On the Use of Filter Bank Based Multicarrier Modulation for Professional Mobile Radio

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Abstract—Our main emphasis is on the use of enhanced OFDM and filter bank based multicarrier (FB-MC) waveforms for utilizing effectively the available fragmented spectrum in heterogeneous radio environments. Special attention is on the broadband-narrowband coexistence scenario of the Professional Mobile Radio (PMR) evolution. The target here is to provide broadband data services in coexistence with narrowband legacy services of the TETRA family. The core idea is a multi-mode radio platform, based on variable filter bank processing, which is able to perform modulation/detection functions simultaneously for different signal formats with adjustable center frequencies, bandwidths and subchannel spacings.

I. INTRODUCTION

Public Safety organizations are using radio communication systems for the day to day operational needs, for exceptional events, and for disaster recovery conditions. These usages are collectively called PPDR (Public Protection and Disaster Relief), which corresponds to the Professional Mobile Radio (PMR) services for Public Safety organizations [1] [2]. Today they use dedicated radio communications systems (APCO25 in North America; TETRA, TETRAPOL and TEDS in Europe and in a large part of the world) primarily for voice communications and also for low-rate data transmissions. This is due to the technological limitations of currently deployed PMR/PPDR systems, which only use a small radio channel bandwidth and have thus limited throughput.

There are various important services that need essentially higher data throughput and cannot be supported by the current networks. The new required capacity can be achieved in two complementary ways: by obtaining new frequency bands for PPDR data services and by fitting a novel broadband data service within the scarcely available spectrum devoted to PMR systems. To satisfy the growing demands, actually both directions have to be followed. The EU FP7 ICT project EMPhAtiC (http://www.ict-emphatic.eu) will focus on the latter approach, which can be seen as the technically more challenging path. One of the major issues is being able to introduce new broadband data services within the current frequency allocation at the 450 MHz frequency band, in coexistence/cohabitation with the current PMR/PPDR systems.

It is natural to consider the highly spectrally efficient 3GPP LTE system as a reference basis in the PMR/PPDR system development due to its modularity and wide adoption in the civil world. However, there is a clear need to go beyond LTE, especially improving the spectral characteristics and striving to maximize the spectral efficiency, while maintaining most of the functionalities intact, especially at the higher layers.

The considered coexistence scenario, aiming at the deployment of a broadband data service in a band already occupied by narrowband PMR channels, is illustrated in Fig. 1. Here high flexibility and spectral agility, in combination with efficient fragmented spectrum use are necessary requirements for the broadband system. To reach good spectral efficiency and minimize interferences between the different services, well-contained spectrum, providing improved adjacent channel protection, is critical. This is a general issue when considering challenging spectrum access scenarios, like cognitive radio and opportunistic dynamic spectrum use.

Various enhancements to the CP-OFDM multicarrier scheme have been proposed in the literature and are under active investigations. In particular, we are witnessing an expansion of technical publications that encourage and support the use of the filter bank modulation schemes as a solution for the drawbacks and limitations of the conventional CP-OFDM scheme, which are critical for the chosen PMR/PPDR concept [3] [4]. The main limitation is the poor spectral containment of the OFDM signal, which would necessitate relatively wide guard bands around the active groups of subcarriers to isolate the new broadband service and legacy narrowband services from each other. Using filter bank schemes, it is also possible to reduce the overhead in data transmission rate due to the cyclic prefix (CP).

Multicarrier signals present a high peak-to-average power ratio (PAPR) which, combined with the nonlinearity of transmitter power amplifiers, produce undesired signal distortion and spectral regrowth. PAPR reduction and mitigation of the nonlinearity effects are important aspects in all multicarrier systems, but since the focus of this paper is on spectral containment, we concentrate here on the reduction of OFDM spectrum sidelobes.

In the following, first in Section II we discuss techniques for sidelobe suppression in OFDM, introduce the filter bank
multicarrier schemes and a fast convolution based flexible multimode filter bank structure. Section II also includes a comparison of the spectral characteristics of an enhanced OFDM scheme and FBMC/OQAM in a non-contiguous LTE like scenario. In Section III channel equalization and synchronization aspects in FBMC/OQAM are briefly discussed, together with important higher-layer aspects. Conclusions are drawn in Section IV.

