and time alignment before starting data transmission. Moreover, comparing to the OFDM approach, FBMC requires no cyclic prefix, exploiting the totality of the symbol period. As a consequence one empty sub-channel is sufficient as a guard-band to isolate different transmissions. This can result to better resource utilization, ether by allocating more users of by increasing the achievable throughput per user. Considering the case that the PMR communications operate as a secondary network, FBMC provides high performance spectrum sensing. In more detail, the same filter bank can be used for sensing and transmission, which ensures performance compatibility. In the case that PMR transmissions coexist with cellular transmissions, the FBMC scheme could be useful for efficient spectrum sensing. Considering the FBMC receiver as an energy detector, the potential spectrum holes can be identified more accurately than in the case that an OFDM receiver is used [27]. This time-frequency window may be determined by predefined probabilities for false alarm and missed detection. Taking into account that the modern cellular systems adopt the OFDM scheme one of the main challenges is the study of the case that an FBMC PMR system coexists with an OFDM cellular one. Both techniques are based on the Fast Fourier Transform (FFT), so there is a common core that could allow an efficient coexistence. The exploitation of the FBMC advantages to amplify the interference tolerance at PMR terminals is also an appealing issue. The role of the cellular base station on how the PMR nodes will be coordinated is very important. The extensive study of the modern cellular networks, such as LTE-A, maybe bring to the surface system-specific tools that can be exploited towards enabling FBMC-based PMR communications.

3.4.2 State-of-the-art

Many approaches in the literature deal with the FBMC scheme and provide the advantages and disadvantages comparing with other physical layer schemes. Considering that the RRM procedures takes place in the MAC layer, for the comparison of the different physical layer technologies in RRM level any resource allocation or scheduling scheme can be used. However, the main challenge is to design FBMC-based RRM schemes, exploiting the FBMC benefits and characteristics in a cross-layer manner.

The common approach in the literature utilizes the FBMC scheme in cognitive radio networks, since the standardization bodies of the modern cellular networks have already adopted the OFDM scheme. However, the study of the contribution of the FBMC characteristics in the future standardization efforts (e.g., for 5G) is also a very appealing task. The superiority of the FBMC scheme over the OFDM in the cognitive radio case is validated in [28] [29] [30] [31] [32]. In [28] FBMC offers higher spectral efficiency and is more applicable for the CR network with small size of spectrum holes than OFDM, while the performance of FBMC is close to that of the perfectly synchronized case because of its frequency localization. The study in [29] leads to the result that FBMC can highly relax the interference to primary system comparing to the OFDM case. Also, authors in [30] [31], exploit the results of the PHYDYAS project [1] for the efficiency of the FBMC scheme in order to propose low complexity resource allocation and power control schemes.

For the comparison of FBMC and OFDM in the modern cellular systems, such as the LTE, few approaches can found in the literature, since for those systems the OFDM scheme has already been adopted. However, here we provide a complete comparison of OFDM- and FBMC- based traffic scheduling [33] in WiMAX cellular systems [34], motivating our future work on cross-layer RRM for cell-based PMR networks. The scheduler used in the present study assumes a WiMAX network, although it can be easily adapted to any similar cellular wireless network with differentiated services based on traffic classes. The system architecture of WiMAX consists of Base Stations (BSs), each one responsible for a specific cell area, and stationary Subscriber Stations (SSs). The communication path between SSs and the BS is divided into two directions: uplink (from SS to BS) and downlink (from BS to SS), multiplexed either with Time Division Duplex (TDD) or Frequency Division Duplex (FDD). Transmission parameters, including the modulation and coding schemes, may be adjusted individually for each SS on a frame-by-frame basis. A TDD frame has a fixed duration and is divided into a downlink subframe, and an uplink subframe. Each connection is associated with a single service flow and specifies a set of parameters that quantify its traffic behavior and QoS expectations. This set includes

- minimum reserved traffic rate (in bits/sec),
- maximum sustained traffic rate (in bits/sec),
- maximum latency (in ms),
- tolerated jitter (maximum delay variation in ms),
- traffic priority (values 0-7, with 7 the highest), etc.

The respective IEEE 802.16 standard [34] defines four different services:

- Unsolicited Grant Service (UGS): This service supports real-time data streams consisting of fixed-size data packets transmitted at periodic intervals, such as Voice over IP without silence suppression. These applications require constant data rate allocation, so data rate requests are not required.
- Real-time Polling Service (rtPS): This service supports data streams consisting of variable-sized data packets that are transmitted at fixed intervals, such as MPEG video. These applications have specific data rate requirements, as well as a maximum acceptable latency. Late packets that miss the deadline are considered useless.
- Non-real-time Polling Service (nrtPS): This service is for non-real-time connections that require better than best effort service, e.g., data rate intensive file transfer. These applications are time-insensitive but require a minimum data rate allocation.
- Best Effort service (BE): This service is for best effort traffic with no QoS guarantee. The applications of this kind of service share the remaining resources after allocation to the rest of the services is completed. BE uses only contention mode.
- Enhanced rtPS (ertPS): This service is defined to better support real-time service flows that generate variable size data packets on a periodic basis, e.g., VoIP with silence suppression.

To efficiently support all types of connections (UGS, rtPS, ertPS, nrtPS and BE) as specified in the standard, the scheduler used in this study is based on ideas found in [35] and uses a combination of strict priority service discipline, earliest deadline first (EDF) and weight fair queue (WFQ) algorithms. The basic scheduling principles of the algorithms are as follows:

1. Overall data rate allocation: The data rate allocation per traffic class follows strict priority, from highest to lowest: UGS, ertPS, rtPS, nrtPS and BE.

2. Data rate allocation for UGS connections: The scheduler allocates fixed data rates to UGS connections based on their fixed requirements. This policy is determined clearly by the IEEE 802.16 standard, without the need for real-time transmission requests.

3. Data rate allocation for ertPS and rtPS connections: The EDF service is adopted for these connections, to allow packets with the earliest deadline to be scheduled first. In case two packets belonging to two different service types (one of ertPS and one of rtPS) expire at exactly the same time, the scheduler will give priority to the ertPS packet, considering this packet of higher priority. Data rate needs are constantly updated through real-time transmission requests.

4. Data rate allocation for nrtPS connections: The weighted fair queue (WFQ) service is applied for this traffic class. For each nrtPS connection, the ratio of its average data to the total nrtPS average data rates is computed, and resources being left from the higher priority classes (UGS,ertPS and rtPS) are distributed according to the computed weights of the connections. No transmission requests are required on this case.

5. Data rate allocation for BE connections: The remaining resources are equally allocated among BE connections following the Round Robin model, without transmission requests.

The scheduler can take advantage of the improved performance of FBMC compared to OFDM, by fairly supporting a larger number of connections. To reveal the effectiveness of the proposed scheduling and resource allocation procedure in terms of differentiated QoS, we execute a scenario involving an increasing number of users, each one with one active connection per service type.

