# Enhanced Multicarrier Techniques for Professional Ad-Hoc and Cell-Based Communications (EMPhAtiC)

FRONT PAGE

# PROJECT FINAL REPORT

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**Abstract:**

This deliverable summarizes and evaluates the main technical achievements and the progress status of the EMPhAtiC project during whole execution. The description includes technical, financial and legal points of view.

# Document Revision History

| Version | Date | Author | Summary of main changes |
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| 0.1 | 04.02.2014 | Xavier Mestre (CTTC) | Initial structure of the document, main sections and description of inputs needed. |
| 1.0 | 01.03.2014 | Xavier Mestre (CTTC) | First version with all inputs integrated. |
| 1.1 | 02.04.2014 | Xavier Mestre (CTTC) | First circulated version. |
| 1.2 | 08.04.2014 | Xavier Mestre (CTTC) | Second circulated version. |
| 1.3 | 16.04.2014 | Xavier Mestre (CTTC) | Third circulated version, incorporating corrections by some of the partners. |
| 1.4 | 27.04.2014 | Xavier Mestre (CTTC) | Final version, incorporating all corrections of partners. |

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# 1. Final publishable summary report

## *1.1 Executive Summary*

The Emphatic project officially started on September 1st, 2012, and has finished on February 28, 2015. This report provides a detailed account of the project activities during the whole project execution. The primary objective of the document is to demonstrate that contractual objectives have been reached with good quality and on a timely manner. To that effect, a synthetic account is given of the most important technical activities and achievements of the project. Additionally, the dissemination measures carried out during the project are summarized, and the potential implications and exploitation possibilities of the obtained results are discussed.

The current document is thus composed of two major sections, respectively devoted to the final publishable summary report and the use and dissemination of foreground.

The aim of Section 1 is to evaluate not only technical achievements of the project, but also its visibility, its real influence and impact. The section begins with a publishable summary, including a summary description of the project context and objectives, together with a description of the work performed and the main scientific and technical achievements on a workpackage basis. The potential socio-economic impact aspects of the project results are then discussed, along with its wider societal implications. The second part of this section presents the main dissemination activities of the project, including: scientific publications, project workshops, public demonstrations, journal special issues, special sessions in conferences, courses, tutorials, seasonal schools, industrial dissemination events and dissemination activities in standardization fora. The last part of Section 1 presents the exploitation plans for the generated foreground. This includes a description of the main intellectual property rights generated in the project (i.e. new patent applications), and a detailed description of the exploitation strategy that will be followed by each partner of the consortium.

The second main section of this document describes the use and dissemination of the foreground generated within the project. First, an exhaustive account of the specific dissemination measures is given, including the complete reference to all the scientific publications generated by the project. Then, a complete list of all the dissemination activities is given, including all pertinent details and the corresponding targeted audiences. The second part of this section provides an exhaustive account of all the patent applications generated within the project, followed by a description of the project exploitable foreground, including its purpose and potential impact. Section 2 concludes with a report on the societal implications of the project.

## *1.2 Project context and objectives*

Today, professional Mobile Radio (PMR) and public protection and disaster relieve (PPDR) systems are used mainly for voice communications and low rate data transmissions. This is due to the technological limitations of currently deployed PMR /PPDR systems, which only use a small frequency bandwidth and have thus limited throughput. However, there is a current need for a number of services that need higher data throughput which cannot be supported by these networks, e.g. video conferencing and streaming, transmission of high resolution photographic images, rapid on-line access to remote data bases, full intranet browsing, file transfer, etc.


Figure 1.2-1 Higher data rates for Public Safety Evolution

The EMPhAtiC project addresses the need to upgrade PMR/PPDR networks towards supporting broadband data communications services. 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. In order to satisfy the growing demands, both directions will have to be followed, although the latter approach appears to be more attractive for several reasons. First, the current PMR spectral bands are located around 400 MHz and 700 MHz, which are very attractive from the electromagnetic propagation point of view. These bands facilitate high coverage areas with a relatively low transmitted power, guaranteeing the availability of PPDR services in remote or sparsely populated areas. On the other hand, a progressive reuse of the currently employed spectrum avoids the competition for additional space in the already congested GHz bands.

Consequently, the general objective of EMPhAtiC is to propose an innovative technological solution allowing increased data throughputs for Public Safety radio-communication systems, in order to satisfy emerging new data service needs in cohabitation with existing networks in the same frequency bands, to facilitate a smooth migration towards broadband systems and to increase spectrum efficiency.  This can be seen as a very challenging evolution path, but also the most realistic opportunity to benefit from the advantages of latest developments in multicarrier waveforms and related signal processing techniques.

One of the major problems for the introduction of new broadband data services within the current frequency allocation is how to guarantee the coexistence with current PMR/PPDR systems, as depicted in Figure 1.2-2. Given the widespread dominance of 3GPP LTE systems in the civil world, it seems only natural to consider this system as a baseline reference for the proposed broadband PMR/PPDR solution. However, the physical layer of LTE poses severe problems in order to guarantee cohabitation with legacy narrowband systems, especially due to the poor spectral containment of the CP-OFDM subcarriers. Additionally, high flexibility is needed to utilize effectively the variable spectral gaps between different narrowband users, since radio implementations have to support non-contiguous spectrum allocations. Filterbank multicarrier modulations (FBMC) are a natural approach to address all these issues.

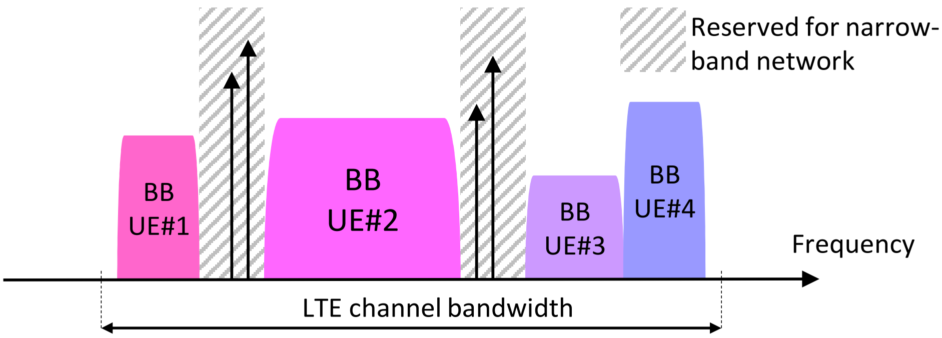



Figure 1.2-2 Proposed future PMR broadband in coexistence and cohabitation with current systems

In the PMR/PPDR context, both cell-based and ad-hoc broadband data networking solutions are needed and are addressed in EMPhAtiC. The coexistence issues and radio environment are similar in both cases. Ad-hoc methods studied for future releases of LTE are potential solutions, but they have to be adapted to the difficult radio environment of the PPDR cohabitation scenario. In addition to the mentioned PMR/PPDR case, the advanced waveforms and signal processing techniques developed and validated in the project also find applications in various other scenarios of flexible spectrum usage.

In order to reach an innovative solution to satisfy the general objective and implement the suggested flexible system using modified waveforms, several technical challenges need to be overcome. In addition, many techniques being currently developed for OFDM-type system (such as LTE) need to be adapted if new waveforms are considered.

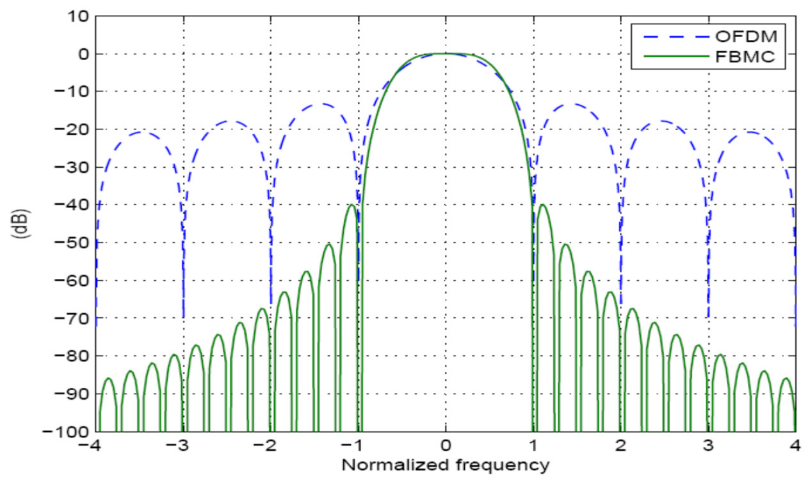



Figure 1.2-3 OFDM and FBMC/QAM spectra for individual subcarriers.

All these different technological challenges are summarized below in terms of specific objectives of the EMPhAtiC project:

- **To develop an efficient and highly flexible/variable filterbank processing structure** for use in heterogeneous environments with irregularly fragmented spectrum. Such filterbanks could accommodate simultaneously different modulation formats with adjustable centre frequencies and bandwidths, possibly with non-equidistant subchannel spacings, and they could be used for the modulation, demodulation and frequency-domain equalization of different filterbank multicarrier (FBMC) and filterbank single carrier (FBSC) waveforms, even simultaneously. Regarding the coexistence between narrow-band and broad-band PMR systems, such a flexible filterbank can also provide, in an efficient way, the functionality of transmitter and receiver channelization for legacy PMR signals, as well as possibility for frequency-domain channel equalization. This will enable a flexible spectrum use for mobile broadband applications, while taking into account commercial and regulatory opportunities and constraints.
- **To develop the needed channel estimation, equalization and synchronization functions, which are compatible with the multimode waveform processing solution**. An efficient unified synchronization and channel equalization concept must be established for different transmission modes in the context of multimode non-uniform filterbanks. Special attention must also be paid to the cases with highly frequency-selective subchannels, which can be easily encountered in current PMR bands given the favourable electromagnetic characteristics of the targeted frequency bands.
- **To combat the high variation of the envelope of the modulated waveform, leading to high peak-to-average power ratio (PAPR)**, which emphasizes the effects of nonlinearities of the transmitter power amplifier (PA). An important objective of EMPhAtiC is to find suitable PAPR reduction methods for the considered multicarrier modulation formats. Additionally, transmitter power amplifier linearization methods need to be provided, as well as techniques for mitigating the effects of the power amplifier nonlinearity and other nonlinearities in the transmission chain.

- **To improve the spectral and energy efficiency through the exploitation of multiple antennas.** While MIMO-OFDM has been well investigated, the problem of combining MIMO and FBMC still poses significant problems. The objective of EMPhAtiC here is to propose efficient transmission schemes, and to develop detection and channel estimation algorithms based on uniform and non-uniform multimode FBMC MIMO signals such as STBC-coded, SFBC-coded and SM-multiplexed. In order to reduce the complexity of these algorithms, efficient suboptimal detection of STBC-coded and SM-multiplexed FBMC MIMO in both synchronous and asynchronous cases need to be considered. Here, again, especial emphasis needs to be given to the presence of highly frequency selective channels, which are commonly encountered in current PMR bands.
- **To evaluate the feasibility and performance of FBMC techniques in specific ad-hoc PMR environments, e.g., relays, multi-hop and cooperative environments, with some loss of synchronization**. The objective here is to study the advantages of FBMC when used in cooperative MIMO schemes and optimize the synchronization and channel estimation aspects of these communication architectures for their use in combination with FBMC.
- **To develop original resource allocation algorithms for FBMC in a non-perfect synchronization context.** In PMR systems, the transmitting nodes will not necessarily be synchronized. This problem may be particularly difficult in ad-hoc PMR systems. In this context, known radio resource allocation schemes may become inefficient, since interference between nodes will become harder to predict. FBMC is more adapted than CP-OFDM for asynchronous transmissions, since it efficiently reduces interference in adjacent carriers. FBMC must however be exploited with consistent resource allocation, in order to maximize the spectral efficiency, while taking into account commercial and regulatory opportunities and constraints.
- **To develop radio scene analysis for flexible spectrum usage in emergency situations**. The multimode non-uniform FBMC will introduce flexibility in cognitive radio systems facilitating also spectrum sensing in heterogeneous radio environments. Feature based algorithms can, spatially and temporally, sense the spectrum occupancy of the used wide frequency band allowing flexible spectrum use for mobile broadband applications.
- **To demonstrate the superiority of the EMPhAtiC spectrum coexistence architecture**. One of the main objectives of the project is to demonstrate, with a hardware platform developed in the project, that the EMPhAtiC concept is a viable alternative for the introduction of broadband PMR services in currently employed PMR bands without disturbing the currently deployed narrowband services.

In order to achieve all these objectives, the project has been structured around ten different workpackage, namely a coordination workpackage (WP1), seven technical workpackages covering different aspects of the PHY-MAC layer design for the EMPhAtiC concept (WP2-WP8), a demonstration workpackage that contains both hardware development and system level simulations (WP9) and finally a dissemination workpackage (WP10) which also covers the standardization aspects of the project.

## *1.3 Main scientific and technical results*

Over the course of the EMPhAtiC project, important advances have been made in order to propose a viable technological PHY-MAC solution that is able to support the emerging broadband PMR services in spectrum coexistence with legacy narrowband transmissions.

At the waveform level, a highly flexible filterbank processing architecture based on fast convolution (FC) has been developed and optimized. Given its inherent non-uniform structure, it is quite suitable for heterogeneous environments with irregularly fragmented spectrum. Interference models and spectrum mask requirements for spectrum coexistence with narrowband PMR have been elaborated, and the proposed filterbank waveform has been shown to outperform other alternative multicarrier signals (including several methods for sidelobe suppression in CP-OFDM) in terms of spectral containment. On the other hand, interference effects due to imperfect channel equalization and multiple access interference of the proposed waveforms were modelled and evaluated.

This waveform characterization has been complemented by novel channel estimation schemes and training signals resulting in high accuracy estimation under challenging PMR scenario conditions, such as in presence of FB-induced interference, channels of high frequency/time selectivity, or requirements on low overhead constraints (complexity and training signal length). In particular, a unified frequency-domain synchronization and channel equalization concept for different transmission modes in the context of multimode non-uniform filter banks was developed. Various studies on Peak to Average Power Ratio (PAPR) reduction methods were carried out, and the non-linear spectral re-growth in FBMC systems was also fully characterized.

Regarding the use of multiple antennas in PMR scenarios, several transmission/detection schemes for spatial multiplexing (SM) and space-time/frequency block coding (STBC/SFBC) for FBMC have been proposed, both under centralized and distributed (coordinated) MIMO architectures. Specific precoders/beamformers, (turbo) receivers and channel estimation methods have been developed, which deal with PMR in severe frequency selective and doubly dispersive MIMO channels. The use of compact antenna arrays in PMR frequency bands has also been addressed.

At the radio resource management (RRM) level, the use of FBMC in both ad-hoc and cell-based PMR networks has been studied and compared with the alternative CP-OFDM technology. It has been shown that the FBMC physical layer can greatly contribute to improving the scheduling process in PMR networks, and a novel traffic scheduler has been proposed in order to effectively deal with critical PMR traffic inside a cell. Several cross-layer RRM policies have also been developed, exploiting the coordination with either the physical or the application layers.

Another important aspect of the project has been the study of cooperative multi-antenna and multi-hop communication techniques in asynchronous, time-varying and partially coordinated scenarios. Several receiver and channel estimation architectures have been proposed for this specific setting, and various coordinated beamforming techniques have been developed in the multi-user FBMC context. This work has been complemented with the study of single and multi-hop relaying strategies for coverage extension of the PMR system, giving special emphasis to the support of the FBMC physical layer and including two-way relay extensions. Also in this context, multiple improved radio scene spectrum analysis techniques have been developed, which specifically take into account the structure of the FBMC receiver and exploit the spatial diversity as well as the sparsity patterns of the wideband PMR scenario.

The practical applicability of all these technological advances has been supported by a system level simulator and by a hardware demonstrator. This hardware transceiver implements a fast convolution filterbank (FC-FB) broadband PMR that is able to coexist with narrowband Tetrapol signals.

In what follows, we provide a more detailed analysis of the project achievements and technical advances made in each workpackage.

### 1.3.1 WP2: Waveform design and filterbank structures

The overall objective of this workpackage is to provide additional enhancements to filterbank and OFDM based physical layer performance concerning primarily their applicability to heterogeneous cell-based, ad-hoc, cooperative and relaying networks, having in mind the standardized LTE down/up-link coexistence with the PMR band. This work has been structured around three different tasks, which specifically target the waveform optimization (Task 2.1), the fast convolution framework (Task 2.2) and the compatibility with the PMR band (Task 2.3). Below we provide more details about the main results obtained in these three tasks.

<u>Task 2.1: Uniform and non-uniform FBMC</u>

In this task, the orthogonality conditions for non-uniform Filterbank Multcarrier (FBMC) modulations have been established and evaluated by simulations in deliverable D2.1. The study has covered both FLO (Frequency Limited Orthogonal), and TLO (Time Limited Orthogonal) FBMC variants, including also the possibility of asymmetrical spectral shaping in FBMC/OQAM. The work included also investigations on certain simplified and robust multicarrier waveforms.

On the other hand, various aspects of prototype pulse optimization, concerning the out-of-band radiation and channel frequency selectivity were studied in deliverable D2.1. An exact analytical description of the FBMC/OQAM signal model and a characterization of the effect of channel frequency selectivity using an asymptotic approach (with large number of subcarriers) were conducted. This has served as a basis to study the residual distortion of the system under severe channel frequency selectivity. The final objective is to optimize the prototype pulses in such a way that this residual distortion is minimized subject to the reconstruction constraints. Optimized pulses for different configurations on the number of subcarriers and overlapping factors have been obtained. Additionally, a semianalytical method was developed in D2.2 for evaluating the interference introduced in FBMC/OQAM transmission link with different frequency selective channel models when using single-tap subcarrier equalization. These results were utilized for accurate FBMC/OQAM PHY layer modelling in the context of system-level simulations of the B-PMR system. This was extended in D2.3, where an analytical model was developed for multiple access interference in OFDM and FBMC/OQAM when non-synchronized users are operating in adjacent groups of sub-carriers.

Finally, a study of the coefficient quantization effects in traditional types of implementations (polyphase, lattice, extended lapped transform) of the transmitter synthesis banks for FBMC/OQAM was presented in D2.3. The arithmetic complexity of the prototype filter implementation was evaluated using the canonical signed digit representation of the filter coefficients. Depending on the overlap factor of the prototype design, coefficient word lengths in the order of 6-8 bits were found to be sufficient.

Task 2.2: Flexible, multimode, variable filterbank

Simple, flexible and low-complexity structures for multimode filterbank signal processing were developed here, in order to accommodate uniform and non-uniform multicarrier and single-carrier waveforms with adjustable center frequencies. The development of general analysis and optimization methods for fast-convolution based filter banks (FC-FB) were completed during the first project year and reported in D2.1. An extensive collection of design examples have been reported and they provide a good idea about the design trade-offs. A basic complexity analysis of FC-FB (in terms of multiplication rates) revealed that FC-FB is competitive with polyphase implementations in terms of implementation complexity, in addition to providing superior flexibility to support multimode waveform processing and simultaneous processing of asynchronous transmissions.

In D2.2 the FC-FB design was further elaborated for the B-PMR application in heterogeneous radio environment. The main focus was on the spectral leakage effects between narrowband TETRA channels and an LTE-like FBMC/OQAM type B-PMR system, assuming non-contiguous spectrum use for the latter. It was demonstrated that the FC-FB structure can be used for simultaneous processing of MC waveforms and narrowband TETRA signals. Trade-offs between FC processing block length, in-band and out-of-band distortion effects, and arithmetic complexity were investigated and highlighted in D2.3.

Finally, a detailed evaluation was made about the FPGA implementation aspects of the core modules of FC-FB based FBMC/OQAM systems. In D2.1, initial results about the studies on FC-FB and polyphase filter bank implementation using FPGAs were presented, and the study was completed in D2.2. The filter bank modules for FBMC/OQAM using the FC-FB structure and polyphase filter bank structure were implemented and tested against the EMPhAtiC Matlab simulator called Fibasim. The FC-FB structure was found to be implementable on FPGA, consuming only slightly more of the FPGA resources in comparison to the corresponding polyphase filterbanks.