II. MULTICARRIER WAVEFORMS FOR FRAGMENTED SPECTRUM USE

At the waveform level, the European project EMPhAtiC [5] focuses on heterogeneous networks in general. The most important example is the prospective evolution of PMR/PPDR to provide a high data-rate service by utilizing fragments of a PMR frequency band partly occupied by narrowband legacy PMR signals with 10, 12.5, 25, 50, and/or 100 kHz channelization. Here it is crucial to exploit the available frequency gaps efficiently while keeping the interferences in both directions at acceptable levels. Similar radio environments are encountered also in cognitive radio applications, however, with much higher variability of the primary waveforms. In cell-based PMR networks, all mobile stations are under the control of a base station. The PMR ad-hoc scenario resembles the cognitive radio case in the sense that different stations are not necessarily well-synchronized and the interferences in the environment are more difficult to handle.

OFDM solves the fundamental channel equalization problem in wideband wireless communications in an elegant and robust way, and it provides efficient means for channel aware scheduling of the transmission resources to different users in an optimal way. Due to the flat-fading channel characteristics, CP-OFDM is also an excellent basis for different multi-antenna (MIMO) techniques which are able to enhance the performance at link and system levels [6]. However, as mentioned above, OFDM has also a number of limitations, which have motivated research on various enhancements as well as on alternative waveforms.

A. Sidelobe Suppression in CP-OFDM

A very flexible way of approaching for facilitating the broadband narrowband coexistence can be named non-contiguous multicarrier modulation, as a generalization of non-contiguous OFDM scheme [7]. Here the idea is that the spectrum of the transmitted waveform can be controlled by activating only those subcarriers which are available and have been allocated for transmission, and modulating zero-symbols on the others. The approach is the same as the basic idea of OFDMA, but now the target is to be able to tolerate asynchronous waveforms in the unused frequency slots. Using basic OFDM in this way, the spectrum leakage would necessitate considerable guardbands between the active subcarriers and occupied frequency channels, and would thus lead to low spectrum efficiency.

OFDM systems maintain orthogonality between spectral components which are synchronized in time and frequency to satisfy the quasi-stationarity conditions. However, the spectral containment of the OFDM waveform is far from ideal, and the attenuation of a basic OFDM receiver for non-synchronized spectral components (interferences, adjacent channels) is limited. A straightforward approach to solve these issues is baseband filtering of the generated waveform on the transmitter side and digital channelization filtering before the FFT on the receiver side [8]. However, sharp filtering, with narrow transition band, increases the computational complexity significantly. More importantly, there is an increasing demand for spectrum agile waveform processing, in which case the post-/pre-filtering solutions would have high structural and computational complexity.

In addition to post- or pre-filtering, a number of techniques have been presented in the literature for reducing the spectral leakage in CP-OFDM based systems. One possibility is to use a tapered time-domain window for OFDM symbols [9], instead of rectangular windowing. Especially, the raised cosine window in combination with extended CP has been widely considered. For effective spectrum leakage suppression, the CP has to be significantly extended to accommodate a higher roll-off of the RC-window, leading to reduced spectrum efficiency. Raised-cosine windowing can be used also on the receiver side for better rejection of interference leakage from the unused spectral slots, with similar trade offs. In [10], it is proposed to use the windowing in edge subcarriers only to improve spectrum efficiency. Other approaches include subcarrier weighting [11], cancellation carrier method [7] [12], and precoding [13].

B. Filter Bank Multicarrier

Another approach for spectrally agile waveforms and signal processing is filter bank based multicarrier modulation (FB-MC) [4] [14] [15] [16]. Here the idea is to use spectrally well-contained synthesis and analysis filter banks in the transmultiplexer configuration, instead of the IFFT and FFT, respectively. The most common approach is to use modulated uniform polyphase filter banks based on a prototype filter design, which determines the spectral containment characteristics of the system. FB-MC is able to reduce the sidelobes to a level which depends in practice only on the spectral leakage (spectral regrowth) resulting from the transmitter power amplifier nonlinearities.