Fig. 3-3 shows the attained throughput per service type as a percentage of the offered traffic for both CP-OFDM and FBMC. The differentiated treatment is clearly revealed forcing BE connections to reduce their throughput first, followed by nrtPS and rtPS. An overall throughput

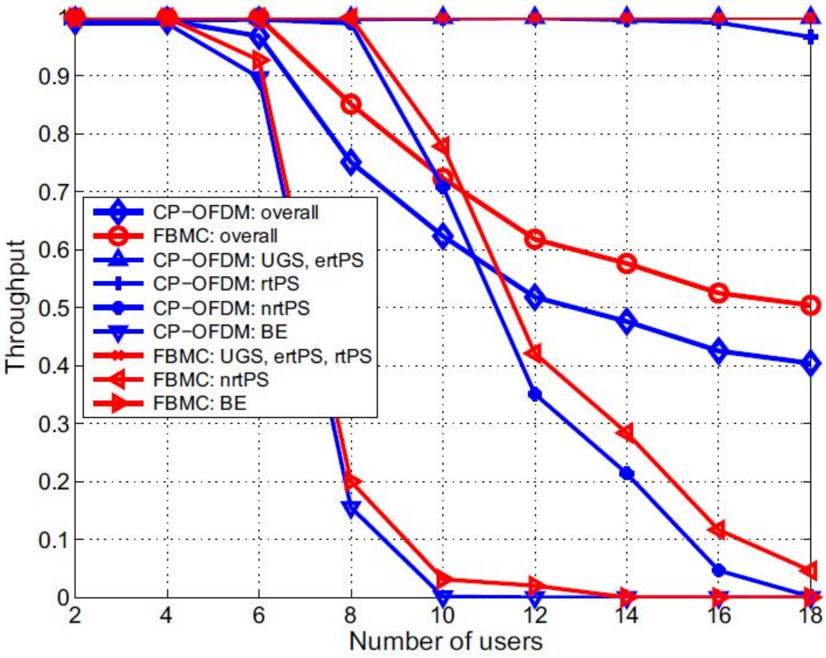

Figure 3-3: Throughput in CP-OFDM and FBMC systems

improvement of approximately up to 18% is attained with FBMC, compared to CP-OFDM, as a result of the improved operation of the physical layer. Finally, the comparative performance of FBMC and CP-OFDM in terms of overall data rates is shown in Fig. 3-4. The effectiveness of FBMC is indicated by an almost stable increase of the data rate for most of the cases.

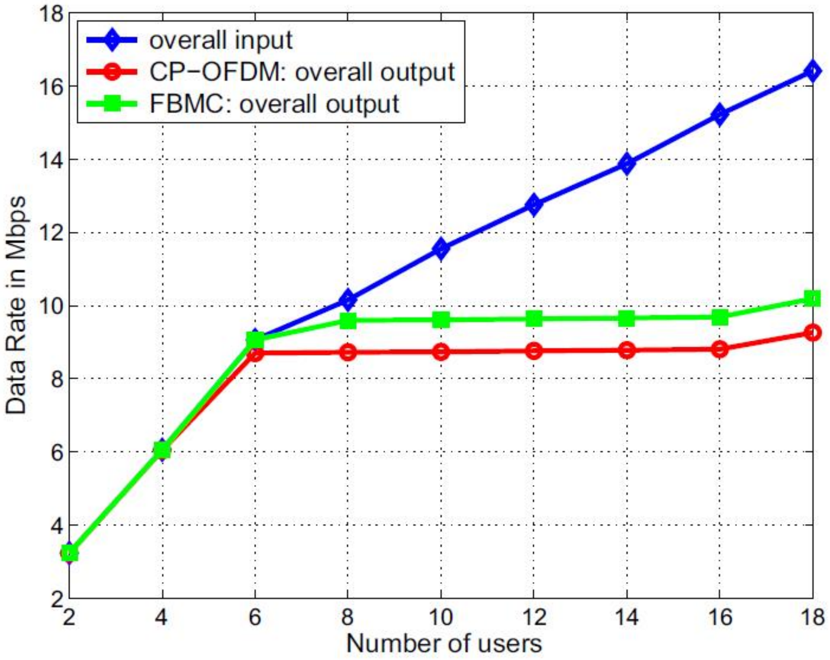

Figure 3-4: Input and output data rates in CP-OFDM and FBMC systems

4. Ad hoc RRM for PMR using FBMC

4.1 Overview

4.1.1 Introduction

Contrary to cellular networks, ad hoc networks do not possess an optimized topology and are not managed by a network controller. In ad hoc networks, the Access Points (or Base Stations) are not located on a pre-defined and optimized hexagonal grid as in cellular networks, but are randomly located. Recently, some stochastic geometry approaches where the cells form a Poisson tessellation of the plane generated by Poisson distributed Base Stations have been proposed and studied in the literature [36]. These approaches may be relevant to ad hoc networks (see Fig. 4-1).