Task 2.3: LTE Compatibility and coexistence in PMR band

In this task, several partners have been jointly working on the integration of LTE-like broadband system in the PMR band, considering OFDM vs. FBMC coexistence capabilities and performance. The study of compatibility and coexistence issues between the B-PMR and TETRA/TEDS systems was reported in D2.2 and it focused on the case where 1.4 MHz, 3 MHz or 5 MHz LTE-like multicarrier system is fitted into the 5 MHz PMR band. The interference analysis between TETRA/TEDS and B-PMR systems was elaborated in detailed manner to take into account the spectral masks based on the TETRA system requirements defined in ETSI standards. The study resulted in a spectrum mask for defining the spectral requirements for the new B-PMR system.

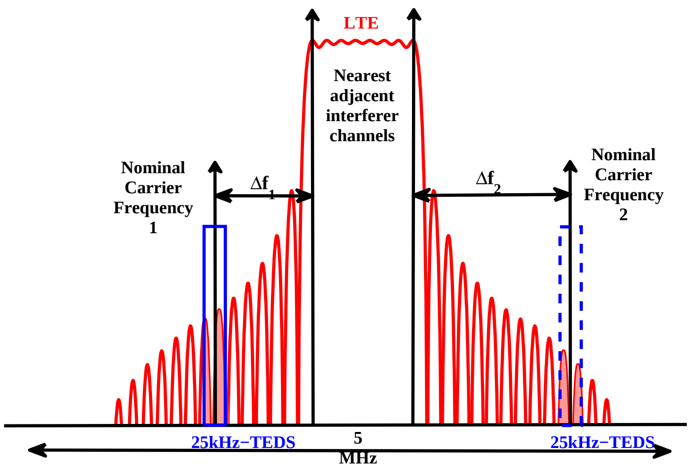



Figure 1.3-1 LTE coexistence issue with narrowband PMR systems.

Based on the waveform PSDs of OFDM and FBMC/OQAM, we then analyzed the interference effect caused by the deployed multi-carrier broadband system on the narrowband TEDS channels (see Figure 1.3-1). The obtained results show that, in order to make the LTE - TEDS cohabitation possible, we need to heavily filter the synthetized CP-OFDM signal. This filtering is made to protect the TEDS systems by reducing the side lobe levels of the modulated OFDM spectrum. Of course, better rejection performance requires filters with long impulse responses thus inducing additional delays, and the filtering also introduces ICI to the LTE subcarriers. On the other hand, the FBMC and FBSC signals fit perfectly within the PMR-TEDS harmful interference protection requirements starting from the minimum frequency offset allowed by the TEDS reception mask. Therefore, LTE-like FB-based broadband system could be a potential candidate to be deployed in the PMR band offering very high data rates to the next generation of broadband PMR/PPDR systems.

Several schemes for CP-OFDM spectral sidelobe control in non-contiguous (NC)-OFDM type PMR scenario have been studied. The work included a general overview of existing methods, as well as evaluation and further development of two central methods (time-domain windowing and cancellation carrier method) in the NC 5 MHz LTE like case. Based on these spectrum mask studies, it was concluded that it is quite difficult to reach the targeted spectral containment with OFDM sidelobe suppression techniques, even when the arithmetic complexity approaches that of FBMC techniques. The alternative waveforms reaching the target were found to be FMT, FBMC/OQAM, and FB based single-carrier (FBSC).

In D2.3, fast-convolution implementations for FBMC/OQAM, FBSC, and FMT waveforms were elaborated and optimized for the B-PMR scenario. A numerical performance and complexity evaluation of spectrally well-contained waveforms, considering both traditional polyphase/time-domain filtering and FC based implementations, was done with the heterogeneous broadband PMR application in mind. Here the 15 kHz sub-carrier spacing of LTE was the basis for the designs, and -60 dB PSD level in a one resource block wide spectrum gap was targeted. Also recent 5G waveform proposals (GFDM, WCP-COQAM, and UFMC) were included in the discussion, but it was concluded that it is difficult to reach the targeted spectrum containment with them. FC-FB implementations FBMC/OQAM and SC waveforms were found to be effective (see Figure 1.3-2). They also have very high flexibility, and effective support for asynchronous multiuser operation, but the increased block length remains as the main drawback. FC-FB was not found to be very effective for implementing FMT, especially when LTE-like parameterization is targeted.

Finally, an integrated link-level simulator (called Fibasim) has been developed, which includes OFDM, polyphase FBMC/OQAM, and FC-FB based schemes. Also uniform TLO, and non-uniform TLO and FLO formats have been integrated into Fibasim. A GIT repository has been arranged. General simulator improvements have been made, including regression test cases, plotting, simulation progress display, etc. Major channel models used in 3GPP standardization (TU, HT, RA, ETU, EPA, etc.) have been included in the simulator. Turbo coding and interleaving have been implemented in cooperation among several partners.

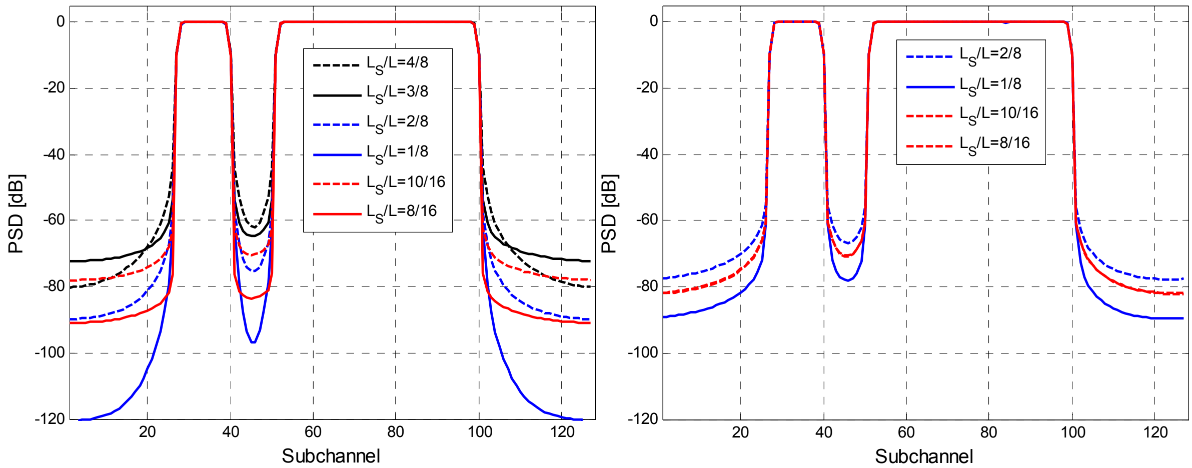



Figure 1.3-2. PSDs of FC-FB implementations with different IFFT lengths and overlap factors. Left: Non-contiguous FBMC/OQAM; the $L_S / L = 1/8$ case equals the polyphase implementation with $K$=4. Right: Non-contiguous (two-user) SC waveform.

### 1.3.2 WP3: SISO channel estimation, equalization and interference reduction

The aim of this WP is to provide performance enhancements through transmitter- and receiver-end signal processing for the FBMC formats introduced and elaborated in WP2. These concern estimation and various forms of equalization and synchronization for doubly dispersive channels, along with means of reducing the impact of non-linear distortions on adjacent channels interference.

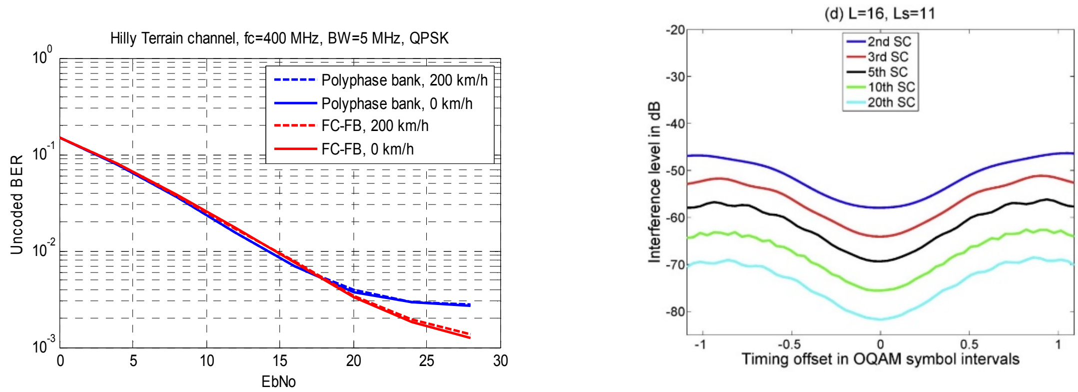
Task 3.1: Channel Estimation

A detailed development of channel estimation procedures was performed, in order to guarantee high accuracy estimation under challenging conditions. This included the presence of FB-induced interference, channels of high frequency and time selectivity, and the need for low overhead (complexity and training signal length).

On the one hand, several methods based on per-subcarrier channel estimation were investigated. The main challenges here were the FB-prototype filter time spread, combined with channels with high frequency selectivity, with the objective to attain relatively low complexity and high spectral efficiency. Distinct methods were here investigated for different pilot and preamble configurations. On the other hand, several methods based on broadband channel estimation were developed. Here, two different approaches were followed, both based on a known preamble to train the channel estimator: a parametric one, relying on a (realistic) delay-path model for the channel together with a MUSIC/LS formulation of the resulting problem, and an alternative approach based on a formulation of the system in terms of the channel impulse response, Additionally, this workpackage has studied several alternatives for FBMC channel estimation according to the Maximum Likelihood (ML) principle.

Task 3.2: Adaptive equalization and Successive (self)-Interference Cancellation (SIC) methods

Fragmented spectrum scenarios, like the heterogenous PMR setting considered here, impose new challenges due to the existence of strong interfering unwanted spectral components between the used spectral slots. In order to address this issue, reliable channel equalization and synchronization schemes for the FC-FB architecture were developed. The proposed architecture utilizes the FFT weights of the FC-FB structure also for channel equalization, timing and frequency offset compensation, and for timing and frequency offset estimation.




(a) (b)

Figure 1.3-3. (a) Channel equalization performance for embedded FC-FB equalizer versus 3-tap equalizer in polyphase FB. (b) Timing offset compensation performance in FC-FB in terms of out-of-band interference.

On the other hand, the application of the inter- and intra-subchannel symbol interference cancellation in the context of real-samples FBMC/OQAM and TLO representation was thoroughly studied, assuming for both uniform and non-uniform subchannels spacing configuration and, exploiting channel sparsity. Furthermore, a widely linear filtering (WLF) based equalization concept with explicit account for the presence of co-channel interference was also developed here.

Task 3.3: Reduction of PAPR and effect of nonlinearities

Various studies on Peak to Average Power Ratio (PAPR) reduction methods were carried out in this task. The work included a general overview of existing methods for OFDM and FBMC and some specific studies on PAPR reduction methods suitable for FBMC. Special attention has been given to simulation and analytical estimation of the non-linear spectral re-growth in FBMC systems.

More specifically, a simple HPA (High Power Amplifier) characterization model has been derived. Two novel schemes based on Selective Mapping (SLM) were developed in order to reduce the PAPR of FBMC modulated signals: Dispersive-SLM (DSLM) and Trellis-based SLM (TSLM). On the other hand, the PAPR characteristics of FB based single carrier waveforms with small roll-off were evaluated and compared to OFDM based SC-FDMA, showing essentially similar characteristics (with slight benefit for FBSC). Tone reservation and windowed clipping based PAPR mitigation was tested for FBMC/OQAM, and the effects of nonlinear power amplifier on the spectral regrowth of FBSC and FBMC/OQAM were evaluated. Finally, the impact of HPA non-linearity on FLO and TLO uniform and non-uniform stacking and number of subchannels has been analysed.

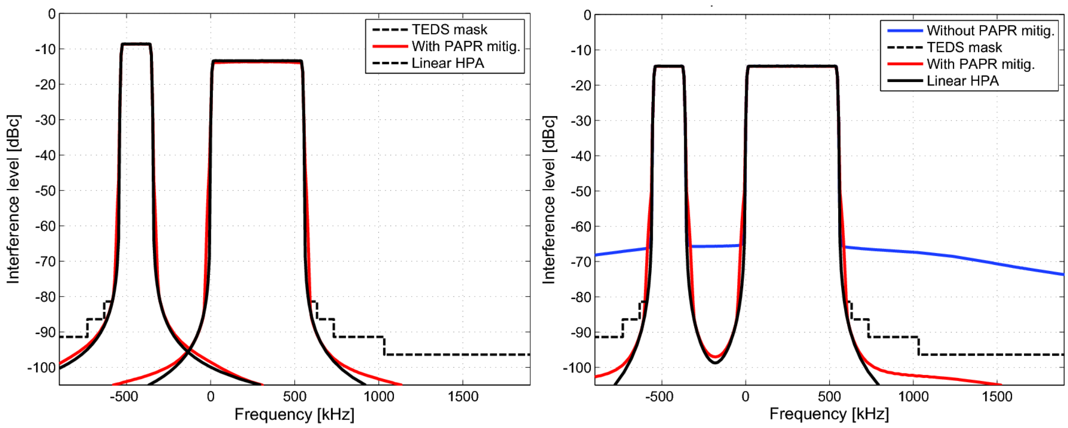



Figure 1.3-4. Spectral characteristics of fast-convolution based waveforms with QPSK modulation, windowed clipping based PAPR mitigation, and SEL model for HPA. Left: Non-contiguous FBMC/OQAM case with 48 active subcarriers and 24 subcarrier wide gap, IBO = 8.6 dB. Without PAPR mitigation IBO = 11 dB is needed. Right: 12 and 36 subcarriers wide SC signals of different users. IBO = 4.8/5.3 dB 12/36 subcarrier cases. Without PAPR mitigation, IBO = 6.8/7.2 dB needed, respectively.

### 1.3.3 WP4: MIMO transmission and reception techniques

The overall objective of this workpackage is to propose efficient MIMO transmission and reception methods for uniform and multimode non-uniform FBMC, to develop channel estimation and detection algorithms, and to demonstrate the FBMC advantages for transmit beamforming and antenna processing at the receiver side in PMR systems. The main scientific and technical results obtained during the project in the workpackage 4 dedicated to MIMO transmission and reception techniques can be summarized as follows.

In Task 4.1, for SM/FBMC-OQAM a partial interference cancellation scheme has been proposed, which is designed to perform a partial interference cancellation for the smallest coefficients of the transmultiplexer impulse response and the largest coefficients are equalized using a Viterbi detector. The interference cancellation scheme based on a combined minimum mean squared error and maximum likelihood criteria (MMSE-ML) has also been studied. This scheme has been also evaluated when associated with channel code in an iterative framework. Regarding the combination of FBMC using QAM symbols, it has been shown that the energy of the intrinsic interference can be significantly reduced using FBMC-QAM.

MIMO and MISO detection schemes have been developed based on the real-valued Successive Interference Cancellation (SIC). Numerical results for flat fading channels have been presented, and it was shown that in the MIMO case the diversity gain is achieved. The combination of STBC and SFBC with FBMC-OQAM has been further studied. While the presence of the inherent interference prevents the use of Alamouti coding scheme, different arrangements in STBC and SFBC have been proposed to reduce the effect of the interference.

Transceiver architectures for FBMC/OQAM that are designed to be robust to the presence of severe channel frequency selectivity have been considered. Several parallel precoders/linear receivers have been proposed, and their performance has been analytically studied in terms of the residual distortion at the output of the analysis filterbank. Explicit transceiver architectures for spatial multiplexing and for SVD based frequency-selective precoding have been proposed and analysed.

As an extension of this work, new beamforming/precoding schemes for MIMO FBMC/OQAM systems have been proposed by adapting a very standard precoding constructed from the eigenvectors of the MIMO channel matrix. A thorough study on the reference phase selection has been conducted. Numerical results show a significant performance improvement that is achieved by carefully selecting the phase function associated with the eigenvector entry with the highest modulus. The proposed second order model for the reference phase leads to enhanced performance for both the traditional construction and the Taylor-based precoding architecture with two parallel stages.

In Task 4.2, the problem of MIMO-FBMC/OQAM channel estimation was addressed in its preamble based version, using preambles of the shortest possible duration. The latter feature is of a high practical importance in highly time-varying environments such as the ones found in PMR applications. The main contribution lies on the derivation of MSE-optimal preambles for estimating MIMO CIRs of high frequency selectivity. The training designs developed here were demonstrated to considerably improve upon the estimation performance of pseudo-random preamble signals.

An adaptive Bell Labs Layered Space- Time (BLAST) Decision Feedback Equalization (DFE) structure has been proposed. This algorithm, enjoying low complexity, fast convergence and numerical stability, was developed and extensively studied as an effective means of equalizing MIMO FBMC/ OQAM channels of high time- and frequency-selectivity. Both the BLAST ordering adaptation and the update of the equalizer filters are performed via an efficient, numerically robust recursive least squares (RLS) algorithm, able to perform satisfactorily in a highly time-/frequency-selective environment.

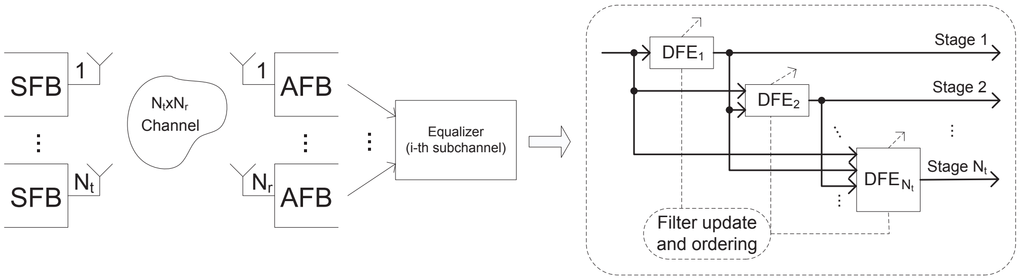



Figure 1.3-5 The per-subchannel DFE structure.

Channel estimation was called to assist in further reducing the requirements for training input. A LTE-compliant pilot configuration was implemented and tested for adapting the equalizer in the payload of the frame. The emphasis was on reducing the training overhead while guaranteeing good performance. Auxiliary pilots were implemented for MIMO-FBMC/OQAM. The use of auxiliary pilots was shown to allow satisfactory adaptation of the BLAST DFE algorithm even in fast fading environments. The algorithm has been extensively evaluated for both FBMC/OQAM and FMT, as well as OFDM systems.

Linear adaptive equalization, of the frequency sampling type, was studied in the context of the FC-FB structure proposed in deliverable D2.1, with emphasis on FBMC/OQAM modulation. One of the important features of this equalization scheme is that the equalizer is effectively embedded in the FB structure itself, resulting in an elegant and computationally efficient implementation. The effectiveness of the proposed equalizer is successfully demonstrated in both low and high mobility scenarios, also for harsh propagation scenarios typical in PMR. Channel estimation was also required here for setting the equalizer filters on the basis of scattered pilots. The computational requirements of this scheme were analyzed and favorably compared to those of the classical polyphase structure.

The challenging task of STC in MIMO-FBMC/OQAM systems was also revisited. When the FBMC transmitter structure is based on space-time Bit Interleaved Coded Modulation (BICM), it is possible to implement an iterative receiver based on the turbo principle. The first stage is a space-time equalizer, which mitigates the interference and provides soft information to the second stage, where a classical soft-input soft-output binary decoder is employed. Two versions were studied. In the first one, the symbols are considered as complex, with the imaginary part corresponding to the intrinsic interference of FMBC/OQAM. The second version stems from the will to further exploit the soft information fed back by the second stage, especially when the reliability of the decoded symbols is increased. It relies on a strictly real domain formulation. In the simulations, a small number of iterations was sufficient for achieving acceptable performance and benefit from the available diversity. The analysis was restricted to a single-tap equalizer but its extension to a multi-tap equalizer is expected to significantly improve the performance, especially in highly frequency selective channels.

In Task 4.3, starting with point-to-point MIMO broadband PMR scenarios, a coordinated beamforming based transmission strategy has been designed, where precoding and decoding are jointly and iteratively performed. Then for the downlink of multi-user MIMO broadband PMR systems, two transmission schemes have been developed. These two techniques have been proposed as a solution to the problem that the state-of-the-art transmission strategies for the downlink of FBMC/OQAM based multi-user MIMO systems cannot be employed or fail to achieve satisfactory performance when the total number of receive antennas is not smaller than the number of transmit antennas of the base station. It is worth noting that, in addition to the suppression of the multi-user interference, the proposed IIM-CBF schemes are effective in mitigating the intrinsic interference that is inherent in FBMC/OQAM based systems. It has been shown that the FBMC/OQAM based multi-user MIMO downlink systems where IIM-CBF is employed achieve a similar performance compared to their CP-OFDM based counterparts but with a higher spectral efficiency and a greater robustness against misalignments in the frequency domain as show in the following figure.