The two basic alternatives are filtered multitone modulation (FMT) [17] [18] and FBMC/OQAM (or OFDM/OQAM) [3] [4]. In FMT, the adjacent subchannels are isolated by designing them to have non-overlapping transition bands, and for each subcarrier basic subcarrier modulation, like QAM with Nyquist pulse shaping, can be used. The principle of FMT is just
frequency division multiplexing / multiple access. It relies on specific uniform multirate filter bank structures, typically based on IFFT/FFT transforms complemented by polyphase filtering structures. To reach high spectral efficiency, narrow transition bands should be used, leading to increased implementation complexity of the filter bank.

In typical FBMC/OQAM designs, each subchannel overlaps with the adjacent ones, but not with the more distant ones, and orthogonality of subcarriers is achieved by using offset-QAM modulation of subcarriers, in a specific fashion [3]. Due to the absence of cyclic prefix and reduced guardbands in frequency domain, FBMC/OQAM has the potential of reaching higher spectral efficiency than CP-OFDM. Within the FP7 PHYDYAS project [19] a significant advantage of FBMC/OQAM over CP-OFDM with the same number of subchannels per frequency band has been convincingly demonstrated [20]. However, the main benefits of FB-MC modulation formats can be found in scenarios benefiting from dynamic and non-contiguous (i.e., fragmented) spectrum allocation [21] [22]. The main drawback is higher computational complexity. In terms of real multiplication rate, the complexity of FBMC/OQAM is typically 3 to 5 times that of OFDM with the same transform size [23].

The primary approach chosen in EMPhAtiC to reach the needed spectral agility is to utilize highly flexible, variable filter bank based waveform generation and detection methods. The idea is to develop a platform able to process simultaneously alternative filter bank based waveforms, with highly adjustable characteristics, and also to do the channelization for the legacy signals following the SDR (software defined radio) model, e.g., in case of a multimode basestation. One strong candidate is the fast convolution based variable filter bank processing approach of [24], the structure of which is illustrated in Fig. 2. Fig. 3 shows an example of the subchannel frequency responses for a multimode filter bank which is able to accommodate simultaneously single carrier, FBMC/OQAM, and FMT waveforms.

To the best of our knowledge, there exists no other multimode variable waveform processing structure with similar efficiency and flexibility. However, also the more traditional polyphase filter bank and tree-structured filter bank configurations are considered as alternative solutions.

Such variable filter bank structures provide also additional flexibility in adapting to the transmission channel’s time- and frequency-selectivity features, as it is possible to use different subchannel bandwidths or prototype filters for each individual user’s signal. The proposed filter bank processing approach is particularly important for the basestation transmitters and receivers, in which case there is a need to process simultaneously different FB-MC waveforms and legacy signals. On the terminal side and in the ad-hoc context, a down-scaled version of the filter bank can be used, supporting a limited set of waveforms with reduced complexity.

C. Example of Non-Contiguous Multicarrier

In summary, FB-MC and enhanced OFDM schemes are alternative approaches for developing flexible spectrum agile waveforms with improved spectral containment, which is particularly important in fragmented spectrum use. In this subsec-

![Fig. 2. Fast convolution based flexible analysis filter bank.](image1)

![Fig. 3. Example of multiplexing different waveforms: Single-carrier signal with bandwidth of 512 bins and 6 % roll-off, FBMC/OQAM multiplex of 4 subchannels with 16 bin spacing and 100 % roll-off, FMT multiplex of 2 subchannels with 32 bin spacing and 33 % roll-off.](image2)
figure, here just the envelope of the power spectrum is visible, not the stopband ripples. It can be seen that FBMC results in much lower spectrum leakage to the spectral gaps in this non-contiguous multicarrier case than plain CP-OFDM or OFDM with raised-cosine windowing. With the used parameters, raised-cosine windowing results in about 31 dB or 50 dB attenuation, with respect to the passband level, for 1 or 2 resource block gaps, respectively, when considering a 30 kHz (2 subcarriers) bandwidth in the center of the gap. The corresponding values with plain OFDM are 15 dB and 18 dB, respectively.