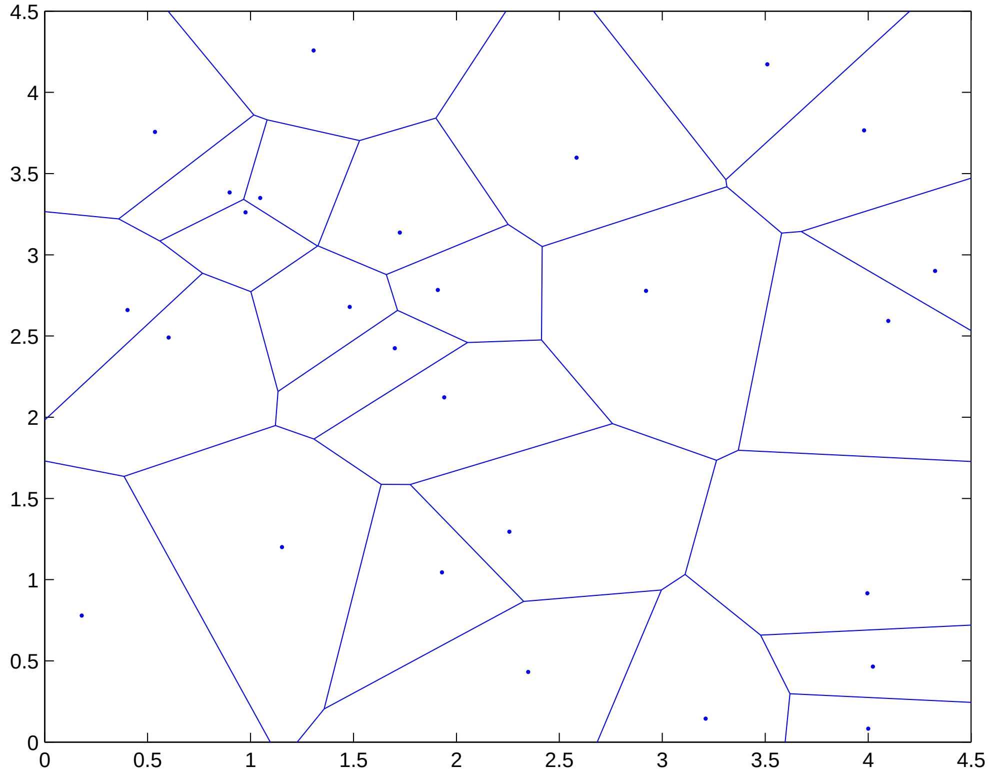

Figure 4-1: Example of BS distribution following a Poisson Point process

From an interference point of view, two main issues arise when considering ad hoc networks, compared to cellular networks: 1) network-wide inter-cell interference management is not feasible, in the absence of a network controller; and 2) the transmission in several ad hoc cells is not synchronized, since ad hoc Base Stations are not jointly controlled.

4.1.2 Absence of network-wide inter-cell interference management

In ad hoc networks, Base Stations are located randomly. There is no network controller (such as the RNC in 3G cellular networks), and no network-infrastructure linking Base Stations together (such as the X2 interference in 4G cellular networks). As a consequence, each cell sees itself as an independent network and is unaware of the surrounding cells, except for the interference that it receives.

This does not necessarily mean that interference cannot be managed; new ad hoc protocols may be added in order to exchange some information between the cells regarding interference. However, a global management imposing, for instance, a specific Frequency Reuse Factor is not feasible. This is due to the fact that the network topology is highly unpredictable and may dynamically change; thus classical multi-carrier Frequency Reuse Factor techniques such as [37][38] cannot be used. Consequently, radio resource allocation algorithms must either consider interference as an imposed parameter that cannot be avoided; or use new protocols to dynamically manage interference given the dynamic topology change and the lack of network infrastructure. This opens new challenges for future research in this area.

4.1.3 Asynchronous transmission

Ad hoc Base Stations are not jointly controlled, and they may access the network at any moment since the topology varies in time. As a consequence, it is highly likely that they are not synchronized with each other. Moreover, the timing offset is different between all couples of adjacent Base Stations and these sets of Base Stations may dynamically vary, which does not allow them to achieve a global synchronization, even after some initialization phase.

Thus, the most accurate model for taking into account inter-cell interference due to asynchronous transmissions is to assume that the timing offset is uniformly distributed. Similarly, the number of interfering cells may not be predictable. The inter-cell interference models described in the next section take these constraints into account and are thus relevant to our studied problem.

4.1.4 State of the art

Up to now in the literature, resource allocation in multi-carrier systems aiming at comparing the performances of FMBC and CP-OFDM has only considered cognitive radio systems with asynchronous transmission between the primary network and the secondary network. Interference modeling and application to radio resource management has been proposed for these multi-carrier techniques in [30][31][39]. In the following, we detail the results obtained in these papers. They will be used as state-of-the-art in the future EMPHATIC studies on ad hoc RRM, after careful extension to the studied scenario.

4.2 Modeling of inter-cell interference depending on the multi-carrier technique

4.2.1 Interference using the power spectral density and interference modeled as Additive White Gaussian Noise

In [30][31], resource allocation in a multi-carrier cognitive radio system is studied. The secondary users are transmitting on the bands that are unused by the primary system, with channel interweave. As the secondary users are not synchronized with the primary users, they cause interference to the primary system. There are L primary user (PU) bands, denoted as $B_1, B_2, ..., B_L$. The non-active bands are used by the secondary system. They are divided into N subcarriers, each with a Δf bandwidth. The interference induced to the l^{th} PU band should not exceed the predefined interference temperature limit, I_{th}.

The interference $I_{i,m}^{l}\left(d_i^l, P_{i,m}\right)$ introduced by the transmission of the i^{th} subcarrier of the secondary system, which is allocated to the m^{th} secondary user, to the l^{th} primary band is the integration of the PSD of the i^{th} subcarrier across the l^{th} primary band, and can be expressed as [40]:

$$I_{i,m}^{l}\left(d_i^l, P_{i,m}\right) = P_{i,m}\Omega_{i,m}^{l} \tag{4.1}$$

with

$$\Omega_{i,m}^{l} = \int_{d_i^l - B_l/2}^{d_i^l + B_l/2} \left|g_{i,m}^{l}\right|^2 \Phi_i(f)df \tag{4.2}$$

where $\Phi_i(f)$ denotes the power spectral density of the i^{th} CP-OFDM or FBMC subcarrier (the detailed description can be find in Section 2.3.1) and d_i^l is the spectral distance between the i^{th} subcarrier and the l^{th} PU band. $g_{i,m}^{l}$ denotes the channel gain (possibly including path loss and shadowing) between the i^{th} subcarrier and the l^{th} PU band, while $P_{i,m}$ is the total transmit power emitted by the i^{th} subcarrier. $\Omega_{i,m}^{l}$ denotes the interference factor of the i^{th}subcarrier to the l^{th} PU band. B_l is the bandwidth of the PU band. The subscript m denotes the case when the i^{th} subcarrier is allocated to the m^{th} secondary user. Similarly, the interference power introduced by the l^{th} PU signal into the band of the i^{th} subcarrier is [40]:

$$J_{i,m}^{l} = \int_{d_i^l - \Delta f/2}^{d_i^l + \Delta f/2} \left|y_{i,m}^{l}\right|^2 \Psi_l(e^{j\omega})d\omega \tag{4.3}$$

Where $\Psi_l(e^{j\omega})$ is the PSD of the l^{th} PU signal, and $y_{i,m}^{l}$ is the channel gain between the i^{th} subcarrier and the l^{th} PU signal.
The maximum achievable transmission rate of the i^{th} subcarrier, R_i, can be evaluated as:

$$R_i\left(P_{i,m}, h_{i,m}\right) = \Delta f \log_2\left(1 + \frac{P_{i,m}\left|h_{i,m}\right|^2}{\sigma_i^2}\right) \tag{4.4}$$