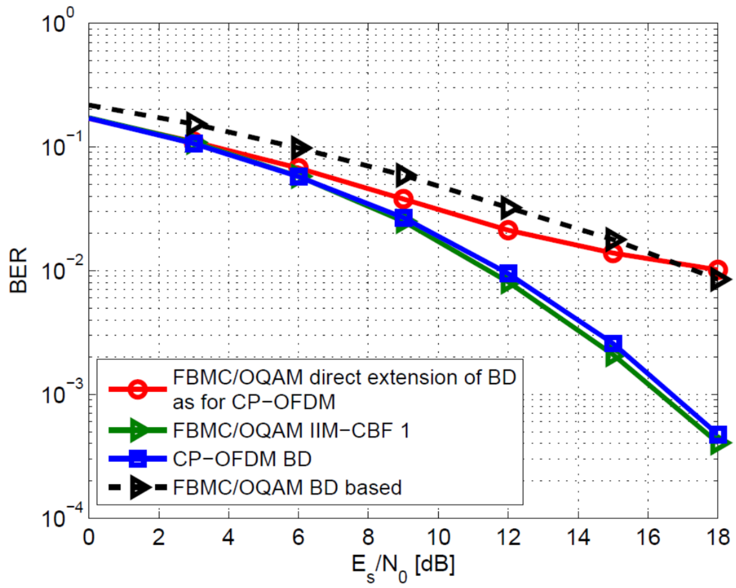



Figure 1.3-6 FBMC/OQAM based multi-user MIMO CBF downlink systems achieve a similar performance compared to CP-OFDM but with a higher spectral efficiency and higher robustness against frequency misalignments.

In addition, the performance of the proposed intrinsic interference mitigation coordinated beamforming (IIM-CBF) algorithms has been evaluated in the presence of imperfect channel state information at the transmitter. Finally, we have investigated more challenging but more realistic PMR scenarios where the channels are highly frequency selective.

We have also analyzed the impact of imperfect CSI at the transmitter due to limited feedback on the performance of FBMC/OQAM based multi-user downlink systems where each user node has a single antenna and the zero-forcing precoding algorithm is employed. The numerical results have shown that FBMC/OQAM achieves similar performance compared to CP-OFDM in case of multi-user downlink systems with imperfect CSIT.

A two-step MAP antenna processing approach has been devised for SIMO broadband PMR systems using FMT modulation scheme as a wideband evolution of the TETRA standard, TEDS. The proposed technique is able to achieve the co-channel interference mitigation without the a priori knowledge of the interfering signals. The first step of this approach is dedicated to the spatial noise whitening using a MAP method, and MRC is employed in the second step. Via simulation results, it is observed that under various fast-varying frequency selective propagation conditions, BER performances are significantly enhanced by the proposed two steps MAP antenna processing approach compared to classical MRC and other variants of the MRC technique.

### 1.3.4 WP5: Radio Resource Management and Cross-Layer aspects

The main target of WP5 is to study the use of FBMC for RRM in both ad-hoc and cell-based PMR networks and compare it with alternative technologies mainly DFT-SC and OFDM, and to optimize RRM performance using cross-layer approaches. In the following a comprehensive description of the work done for each task of WP5 is provided. For each one of the tasks the planned activities and the major advances are listed.

T5.1: Advantages of FBMC for RRM

The aim of this task was to analyze how filter based multicarrier waveforms can reduce the interference between nodes in PMR networks, and to investigate the effects of this on the RRM process to assess the advantages for network and resource management before proceeding with detailed solutions.  The main achievements of this task can be summarized as follows:

- A study of the interference introduced by cognitive radio PMR transmissions to primary receivers in both OFDM and FBMC configurations has been carried out by characterizing the associated subcarrier power spectrum density (PSD). The interference generated due to asynchronous ad-hoc PMR transmission in both OFDM and FBMC configurations has been characterized, using interference tables.
- The Resource Allocation optimization problem targeting at maximizing the sum rate for OFDM and FBMC in the context of cognitive radio-based PMR has been studied. The formulation is similar to the classical RA optimization problem; however, the interference from adjacent subcarriers is included (in the OFDM case this interference is much higher). The problem is non-convex calling for sub-optimal solutions with reasonable complexity.
- The Resource Allocation optimization problem targeting at minimizing secondary-PMR transmission power for both OFDM and FBMC configurations has been studied. Similarly to the sum rate maximization, this problem is non-convex. A common solution that makes the problem convex is to first assign the subcarriers to the users, and then allocate power to these subcarriers.

T5.2: Cell-based RRM

The main purpose of this task was to compare FBMC and DFT-SC schemes in terms of resource allocation for cell-based networks in PMR channel, and to develop novel traffic scheduling algorithms for QoS provision with emphasis on energy efficiency and low complexity. This includes a description of a complete resource request/grant cycle, providing uplink/downlink traffic coordination.

A comprehensive study on current advances on commercial cellular and dedicated public safety networks was carried out, discussing the expected convergence of the standardization efforts in these two network types. Specific PMR scenarios (see figure below) were defined focusing on various network deployments, and synchronization/cooperation levels.

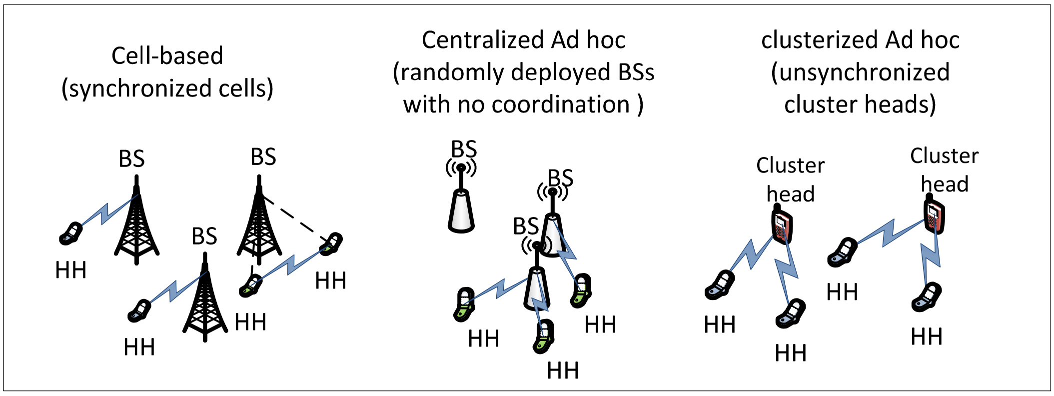



Figure 1.3-7 PMR Scenarios considered in the project.

In particular, for the cell based scenario, recognizing the importance of incorporating direct communications for public safety in future cellular networks, a complete resource request/grant cycle for DMO (Direct Mode Operation) in cellular systems was described, using as a benchmark system the Long Term Evolution (LTE). Radio resource management is an open challenge for the enabling of ProSe in LTE. In this concept, a dynamic resource request/allocation scheme is required for allocating a spectrum portion to DMO transmissions. Differing from the conventional resource allocation procedure, in the proposed resource allocation for DMO the BS must inform both the transmitter and receiver about the allocation grant, tuning them to the same allocated resources.

Focusing on scheduling the critical PMR traffic in the cell based scenario, a traffic scheduling algorithm was proposed, borrowing the principles of the Proportional Fair (PF) scheduling. The idea was to change dynamically the behaviour of the algorithm without losing its proportional fairness characteristic when critical PMR traffic should be served with priority. The proposed scheduling scheme was extended with a resource allocation policy applicable to the adopted physical layer scheme. The main evaluation result is given in the figure below.

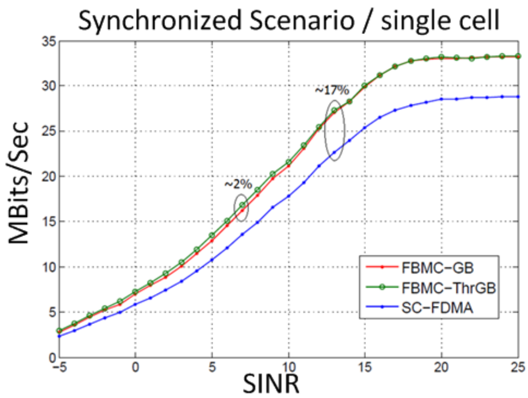



Figure 1.3-8 Performance of the proposed traffic scheduler.

T5.3: Ad-hoc RRM

The aim of this task was to compare FBMC and DFT-SC in terms of resource allocation for ad-hoc networks, and to study resource allocation algorithms on top of FBMC and DFT-SC physical layers adapted to a clusterized ad hoc PMR network. This included the development of specific coordinated and distributed resource allocation algorithms taking into account the lack of synchronicity of these ad-hoc networks. A series of different resource allocation schemes for PMR were developed, each one of them applicable to different crisis scenario and network deployment and optimized.

More specifically, the problem of downlink resource and power allocation for ad-hoc clusterized scenarios has been addressed. For the clusterized scenario, the focus was on both the peer-to-peer communications within a single cluster, and the resource sharing among multiple non-centralized clusters. In this concept, an RRM heuristic algorithm (Distributed bUffer Stabilization- DUST) has been proposed and evaluated under limited information exchange among clusters. The performance is directly affected by the in-channel and adjacent-channel interference, leading to better performance for the FBMC case. Generally, the impact of the OFDM vs FBMC on the RRM performance, was shown to be more pronounced when the traffic requirement increases. This is because higher throughput necessarily requires more transmit power, and since OFDM exhibits larger interference than FBMC, the inter-cluster interferences become more pronounced and an additional increase in power is required to compensate (to a certain limit since what count is the SINR and not only the received power).

Additionally, sum-rate maximization and rate adaptive RRM optimization approaches have been studied and evaluated for the centralized asynchronous ad-hoc scenario. For the proposed rate adaptive optimization, the idea was to maximize the minimum rate subject to a total power constraint. To this end, the optimization problem is decomposed into iterative Margin Adaptive (MA) optimization problems, while in order to tackle the computational complexity of the MA optimization problem, a suboptimal resource allocation scheme that solves the problem in a two step fashion was proposed. In the first step, subcarrier allocation is performed, while in the second one, power allocation is performed assuming subcarrier allocation is done.

From a more general perspective, an important outcome of both Tasks T5.2 and T5.3 is the quantification of the FBMC superiority against CP-based approaches such as the OFDM, from the RRM point of view. A key parameter for this quantification is the adopted scenario and especially the available synchronization and coordination level. In centrally controlled networks, the absence of the CP for the FBMC case provides more resources for data transmission, whereas under loose synchronization FBMC provides reduced adjacent channel interference and consequently higher bit rates.

T5.4: Cross-layer optimization

The objective of this task was to design solutions for RRM coordination with the Application layer (e.g., adaptive audio and video codecs) and with the PHY layer (e.g., adjust modulation, coding, and transmit power). Hence, the major achievements in task T5.4 are related to cross-layer techniques and Radio Resource Management (RRM) algorithms for broadband PMR networks.

More specifically, cross-layer adaptation in cell-based PMR communications was investigated, and a cross-layer scheme was devised to offer an increased number of PMR connections with guaranteed Quality of Experience (QoE) levels. As shown in the following figure, the performance of the proposed scheme has negligible variations for different PHY schemes (OFDMA and FBMC), since it is based on scheduling and application layer procedures. Taking this result into account, cross layer schemes that involve physical layer parameters, e.g., the interference level, were studied and proposed.

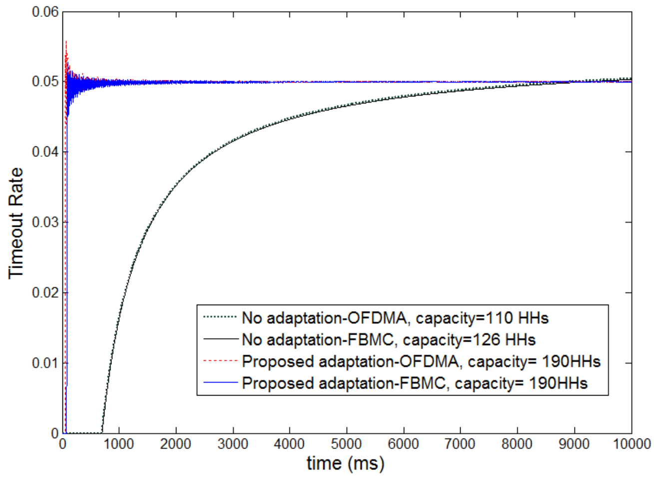



Figure 1.3-9 Performance of the proposed cross-layer scheme.

More specifically, for clusterized ad hoc PMR transmissions, the cross layer evolution of the heuristic resource allocation algorithm proposed in the context of Task T5.2 was proposed and evaluated on top of FBMC and CP-OFDM. This scheme exploits information about inter-cluster interference in a cross layer manner end can trade between energy reduction and buffer latency thanks to a tunable parameter.

In the same cross-layer concept, i.e., use of the interference information for RRM, an efficient margin adaptive scheduling algorithm was also proposed. The solution is tailored to FBMC and focuses on multi-user MISO downlink scenarios. The major contribution of this scheme is the analytical study of the impact of the interference level awareness on the designing of transmit and receive processing, the channel assignment, and the power allocation.

### 1.3.5 WP6: Cooperative and coordinated communications

The main objective of this workpackage was to study the applicability of the EMPhAtiC concept for broadband PMR in combination with cooperative and coordinated communication architectures. The work was developed around two different tasks: Task 6.1, focusing on cooperative communications, and Task 6.2, focusing on coordinated multipoint and distributed beamforming architectures.

Task 6.1: Cooperative communications.

A detailed performance comparison study of CP-OFDM and FBMC was conducted under a variety of asynchronous scenarios. First, a multi-user MIMO uplink scenario in the presence of symbol timing offset or carrier frequency offset was considered. In this scenario, the nodes were equipped with multiple antennas and different frequency selective channel models were considered. The robustness of FBMC against time and frequency misalignments was studied and corroborated via numerical results. On the other hand, cooperative MIMO relays for asynchronous multi-user transmissions were analysed in detail, and the effect of asynchronous interference due to co-channel interference was further analysed. Simulation and analytical results allowed to conclude that the CP-OFDM performance in this scenario suffers from a severe degradation resulting from the loss of the orthogonality, and a multi-tap subchannel equalizer is able to counteract the detrimental effect of timing asynchronism on the FBMC performance. One example of the obtained numerical results as well as the illustration of the scenario considered is shown below.

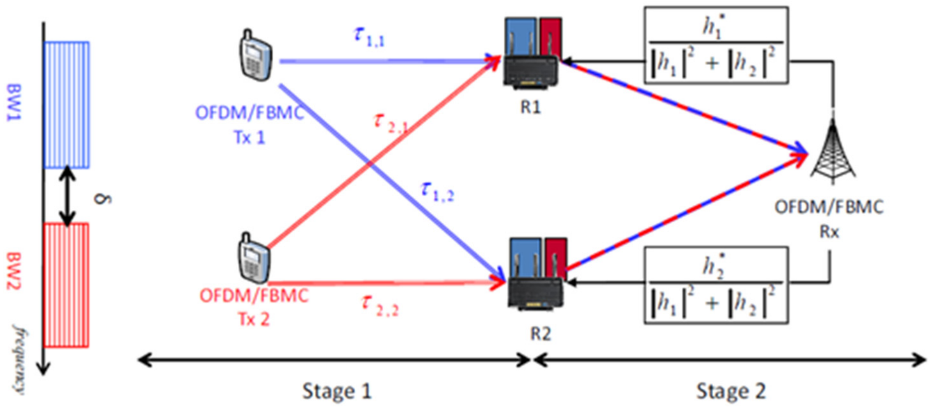



Figure 1.3-10. Cooperative MIMO relay for asynchronous multiuser transmission.

On the other hand, Mean Square Error (MSE)-optimal preamble designs were proposed for Least Squares (LS) channel estimation in FBMC/OQAM based single-relay systems with amplify-and-forward (AF) as relaying strategy. Both full (i.e., with pilots at all the subcarriers) and sparse (i.e., with isolated pilot subcarriers surrounded by nulls) preambles were considered in the study.

Finally, the application of widely linear processing in the context of FBMC was investigated. A two-step receiver was designed for FMBC/OQAM based MIMO systems, where linear processing and widely linear processing are combined. A linear MMSE receiver was first applied to the receive signals such that an estimate of the interference is obtained. After subtracting the interference component from the receive signals, a widely linear MMSE receiver was applied to the resulting equivalent received signals, where now the desired signals are real-valued. Numerical results showed that the proposed widely linear scheme significantly outperforms its linear counterpart.

Task 6.2: Coordinated multipoint and distributed beamforming.

In this task, different coordinated beamforming based transmission strategies were designed for the downlink of FBMC/OQAM based multi-use and Coordinated Multi-Point (CoMP) MIMO systems, assuming that the channel on each subcarrier is flat. First, considering the symmetric single-cell multi-user MIMO downlink setting where the number of transmit antennas at the base station is equal to the total number of receive antennas of the users, we proposed to compute the precoding matrix and the decoding matrix jointly in an iterative procedure for each subcarrier. Different choices of the decoding matrix in the initialization step were recommended for different scenarios. Then, an Intrinsic Interference Mitigating Coordinated Beamforming (IIM-CBF) scheme for FBMC/OQAM systems was developed in order to alleviate the classical dimensionality constraint of these systems. This approach handled the mitigation of the multi-user interference as well as the intrinsic interference without assuming flatness of the propagation channel.

On the other hand, FBMC/OQAM based CoMP techniques were investigated, and an extension of the IIM-CBF scheme designed for the FBMC/OQAM based multi-user MIMO downlink system was studied. It was shown that the FBMC/OQAM based multi-user MIMO and CoMP downlink IIM-CBF-based systems achieve a similar performance compared to their CP-OFDM based counterparts, but with a higher spectral efficiency and a greater robustness against misalignments in the frequency domain.

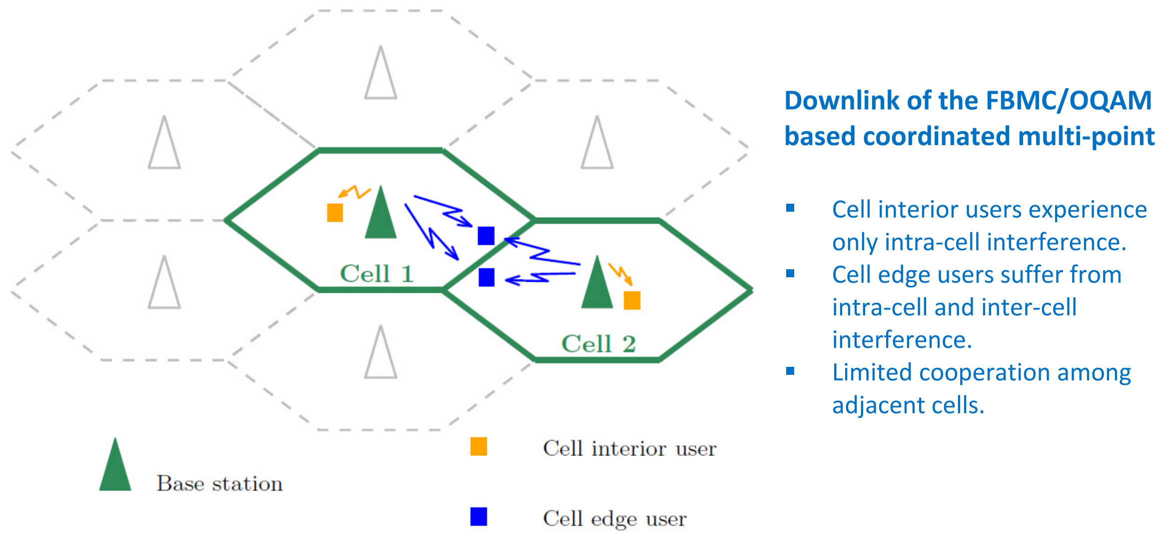



Figure 1.3-11 Downlink of the FBMC/OQAM based coordinated multi-point.