III. MULTICARRIER SYSTEM DEVELOPMENT FOR PMR

A. Channel equalization and Synchronization Aspects

Both FMT and FBMC/OQAM systems can be designed to have similar number of subcarriers as an OFDM system, in which case the channel can usually be considered as flat-fading at subcarrier level, and one-tap complex subcarrier-wise equalizers are sufficient. However, there is also the possibility of increase the subcarrier spacing, e.g., in order to relax the ICI effects with high mobility, in which case multi-tap equalizers are needed [16]. A convenient approach for realizing multitap subcarrier equalizers is based on frequency sampling [25]. This method can be adapted to the multi-mode receiver architecture in an effective way by modifying the weights in Figure 2.

The special OQAM-type signal structure has to be taken into account when designing the pilot structures for channel estimation and synchronization [26], and it introduces also difficulties in adapting certain multiantenna schemes to the FBMC/OQAM context.

The broadband PMR system should be able to support a wide range of link distances and thus relatively long channel delay spreads. This requirement is also emphasized by the propagation characteristics at the used relatively low frequency band. Also relaxed synchronization and power control requirements for mobile terminals are important targets. These aspects are in favor of using FB-MC waveforms which is able to support frequency division multiplexing of asynchronous transmissions with high spectral efficiency.

Regarding asynchronous FDMA channelization, including cell-based uplink and ad-hoc scenarios, the baseline approach is to use a narrow guard band (usually one subchannel) between different non-synchronized frequency channels. Then the filter bank based transmission modes allow fully asynchronous operation regarding timing offsets between transmissions and relatively coarse mutual frequency synchronization is sufficient. This allows the transmission of short data packets without initial synchronization, and maintaining the synchronization of idle stations is not critical. Also the latency due to initial synchronization can be minimized. The required timing and frequency offset compensation algorithms will be integrated with the variable filter bank structure. However, in case of continuous transmission in cell-based systems, there are good reasons for establishing synchronism between the uplink signals. These reasons include reduced signal processing complexity and minimization of the overheads in TDD and TDMA operation modes due to time-domain guard intervals between transmission bursts, which have to be able to absorb the timing uncertainties. The overall synchronization process for

![Figure 4](image-url)
B. Higher Layers and Demonstrator Development

In addition to the waveform and basic signal processing aspects of the physical layer, EMPhAtiC will also develop effective multi-antenna techniques for the FB-MC transmission schemes, and address relay and ad-hoc networking, radio resource management and cross-layer aspects as well as spectrum sensing methods utilizing the flexible multichannel architecture. The developed broadband PMR scheme and its coexistence with narrowband PMR services is planned to be highlighted through a demonstrator development.

IV. CONCLUDING REMARKS

We have discussed non-contiguous multicarrier schemes for heterogeneous radio environments aimed at effective use of fragmented spectrum for broadband data communications. The Professional Mobile Radio evolution, along with general cognitive radio development are important applications for these techniques. We have seen that while sidelobe suppression techniques for CP-OFDM are able to significantly reduce the spectrum leakage to the frequency slots of non-active subcarriers, the FBMC/OQAM approach has superior characteristics in this respect.

The main challenge, and the main topic for future studies is to include the effects of the power amplifier nonlinearity into consideration. In this context, methods for reducing the peak-to-average power ratio (PAPR) of the modulated waveform and power amplifier linearization techniques are central issues.

The multimode filter bank structure of Fig. 2 gives the opportunity to use single-carrier waveforms with the same spectral characteristics and reduced PAPR. This is especially the case on the terminal transmitter side. Unfortunately, it is not easy use fragmented spectrum by a single-carrier waveform. However, in the uplink case the user data rates are often lower than in the cellular downlink, and there are less demands for non-contiguous transmission by a mobile station.

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