Where $P_{i,m}$ is the transmission power and $h_{i,m}$ is the i^{th} subcarrier fading gain from the m^{th} secondary user to the secondary Base Station. Additionally, $\sigma_i^2 = \sigma_{\text{AWGN}}^2 + \sum_{l=1}^{L} J_i^l$, where σ_{AWGN}^2 is the variance of the additive white Gaussian Noise and J_i^l is the interference introduced by the l^{th} PU band into the ith subcarrier, whose expression is given in (4.3).
The interference generated by the Primary Transmitter in the i^{th} subcarrier is assumed to be the superposition of large number of independent components, $\sum_{l=1}^{L} J_i^l$.
Using the central limit theorem, the interference is then modeled as Additive White Gaussian Noise [41].
This assumption may not be valid for a low number of PU bands, but it can be considered as a good approximation for a large number of PU bands. It has been taken in several papers, for instance [41][42][43]. We can notice that the nature of the PUs interference on the secondary users bands is the same with both CP-OFDM and FBMC, with this assumption.
It should be noted that in many cases, the probability density function of the interference exhibits results strongly different from those predicted by the Gaussian model [44]. Indeed, the central limit theorem does not apply when the number of interferers is low, or when the number of interferers is large, but there are dominant interferers [45][46].
This model is consequently not used for the secondary users interference to the PU band. The interference is then given by equation (4.3), and it depends on the power spectral density. It is thus different, whether FBMC or CP-OFDM is used. Since FBMC has lower sidelodes than

those of CP-OFDM, the interference it generates is far lower.
The interference generated by the secondary users to the l^{th} PU is:

$$I^l = \sum_{m=1}^{M} \sum_{i=1}^{N} v_{i,m} P_{i,m} \Omega_i^l \tag{4.5}$$

Where N denotes the total number of subcarriers, M is the number of secondary users, and $v_{i,m}$ is a Boolean that indicates that the secondary user m is allocated to subcarrier i.
The power spectral density model does not always give accurate results [47] because it does not take the cyclic prefix into account in CP-OFDM. For example, in multi-user CP-OFDM when the timing offset does not exceed the cyclic prefix duration, the interference comes only from the same subcarrier, and the other subcarriers do not contribute to the interference. Unfortunately, in this case the PSD modeling still shows that the other carriers contributed in the resulting interference.
The asynchronous interference is always a function of the timing offset between the primary and secondary systems, and this is not considered in the PSD modeling. Consequently, another model has been introduced in [48]. It uses the so-called 'interference tables'. These interference tables are different from the PSD-based interference evaluation from [30][31], since they take into account the timing offset, on top of the subcarrier distance between the transmitter and the interfered receiver, while the PSD modeling only considered the subcarrier distance.
This method is detailed in the next subsection.

4.2.2 Inter-cell interference power tables

In [39], the author uses the results from [47][48] to evaluate the inter-cell interferences of OFDM and FBMC in an unsynchronized Frequency Division Duplex (FDD) system. All the cells present in the system use the same frequency bands and a perfect frequency and time synchronization between the users of interest and its own base station is assumed, which means that the interference will only come from the other cells. In the analysis process, frequency offset is not considered, but the different cells are not time-synchronized. To estimate the detrimental effects of interference caused by adjacent cells, a two-cell layout with one user located at the border of the interest cell (the other cell is referred to as interfering cell) is assumed.
The mean inter-cell interference of the interest user from the interfering cell is computed when the base station in the interfering cell transmits a single complex symbol with power that equals to 1 on the k^{th} frequency slot and the n^{th} time slot. The explicit interference formulas of OFDM and FBMC have been derived in [48]. It is found that the inter-cell interference of OFDM only depends on the timing offset, and the inter-cell interference of FBMC depends both on the timing offset and on the phase offset. The interference level will become lower when the prefix cyclic duration increases. [48] then provides the mean interference table of CP-OFDM with a cyclic prefix duration equal to $\Delta = T/8$ (with T the symbol period), for an uniformly distributed timing offset $\tau \in \left[\frac{\Delta}{2}; T + \frac{3\Delta}{2}\right]$. The mean interference is given in Table 4-1.
On the other hand, a filter bank with an overlapping factor 4 designed using the method in the project PHYDYAS [1] is chosen. Generally, FBMCs with frequency-localized prototype filters have negligible inter-cell interference because of their special filter configurations. Consequently, the interference level almost does not change if we use other types of FBMCs. The mean interference table of FBMC in the project PHYDYAS for a uniformly distributed timing offset $\tau \in \left[\frac{T}{2}; \frac{3T}{2}\right]$ and also for a uniformly distributed phase offset $\Phi \in [0; 2\pi]$ is given in Table 4-2.

In the mean interference tables, only main interfering slots whose interference powers are larger than 10^{-4} are considered. We can see that for CP-OFDM systems, inter-cell interference

Table 4-1: Mean interference power table of OFDM

f/t	n	$n+1$
$k+7$	9.14×10^{-4}	9.14×10^{-4}
$k+6$	1.25×10^{-3}	1.25×10^{-3}
$k+5$	1.80×10^{-3}	1.80×10^{-3}
$k+4$	2.81×10^{-3}	2.81×10^{-3}
$k+3$	5.00×10^{-3}	5.00×10^{-3}
$k+2$	1.13×10^{-2}	1.13×10^{-2}
$k+1$	4.50×10^{-2}	4.50×10^{-2}
k	3.52×10^{-2}	3.52×10^{-2}
$k-1$	4.50×10^{-2}	4.50×10^{-2}
$k-2$	1.13×10^{-2}	1.13×10^{-2}
$k-3$	5.00×10^{-3}	5.00×10^{-3}
$k-4$	2.81×10^{-3}	2.81×10^{-3}
$k-5$	1.80×10^{-3}	1.80×10^{-3}
$k-6$	1.25×10^{-3}	1.25×10^{-3}
$k-7$	9.14×10^{-4}	9.14×10^{-4}

comes from many frequency slots and only two consecutive time slots. On the contrary, the inter-cell interference of FBMC with 15 interfering slots is more localized in frequency than that of OFDM, which has 30 interfering slots. However, the inter-cell interference of FBMC spreads over more time slots which depends on the length of the prototype filter.
When a burst of independent complex symbols is transmitted, the interference incurred on one subcarrier is equal to the sum of the interference for all the time slots. The corresponding frequency inter-cell interference powers which are larger than 10^{-3} for OFDM, FBMC, and the Perfectly Synchronized (PS) cases are given in Table 4-3. It can be observed that the number of subcarriers that induce harmful interference to primary user of OFDM and FBMC are 8 and 1, respectively.

Finally, for resource allocation algorithms, the simplified interference vectors of OFDM and FBMC are defined as:

$$\begin{aligned} V_{\text{OFDM}} = \Big[&8.94 \times 10^{-2}, 2.23 \times 10^{-2}, 9.95 \times 10^{-3}, 5.60 \times 10^{-3}, \\ &3.59 \times 10^{-3}, 2.5 \times 10^{-3}, 1.84 \times 10^{-3}, 1.12 \times 10^{-3}\Big] \end{aligned} \tag{4.6}$$

and

$$V_{\text{FBMC}} = \Big[8.81 \times 10^{-2}, 0, 0, 0, 0, 0, 0, 0\Big] \tag{4.7}$$

These vectors are used to evaluate the interference received by the non-synchronized cells.