Regarding PMR-based highly frequency selective channels, several partners have collaborated on the design of transmission strategies for FBMC/OQAM based multi-user MIMO downlink systems. The goal here was to overcome the limits on the channel frequency selectivity and/or the allowed number of receive antennas per user terminal that are imposed by the state-of-the-art solutions. An iterative approach was first developed, where MMSE based multi-tap precoders were designed to effectively mitigate the MUI, inter-symbol interference (ISI), and inter-carrier interference (ICI). At each user terminal equipped with multiple antennas, only a receive spatial filter was applied. Via an iterative design, both precoders and receive spatial filters are jointly optimized. Additionally, a novel closed-form Signal-to-Leakage Ratio (SLR) based design of the precoders was proposed, giving special emphasis to the multi-stream context. At the base station, per-subcarrier fractionally spaced multi-tap precoders were computed based on this metric to mitigate the MUI, the ISI, as well as the ICI, and to map the multiple data streams of each user to the transmit antennas. Each user terminal only employed a zero-forcing (ZF) based one-tap spatial equalizer to recover the desired streams.

On the other hand, different preamble-based channel estimation methods were proposed for distributed MIMO systems using multicarrier modulations. Two subcarrier assignment schemes (SAS), the block SAS and the equispaced SAS, were considered to optimize the estimation procedure in the distributed scenario. The influence of synchronization issues was taken into account during this preamble. According to this approach, each user recovered a part of the channel frequency response (CFR) from each base station. We then considered two methods to reconstruct the whole CFR exploiting the sparsity of the channel impulse response (CIR): an MMSE estimator, which requires information on the channel and noise covariance matrices, and an iterative estimator, which only requires information about the channel length. Numerical results have shown that the MMSE estimator always outperforms the iterative estimator while for a given number of iterations, the iterative estimator performs as well as the MMSE estimator at a certain SNR.

Finally, a method to estimate MIMO channel coefficients was devised for a distributed MIMO system using FBMC/OQAM modulation in a tracking scenario. The method was based on the application of small perturbations to the signal by the base stations. It only required SNR measurements to be fed back from the receivers. Simulation results showed that a good estimate can be obtained in a reasonable amount of time.

### 1.3.6 WP7: Relaying and coverage extension

The objective of this workpackage was the study of relaying techniques in an ad-hoc and centralized PMR scenario using FBMC.

The first part of WP7 was focused on the use of relaying techniques for range extension. TETRA systems in the DMO (direct mode operation) mode were considered in a multi-hop relay network. Different transmission schemes for multiple stream multiple hop MIMO FBMC/OQAM systems were investigated. More specifically:

- A simple one-dimensional linear relay model was reviewed. The effect of frequency selective fading was considered among the transmission links. Two relaying strategies at the relay nodes, with joint design of the precoding and decoding matrix at each hop, were compared by taking into account the existence of the intrinsic interference inherited from the FBMC/OQAM modulation. Numerical results with respect to the range extension by using multi-hop relays in PMR TETRA networks were derived. Compared to multi-hop relaying in CP-OFDM with ZF precoding, for 1 or 2 relays the proposed technique has better performance for low SNRs levels, in which the intrinsic interference of the FBMC scheme can be neglected.

- Further investigations were later performed, considering multi-tap equalization at each hop in order to relax the limits on the frequency selectivity of the channel and mitigate the associated ISI and ICI. The influence of the number of hops on the performance of the network is illustrated in Figure 1.3-12. These results show that the optimal number of hops in an FBMC/OQAM based multi-hop relaying network has to perform a trade-off between the enhanced receive SNR on one hand and the error propagation on the other hand.
- The SONIR simulator was then further developed to incorporate the FBMC/OQAM physical layer. Different methods for clustering, mobility management, routing were implemented in order to be able to visualize the multi-hop system and to investigate its end-to-end performance.
- The characterization of the rate region of a FBMC/OQAM based two-way relaying system with decode and forward (DF) was investigated. An analysis of FBMC in multi-hop relaying networks for the range extension was conducted. Simulation results concluded that the FBMC-based systems can provide a higher data rate than OFDM-based ones especially when multi-tap equalizer or pre-equalizer is applied at the terminals.

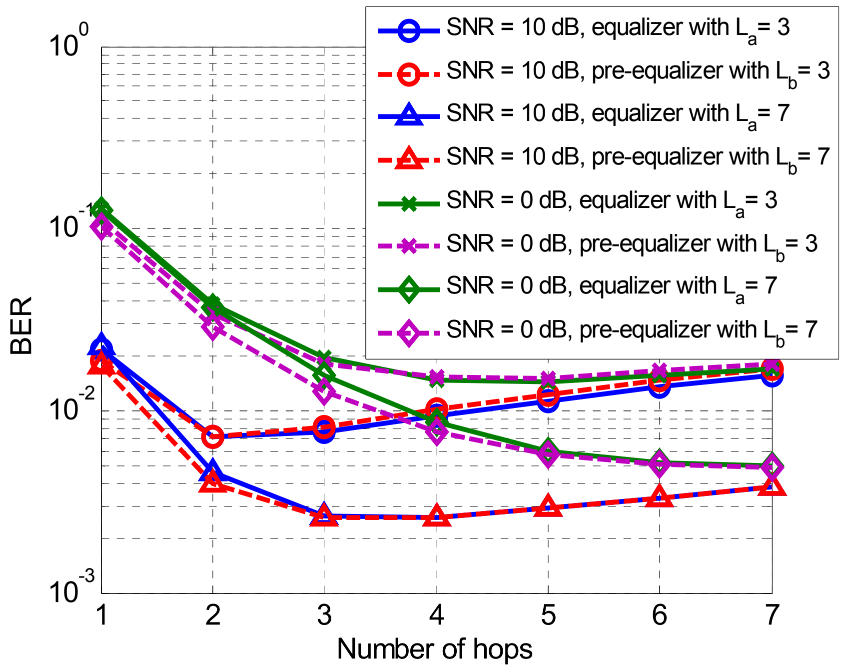



Figure 1.3-12. Comparison of the BER performance in case of SNR = 0 dB and SNR = 10 dB for the FBMC/OQAM based multi-hop relaying network where a multi-tap equalizer or a multi-tap pre-equalizer is employed; ITU Veh-A channel.

The second part of WP7 focused on the study of relaying techniques, with specific emphasis on the two-way relaying architecture. This relaying technique can be useful in many different scenarios for PMR communications, for instance, for clusterized ad hoc network. In a crisis situation, when the standard cellular network is not available or down due to some human of natural event (damaged, destroyed network), a wireless ad hoc network can be quickly deployed. The network creates different clusters (cells) which are interconnected by a wireless back-bone. Some bridging nodes are in charge of exchanging traffic among two clusters. In this situation it seems reasonable to have also some bi-directional traffic. Two-way relaying may be used by the bridging nodes in this context to lower latency and improve efficiency. This situation is schematically represented in Figure 1.3-13 below.

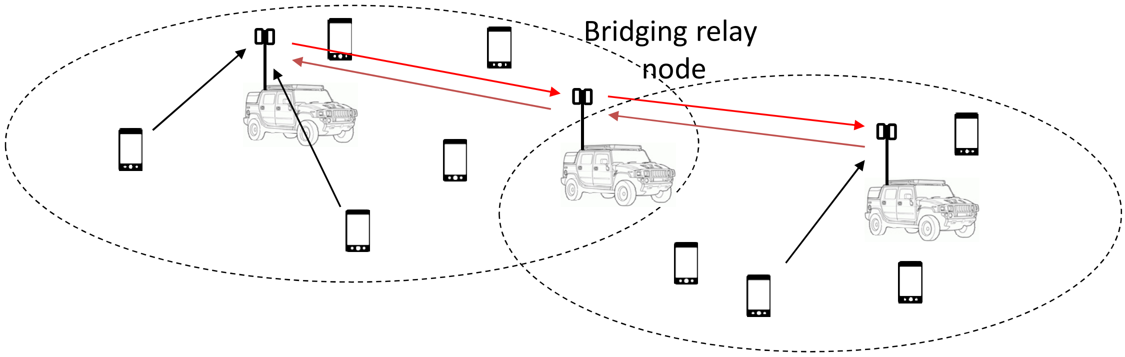



Figure 1.3-13. Clustered wireless ad hoc network with bridging relay.

The two-way Decode-and-Forward (DF) relaying architecture was studied over different angles:

- The fundamental limits in terms of achievable exchange rates were analysed for CP-OFDM and FBMC based two-way DF relaying systems. Simulation results showed that the FBMC-based systems can provide a higher data rate than OFDM-based ones especially when multi-tap equalizer or pre-equalizer is applied at the terminals.
- The channel estimation problem for a two-way relaying protocol under SC-FDMA based DF strategy was also investigated. The standard LS channel estimation algorithm was compared to another ML algorithm, which was shown to improve the estimation quality, especially for frequency selective channels with delay spread lower than the CP length. Extensive simulations were carried out in order to have a characterization of the behaviour of the LS and ML algorithms over multi-tap channels with a degree of frequency selectivity going from mild to severe.
- An AF and DF two-way relaying protocol for FBMC was proposed, in which the relay applies a successive interference cancellation receiver. It was shown that the AF method suffers from degradation with respect to the SISO reference and the multiple access phase of the two-way DF relaying protocol has not yet been demonstrated as feasible with just one antenna at the relay.
- The use of non-binary channel coding in combination with higher-order modulations was studied for both single-carrier and multi-carrier symmetric two-way relay channels. In this setting, both complete decoding and functional decoding were considered in order to estimate the binary sum, a.k.a. the XOR, of both source packets at the relay. It was demonstrated that functional decoding outperforms complete decoding for a sufficiently high SNR.
- Finally, in order to investigate how soft detectors at the relay can affect the system performance of FBMC coded two-way relay systems, a joint channel decoding and XOR-based physical layer network coding algorithm was developed for this setting.

In order to compare the various relaying techniques, an extensive performance evaluation and comparison of two SC-FDMA transmission schemes using either DF relaying or two-way

(XOR) relaying was conducted. The simulation method was based on an abstraction of the PHY Layer for SC-FDMA transmissions. This abstraction was then used to create a MAC layer simulator and to compare different two-way relaying strategies with DF in terms of PER and throughput.

Finally, it is worth pointing out that, apart from the above techniques, other relaying approaches were also studied in this workpackage. More specifically:

- An adaptation of the compress and forward (CoF) protocol to FBMC based multiple-access relay channel network was proposed. This strategy can be applied to the PMR cell-based scenario, in which the PMR users are helped in the uplink transmission by a certain relay. A precoding strategy of the data at the input of the FBMC transmitters was proposed in order to generate an interference-free linear combination at the relay. Furthermore, several relaying protocols have been compared in terms of complexity, performance and suitability to the PMR case.
- A detailed analysis of the performance AF relays was performed for a point-to-point link where FBMC/OQAM modulation is employed, taking into account highly frequency selective channels. The parallel multistage demodulator/equalizer presented in WP4 was used here in order to deal with the highly frequency selective channel.

In the third and last part of WP7, the problem of resource allocation for FBMC-based relaying schemes was investigated. Most of the existing techniques for CP-OFDM can be applied almost directly in a synchronous FBMC scenario, as long as the interference between nodes remains low. However, one of the advantages of FBMC is its robustness to timing asynchronism by using frequency well-localized prototype filters. The focus here was therefore to investigate the resource allocation issue in an asynchronous scenario. In particular, an asynchronous relaying scenario was considered, with multiple destinations receiving information from a single source and sharing a single relay. Subcarrier allocation and power allocation methods were investigated to maximize the sum rate in OFDM or FBMC-based DF-relay transmission, taking into account the interference created by the absence of synchronization between the different nodes. OFDM and FBMC interference power tables were used in asynchronous interference modelling. Based on the resulting mutual interference, a joint iterative subcarrier and power allocation algorithm was proposed.

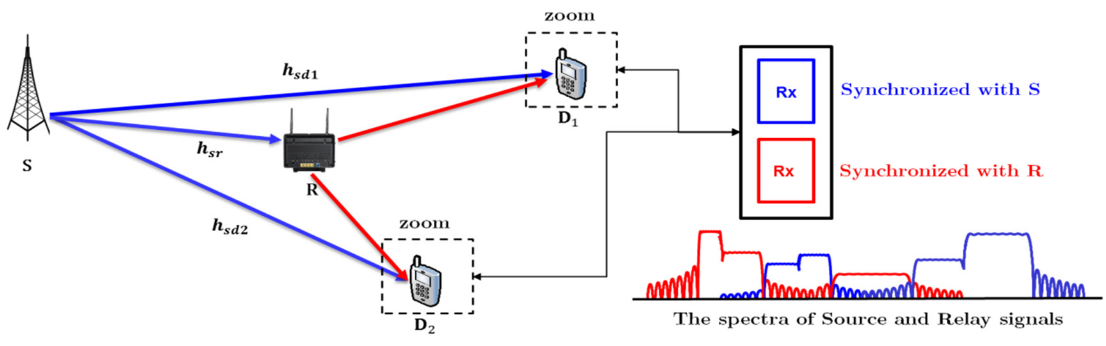



Figure 1.3-14. Structure of the DF-relayed system

### 1.3.7 WP8 Multi-modal, multi-access, flexible spectrum usage

One of the objectives of PPDR/PMR networks is to allow Public Service organisations to communicate in situations where the commercial networks are insufficient or unavailable (e.g., exceptionally crowded events or emergency situations). In the event of a total network shutdown, it may be interesting to have broadband PMR ad-hoc transmissions in potential coexistence on the same area and spectrum with other licensed communications. In these extreme situations, the broadband PMR systems will need to deploy spectrum sensing procedures in order to guarantee that legacy narrowband systems are not interfered. The study of optimized sensing capabilities for the filterbank receive architecture was the main objective of this workpackage.

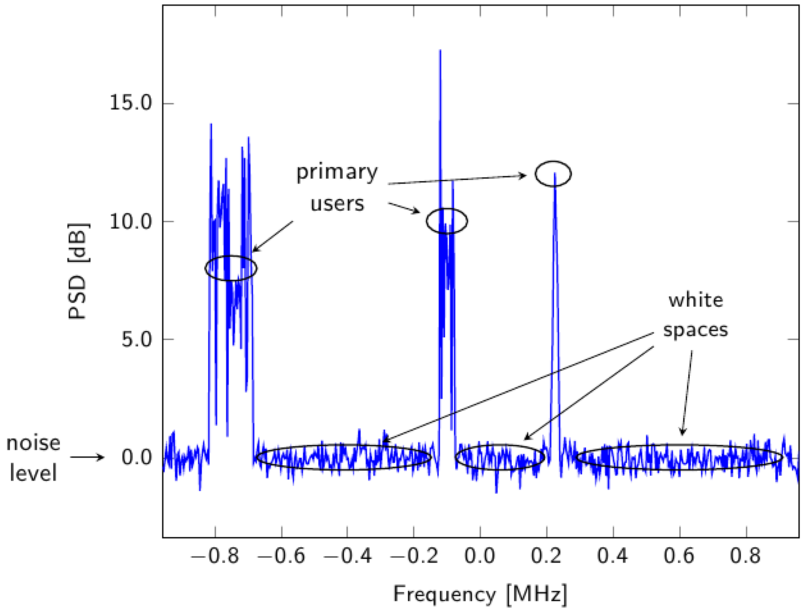



Figure 1.3-15. Typical sensed spectrum with primary users and white spaces.

As mentioned above, the targeted scenario was inherently based on the ad-hoc networking paradigm, whose self-organised nature matches best with the need for sharing a common spectrum. The primary users were modelled in accordance with existing narrowband PPDR/PMR communications standards, such as TETRA, TETRAPOL and TEDS.

A classic approach in spectrum sensing is the Energy Detector (ED), which decides whether a channel is occupied or not based on the measured energy on the corresponding frequency band. The solutions proposed in this workpackage extended this idea by taking advantage of the multicarrier structure of the EMPhAtiC B-PMR system, as depicted in Figure 1.3-16. According to this approach, the complex task of detecting narrowband signals in a large spectrum is decomposed by the Analysis Filterbank (AFB) into multiple simpler problems, wherein the analysed spectral band and the frequency band of the primary signal have comparable widths. The statistics obtained by solving these problems (typically, the energy level of the subbands) are processed jointly to estimate the occupancy of the spectrum and the characteristics of the primary signal.

According to the first proposed spectrum analysis solution, referred to as Subband Energy Detector (SED), each subband is declared occupied or free according to its energy level. The decision threshold is computed according to the minimum per-subcarrier energy level, which is assumed to be the noise level. In Deliverable D8.1 the performances of this simple approach was shown to be extremely good when combined with a nonuniform filterbank. Indeed, by means of the fast convolution technique, the subbands of the analysis filterbank can be tailored to match with the potential position and bandwidth of a specific primary signal. Hence, for a TETRA primary signal, the specifics of the filterbank were chosen in order to maximize detection performances (in terms of ROC curves) while limiting some annoying side effects that are intrinsic to filterbanks, such as power leakage in both time and frequency domains. Deliverable D8.2 delved further into this detector and showed that it has similar performances as compared to more complex methods such as eigenvalue-based sensing, which is known for being robust under noise uncertainty.

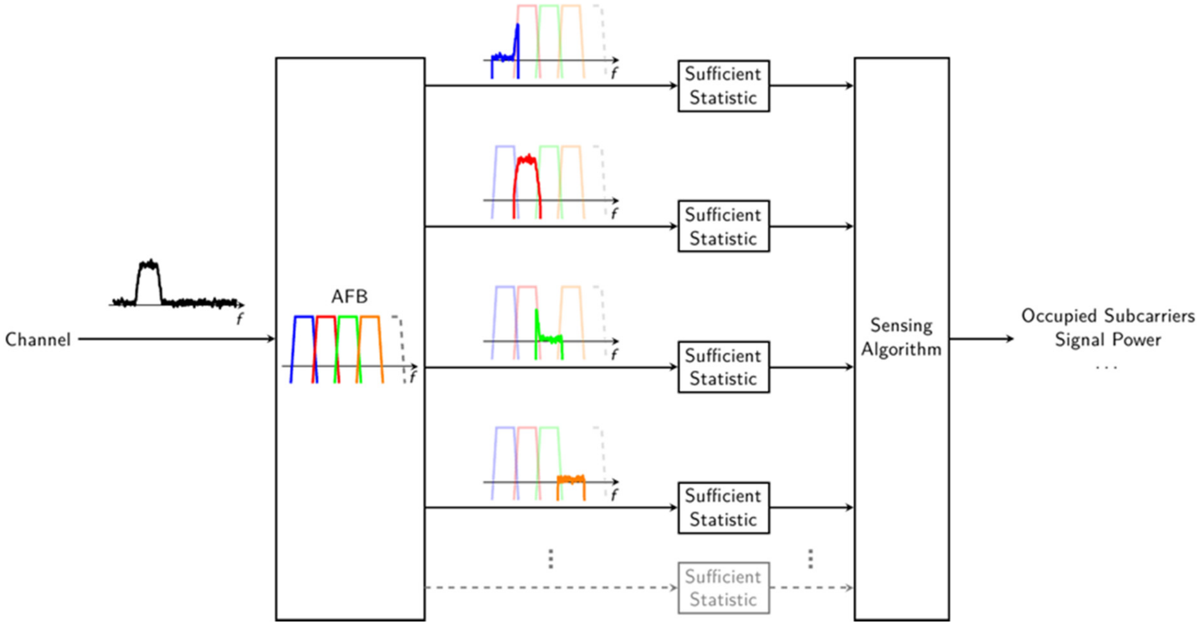



Figure 1.3-16. Subcarrier-based spectrum sensing.

In the SED method, each subband is analysed almost independently of the others, thus ignoring any information that can be gathered by considering the spectrum in its totality. As a consequence, two different additional approaches were proposed that tackle this weakness. The first one, described in Deliverable D8.1, was based on *model-order selection*. Again, the energy level was estimated for each one of the subbands. Here, however, decisions were not taken based on a simple comparison of these levels with a precomputed threshold, but by means of a more sophisticated detector that exploited some *information theoretic criteria*. The number of occupied subbands was now one of the unknowns of a maximum likelihood problem together with the noise variance and the power of the primary signals. Solving this problem was hence equivalent to estimating both the occupancy of the spectrum and the characteristics of the primary users. Simulation results showed the effectiveness of this approach, which presented a high probability of detecting the correct number of primary users with data samples of reasonable size.

The second approach, reported in Deliverable D8.2, mapped the problem of identifying the occupied subcarriers to a *Bayesian inference* problem. More specifically, we proposed a *belief-propagation* algorithm that returned the set of subcarriers with the highest probability of being occupied given the power measurements at the AFB output. When compared with the previous one, the Bayesian method provided significant improvements, especially at low SNR.

As mentioned before, one of the important requirements of spectrum sensing is a high sensitivity in order to spot low SNR signals. To tackle this issue (and related ones like the hidden terminal problem), we also investigated the benefits of space diversity in FBMC-based sensing. In the new scheme, the sensor was assumed to be provided with multiple antennas, each one feeding a different AFB. In Deliverable D8.1 it was proven that the best way to extend the SED above to this case is to substitute the estimated per-subcarrier energy with the maximum eigenvalue of the sample covariance matrix corresponding to the subcarrier (whose size is equal to the number of antennas). A gain of more than 1 dB over the single-antenna SED was shown to be achieved with just four antennas.

The underlying idea of all the above methods is to exploit the AFB and to process the energy values measured at each subcarrier. While this approach turns out to be very simple and effective, it presents some limitations: the detection of a primary user is based on the energy level of the subcarriers, which gives little/no information about the type of user (i.e., its modulation or, generally, its radio standard). To obtain this information, one should abandon the subband framework offered by the AFB and process directly the critically sampled input signal. In Deliverable D8.2 we showed how to detect specific type of users by comparing the sensed spectrum with candidate templates. More specifically, our contribution made use of sparse representation tools (e.g., the LASSO method) to separate successfully two types of users, namely primary TETRA users and secondary B-PMR users transmitting according to the EMPhAtiC specifics.

Wrapping up, a few solutions for spectrum sensing in the EMPhAtiC B-PMR system were proposed in this workpackage. When occupancy is the only required output, interesting performances can be achieved by simply processing the per-subcarrier energy levels measured at the output of the AFB, as evidenced from the examples above. Most of the solutions can be combined together to improve further the accuracy of detection: for example, one can think about a multiple-antenna sensor with a nonuniform analysis filterbank and to process the subcarriers according to either the model-order selection method or the belief-propagation method. Finally, we have also shown that more detailed information can be gathered about the spectrum users if we allow for more complexity, as in the sparse candidate shape detection method.

### 1.3.8 WP9: Full system performance evaluation

The primary goal of this workpackage was to use the research output of WP2, WP3, WP4, and WP8 in order to implementing the required software and hardware demonstration platforms for the evaluation of the EMPhAtiC coexistence PMR solution. The objective was to evaluate the proposed system in practical conditions, and to quantify the advantages of highly spectral/power efficient and flexible multicarrier modulation schemes for broadband PMR coexistence. This workpackage was divided into four tasks, the main results of which explained below.

Task 9.1: Definition and specification of HW and SW platform

The basic demonstrator parameters (LTE-like PHY-layer specifications, scenarios to be considered, basic hardware setup that will be utilized, etc.) were specified in this task. Frame formats for both CP-OFDM (LTE downlink) and FBMC (LTE-like downlink) were also defined. Some important unsolved issues regarding synchronisation and channel estimation were sorted out, using inputs from work packages WP2 and WP3. A basic Matlab-based FBMC/OQAM transceiver model based on FC was provided by WP2. The corresponding Matlab modules for the simulator were created, analysed and tested.

Task 9.2 Software simulations and experiments

In this task, a software simulation code was produced, incorporating PMR waveforms, Matlab scripts and dll SW generators for TETRAPOL, TETRA1 and TETRA2/TEDS standards. A specific Matlab code for testing link-level results was developed, and the calibration of these results was further studied in terms of the effective SINR (which includes the FBMC distortion effect in frequency selective channels). Results for BLER curves for different mappings were obtained.

In parallel, an ns-3 based simulator was developed, together with an LTE calibration scenario for system-level simulations. The LTE PHY to MAC interface was implemented, together with the CQI to MCS mapping and the frame structure. A selection of the CQI set and corresponding coding rates was agreed and transport/Coding block size and coding rate selection for the further system level simulations were analysed. The simulator incorporated HandOver (HO) and Radio Link Failure (RLF) implementations for the cell-based scenario. A Data Collection Framework for events in the system level simulator was also implemented, and a Network Event File (NEF) player was integrated to allow advanced display feature such as node/connection state visualization.

Task 9.3: Hardware platform

The implementation of the demonstrator is divided between two partners in the project (CTTC for the transmitter and SINTEF for the receiver).

The Xilinx Zynq (ZC706) development board was chosen for the transmitter implementation, featuring the largest Zynq FPGA-device and an embedded ARM dual-core processor, ideal for HW/SW co-design. The AD-FMCOMMS2-EBZ 2x2 RF transceiver is used as RF front end.

The receiver was implemented using one (SISO) or two (MIMO) USRP N210 for down conversion, sampling, initial filtering and decimation. The actual FBMC signal processing took place in software on a Linux lap-top. The software defined radio (SDR) component of the demonstrator was implemented using the IRIS framework from Trinity College, Dublin, which also is a part of the FP7 CREW Project. The detailed signal processing algorithms were written in C++ language and speed optimized for efficient execution on the Linux platform. Algorithms both for transmitter and receiver were developed. The receiver software contained also algorithms for frame sync, carrier frequency offset estimation and correction, and channel estimation and equalization.

The whole hardware platform was set up and configured according the specified test scenario specifying a bandwidth of 1.08 MHz. This bandwidth corresponds to 72 channels having 15 kHz separation. The FBMC was implemented using Fast Convolution Filter Bank. At the transmit side it was implemented in VHDL in hardware whereas the receiver used a software implementation.

A Matlab model of a LTE CP-OFDM broadband transceiver (featuring a 20 MHz BW) was tested according the PHY-layer specifications agreed with the consortium (i.e., 1.4 MHz BW). This LTE CP-OFDM Matlab transmitter was then translated to VHDL (i.e., real-time FPGA-based implementation). Matlab/VHDL co-simulations were conducted, in order to verify the behavioural-match of both models. Both Matlab and VHDL models of the (SISO) LTE CP-OFDM transmitter were then extended, in order to implement the open-loop spatial-multiplexing functions required towards the 2x2 MIMO system configuration.

An LTE-based FBMC Matlab transmitter, based on the Matlab-code initially provided by WP2 was built. This transmitter was later refined and validated, taking into account the agreed frame-format (i.e., as described in D9.1). The FC-FB part of the corresponding receiver was also implemented. Both models were against WP2's Matlab-code. The VHDL code of the LTE-based SISO FBMC transmitter (i.e., fixed-point RTL model targeting a real-time FPGA execution) was also implemented.

Task 9.4: Evaluation of the implemented communication system

In this task, a simulator-based and experimental evaluation of the performance of FBMC over CP-OFDM when in coexistence with a PMR system was carried out.

The initial version of system-level simulation scenario of wideband PRM FBMC-base scenario has been implemented in accordance with the cellular network parameters formulated in D9.1. New Claussen site-correlated shadowing model has been realised. The scenario was integrated with visualisation tool (NEF player), where user mobility and statistic can be presented in dynamics. Initial system-level statistics for the baseline OFDM scenario were prepared.

On the other hand, a preliminary version of the EMPhAtiC demonstrator was shown in at the EuCNC conference in Bologna June 23 – 26, 2014 (see Figure 1.3-17). In this exhibition, the broadband FBMC system was demonstrated to coexist with TETRA terminals as interfering signals. Posters dedicated to the project were also prepared as part of the demonstration.

A fully operational SISO setup was demonstrated at the ETSI RRS workshop at ETSI headquarters in Sophia Antipolis, France at December 3-4 2014 (see Figure 1.3-18). The demonstration was successfully conducted, combining SINTEF and CTTC platforms, and using CASSIDIAN's TETRAPOL equipment. It had a very positive impact for EMPhAtiC, with visibility and general interest as expressed by a high number of visitors.

An experimental validation of the implemented FBMC transmitter, utilizing a similar hardware-setup to the one used for the live demonstration for the ETSI Workshop, are being conducted, both over-the-air and cabled transmissions. Results are documented in deliverable D9.4.

Figure 1.3-17. Demo at EuCNC in Bologna.

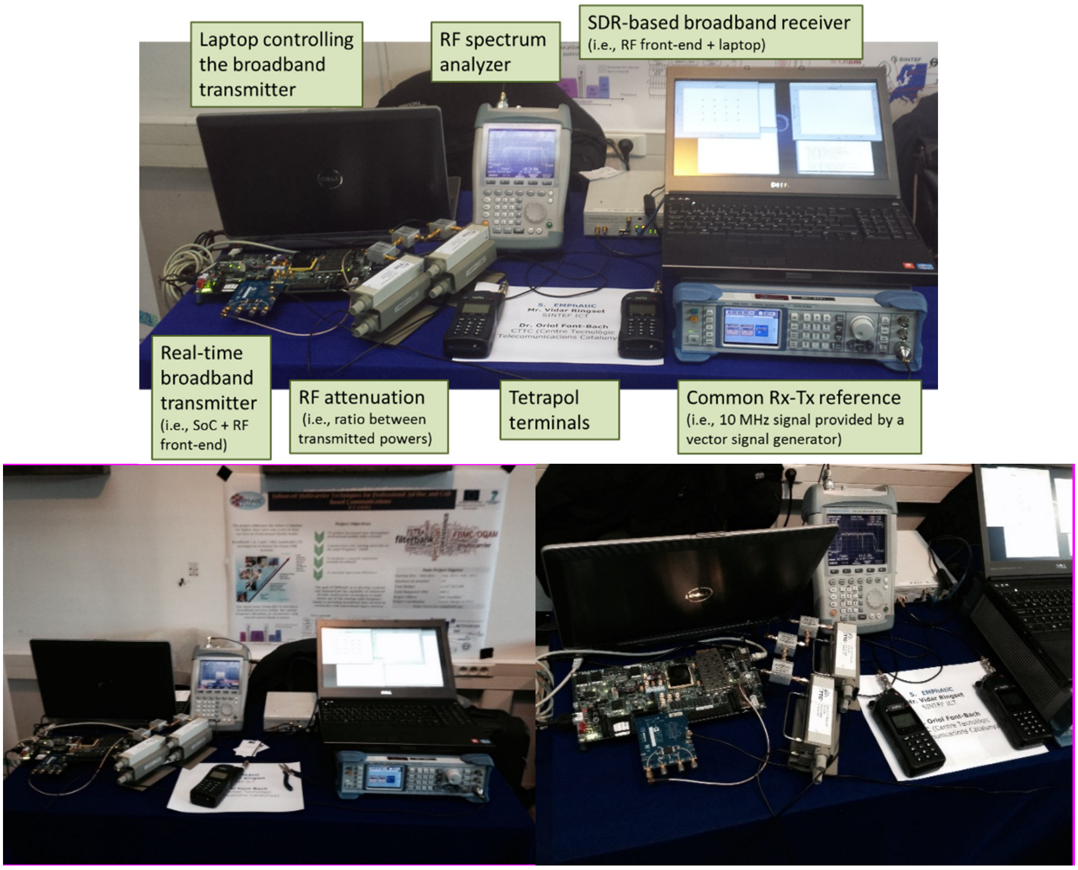



Figure 1.3-18. The superiority of the EMPhAtiC architecture has been illustrated in real hardware during the last ETSI RRS workshop in Sophia Antipolis (France), which was held at ETSI hearquarters.

## *1.4 Potential impact, dissemination activities and exploitation of results*

### 1.4.1 Potential Impact

The EMPhAtiC project will introduce strategic improvements in the domain of mobile wireless broadband signals, thus strengthening the position of the European industry in the field. Even if the main interest of the industrial partners involved in the EMPhAtiC project is Professional Mobile Radio (PMR), the technical approach of the EMPhAtiC project can be globally applicable to all mobile broadband wireless systems. Being a step forward in these critical topics is an important way to develop the European leadership in the wireless broadband arena, improving the positioning of European industry in the PMR domain in terms of research, technology mastery and evolution in the near future. The project results will therefore strengthen European research in advanced technologies based on filterbank based communications, flexible spectrum use and enhanced coexistence of existing and new communication signals in heterogeneous radio spectrum environments

From the technical perspective, the EMPhAtiC project has introduced strategic improvements in the domain of mobile wireless broadband signals, which will certainly have a substantial impact that will go far beyond the project context. So, even if the main interest of the industrial partners involved in the EMPhAtiC project is PMR, the technical approach of the EMPhAtiC project can be globally applicable to all mobile broadband wireless and wired systems. Thanks to the proposed efficient filterbank processing structure, the EMPhAtiC project has made a major contribution towards the next generation PHY layer which improves the data throughput and cohabitation with existing networks. The project will therefore strengthen European research in advanced technologies based on filterbank based communications, flexible spectrum use and enhanced coexistence of existing and new communication signals in heterogeneous radio spectrum environments.

The EMPhAtiC project has ultimately produced strategies to reduce the cost per exchanged information (cost per bit), both in terms of investments and in terms of operation of networks. One of the main advantages of the project physical layer approach is the increased efficiency of mobile broadband networks especially in term of radio coverage and capacity, which will ultimately enable major cost savings in radio network deployment. This will lower the network cost by using more efficiently the scarce resource of radio frequencies, increasing the efficiency of communication infrastructures. On the other hand, a global improvement of the network capacity and coverage will be provided thanks to the adoption of cooperative communication systems, distributed MIMO and advanced relaying techniques in combination with the proposed filterbank based transmission architecture. This higher capacity will be of interest for European industries trying to develop new services in an already highly used bandwidth.

In this sense, one of the key challenges of future 5G wireless communication systems is the fact that they will need to provide 1000 times higher wireless area capacity and more varied service capabilities. In order to cope with this exponential growth of traffic, 5G wireless systems will need to deliver an exceedingly higher data throughput, with average data rates beyond 10 Gbps. Given this unprecedented growth in traffic demand, new air interfaces will need to be designed in order to make better use of bandwidth, increasing the spectrum efficiency and reducing the amount of energy that is employed for the transmission of each bit. In this sense, it seems clear that next generation of mobile communication systems will have to rely on novel modulation and detection schemes that avoid the inefficiencies of currently deployed OFDM modulations (such as cyclic prefixes, guard bands, vulnerability to co-channel interference effects and spectral smearing in presence of non-liner amplification). Clearly, filterbank multicarrier modulations are very well positioned to become the basis of the future 5G physical layer. In this context, research conducted within the EMPhAtiC project, and in particular novel filterbank based waveform processing techniques, will certainly be of significant value for future 5G wireless systems. Most of the studies carried out by the project within the PMR framework can be fully extrapolated to other future wireless communication standards such as 5G.

As far as standardization is concerned, the members of the EMPhAtiC consortium will further promote the advantages and main benefits of the adoption of filterbank multicarrier approaches in future standard evolutions of radio-communications system. For example, the ETSI RRS WG4 approach exploiting the synergies between civil security, military and commercial domains, will be further pursued. Furthermore, the adoption of filterbank solutions for the physical layer of future wireless communication standards (such as 5G) will be further promoted by the members of this consortium.

### 1.4.2 Dissemination activities

The project has maintained a very active dissemination strategy during the whole execution, both from a purely scientific as well as application-oriented industrial perspectives.

<u>Scientific Publications</u>

From the scientific point of view, the project has actively disseminated the obtained results in international peer-reviewed conferences and workshops, with more than 70 papers published so far. On the other hand, the project has also been very active in the publication of scientific results in peer-reviews journal papers. So far, a total of 17 scientific papers have been published in top-ranked journals of the field, plus 6 additional submitted articles that are currently under review. We can highlight 3 published papers at IEEE Transactions on Signal Processing (Impact Factor 3.198 according to SCI2013), plus three additional ones still under review, one paper at IEEE Journal on Selected Areas in Communications (Impact Factor 4.138), and 9 papers at the EURASIP Journal on Advances in Signal Processing (Impact Factor 0.808). Furthermore, a global paper presenting the main EMPhAtiC results has been submitted to IEEE Communications Magazine and is currently under review.

Complete references and links to the actual articles may be found in the project webpage: http://ict-emphatic.eu/dissemination.html

<u>Organization of special issues and special sessions:</u>

Several EMPhAtiC partners have actively participated in the organization of journal special issues and special sessions in conferences, which were directly related to the project:

- Special issue in the EURASIP Journal on Advances in Signal Processing, titled "Advances in flexible multicarrier waveforms for future wireless communications" (http://asp.eurasipjournals.com/series/AFMWF) Guest editors: E. Kofidis (lead), M. Renfors, P. Siohan, f. harris, F. Bader).
- Special session on "Filter bank-based techniques for future wireless comms", held at the European Wireless Conference, held in Barcelona on May 14-16, 2014. This special session, organized by E. Kofidis (CTI), aimed at comparing several waveform candidates for future PHY communication standards. Several papers from EMPhAtiC and METIS contributed to this special session.
- Special session on "5G waveforms", to be held at the IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC) 2015, in Stockholm (Sweden) on June 28, 2015. The objective of special session, organized by X. Mestre (CTTC) and E. Kofidis (CTI), is to provide a broad picture of potential waveform candidates for 5G. Several papers from EMPhAtiC, 5GNow and METIS contributed to this special session.

Project Workshops

EMPhAtiC has organized a total of two project workshops, which have been collocated with the 2013 and 2014 editions of the International Symposium on Wireless Communication Systems:

- The first EMPhAtiC Workshop at the IEEE ISWCS 2013 in Ilmenau, Germany, was held on August 27, 2013. The workshop was entitled "Advanced Multicarrier Waveforms and Mechanisms for Future Ad-Hoc and Cell-Based Systems". Three invited talks were given by prestigious researchers in the areas of filterbank multicarrier modulations, namely Prof. Maurice Bellanger (CNAM), Dr. Pierre Siohan (Orange Lab) and Prof. Andrea M. Tonello (University of Udine).
- The Second EMPhAtiC Workshop was entitled "Advanced Multi-Carrier Techniques for Next Generation Commercial and Professional Mobile Systems", and was held at the ISWCS 2014 conference in Barcelona, August 2014. One of the observations made by the reviewers regarding the first EMPhAtiC workshop during the first technical review was the fact that the number of papers coming from the project was much too high. For this reason, the second workshop was organized in cooperation with FP7-ICT project 5GNOW. This helped to disseminate the EMPhAtiC achievements in other ICT projects with common technical interests.

Courses, tutorials, seasonal schools and industrial dissemination events:

Several partners have given courses and lectures disseminating the EMPhAtiC project results in different scientific and industrial oriented events:

- The project actively participated in the NEWCOM# Summer School on Flexible Multi-carrier Waveforms for Future Communications Wireless Networks, organized on May

21-23, 2014 in Rennes, France. It was a summer school jointly organized by the project EMPhAtiC and 5GNOW under the umbrella of Newcom#. Several lectures were made by EMPhAtiC partners, namely:

- “Fast Convolution Based Flexible Multimode Communication Waveform Processing” by Markku Renfors (TUT).
- “Equalization in FBMC/OQAM” by Jerome Louveaux (UCL).
- “Effect of channel frequency selectivity on filterbank multicarrier modulations” by Xavier Mestre (CTTC).
- “Flexible multicarrier waveforms: implementation issues and baseband processing technologies” by Nikolaos Bartzoudis (CTTC).

- The project co-organized the lecture entitled “Beyond OFDM Radio Interfaces Facilitating Spectrum Coexistence and Secondary Access” at the 24th Jyväskylä Summer School that took place from the 6th till 22nd of August 2014 at University of Jyväskylä, Finland. The lecture was held from $6^{th}$ to $8^{th}$ August 2014 and contained 20 hours.
- A half-day tutorial entitled “Advanced Multicarrier Waveforms for Future Wireless Communications” was given at CROWNCOM 2014 conference, June 5-6, Oulu Finland, by Markku Renfors (TUT).
- A workshop on FBMC was organized at TCS premises in Gennevilliers, France, on January 21st 2015. The main lecturer was Prof. M. Renfors (TUT). The main objective of this workshop was to disseminate to TCS community of communications’ experts, tutorial and recent EMPhAtiC results on FBMC as a hot topic for future 5G communications. The audience (around 20 persons) was composed of TCS technical experts, specialists, engineers and managers. Two professors from ENSEA, an institute of the university of Cergy-Pontoise (France), were present too.