Table 4-2: Mean interference power table of FBMC

f/t	$n-2$	$n-1$	n	$n+1$	$n+2$
$k-1$	1.08×10^{-3}	1.99×10^{-2}	4.60×10^{-2}	1.99×10^{-2}	1.08×10^{-3}
k	1.05×10^{-3}	1.26×10^{-1}	5.69×10^{-1}	1.26×10^{-1}	1.05×10^{-3}
$k+1$	1.08×10^{-3}	1.99×10^{-2}	4.60×10^{-2}	1.99×10^{-2}	1.08×10^{-3}

4.3 Examples of resource allocation algorithms with OFDM and FBMC and comparison of their performances

4.3.1 Uplink multi-user case: scenario and optimization problem

Resource allocation with FBMC and CP-OFDM has been studied in [39], but only in the context of cognitive radio. The studied scenario is the following: one primary system is occupying a licensed bandwidth B. The primary system however does not use the whole bandwidth, and several spectrum holes are present. A secondary system is the trying to access the secondary system's bandwidth with channel interweave: it is allowed to transmit only in the primary sprectrum holes. The secondary users transmission is however not synchronized with the primary users transmission. Consequently, even though the secondary system uses channel interweave, there will be inter-cell interference between both systems, because of the desynchronization. Figure 4-2 illustrates the studied scenario. The details of how inter-cell interference is modeled, using the inter-cell interference Tables 1, 2 and 3 from [48], is given hereunder.

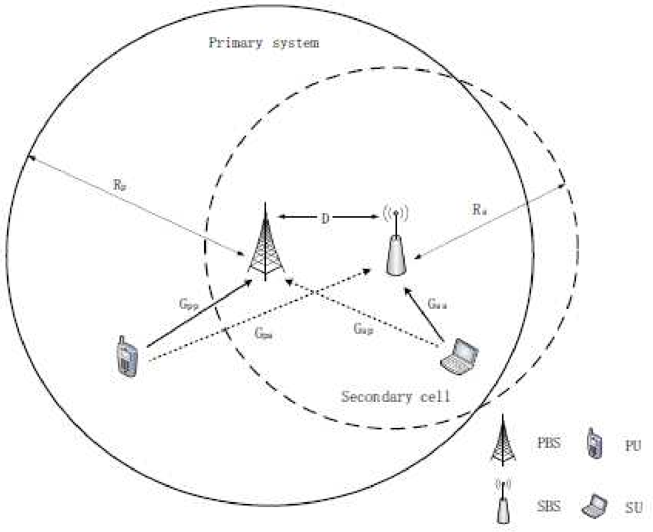

Figure 4-2: Cognitive scenario studied in [39]

The secondary system is composed of one Base Station and M users, and we study the uplink. The Primary Users are denoted PU, and the Secondary Users SU. The secondary cell wants to maximize its sum data rate by allocating power into the detected spectrum holes for

Table 4-3: Inter-cell interference power tables for three different cases

f/ cases	OFDM	FBMC	Perfect synchronization
$k+8$	1.12×10^{-3}	0	0
$k+7$	1.84×10^{-3}	0	0
$k+6$	2.50×10^{-3}	0	0
$k+5$	3.59×10^{-3}	0	0
$k+4$	5.60×10^{-3}	0	0
$k+3$	9.95×10^{-3}	0	0
$k+2$	2.23×10^{-2}	0	0
$k+1$	8.94×10^{-2}	8.81×10^{-2}	0
k	7.05×10^{-1}	8.23×10^{-1}	1
$k-1$	8.94×10^{-2}	8.81×10^{-2}	0
$k-2$	2.23×10^{-2}	0	0
$k-3$	9.95×10^{-3}	0	0
$k-4$	5.60×10^{-3}	0	0
$k-5$	3.59×10^{-3}	0	0
$k-6$	2.50×10^{-3}	0	0
$k-7$	1.84×10^{-3}	0	0
$k-8$	1.12×10^{-3}	0	0

its own users. This optimization problem can be formulated as:

$$\begin{aligned}
&\text{max } C(p) = \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{f=1}^{F_k} \Theta_m^{kf} \log_2\left(1+\frac{p_m^{kf} G_{ss}^{mkf}}{\sigma_n^2 + I_k^f}\right) \qquad (4.8)\\
&\text{s.t. } \sum_{k=1}^{K}\sum_{f=1}^{F_k} \Theta_m^{kf} p_m^{kf} \leq P_{\text{th}}\ , \forall m\\
&\text{s.t. } 0 \leq p_m^{kf} \leq P_{\text{sub}}\ , \forall m, k\\
&\text{s.t. } \sum_{m=1}^{M}\sum_{n=1}^{N} \Theta_m^{k_{l(r)}n} p_m^{k_{l(r)}n} G_{sp}^{mk_{l(r)}} \leq I_{\text{th}}\ , \forall m, k
\end{aligned}$$

Where M is the number of secondary users, K is the number of spectrum holes, and F_k is the number of subcarriers in the the k^{th} spectrum hole. Θ_m^{kf} is the subcarrier assignment indicator, i.e., $\Theta_m^{kf} = 1$ if the f^{th} subcarrier in the k^{th} spectrum hole is allocated to SU m. p_m^{kf} is the power of SU m on the f^{th} subcarrier in the k^{th} spectrum hole, G_{ss}^{mkf} is the propagation channel magnitude from SU m to the secondary Base Station (SBS) on the f^{th} subcarrier in the k^{th} spectrum hole, σ_n^2 is the noise power, and I_k^f is the inter-cell interference from PU to SU on the f^{th} subcarrier in the k^{th} spectrum hole. P_{th} and P_{sub} are the maximum user power limit and per subcarrier power limit, respectively. N is the length of the interference vector

V, $p_m^{k_{l(r)}n}$ is the power of SU m on the left (right) n^{th} subcarrier in the k^{th} spectrum hole, $G_{sp}^{mk_{l(r)}}$ is the propagation channel magnitude from SU m to the primary Base Station (PBS) on the left (right) first primary subcarrier adjacent to the k^{th} spectrum hole, and I_{th} denotes the interference threshold prescribed by the PU on the first primary subcarrier adjacent to SU. The inter-cell interference from PU to SU I_k^f can be expressed in the mathematical form as follows:

$$I_k^f = \begin{cases} \sum_{n=1}^{N} P_p^{k_l} G_{ps}^{k_l f} V_n \ f = 1, 2, .., N \\ \sum_{n=F_k-f+1}^{N} P_p^{k_r} G_{ps}^{k_r f} V_n \ f = F_k - N + 1, .., F_k \end{cases} \tag{4.9}$$

Where $P_p^{k_{l(r)}}$ is the transmission power of PU located in the left (right) of the k^{th} spectrum hole, and $G_{ps}^{k_{l(r)}f}$ is the channel magnitude from PU located in the left (right) of the k^{th} spectrum hole to SBS on the f^{th} subcarrier of the k^{th} spectrum hole. Practically, the secondary cell is not capable of obtaining the transmission power of PU and the channel information from PU to SU, but I_k^f can be measured during spectrum sensing by SBS without need to know any prior information.

I_{th} is an interference threshold which is predetermined by a practical licensed system. For instance, in [49], it is set according to a capacity loss that the PU can tolerate, compared with a case without SU.

The last constraint in the optimization problem is related to the interference introduced by the secondary user to the primary base station. This constraint is quite difficult to manage because of the two following reasons: first of all, the threshold I_{th} has to be prescribed by the primary system. It represents the amount of interference that the primary system can accept from the secondary system. Standards for multi-carriers cognitive radio systems are still under study and no common definition for interference threshold is available in the literature. Different thresholds corresponding to different penalties in terms of primary system capacity degradation may be used.

Secondly, the SU needs to have channel knowledge. Without the information of the channel magnitude $G_{sp}^{mk_{l(r)}}$ between SU and PBS, the third term of the last inequality constraint cannot be computed. This difficulty is common to all CR systems: in order to adjust its emitted power, the SU must know the amount of interference brought to the PBS. Under the hypothesis that primary and secondary systems are unsynchronized, it is hard to perfectly estimate the channel magnitude $G_{sp}^{mk_{l(r)}}$.

Nevertheless, a rough estimate of this magnitude can be implemented by the SU during the spectrum sensing phase. The modulus of the channel gain from PBS to SU can be estimated on the subcarriers used by the primary system and, by interpolation, the channel magnitude from PBS to SU on free subcarriers can be computed. Alternatively, the information about $G_{sp}^{mk_{l(r)}}$ can be carried out by a band manager that mediates between the primary and secondary users [49]. The channel magnitude of the downlink path (PBS to SU) is not equal to the reverse channel magnitude (SU to PBS) if Frequency Division Duplexing (FDD) is used. However, this downlink channel magnitude can be used as a rough estimate of the uplink channel magnitude. In this case it will be necessary to add some margin on the threshold I_{th} in order to take into account the channel estimation error. Since OFDM based secondary system introduces more interference to primary users than the case of FBMC, the knowledge of $G_{sp}^{mk_{l(r)}}$ is much more important for OFDM, in this case, larger margin value should be added for OFDM based cognitive systems.

4.3.2 Uplink multi-user case: resource allocation algorithm and results

The optimization problem (3) is an integer programming problem, which has a high computational complexity. In general, in resource allocation algorithms, a sub-optimal solution with reasonable complexity is preferred. The most classical method is to first assign the subcarriers to the users, and then to allocate power to these subcarriers. The power allocation of the multi-user system can then be regarded as a single-user system.

Subcarrier allocation may be performed in order to achieve approximately the same data rate for each users (max min objective); or to maximize the sum rate. These two objectives lead to opposite allocations; the first one is fair but leads to poor sum rate, whereas the second one is totally unfair. Other optimization objectives (proportional fair, weighted proportional fair, harmonic mean fair may be used.

Once subcarriers have been allocated, the power allocation problem with only one secondary cell (3) becomes convex and can be solved with classical convex optimization problems, such as the Gradient Projection Method, that was used in [39]. It may also be solved with the Karush-Kuhn-Tucker conditions, as in [30].

The simulation results obtained in [30] and [39] both show that FBMC leads to higher spectral efficiency than CP-OFDM when considering the same resource allocation algorithm and the same configuration, in asynchronous cognitive radio networks. The spectral efficiency achieved with FBMC is even quite close to that obtained with perfect synchronization. Other simulations in the downlink [31] lead to the same conclusions.

4.3.3 Adaptation to ad hoc scenarios

Although this scenario is limited to a cognitive case with two cells, the inter-cell interference modeling may be extended to ad hoc networks scenarios in EMPHATIC studies. Several differences will however need to be considered:

- First, all cells in the ad hoc networks are equal with respect to bandwidth access; none of them has a higher priority such as the Primary cell in the cognitive scenario. Consequently, all cells can be seen as secondary cells with equal priority.

- Second, there is no more interference threshold. Each cell may receive as much inter-cell interference as the others generate, and it cannot limit it; unless an extra coordination is added to the network. However, as we have already said, ad hoc networks should be totally uncoordinated.

- Third, interweave is no longer used: all cells may use all subcarriers. As a consequence, inter-cell interference is no longer only due to the lack of synchronization, but also in-band inter-cell interference. It may also be due to several cells at the same time. This may mitigate the benefits of FBMC over CP-OFDM, since, as shown in Table 4-3, inter-cell interference in the same carrier k is slightly higher with FBMC than with CP-OFDM.

- Fourth, channel sensing for each cell will not be able to differentiate the interference from different sources; it will only sense the resulting sum interference.

- Finally, all cells must optimize their resource allocation independently, since they are uncoordinated. In [39], only the secondary cell made this optimization, given that resources were already allocated to the primary cell. With several uncoordinated cells, resource allocation in each cell may generate high inter-cell interference to the others. If each cell individually performs its resource allocation to maximize its own optimization objective, then the whole problem becomes a non-cooperative game, and Game Theory may be needed to assess the performances of its solution [50]. However, non-cooperative games may lead to very poor outcomes in terms of network sum rate. Thus, is may be necessary to add some level of cooperation or to determine distributed criteria that allow to turn the non-cooperative game into a semi-cooperative game.

All these differences will have to be taken into account in order to study ad hoc networks. But the inter-cell interference modeling can still be used, which will allow a fair comparison of FBMC and CP-OFDM regarding resource allocation.

5. Conclusions

This report described the work undertaken in Task 5.1 of "Advantages of filter bank-based multicarrier for Radio resource management" of the EMPhAtiC project. The work has focused on the use of FB-MC for RRM in both ad-hoc and cell-based PMR networks and compared it with the alternative CP-OFDM technology.

This report first represented an overview of the proposed PMR concept, including the motivation of using FB-MC against OFDM multi-carrier technology. Then a qualitatively analysis of the benefits of FB-MC RRM was conducted. In the literature review, the theoretical analysis and numerical results in the evaluation of the performance of FB-MC in asynchronous scenario were given. This report also introduced quantitative analysis of the benefits of FB-MC in RRM by using one example in CR networks, the mathematical expressions of the interference was then presented. By constructing and solving a power minimization problem, via numerical results, it was shown that FB-MC has superiority over CP-OFDM.

Furthermore, it was described in detail that how the proposed PMR concept can be realized with a focus on PMR communications under cellular networks. By using cognitive radio and combing PMR communications with cellular systems, potential benefits were elaborated. A study of the difference between the RRM in PMR communications and that in cellular networks was given.