White Papers

The project has produced three white papers, which are publicly available at the project website:

- White paper on “Flexible and Spectrally Localized Waveform Processing for Next Generation Wireless Communications”, edited by Markku Renfors (TUT).
- White paper on “EMPhAtiC: Contributions to Filter Bank-Based Multicarrier MIMO, Cooperative Communications and Relaying”, edited by Didier Le Ruyet (CNAM).
- White paper on “EMPhAtiC: Progress towards standardization and Regulation. Reconfigurable Radio Systems potentialities for the civil security domain”, edited by Philippe Mège (Airbus).

EMPhAtiC Edited Book

The project has prepared an edited book proposal at Elsevier/AP, summarizing the main project results and providing a general introductory text to the use of advanced multicarrier waveforms for PMR and future 5G wireless communication standards. The editorial board is formed by Markku Renfors (TUT), Eleftherios Kofidis (CTI), Carlos Bader (Supélec) and Xavier Mestre (CTTC).

Other lectures devoted to the dissemination of the project activities:

- A global project presentation, was given at the Future Networks 10th FP7 Concertation Meeting, held in Brussels on October 10-11, 2012. The objective of this presentation was to introduce the EMPhAtiC framework and technical approach to other projects in the RAS cluster.

- A project presentation entitled "EMPhAtiC – Standardization Strategy" was given at the Conference on "Spectrum Management: Perspectives, Challenges and Strategies" hosted by the regulator ANACOM in Lisbon on 20 September 2013.

- A project presentation entitled "EMPhAtiC Project" was given at the IEEE ISWCS 2013 in Ilmenau, Germany, held on August 27, 2013. This presentation introduced the first EMPhAtiC workshop described above.

- A project presentation entitled "EMPhAtiC Project– The Filter Bank Multi-Carrier approach" was given at the ETSI RRS Meeting held in Mainz on December 12, 2013. The presentation introduced the EMPhAtiC FBMC approach for coexistence between narrowband and Broadband PMR signals.

- A presentation on the EMPhAtiC project "Intermediate results and standardization strategy" was given at the RAS cluster workshop entitled "Workshop on Radio Access and Spectrum", which was organized on 23 June 2014 at the EuCNC conference in Bologna, Italy.

- A project presentation entitled "Reconfigurable Radio Systems potentialities for the civil security domain" was given at the ETSI RRS Workshop – 3 & 4 December 2014 in Sophia Antipolis (France).

- A presentation on the EMPhAtiC project "Final results and plans for exploitation" was given at the RAS cluster concertation meeting held in Brussels on March 25, 2015, collocated with the NET FUTURES conference.

Public Demonstrations

- A project booth was installed at the EuCNC conference in Bologna. This exhibitor provided a preliminary version of the project demonstrator, deploying several spectrum coexistence scenarios. Additionally, the exhibitor displayed several posters of the EMPhAtiC project and its intermediate results.

- An experimental validation of the EMPhAtiC transceiver was performed in the live demonstration held at the ETSI RRS workshop in Sophia Antipolis on December 3, 2014. The aim of this activity was to demonstrate the practical validity of the project approach in several coexistence scenarios with real TETRAPOL terminals in the 400 MHz band.


Figure 1.4-1. The EMPhAtiC project booth at EuCNC in Bologna, including a hardware demonstration.

Dissemination in Standardization Fora

The EMPhAtiC project has actively contributed to the ETSI technical committee on Reconfigurable Radio Systems (RRS). More specifically, the project has regularly been interacting with the Working Group on Civil Security and Inter-Domain Synergies. Apart from the technical presentations and meetings mentioned above, the project was represented at ETSI RRS WG4 meeting in Maisons-Alfort (France) on 4/3/2014, at ETSI RRS meeting in Maisons-Alfort (France) on 6 and 7/3/2014, at ETSI RRS WG4 conference call on 28/3/2014, at ETSI RRS WG4 conference call on 22/4/2014 and at ETSI RRS WG4 conference call on 27/5/2014. The project has contributed to the technical report ETSI TR 103 217: “Reconfigurable Radio Systems (RRS); Feasibility study on inter-domain synergies; Synergies between civil security, military and commercial domains”.

### 1.4.3 Exploitation of results

The EMPhAtiC project has permitted to reach important progresses in the theoretical and practical study of FBMC and other related waveforms. Important studies have been made about synchronization, channel estimation, antenna processing and other fundamental features for such types of waveforms. The knowledge gain in the area of these new waveforms and their application to the domain of PMR (Professional Mobile Radio), notably for Public Safety organisations usage, has enabled to identify possible future evolutions of PMR systems for providing Broadband communications for Public Safety by deploying such PMR Broadband systems in bands where other systems are already present. This is particularly the case for The 400 MHz band, which is considered as one of the best fitted for deployment of new Broadband PMR systems for Public Safety.

On the other hand, it is also clear that the impact of the research activities carried out in the project will certainly have an impact much beyond the strict framework of PMR. For example, it is widely recognized that the future 5G mobile communication standard will be based on either a multicarrier filterbank physical layer, or a very similar technological solution, and it is therefore quite clear that the EMPhAtiC results will have a clear impact in the definition of this standard.

The activities carried out within the project have resulted in four patents filed by members of the EMPhAtiC consortium, namely:

- Xavier Mestre, Marc Majoral, Stephan Pfletschinger. Patent EP13159897A1, US2013847020 “Method for equalizing filterbank multicarrier (FBMC) modulations”. CTTC. Priority Filing.
- Philippe Mège, Laurent Martinod, Luc Fety, Olivier Perrin, Nicolas Gregis. Patent US2014321584 “Interference reduction method”. CASSIDIAN SAS, CNAM. Priority Filing.
- Philippe Mège, Laurent Martinod, Luc Fety, Olivier Perrin. Patent US2014334569 “Method for estimating a channel”. CASSIDIAN SAS, CNAM. Filing.
- Philippe Mège, Laurent Martinod. Patent FR3002709 WO2014128369 “Method for demodulating a signal”, CASSIDIAN SAS, CNAM. Filing.

Apart from that, the acquired knowledge will certainly be the basis for novel industrial activities that will capitalize on the EMPhAtiC research achievements.

In what follows, we present the separate exploitation plans of all the partners of the EMPhAtiC consortium.

<u>CASSIDIAN SAS/Airbus Defense and Space:</u>

The studies carried out in the EMPhAtiC project together with the standardization actions made by the project, in particular by AIRBUS Defence and Space, in the frame of ETSI RRS has led to the following approach for introduction of Broadband PMR in the 400 MHz band. The approach for AIRBUS Defence and Space, obtained from the work done by AIRBUS Defence and Space and the other EMPhAtiC project partners, is presented in the contribution made by AIRBUS Defence and Space, for the EMPhAtiC project, to ETSI Technical Report 103 217 and in the presentation made by AIRBUS Defence and Space at ETSI RRS Workshop in December 2014.

The approach can be summarized as follows:

- In order to cover the needs expressed by Public Safety organisations for high data rate communications, the approach proposed is to use both 400 and 700 MHz bands, the 400 MHz band being used in order to ensure economically the deployment of the network in low density areas and the 700 MHz band used mainly in more dense areas.

- In the 400 MHz band, in a first step a refarming (a frequency band reorganization) is necessary in order to free a significant part of the spectrum through a better usage of the frequency channels.

- This is possible to deploy BB LTE as it is today using 1.4, 3 or 5 MHz bandwidth depending on the amount of spectrum available.

- A step further will be to organize the refarming of narrowband systems in such a way that they would impact a minimum number of LTE Resource Blocks (RBs) at each LTE Base Station (eNodeB). This enables to optimize the usage of the spectrum by adding a broadband capability while maintaining Narrowband (TETRA, TETRAPOL) services, even if narrow band systems are already fully optimising the band. This is a way to add Broadband capability to narrowband existing one.
- A further element will be necessary, the usage of a well frequency-contained Broadband waveform. This leads to the introduction of FBMC, in order to fully protect the narrowband systems in their services as well as in their coverage.

So the main aspect of the exploitation plan for AIRBUS Defence and Space (ex-CASSIDIAN) will be to follow the approach described above, the objective being to add to the Narrowband capacity a Broadband capacity corresponding to approximately 2/3 of a full Broadband capability.

AIRBUS Defence and Space is also aiming to exploit other more specific aspects of the EMPhAtiC project notably concerning some advanced techniques for Broadband systems using MIMO and antenna processing techniques.

Thales Communications and Security SA:

TCS will use the knowledge and results of the project in order to disseminate internally the knowledge on FBMC, this new technology which seems promising not only for future broadband PMR and possibly 5G cellular systems, but also for any other system which has strict spectral coexistence requirements. The knowledge accumulated during the project will help TCS to understand the strong and weak points of the technology studied in EMPhAtiC in order to being able to steer future technical decisions for future research or developments on a solid basis. Disseminating inside TCS information about results on FBMC, in particular on spectrum coexistence for PMR may have important impacts on strategic choices.

Moreover the results produced by the project, i.e. new resource allocation algorithms, new channel estimation and a study of different relaying techniques, can be useful for product lines concerning PMR applications including safety. The results will be exposed to technical directors and bridges towards TCS products will be further investigated.

Bitgear Wireless Design Services:

Bitgear plans to exploit the project results along 3 lines:

- Creation of a product portfolio to present FBMC capabilities to existing and potential partners.
- Evaluation of product ROI parameters for primarily IP based set of products – IP cores for FPGAs and potentially ASIC.
- Additional effort in order to create FBMC FPGA IP core, as described in the exploitable foreground section below.

Conservatoire National des Arts et Métiers:

The work carried during the EMPhAtiC project was a continuation of the one started by the PHYDYAS project, six years ago. During this time, many master and PhD thesis were carried out, allowing the publication of multiple original results. These results will also be used in enriching the engineering and master's lectures given at CNAM. On the other hand, the knowhow on FBMC systems will give to our research team a better national and European visibility for leading or contributing to future projects on this field.

Computer Technology Institute & Press Diophantus:

The participation of CTI in the EMPhAtiC project will allow training PhD students as well as postdoc researchers in modern signal processing and communications subjects, such as sparse signal processing in FB-based multicarrier, radio resource management and cognitive radio, especially in the PMR application context. Previous research experience in these topics will be refined and extended, also incorporating parallel research activities of the group and enriching them with the project's tools and applications. Interacting with the other partners within the project is expected to promote collaboration, extend knowledge and expertise (especially in the PMR application context), and provide material for more future research projects in the area.

Technische Universitaet Ilmenau:

With the results of the project and insights gained on FBMC as well as broad PMR, follow-up research projects will be applied. Based on the outcome and future work of the project, Master thesis topics and student research project topics will be proposed. The innovations in the project will be integrated into lectures on mobile communications.

Magister Solutions:

Magister Solutions is a consulting company specializing in the research of wireless systems. Its core competence team has long traditions in wireless communications, especially in development of system simulators supporting standardization activities. This project increased Magister Solutions' spectrum of own wireless network simulative tools. In the project the company has developed new models for link and system level simulators necessary for the R&D of new wideband PMR systems. Some of these universal techniques and tools (e.g. scenarios creation, statistics collection, simulation visualization, etc.) have been already proposed to potential clients.

Moreover, Magister was able to get new knowledge and expertise with PMR systems, what has a clear positive impact on company's service offering. In the future, developed simulators can be further extended to the needs of equipment vendors. Magister Solutions' profile became stronger because new models complement well the other tools already proposed by the company, such as Satellite Network Simulator (SNS-3), mesh and cellular networks simulations.

Stieftelsen SINTEF:

The main activity for SINTEF is contract research. Our customers are companies both national and international, public sector and EU-funded projects. A large part of our revenue comes from companies. The knowledge and experience gained through projects like EMPhAtiC is a valuable resource that will be exploited in both on-going and future projects.

Centre Tecnològic de Telecomunicacions de Catalunya:

CTTC, as a non-profit research institute, does not plan for a direct commercial exploitation of products developed within the EMPhAtiC project. However, CTTC is very active in providing technological support to the industry through multiple technology transfer projects at national and European levels. The knowledge acquired in the course of the project will certainly contribute to the development of new technology that will directly benefit the European industrial sector. In this sense, CTTC has already begun a collaboration with a European company that manufactures commercial modems for powerline communcations, in order to develop a commercial product based on filterbank multicarrier technology. Research results carried out within EMPhAtiC will certainly have a major impact in these industrial developments.

Technische Universitaet Muenchen:

TUM will exploit the results in two fronts. First, to support teaching in higher semesters of the bachelor course and mainly in master level lectures. Furthermore, due to the planed cooperation with industry partners interested in advance multicarrier modulation, results of the project could serve as the basis for further developments.

TTY-SAATIO:

TUT has exploited and will intend to exploit the results of the project in parallel and future research activities, both in academic and industry driven projects. These include company-driven projects targeted at advanced waveform development for 5G, on one hand, and for narrowband communications in the high-frequency (HF) band, on the other. There has been a close cooperation within the spectrum sensing topic with a national cognitive radio related project (ENCOR2 project in the TRIAL programme of Tekes). TUT also hopes to participate in future projects, e.g., in the Horizon2020 and EUREKA/CELTIC programmes, e.g., with applications in broadband PMR further development and 5G systems. Central learnings from the Emphatic project have also been included in certain advanced level courses in the curriculum of TUT.

Université Catholique de Louvain:

The Emphatic project will contribute to increase the know-how of the teams at UCL working on FBMC system design. Most results have lead or will lead to publications. The teams will continue working on similar topics within other projects targeting 5G communication networks and optical communications among others. Further investigation topics are considered such as RF impairments and high mobility scenarios. Besides, the results will also be used for education purposes including developments in the framework of Master theses.

Univerzitet u Novom Sadu:

UNS will exploit the results of the conducted research for extending the Wireless Communications graduate studies curriculum, and strengthening its R&D potential towards participation in future projects funded by EC, along the collaboration with industry organizations.

# 2. Use and dissemination of foreground

## 2.1 Section A: Dissemination Measures

**TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES**

| NO. | Title | Main author | Title of the periodical or the series | Number, date or frequency | Publisher | Place of publication | Year of publication | Relevant pages | Permanent identifiers[2] (if available) | Is/Will open access[3] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | *Efficient energy detection methods for spectrum sensing under non-flat spectral characteristics* | *S. Dikmese, P C. Sofotasios, T. Ihalainen, M. Renfors, and M. Valkama* | *IEEE J. Selected Areas in Communications - Cognitive Radio Series* | *Vol.33, No. 5* | *IEEE* | *USA* | *2015* | *755 - 770* | *http://dx.doi.org/10.1109/JSAC.2014.2361074* | *No* |
| 2 | *An Asymptotic Approach to Parallel Equalization of Filter Bank Based Multicarrier* | *X. Mestre, M. Majoral, S. Pfletschinger* | *IEEE Transactions on Signal Processing* | *Vol. 61 No. 15* | *IEEE* | *USA* | *2013* | *3592-3606* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6512591* | *No* |
| 3 | *Multi-stream transmission for highly frequency selective channels in MIMO-FBMC/OQAM systems* | *M. Caus, A.I. Pérez-Neira* | *IEEE Transactions on Signal Processing* | *Vol. 62, No. 4* | *IEEE* | *USA* | *2014* | *786-796* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6678253* | *No* |

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

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| 4 | *Analysis and design of efficient and flexible fast-convolution based multirate filter banks* | *M. Renfors, J. Yli-Kaakinen, and f. harris* | *IEEE Trans. Signal Processing* | *Vol. 62, No. 15* | *IEEE* | *USA* | *2014* | *3768–3783* | *http://dx.doi.org/10.1109/TSP.2014.2330331* | *No* |
| 5 | *Adaptive resource allocation and decoding strategy for underlay multi-carrier cooperative cognitive radio systems* | *M. Pischella and D. Le Ruyet* | *Transactions on Emerging Telecommunications Technologies (ETT)* | *Vol. 24, No. 7-8* | *ETT* | *Europe* | *2013* | *748–761* | *http://onlinelibrary.wiley.com/doi/10.1002/ett.2729/abstract* | *Yes* |
| 6 | *Enhanced OFDM for fragmented spectrum use* | *A. Loulou and M. Renfors* | *Trans. on Emerging Telecommunications Technologies* | *Vol. 26, No. 1* | *Wiley* | *Europe* | *2014* | *31 – 45* | *http://dx.doi.org/10.1002/ett.2898* | *No* |
| 7 | *Low-complexity interference variance estimation methods for coded multicarrier systems: application to SFN* | *M. Caus, A. Perez Neira, and M. Renfors* | *EURASIP Journal on Advances in Signal Processing* | *Vol. 2013, No. 163* | *EURASIP* | *Europe* | *2013* | *N/A* | *http://dx.doi.org/10.1186/1687-6180-2013-163* | *Yes* |
| 8 | *Interference Tables: a useful model for interference analysis in asynchronous multi-carrier transmission* | *Y. Medjahdi, M. Terré, D. Le Ruyet, D. Roviras* | *EURASIP Journal on Advances in Signal Processing* | *Vol. 2014, No. 54* | *EURASIP* | *Europe* | *2014* | *N/A* | *http://asp.eurasipjournals.com/content/2014/1/54* | *Yes* |
| 9 | *Theoretical analysis of BER performance of nonlinearly amplified FBMC/OQAM and OFDM signals* | *H. Bouhadda, H. Shaiek, D. Roviras, R. Zayani, Y. Medjahdi and R. Bouallegue* | *EURASIP Journal on Advances in Signal Processing* | *Vol. 2014, No. 60* | *EURASIP* | *Europe* | *2014* | *N/A* | *http://asp.eurasipjournals.com/content/2014/1/60/abstract* | *Yes* |
| 10 | *Preamble-based channel estimation in single-relay networks using FBMC/OQAM* | *C. Mavrokefalidis, E. Kofidis, A. Rontogiannis, and S. Theodoridis* | *EURASIP Journal on Advances in Signal Processing* | *Vol. 2014, No. 66* | *EURASIP* | *Europe* | *2014* | *N/A* | *http://link.springer.com/article/10.1186%2F1687-6180-2014-66* | *Yes* |
| 11 | *Spectrum sensing and resource allocation for multicarrier cognitive radio systems under interference and power constraints* | *S. Dikmese, S. Srinivasan, M. Shaat, F. Bader, and M. Renfors* | *EURASIP Journal on Advances in Signal Processing* | *Vol. 2014, No. 68* | *EURASIP* | *Europe* | *2014* | *N/A* | *http://dx.doi.org/10.1186/1687-6180-2014-68* | *Yes* |
| 12 | *Intrinsic interference mitigating coordinated beamforming for the FBMC/OQAM based downlink* | *Y. Cheng, P. Li and M. Haardt* | *EURASIP Journal on Advances in Signal Processing* | *Vol. 2014 No. 86* | *EURASIP* | *Europe* | *2014* | *N/A* | *http://asp.eurasipjournals.com/content/pdf/1687-6180-2014-86.pdf* | *Yes* |
| 13 | *Preamble-based frequency-domain joint CFO and STO* | *S. Van Caekenberghe, A. Bourdoux, L. Van der Perre, and J. Louveaux* | *EURASIP Journal on Advances in Signal Processing* | *Vol. 2014 No. 118* | *EURASIP* | *Europe* | *2014* | *N/A* | *http://asp.eurasipjournals.com/content/2014/1/118* | *Yes* |