Finally, the last part of the document was concentrated on an ad-hoc scenario, specific characteristics different from those of a cellular network were introduced. The challenges of lacking global interference management and synchronism were discussed. Two interference models namely power spectral density and inter-cell interference table were suggested. Some numerical results were reported, and they imply that FB-MC leads to a higher spectral efficiency in asynchronous cognitive radio networks.

6. References

[1] FP7-ICT Project PHYDYAS - Physical Layer for Dynamic Spectrum Access and Cognitive Radio. http://www.ict-phydyas.org.

[2] M. Payaro, A. Pascual-Iserte, A. Garcia-Armada, and M. Sanchez-Fernandez. Resource allocation in multi-antenna mac networks: Fbmc vs ofdm. In *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, pages 1–5, 2011.

[3] D. Xenakis, D. Tsolkas, N. Passas, and L. Merakos. Dynamic resource allocation in adaptive wireless multiuser multicarrier systems. In *Wireless Conference (EW), 2010 European*, pages 1059–1066, 2010.

[4] M. Shaat and F. Bader. Comparison of ofdm and fbmc performance in multi-relay cognitive radio network. In *Wireless Communication Systems (ISWCS), 2012 International Symposium on*, pages 756–760, 2012.

[5] Musbah Shaat and Faouzi Bader. Computationally efficient power allocation algorithm in multicarrier-based cognitive radio networks: Ofdm and fbmc systems. *EURASIP Journal on Advances in Signal Processing*, 2010(1):528378, 2010.

[6] Simon Haykin. Cognitive radio: brain-empowered wireless communications. *Selected Areas in Communications, IEEE Journal on*, 23(2):201–220, 2005.

[7] J. Mitola. Cognitive radio for flexible mobile multimedia communications. In *Mobile Multimedia Communications, 1999. (MoMuC '99) 1999 IEEE International Workshop on*, pages 3–10, 1999.

[8] Qing Zhao and B.M. Sadler. A survey of dynamic spectrum access. *Signal Processing Magazine, IEEE*, 24(3):79–89, 2007.

[9] T. Yucek and H. Arslan. A survey of spectrum sensing algorithms for cognitive radio applications. *Communications Surveys Tutorials, IEEE*, 11(1):116–130, 2009.

[10] Qing Zhao, Lang Tong, A. Swami, and Yunxia Chen. Decentralized cognitive mac for opportunistic spectrum access in ad hoc networks: A pomdp framework. *Selected Areas in Communications, IEEE Journal on*, 25(3):589–600, 2007.

[11] Juncheng Jia, Qian Zhang, and Xuemin Shen. Hc-mac: A hardware-constrained cognitive mac for efficient spectrum management. *Selected Areas in Communications, IEEE Journal on*, 26(1):106–117, 2008.

[12] Hang Su and Xi Zhang. Cream-mac: An efficient cognitive radio-enabled multi-channel mac protocol for wireless networks. In *World of Wireless, Mobile and Multimedia Networks, 2008. WoWMoM 2008. 2008 International Symposium on a*, pages 1–8, 2008.

[13] B. Hamdaoui and K.G. Shin. Os-mac: An efficient mac protocol for spectrum-agile wireless networks. *Mobile Computing, IEEE Transactions on*, 7(8):915–930, 2008.

[14] Y.R. Kondareddy and P. Agrawal. Synchronized mac protocol for multi-hop cognitive radio networks. In *Communications, 2008. ICC '08. IEEE International Conference on*, pages 3198–3202, 2008.

[15] 3gpp tr 23.979: 3gpp enablers for open mobile alliance (oma) push-to-talk over cellular (poc) services, stage 2, version 11.0.0, release 11.

[16] A.K. Salkintzis. Evolving public safety communication systems by integrating wlan and tetra networks. *Communications Magazine, IEEE*, 44(1):38–46, 2006.

[17] Crystal code website,@ONLINE.

[18] Open mobile alliance (oma) website,@ONLINE.

[19] P. Jänis, C. Yu, K. Doppler, C. Ribeiro, C. Wijting, K. Hugl, O. Tirkkonen, and V. Koivunen. Device-to-device communication underlaying cellular communications systems. *Int'l Journal of Comm., Network and System Sciences*, 2(3):169–178, 2009.

[20] Chen Xu, Lingyang Song, Zhu Han, Qun Zhao, Xiaoli Wang, and Bingli Jiao. Interference-aware resource allocation for device-to-device communications as an underlay using sequential second price auction. In *Communications (ICC), 2012 IEEE International Conference on*, pages 445–449, 2012.

[21] D. Tsolkas, E. Liotou, N. Passas, and L. Merakos. A graph-coloring secondary resource allocation for d2d communications in lte networks. In *Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), 2012 IEEE 17th International Workshop on*, pages 56–60, 2012.

[22] Shaoyi Xu, Haiming Wang, Tao Chen, Qing Huang, and Tao Peng. Effective interference cancellation scheme for device-to-device communication underlaying cellular networks. In *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*, pages 1–5, 2010.

[23] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. MikloÌĄs, and Z. TuraÌĄnyi. Design aspects of network assisted device-to-device communications. *Communications Magazine, IEEE*, 50(3):170–177, 2012.

[24] Mi Jeong Yang, Soon Yong Lim, Hyeong Jun Park, and Nam Hoon Park. Solving the data overload: Device-to-device bearer control architecture for cellular data offloading. *Vehicular Technology Magazine, IEEE*, 8(1):31–39, 2013.

[25] Wonjong Rhee and J.M. Cioffi. Increase in capacity of multiuser ofdm system using dynamic subchannel allocation. In *Vehicular Technology Conference Proceedings, 2000. VTC 2000-Spring Tokyo. 2000 IEEE 51st*, volume 2, pages 1085–1089 vol.2, 2000.

[26] Ying Jun Zhang and K.B. Letaief. Multiuser adaptive subcarrier-and-bit allocation with adaptive cell selection for ofdm systems. *Wireless Communications, IEEE Transactions on*, 3(5):1566–1575, 2004.

[27] B. Farhang-Boroujeny. Filter bank spectrum sensing for cognitive radios. *Signal Processing, IEEE Transactions on*, 56(5):1801–1811, 2008.

[28] D. Roviras Y. Medjahdi H. Zhang, D. Le Ruyet and H. Sun. Spectral efficiency comparison of ofdm/fbmc for uplink cognitive radio networks. *EURASIP J. Adv. Signal Process.*, page 621, 2010.

[29] Haijian Zhang, D. Le Ruyet, D. Roviras, and Hong Sun. Noncooperative multicell resource allocation of fbmc-based cognitive radio systems. *Vehicular Technology, IEEE Transactions on*, 61(2):799–811, 2012.