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| | *estimation for OQAM-based filter bank multicarrier* | | | | | | | | | |
| 14 | *Multicarrier waveforms with I/Q staggering: uniform and nonuniform FBMC formats* | *S. Jošilo, M. Pejović, B. Đorđević, M. Narandžić and S. Nedić,* | *EURASIP Journal on Advances in Signal Processing* | *Vol. 2014, No. 167* | *EURASIP* | *Europe* | *2014* | *N/A* | *http://asp.eurasipjournals.com/content/2014/1/167* | *YES* |
| 15 | *Link performance model for filter bank based multicarrier systems* | *D. Petrov, A. Oborina, L. Giupponi and T. H. Stitz* | *EURASIP Journal on Advances in Signal Processing* | *Vol. 2014 No. 169* | *EURASIP* | *Europe* | *2014* | *N/A* | *http://asp.eurasipjournals.com/content/2014/1/169* | *Yes* |
| 16 | *Inherent interference reduction in filter bank based multicarrier using QAM modulation* | *R. Zakaria, D. Le Ruyet* | *Physical Communication* | *Vol. 11* | *Elsevier* | *Europe* | *2014* | *15–24* | *http://www.sciencedirect.com/science/article/pii/S1874490713000633* | *Yes* |
| 17 | *Closed-form BER expression for (QAM or OQAM) based OFDM system under nonlinear Rayleigh fading channel* | *R. Zayani, H. Shaiek, D. Roviras and Y. Medjahdi* | *IEEE Wireless Communication Letters* | *Vol. 4, No. 1* | *IEEE* | *USA* | *2015* | *38 - 41* | *http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&arnumber=6936335* | *No* |
| 18 | *Reducing the PAPR in FBMC-OQAM Signals by Trellis-based SLM Technique* | *K. C. Bulusu, H. Shaiek and D. Roviras* | *IEEE Transaction on Signal Processing* | *submitted* | *IEEE* | *USA* | *2014* | *N/A* | *N/A* | *No* |
| 19 | *MIMO Signal Processing in Filter Bank-based Multicarrier Systems'* | *A. I. Pérez-Neira, M. Caus, R. Zakaria, D. Le Ruyet, E. Kofidis, M. Haardt, X. Mestre and Y. Cheng* | *IEEE Transaction on Signal Processing* | *submitted* | *IEEE* | *USA* | *2015* | *N/A* | *N/A* | *No* |
| 20 | *Parallelized Structures for MIMO FBMC under Strong Channel Frequency Selectivity* | *X. Mestre, D. Gregoratti* | *IEEE Transactions on Signal Processing* | *submitted* | *IEEE* | *USA* | *2015* | *N/A* | *N/A* | *No* |
| 21 | *Flexible Multi-Carrier Structure Enabling Migration to Future Generation Broadband Professional Communication Services* | *M. Renfors, J. Yli-Kaakinen, F. Bader, A. Amri, Y. Medjahdi, D. Roviras, D. Le Ruyet, H. Shaiek B. C. Bulusu, L. Martinod and P. Mège* | *IEEE Communication Magazine* | *submitted* | *IEEE* | *USA* | *2015* | *N/A* | *N/A* | *No* |
| 22 | *Optimization of Flexible Filter Banks Based on Fast-Convolution* | *M. Renfors and J. Yli-Kaakinen* | *Journal of Signal Processing Systems* | *Accepted, pending publication* | *Elsevier* | *Europe* | *2015* | *N/A* | *N/A* | *No* |
| 23 | *Reduced Complexity Subband Energy Based Spectrum Sensing under Noise Uncertainty and Frequency-* | *S. Dikmese, P C. Sofotasios, M. Renfors, and M. Valkama* | *IEEE Trans. Signal Processing* | *submitted* | *IEEE* | *USA* | *2015* | *N/A* | *N/A* | *No* |

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| | *Selective Spectral Characteristics* | | | | | | | | | |
| 24 | *Multi-stream transmission in MIMO-FBMC systems* | *M. Caus, A.I. Pérez Neira,* | *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP) 2013* | *26/05/2013* | *IEEE* | *Vancouver, Canada* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6638621* | *No* |
| 25 | *SDMA for filterbank with Tomlinson Harashima precoding* | *M. Caus, A.I. Pérez Neira,* | *Proceedings of the IEEE International Conference on Communications (ICC) 2013* | *09/06/2013* | *IEEE* | *Budapest (Hungary)* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6655290* | *No* |
| 26 | *Optimal training design for channel estimation in OFDM/OQAM cooperative systems* | *C. Mavrokefalidis, E. Kofidis, A. Rontogiannis, and S. Theodoridis* | *Proc. IEEE Int'l Workshop on Signal Processing Advances in Wireless Communications (SPAWC-2013)* | *16/06/2013* | *IEEE* | *Darmstadt, Germany* | *2013* | *N/A* | *http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6612046&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D6612046* | *No* |
| 27 | *Enhanced OFDM techniques for fragmented spectrum use* | *A. Loulou, S. Afrasiabi, and M. Renfors* | *Proc. IEEE Future Networks and Mobile Summit* | *03/07/2013* | *IEEE* | *Lisbon, Portugal* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6633529&isnumber=6633516* | *No* |
| 28 | *Fast-convolution filter bank approach for non-contiguous spectrum use* | *J. Yli-Kaakinen and M. Renfors* | *Proc. IEEE Future Networks and Mobile Summit* | *03/07/2013* | *IEEE* | *Lisbon, Portugal* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6633530&isnumber=6633516* | *No* |
| 29 | *Link Performance Model for System Level Simulations of Filter Bank Multicarrier-Based Systems in PMR Networks* | *A. Oborina, C. Ibars, L. Giupponi, F. Bader* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629692* | *No* |
| 30 | *Preamble design for channel estimation in OFDM/OQAM cooperative systems* | *C. Mavrokefalidis, E. Kofidis, A. Rontogiannis, and S. Theodoridis* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *N/A* | *http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6629686* | *No* |

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| 31 | *Link to System Mapping for FBMC Based Systems in SISO case.* | *D. Petrov, P. Gonchukov, and T. Hidalgo Stitz* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *1-5* | *http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6629694&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D6629694* | *No* |
| 32 | *Low feedback downlink MIMO channel estimation for distributed FBMC systems using SNR measurements* | *J. Louveaux, A. Bourdoux, F. Horlin* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629687* | *No* |
| 33 | *Widely linear processing in MIMO FBMC/OQAM systems* | *J. Zhang and M. Haardt* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *743 - 747* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629839* | *No* |
| 34 | *EM based Per-Subcarrier ML Channel Estimation for Filter Bank Multicarrier Systems* | *L. G. Baltar, A. Mezghani, J. A. Nossek* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *31-35* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=06629690&tag=1* | *No* |
| 35 | *Sum rate maximization in asynchronous ad hoc networks: comparison of multi-carrier modulations* | *M. Pischella, D. Le Ruyet, Y. Medjahdi* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629842* | *No* |
| 36 | *Timing offset compensation in fast-convolution filter bank based waveform processing* | *M. Renfors and J. Yli-Kaakinen* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *1 – 5* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629684&isnumber=6629683* | *No* |
| 37 | *Comparison of linear and widely linear processing in MIMO-FBMC systems* | *M. Caus, A.I. Pérez Neira* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629688* | *No* |

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| 38 | *On interference cancellation in Alamouti coding scheme for filter bank based multicarrier systems* | *R. Zakaria, D. Le Ruyet* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629689* | *No* |
| 39 | *Analysis of the nonlinear spectral re-growth in FBMC systems for cognitive radio context* | *S. Sall, H. Shaiek, D. Roviras, Y. Medjahdi* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmeneau, Germany* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629685* | *No* |
| 40 | *Non-uniform FBMC - A pragmatic approach* | *S. Josilo, M. Pejovic, S. Nedic* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629691* | *No* |
| 41 | *Widely linear signal processing for two-way relaying with MIMO amplify and forward relays* | *Y. Cheng and M. Haardt* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2013* | *27/08/2013* | *VDE* | *Ilmenau, Germany* | *2013* | *264 - 268* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6629737* | *No* |
| 42 | *MMSE Training Design for Filter Bank Multicarrier Systems with Per-Subcarrier Channel Estimation* | *M. Newinger, L. G. Baltar, J. A. Nossek,* | *Proc. IEEE Int. Conf. Vehicular Technology Conference (VTC Fall) 2013* | *02/09/2013* | *IEEE* | *Las Vegas, USA* | *2013* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6692287* | *No* |
| 43 | *On the use of filter bank based multicarrier modulation for professional mobile radio* | *M. Renfors, F. Bader, L. Baltar, D. Le Ruyet, D. Roviras, P. Mege, M. Haardt, and T Hidalgo Stitz* | *Proc. IEEE Int. Conf. Vehicular Technology Conference (VTC Spring) 2013* | *02/09/2013* | *IEEE* | *Dresden, Germany* | *2013* | *1 – 5* | *http://dx.doi.org/10.1109/VTCSpring.2013.6692670* | *No* |
| 44 | *Effective schemes for OFDM sidelobe control in fragmented spectrum use* | *A. Loulou and M. Renfors* | *Proc. IEEE Int. Symp. Personal Indoor and Mobile Radio Communications (PIMRC)* | *08/09/2013* | *IEEE* | *London, United Kingdom* | *2013* | *471 – 475* | *http://dx.doi.org/10.1109/PIMRC.2013.6666182* | *No* |

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| 45 | *Sum rate maximization in multi-operator two-way relay networks with a MIMO AF relay via POTDC* | *J. Zhang, S. A. Vorobyov, A. Khabbazibasmenj, and M. Haardt* | *Proc. European Signal Processing Conference (EUSIPCO 2013)* | *09/09/2013* | *EURASIP* | *Marrakech, Morocco* | *2013* | *N/A* | *http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6811690* | *No* |
| 46 | *MISO Broadcasting FBMC System for Highly Frequency Selective Channels* | *M. Newinger, L. G. Baltar, A. Lee Swindlehust, J. A. Nossek* | *Proceedings of the ITG WSA 2014* | *12/03/2014* | *VDE* | *Erlangen, Germany* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6776898* | *No* |
| 47 | *FBMC/OQAM for the asynchronous multi-user MIMO uplink* | *Yao Cheng, Peng Li and Martin Haardt* | *Proceedings of the ITG WSA 2014* | *12/03/2014* | *VDE* | *Erlangen (Germany)* | *2014* | *N/A* | *http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6776881* | *No* |
| 48 | *Short preamble-based estimation of highly frequency selective channels in FBMC/OQAM* | *E. Kofidis* | *Proc. IEEE International Conf. Acoustics, Speech, and Signal Processing (ICASSP-2014)* | *04/05/2014* | *IEEE* | *Florence, Italy* | *2014* | *N/A* | *http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&arnumber=6855170* | *No* |
| 49 | *Optimization of Flexible Filter Banks Based on Fast-Convolution* | *J. Yli-Kaakinen, and M. Renfors* | *Proc. IEEE International Conf. Acoustics, Speech, and Signal Processing (ICASSP-2014)* | *04/05/2014* | *IEEE* | *Florence, Italy* | *2014* | *8317 – 8320* | *http://dx.doi.org/10.1109/ICASSP.2014.6855223* | *No* |
| 50 | *A parallel processing approach to filterbank multicarrier MIMO transmission under strong frequency selectivity* | *X. Mestre, D. Gregoratti* | *Proc. IEEE International Conf. Acoustics, Speech, and Signal Processing (ICASSP-2014)* | *04/05/2014* | *IEEE* | *Florence, Italy* | *2014* | *N/A* | *http://www.cttc.es/publication/a-parallel-processing-approach-to-filterbank-multicarrier-mimo-transmission-under-strong-frequency-selectivity/* | *No* |
| 51 | *Coordinated beamforming in MIMO FBMC/OQAM systems* | *Y. Cheng, P. Li and M. Haardt* | *Proc. IEEE International Conf. Acoustics, Speech, and Signal Processing (ICASSP-2014)* | *04/05/2014* | *IEEE* | *Florence, Italy* | *2014* | *484 - 488* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6853643* | *No* |

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| 52 | *Dominant eigenmode transmission in MIMO FBMC for frequency-selective channels* | *F. Rottenberg, J. Louveaux* | *Proc. IEEE Symposium on Information Theory in the Benelux* | *12/05/2014* | | *Eindhoven, Neetherlands* | *2014* | *N/A* | *http://www.win.tue.nl/sitb2014/proceedings.pdf* | *No* |
| 53 | *Channel equalization in fast-convolution filter bank based receivers for professional mobile radio* | *J. Yli-Kaakinen, and M. Renfors* | *Proceedins of the European Wireless Conference 2014* | *14/05/2014* | *VDE* | *Barcelona, Spain* | *2014* | *1 – 5* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6843197&isnumber=6843048* | *No* |
| 54 | *Adaptive Predistortion techniques for non-linearly amplified FBMC-OQAM signals* | *Rafik Zayani, Yahia Medjahdi, Hanen Bouhadda, Hmaied Shaiek, Daniel Roviras and Ridha Bouallegue* | *Proc. IEEE Int. Conf. Vehicular Technology Conference (VTC Spring) 2014* | *19/05/2014* | *IEEE* | *Seoul, Korea* | *2014* | *N/A* | *http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7022810* | *No* |
| 55 | *Channel estimation in filter bank-based multicarrier systems: Challenges and solutions* | *E. Kofidis* | *Proc. IEEE Int'l Symp. Communications, Control, and Signal Processing (ISCCSP-2014)* | *21/05/2014* | *IEEE* | *Athens, Greece* | *2014* | *N/A* | *http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6877911&url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel7%2F6862736%2F6877795%2F06877911.pdf%3Farnumber%3D6877911* | *No* |
| 56 | *Coordinated beamforming for the multi-user MIMO downlink using FBMC/OQAM* | *Y. Cheng, P. Li and M. Haardt* | *Proc. IEEE Int'l Symp. Communications, Control, and Signal Processing (ISCCSP-2014)* | *21/05/2014* | *IEEE* | *Athens, Greece* | *2014* | *506 - 510* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6877914* | *No* |
| 57 | *Spectrum sensing and resource allocation models for enhanced OFDM based cognitive radio* | *S. Dikmese, A. Loulou, S. Srinivasan, and M. Renfors* | *Proc. Int. Conf. Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)* | *02/06/2014* | *IEEE* | *Oulu, Finland* | *2014* | *360 – 365* | *http://dx.doi.org/10.4108/icst.crowncom.2014.255375* | *No* |
| 58 | *Maximum-Minimum Energy Based Spectrum Sensing under Frequency Selectivity for Cognitive Radios* | *S. Dikmese, P. C. Sofotasios, M. Renfors, and M. Valkama* | *Proc. Int. Conf. Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)* | *02/06/2014* | *IEEE* | *Oulu, Finland* | *2014* | *347 – 352* | *http://dx.doi.org/10.4108/icst.crowncom.2014.255376* | *No* |

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|---|---|---|---|---|---|---|---|---|---|---|
| 59 | *Sensitivity analysis of FBMC signals to non-linear phase distortion* | *H. Bouhadda, H. Shaiek, Y. Medjahdi, D. Roviras, R. Zayani and R. Bouallegue* | *Proc. IEEE International Conference on Communications 2014* | *10/06/2014* | *IEEE* | *Sydney, Australia* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6881175* | *No* |
| 60 | *Multi-mode filter bank solution for broadband PMR coexistence with TETRA* | *J. Yli-Kaakinen and M. Renfors* | *Proceedings of the European Conference on Networks and Communications (EuCNC) 2014* | *23/06/2014* | | *Bologna, Italy* | *2014* | *N/A* | *http://dx.doi.org/10.1109/EuCNC.2014.6882664* | *No* |
| 61 | *AF Relaying for FBMC Signals* | *D. Gregoratti, X. Mestre* | *Proceedings of the European Conference on Networks and Communications (EuCNC) 2014* | *23/06/2014* | | *Bologna, Italy* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6882625* | *No* |
| 62 | *EMPhAtiC intermediate results and standardization strategy* | *M. Renfors, D. Le Ruyet, D. Tsolkas, O. Font-Bach, N. Bartzoudis, P. Mege, L. Baltar, V. Ringset, and X. Mestre* | *Proceedings of the European Conference on Networks and Communications (EuCNC) 2014* | *23/06/2014* | | *Bologna, Italy* | *2014* | *N/A* | *N/A* | *No* |
| 63 | *On Spatial multiplexing receivers for FBMC* | *R. Zakaria, D. Le RuyetEuCNC* | *Proceedings of the European Conference on Networks and Communications (EuCNC) 2014* | *23/06/2014* | | *Bologna, Italy* | *2014* | *N/A* | *N/A* | *No* |
| 64 | *Widely Linear Filtering based kindred Co-Channel Interference Suppression in I/Q Staggered Multicarrier Waveforms* | *S. Josilo, M. Narandzic, S. Tomic and S. Nedic* | *Proceedings of the European Conference on Networks and Communications (EuCNC) 2014* | *23/06/2014* | | *Bologna, Italy* | *2014* | *N/A* | *N/A* | *No* |
| 65 | *Real-domain SIC for MIMO with FBMC Waveforms* | *V. Stanivuk, S. Tomić, M. Narandžić, S. Nedić* | *Proceedings of the European Conference on Networks and Communications (EuCNC) 2014* | *23/06/2014* | | *Bologna, Italy* | *2014* | *N/A* | *N/A* | *No* |

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| 66 | *On the performance of FBMC-based AF and DF multiple access relay networks* | *Y. Medjahdi, A. Dziri, J. Louveaux* | *Proceedings of the European Conference on Networks and Communications (EuCNC) 2014* | *23/06/2014* | | *Bologna, Italy* | *2014* | *N/A* | *N/A* | *No* |
| 67 | *Efficient adaptive equalization of doubly dispersive channels in MIMO-FBMC/OQAM systems* | *C. Mavrokefalidis, A. Rontogiannis, E. Kofidis, A. Beikos, and S. Theodoridis* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933367* | *No* |
| 68 | *On precoding MIMO-FBMC with imperfect channel state information at the transmitter* | *D. Le Ruyet, R. Zakaria, B. Özbek* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933464* | *No* |
| 69 | *A Conservative Approach to Sum Rate Maximization in Asynchronous Ad Hoc Networks using Multi-Carrier Modulation Schemes* | *J. Denis, M. Pischella, D. Le Ruyet* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933370* | *No* |
| 70 | *Reduction of PAPR for FBMC-OQAM Systems using Dispersive SLM Technique* | *K. C. Bulusu, H. Shaiek, D.Roviras and R.Zayani* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933418* | *No* |
| 71 | *Spectral Efficient Channel Estimation Algorithms for FBMC/OQAM Systems: A Comparison* | *L. G. Baltar, A. Mezghani, J. A. Nossek* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *707-711* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933445* | *No* |
| 72 | *Fast-convolution implementation of linear equalization based multiantenna detection schemes* | *M. Renfors and J. Yli-Kaakinen* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://dx.doi.org/10.1109/ISWCS.2014.6933446* | *No* |

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|---|---|---|---|---|---|---|---|---|---|---|
| 73 | *Widely linear filtering based kindred co-channel interference suppression in FBMC waveforms* | *S. Josilo, M. Narandzic, S. Tomic and S. Nedic* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933458* | *No* |
| 74 | *Real-domain SIC for MIMO with FBMC Waveforms* | *V. Stanivuk, S. Tomic, M. Narandzic and S. Nedic* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933454* | *No* |
| 75 | *Integrating LTE Broadband System in PMR Band: OFDM vs. FBMC Coexistence Capabilities and Performances* | *Y. Medjahdi, D. le Ruyet, F. Bader and L. Martinod* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933433* | *No* |
| 76 | *SINR Tight Lower bound for Asynchronous OFDM-based Multiple-Access Networks* | *Y. Medjahdi, M. Amara, J. Louveaux* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933455* | *No* |
| 77 | *On the Accuracy of PSD-based Interference Modeling of Asynchronous OFDM/FBMC in Spectrum Coexistence Context* | *Y. Medjahdi, M. Terré, D. le Ruyet, D. Roviras* | *Proc. International Symposium on Wireless Communication Systems (ISWCS) 2014* | *26/08/2014* | *IEEE* | *Barcelona, Spain* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6933432* | *No* |
| 78 | *Enhancing Spectral Efficiency in Advanced Multicarrier Techniques: A Challenge* | *L. G. Baltar, Tobias Laas, M. Newinger, A. Mezghani, J. A. Nossek* | *Proceedings of the European Signal Processing Conference 2014* | *01/09/2014* | *EURASIP* | *Lisbon, Portugal* | *2014* | *1875-1879* | *http://www.eurasip.org/Proceedings/Eusipco/Eusipco2014/HTML/papers/1569921363.pdf* | *No* |
| 79 | *Correlation Test for High Dimensional Data with Application to Signal Detection in Sensor Networks* | *X. Mestre, P. Vallet, W. Hachem* | *Proceedings of the European Signal Processing Conference 2014* | *01/09/2014* | *EURASIP* | *Lisbon, Portugal* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6952793* | *No* |