[30] M. Shaat and F. Bader. An uplink resource allocation algorithm for ofdm and fbmc based cognitive radio systems. In *Cognitive Radio Oriented Wireless Networks Communications (CROWNCOM), 2010 Proceedings of the Fifth International Conference on*, pages 1–6, 2010.

[31] M. Shaat and F. Bader. Computationally efficient power allocation algorithm in multicarrier-based cognitive radio networks: Ofdm and fbmc systems. *EURASIP Adv. Signal Process*, 2010.

[32] M. Bellanger. Filter banks and ofdm-oqam for high throughput wireless lan. In *Communications, Control and Signal Processing, 2008. ISCCSP 2008. 3rd International Symposium on*, pages 758–761, 2008.

[33] Qing Bai, N. Passas, and J.A. Nossek. Scheduling and resource allocation in ofdm and fbmc systems: An interactive approach and performance comparison. In *Wireless Conference (EW), 2010 European*, pages 1042–1050, 2010.

[34] IEEE Std 802.16-2004. IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed Broadband Access Systems. Oct. 2004.

[35] K. Wongthavarawat and A. Ganz. Packet scheduling for qos support in ieee 802.16 broadbandwireless access systems. *International Journal of Communication Systems*, 16:81–96, 2003.

[36] J. G. Andrews, F. Baccelli, and R. K. Ganti. A tractable approach to coverage and rate in cellular networks. *IEEE Transactions on Communications*, 59(11):3122–3134, 2011.

[37] M. Rahman and H. Yanikomeroglu. Enhancing cell-edge performance: a downlink dynamic interference avoidance scheme with inter-cell coordination. *IEEE Transactions on Wireless Communications*, 9(4):1414–1425, 2010.

[38] D. Kim, J. Y. Ahn, and K. Kim. Downlink transmit power allocation in soft fractional frequency reuse systems. *ETRI Journal*, 33:1–4, 2011.

[39] H. Zhang, D. Le Ruyet, D. Roviras, Y. Medjahdi, and H. Sun. Spectral efficiency comparison of ofdm/ fbmc for uplink cognitive radio networks. *EURASIP Journal on Advances in Signal Processing*, 2010.

[40] T. Weiss, J. Hillenbrand, A. Krohn, and F. K. Jondral. Mutual interference in ofdm-based spectrum pooling systems. In *2004 IEEE 59th Vehicular Technology Conference, 2004. VTC 2004-Spring.*, volume 4, pages 1873–1877 Vol.4.

[41] G. Bansal, J. Hossain, and V. K. Bhargava. Optimal and suboptimal power allocation schemes for ofdm-based cognitive radio systems. *IEEE Transactions on Wireless Communications*, 7(11):4710–4718, 2008.

[42] Zhang Yonghong and C. Leung. An efficient power-loading scheme for ofdm-based cognitive radio systems. *IEEE Transactions on Vehicular Technology*, 59(4):1858–1864, 2010.

[43] B. Farhang-Boroujeny and R. Kempter. Multicarrier communication techniques for spectrum sensing and communication in cognitive radios. *IEEE Communications Magazine*, 46(4):80–85, 2008.

[44] M. Z. Win, P. C. Pinto, and L. A. Shepp. A mathematical theory of network interference and its applications. *Proceedings of the IEEE*, 97(2):205–230, 2009.

[45] M. A. Landolsi and W. E. Stark. On the accuracy of gaussian approximations in the error analysis of ds-cdma with oqpsk modulation. *IEEE Transactions on Communications*, 50(12):2064–2071, 2002.

[46] A. Giorgetti and M. Chiani. Influence of fading on the gaussian approximation for bpsk and qpsk with asynchronous cochannel interference. *IEEE Transactions on Wireless Communications*, 4(2):384–389, 2005.

[47] Y. Medjahdi. *Interference modelling and performance analysis in asynchronous OFDM and FBMC wireless communications systems*. PhD thesis, 2012.

[48] Y. Medjahdi, M. Terre, D. Le Ruyet, D. Roviras, J.A. Nossek, and L. Baltar. Inter-cell interference analysis for ofdm/fbmc systems. In *IEEE 10th Workshop on Signal Processing Advances in Wireless Communications, 2009. SPAWC '09.*, pages 598–602, 2009.

[49] J. M. Peha. Approaches to spectrum sharing. *IEEE Communications Magazine,*, 43(2):10–12, 2005.

[50] D. Fudenberg and J. Tirole. *Game Theory*. Cambridge University Press, 1991.

Glossary and Definitions

Acronym	**Meaning**
OFDM	Orthogonal Frequency Division Multiplexing
CP	Cyclic Prefix
OQAM	Offset Quadrature Amplitude Modulation
QAM	Quadrature Amplitude Modulation
SNR	Signal to Noise Ratio
NMSE	Normalized Mean Square Error
BER	Bit Error Rate
QPSK	Quadrature Phase Shift Keying
FB-MC	Filter Bank-based Multi-Carrier
FBMC/OQAM	Filter Bank-based Multi-Carrier with OQAM subcarrier modulation
PMR	Professional Mobile Radio
MIMO	Multiple-Input Multiple-Output
MMSE	Minimum Mean Square Error
BER	Bit Error Rate
AF	Amplify-and-Forward
DF	Decode-and-Forward
AP	Access Point
LTE	Long Term Evolution
FFT	Fast Fourier Transform
iFFT	inverse Fast Fourier Transform
TDL	Tapped Delay Line
ITU-R	International Telecommunication Union Radiocommunication sector
ISI	Inter-Symbol Interference
CFO	Carrier Frequency Offset
RRM	Radio Resource Management
PSD	Power Spectral Density
PU	Primary User
PPDR	Public Protection and Disaster Relief
TETRA	Terrestrial Trunked Radio
QoS	Quality of Service
SBS	Secondary Base Station
MIP	Mixed-Integer Programming
CR	Cognitive Radio
OSA	Opportunistic Spectrum Access

Acronym	**Meaning**
CRN	Cognitive Radio Network
SU	Secondary Users
MAC	Medium Access Control
CCC	Common Control Channel
D2D	Device-to-Device
PoC	Push-to-Talk over Cellular
OMA	Open Mobile Alliance
SwMI	Management Infrastructure
PTT	Push-To-Talk
IMS	IP Multimedia Subsystem
TDMA	Time Division Multiple Access
MSR	Maximum Sum Rate
PRC	Proportional Rate Constraints
WiMAX	Worldwide Interoperability for Microwave Access
SS	Subscriber Station
TDD	Time Division Duplex
FDD	Frequency Division Duplex
UGS	Unsolicited Grant Service
rtPS	Real-time Polling Service
nrtPS	Non-real-time Polling Service
BE	Best Effort Service
ertPS	Enhanced rtPS
BE	Best Effort Service
EDF	Earliest Deadline First
WFQ	Weight Fair Queue
PS	Perfectly Synchronized
PBS	Primary Base Station