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|---|---|---|---|---|---|---|---|---|---|---|
| 80 | *Prediction of Spectral Regrowth for FBMC-OQAM system using Cumulants* | *K. C. Bulusu , H. Shaiek , D. Roviras* | *Proc. IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob) 2014ç* | *08/10/2014* | *IEEE* | *Larnaca, Cyprus* | *2014* | *N/A* | *http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6962202* | *No* |
| 81 | *Multi-Carrier Two-Way Relaying with Non-Binary Coding* | *S. Pfletschinger, D. Wübben, D. Gregoratti* | *Proc. International ITG Conference on Systems Communications and Coding (SCC)* | *02/02/2015* | *IEEE* | *Hamburg, Germany* | *2015* | *N/A* | *N/A* | *No* |
| 82 | *SIMO/MISO MSE-Duality for Multi-User FBMC with Highly Frequency Selective Channels* | *Oliver De Candido, Leonardo G. Baltar, Amine Mezghani and Josef A. Nossek* | *Proceedings of the ITG WSA 2015* | *03/03/2015* | *VDE* | *Ilmenau, Germany* | *2015* | *N/A* | *N/A* | *No* |
| 83 | *Downlink per-user multi-streaming for FBMC/OQAM based multi-user MIMO with highly frequency selective channels* | *Y. Cheng, M. Haardt, L. G. Baltar and J. A. Nossek* | *Proceedings of the ITG WSA 2015* | *03/03/2015* | *VDE* | *Ilmenau, Germany* | *2015* | *N/A* | *N/A* | *No* |
| 84 | *Non-linear precoding for the downlink of FBMC/OQAM based multi-user MIMO systems* | *Y. Cheng, V. Ramireddy, and M. Haardt* | *Proceedings of the ITG WSA 2015* | *03/03/2015* | *VDE* | *Ilmenau, Germany* | *2015* | *N/A* | *N/A* | *No* |
| 85 | *Joint design of multi-tap filters and power control for FBMC/OQAM based two-way decode-and-forward relaying systems in highly selective channels* | *J. Zhang, A. Nimr, and M. Haardt* | *Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP15.* | *19/04/2015* | *IEEE* | *Brisbane, Australia* | *2015* | *N/A* | *N/A* | *No* |
| 86 | *Asymptotic Analysis of Linear Spectral Statistics of the Sample Coherence Matrix* | *X. Mestre, P. Vallet, W. Hachem* | *Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP15.* | *19/04/2015* | *IEEE* | *Brisbane, Australia* | *2015* | *N/A* | *N/A* | *No* |

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|---|---|---|---|---|---|---|---|---|---|---|
| 87 | *Precoder and equalizer design for multi-user MIMO FBMC/OQAM with highly frequency selective channels* | *Y. Cheng, L. G. Baltar, M. Haardt and J. A. Nossek* | *Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP15.* | *19/04/2015* | *IEEE* | *Brisbane, Australia* | *2015* | *N/A* | *N/A* | *No* |
| 88 | *Receiver Technique for Detection and Correction of Nonlinear High Power Amplifier Distortion Errors* | *H. Bouhadda, R. Zayani, H. Shaiek, D. Roviras and R. Bouallegue* | *Proc. IEEE Int. Conf. Vehicular Technology Conference (VTC Spring) 2015* | *11/05/2015* | *IEEE* | *Glasgow, UK* | *2015* | *N/A* | *N/A* | *No* |
| 89 | *Fast-convolution implementation of filter bank multicarrier waveform processing* | *Kai Shao, J. Alhava, J. Yli-Kaakinen, and M. Renfors* | *Proc. IEEE Int. Symp. Circuits and Systems (ISCAS) 2015* | *24/05/2015* | *IEEE* | *Lisbon, Portugal* | *2015* | *N/A* | *N/A* | *No* |
| 90 | *Efficient Filter Bank Multicarrier Realizations for 5G* | *L. G. Baltar, I. Slim and J. A. Nossek* | *Proc. IEEE Int. Symp. Circuits and Systems (ISCAS) 2015* | *24/05/2015* | *IEEE* | *Lisbon, Portugal* | *2015* | *N/A* | *N/A* | *No* |
| 91 | *Potency of Trellis-based SLM over the symbol-by-symbol approach in reducing PAPR for FBMC-OQAM Signals* | *K. C. Bulusu, H. Shaiek and D. Roviras* | *Proceedings of the IEEE International Conference on Communications (ICC) 2015* | *09/06/2015* | *IEEE* | *London, UK* | *2015* | *N/A* | *N/A* | *No* |
| 92 | *Towards a non-error floor multi-stream beamforming design for FBMC/OQAM* | *M. Caus, A. I. Perez-Neira, Y. Cheng, and M. Haardt* | *Proceedings of the IEEE International Conference on Communications (ICC) 2015* | *09/06/2015* | *IEEE* | *London, UK* | *2015* | *N/A* | *N/A* | *No* |
| 93 | *Flexible fast-convolution implementation of single-carrier waveform processing* | *M. Renfors and J. Yli-Kaakinen* | *Proceedings of the IEEE International Conference on Communications (ICC) 2015* | *09/06/2015* | *IEEE* | *London, UK* | *2015* | *N/A* | *N/A* | *No* |

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|---|---|---|---|---|---|---|---|---|---|---|
| 94 | *Eigenvector Precoding for FBMC Modulations under Strong Channel Frequency Selectivity* | *X. Mestre, D. Gregoratti* | *Proceedings of the IEEE International Conference on Communications (ICC) 2015* | *09/06/2015* | *IEEE* | *London, UK* | *2015* | *N/A* | *N/A* | *No* |
| 95 | *Distortion Analysis in OQAM/FBMC-based OFDMA* | *D. Gregoratti, X. Mestre* | *IEEE International Workshop on Signal Processing Advances in Wireless Communications, SPAWC 2015* | *28/06/2015* | *IEEE* | *Stockholm, Sweden* | *2015* | *N/A* | *N/A* | *No* |
| 96 | *Optimized Burst Truncation in Fast-Convolution Filter Bank Based Waveform Generation* | *M. Renfors and J. Yli-Kaakinen* | *IEEE International Workshop on Signal Processing Advances in Wireless Communications, SPAWC 2015* | *28/06/2015* | *IEEE* | *Stockholm, Sweden* | *2015* | *N/A* | *N/A* | *No* |
| 97 | *Power Amplifier Effects on Advanced Frequency Localized Waveforms* | *M. Renfors, J. Yli-Kaakinen, and M. Valkama* | *Submitted to IEEE Global Communications Conference, Globecom 2015* | *6/12/2015* | *IEEE* | *San Diego, CA, USA* | *2015* | *N/A* | *N/A* | *No* |
| 98 | *Analysis of Noise Uncertainty and Frequency Selectivity Effects in Wideband Multimode Spectrum Sensing* | *S. Dikmese, P. Sofotasios, M. Renfors, M. Valkama, M. Ghogho* | *Submitted to IEEE Global Communications Conference, Globecom 2015* | *6/12/2015* | *IEEE* | *San Diego, CA, USA* | *2015* | *N/A* | *N/A* | *No* |
| 99 | *Addressing traffic demanding scenarios in cellular networks through QoE-based rate adaptation* | *D. Tsolkas, N. Passas, L. Merakos* | *Submitted to IEEE Personal Indoor and Mobile Radio Communications PIRMC 2015* | *30/08/2015* | *IEEE* | *Hong Kong, China* | *2015* | *N/A* | *N/A* | *No* |

| TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| NO. | Type of activities[4] | Main leader | Title | Date/Period | Place | Type of audience[5] | Size of audience | Countries addressed |
| 1 | *Exhibition* | *SINTEF* | *EMPhAtiC* | *June 23 – 2, 2014* | *Bologna (EuCNC 2014)* | *Scientific Community* | *300* | *Europe* |
| 2 | *Exhibition* | *SINTEF* | *Exhibition during RRS Workshop* | *December 3-4, 2014* | *Sofia Antipolis (RRS workshop)* | *Industry* | *100* | *All Europe* |
| 3 | *Poster* | *CTTC* | *The EMPhAtiC Project* | *June 23 – 2, 2014* | *Bologna (EuCNC 2014)* | *Scientific Community* | *300* | *Europe* |
| 4 | *Presentation* | *CASSIDIAN* | *Reconfigurable Radio Systems Potentialities for the Civil Security Domain* | *December 3-4, 2014* | *Sophia Antipolis (ETSI RRS Workshop)* | *Policy makers* | *80* | *Europe* |
| 5 | *Presentation* | *CTTC* | *EMPhAtiC project: final results and plans for exploitation* | *March 25, 2015* | *Brussels (RAS Cluster Meeting)* | *Scientific Community & Industry* | *30* | *Europe* |
| 6 | *Presentation* | *TUT* | *Fast-Convolution Based Flexible Multimode Communication Waveform Processing" in NEWCOM summer school "Flexible Multicarrier Waveforms for Future Communications Wireless Networks* | *May 21-23, 2014* | *Rennes (SUPELEC campus, Newcom # summer school)* | *Scientific Community & Industry* | *60* | *Europe* |
| 7 | *Presentation* | *CTTC* | *Effect of channel frequency selectivity on filterbank multicarrier modulations* | *May 21-23, 2014* | *Rennes (SUPELEC campus, Newcom # summer school)* | *Scientific Community & Industry* | *60* | *Europe* |

[4] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[5] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

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|---|---|---|---|---|---|---|---|---|
| 8 | *Presentation* | *UCL* | *Equalization of FBMC/OQAM* | *May 21-23, 2014* | *Rennes (SUPELEC campus, Newcom # summer school)* | *Scientific Community & Industry* | *60* | *Europe* |
| 9 | *Presentation* | *CTTC* | *Flexible multicarrier waveforms: implementation issues and baseband processing technologies* | *May 21-23, 2014* | *Rennes (SUPELEC campus, Newcom # summer school)* | *Scientific Community & Industry* | *60* | *Europe* |
| 10 | *Presentation* | *TUT* | *Advanced multicarrier waveforms for future wireless communications", tutorial in Int. Conf. Cognitive Radio Oriented Wireless Networks and Communication* | *June 5, 2014* | *Oulu, Finland* | *Scientific Community & Industry* | *35* | *Europe* |
| 11 | *Presentation* | *TUT* | *Advanced multicarrier waveforms for future wireless communications* | *Jan. 21, 2015* | *Paris, France* | *Scientific Community & Industry* | *15* | *Europe* |
| 12 | *Presentation* | *Bitgear* | *FBMC Implementation Aspects* | *Nov. 05, 2014* | *Belgrade/Novi Sad* | *Industry* | *5* | *Serbia* |
| 13 | *Presentation* | *Bitgear* | *5G implementation potential* | *June 10, 2014* | *Princeton* | *Industry* | *7* | *USA* |
| 14 | *Presentation* | *Magister* | *Beyond OFDM Radio Interfaces Facilitating Spectrum Coexistence and Secondary Access at 24th Jyväskylä University Summer School* | *August 6–8, 2014* | *Jyväskylä University, Finland* | *Scientific Community* | *25* | *Any* |
| 15 | *Presentation* | *CTTC* | *The EMPhAtiC Project* | *October 10-11, 2012* | *Brussels (RAS Cluster Meeting)* | *Scientific Community & Industry* | *30* | *Europe* |
| 16 | *Presentation* | *CASSIDIAN* | *EMPhAtiC- Standardization Strategy* | *September 20, 2013* | *Lisbon (ANACOM meeting)* | *Policy makers* | *30* | *Europe* |
| 17 | *Presentation* | *TUT* | *The EMPhAtiC Project* | *August 27, 2013* | *Ilmenau (Germany), ISWCS* | *Scientific Community* | *100* | *Europe* |
| 18 | *Presentation* | *CASSIDIAN* | *EMPhAtiC project the filterbank multicarrier approach* | *December 12, 2013* | *Mainz (ETSI RRS Meeting)* | *Policy makers* | *50* | *Europe* |
| 19 | *Presentation* | *CTTC* | *EMPhAtiC Intermediate results and standardization strategy* | *June 23, 2014* | *Bologna (RAS cluster workshop)* | *Scientific Community & Industry* | *30* | *Europe* |
| 20 | *Publication* | *Airbus Defence & Space (CASSIDIAN)* | *ETSI Technical Report 103 217* | *04/12/2014* | *Sofia Antipolis* | *Industry* | *N/A* | *Europe* |

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|---|---|---|---|---|---|---|---|---|
| 21 | *Thesis* | *TUT* | *MSc Thesis: AlaaEddin Loulou, Enhanced OFDM for fragmented spectrum use* | *2013* | *Tampere, Finland* | *Scientific Community* | *N/A* | *Europe* |
| 22 | *Thesis* | *TUT* | *MSc Thesis: Saeed Afrasiabi, Peak power reduction in multicarrier waveforms* | *2014* | *Tampere, Finland* | *Scientific Community* | *N/A* | *Europe* |
| 23 | *Thesis* | *TUT* | *PhD Thesis: Sener Dikmese, Enhanced Spectrum Sensing Techniques for Cognitive Radio Systems* | *2015* | *Tampere, Finland* | *Scientific Community* | *N/A* | *Europe* |
| 24 | *Thesis* | *TUM* | *MSc Thesis: Michael Newinger, MISO Broadcasting for Filter Bank based Multicarrier Systems,* | *2014* | *München, Germany* | *Scientific Community* | *N/A* | *Europe* |
| 25 | *White paper* | *TUT* | *Flexible and Spectrally Localized Waveform Processing for Next Generation Wireless Communications* | *2015* | *N/A* | *Scientific Community & Industry* | *N/A* | *Worldwide* |
| 26 | *White paper* | *CNAM* | *EMPhAtiC: Contributions to Filter Bank-Based Multicarrier MIMO, Cooperative Communications and Relaying.* | *2015* | *N/A* | *Scientific Community & Industry* | *N/A* | *Worldwide* |
| 27 | *White paper* | *Cassidian* | *EMPhAtiC: Progress towards standardization and Regulation. Reconfigurable Radio Systems potentialities for the civil security domain* | *2015* | *N/A* | *Scientific Community & Industry* | *N/A* | *Worldwide* |
| 28 | *Web* | *CTTC* | *EMPhAtiC website* | *2012-2015* | *Barcelona* | *Scientific Community & Industry* | *N/A* | *Worldwide* |
| 29 | *Workshop* | *TCS* | *Workshop on FBMC (industrial dissemination event)* | *26 Nov. 2014* | *"Gennevilliers (Industrial Dissemniation Event at TCS)* | *Industry, Scientific community* | *20* | *France* |
| 30 | *Workshop* | *All* | *Advanced Multicarrier Waveforms and Mechanisms for Future Ad-Hoc and Cell-Based Systems* | *27 Aug. 2013* | *Ilmenau, Germany* | *Scientific Community* | *60* | *Europe* |
| 31 | *Workshop* | *All* | *Advanced Multi-Carrier Techniques for Next Generation Commercial and Professional Mobile Systems* | *26 Aug. 2014* | *Barcelona, Spain* | *Scientific Community* | *60* | *Europe* |

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|---|---|---|---|---|---|---|---|---|
| 32 | *Workshop* | *CTI* | *Filter bank-based techniques for future wireless systems* | *May 14-16, 2014* | *Barcelona (Special Session within the European Wireless Conf)* | *Scientific Community* | *30* | *Europe* |
| 33 | *Workshop* | *CTTC/CTI* | *5G Waveforms* | *June 28, 2015* | *Stockholm (Special Session within SPAWC)* | *Scientific Community* | *20* | *Europe* |

## *2.2 Section B: Exploitable Foreground and Plans for Exploitation*

### 2.2.1 List of applications for patents, trademarks, registered designs, etc.

| TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC. | | | | | |
|---|---|---|---|---|---|
| Type of IP Rights[6]: | Confidential Click on YES/NO | Foreseen embargo date dd/mm/yyyy | Application reference(s) (e.g. EP123456) | Subject or title of application | Applicant (s) (as on the application) |
| Patent | NO | | EP13159897A1, US2013847020 | METHOD FOR EQUALIZING FILTERBANK MULTICARRIER (FBMC) MODULATIONS | Fundació Centre Tecnologic de Telecomunicacions de Catalunya |
| Patent | NO | | US2014321584 | Interference reduction method | CASSIDIAN SAS [FR] CNAM CONSERVATOIRE NATIONAL DES ARTS ET MÉTIERS [FR] |
| Patent | NO | | US2014334569 | Method for estimating a channel | CASSIDIAN SAS [FR] CNAM CONSERVATOIRE NATIONAL DES ARTS ET MÉTIERS [FR] |
| Patent | NO | | FR3002709, WO2014128369 | Method for demodulating a signal | CASSIDIAN SAS [FR] |

[6] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

### 2.2.2 Exploitable Foreground

| Type of Exploitable Foreground[7] | Description of exploitable foreground | Confiden-tial Click on YES/NO | Foreseen embargo date dd/mm/yyyy | Exploitable product(s) or measure(s) | Sector(s) of application[8] | Timetable, commercial or any other use | Patents or other IPR exploitation (licences) | Owner & Other Beneficiary(s) involved |
|---|---|---|---|---|---|---|---|---|
| General advancement of knowledge | NB/BB COEXISTENCE | NO | | | J61.2.0 - Wireless telecommunica-tions activities | 2016 | Patent US2012250564 | Owner: CASSIDIAN SAS |
| General advancement of knowledge | Antenna processing techniques | NO | | | J61.2.0 - Wireless telecommunica-tions activities | 2015 | PATENTS US2014321584 FR3002709 WO2014128369 | Owner: CASSIDIAN SAS |
| General advancement of knowledge | Channel estimation | NO | | | J61.2.0 - Wireless telecommunica-tions activities | 2014 | US2014334569 | Owner: CASSIDIAN SAS |
| General advancement of knowledge | CHANNEL ESTIMATION for FBMC using pilots | NO | | | J61.2.0 - Wireless telecommunica-tions activities | 2016 | | Owner: CASSIDIAN SAS & CNAM DE PARIS |
| General advancement of knowledge | Equalization for FBMC | NO | | | J61.2.0 - Wireless telecommunica-tions activities | 2016 | Patents EP13159897A1, US2013847020 | Owner: CTTC |
| Commercial exploitation of R7D results | FBMC FPGA implementation | YES | 2015-2017 | FPGA IP core | J61.2.0 - Wireless telecommunica-tions activities | TBD | Licence | Owner: Bitgear |
| General advancement of knowledge | New models for wideband PMR systems | NO | | R&D services, Development of algorithms | J61.2.0 - Wireless telecommunica-tions activities | 2015-2016 | | Owner: Magister Solutions, services for equipment manufacturers |

[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.
[8] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

| Type of Exploitable Foreground[7] | Description of exploitable foreground | Confiden-tial Click on YES/NO | Foreseen embargo date dd/mm/yyyy | Exploitable product(s) or measure(s) | Sector(s) of application[8] | Timetable, commercial or any other use | Patents or other IPR exploitation (licences) | Owner & Other Beneficiary(s) involved |
|---|---|---|---|---|---|---|---|---|
| Commercial exploitation of R&D results | System-level simulations for wideband PMR systems | YES | | Computer simulator for R&D services, standartization support, algorithms development, study of coexistence scenarios etc. | J61.2.0 - Wireless telecommunica-tions activities | 2016-2017 | | Owner: Magister Solutions, services for equipment manufacturers |
| Commercial exploitation of R&D results | Communication equipment | Yes | unknown | Filterbank techniques | C26.3.0 - Manufacture of communication equipment | unknown | None | Owner: SINTEF Beneficiary: Private Company |
| Commercial exploitation of R&D results | Communication equipment | Yes | unknown | Filterbank modem for powerline communications | C26.3.0 - Manufacture of communication equipment | 2016 | None | Owner: SINTEF Beneficiary: Private Company |
| General advancement of knowledge | Resource allocation algorithm for ad-hoc networks based on the back-pressure algorithm approach adapted for the distributed problem | No | not applicable | Internal communication to product lines and to technical directors | J61.2 - Wireless telecommunications activities | few months for internal communciation | None | Owner: Thales Communications and Security |
| General advancement of knowledge | Channel estimation algorithm for SC-FDMA multi-user | No | not applicable | Internal communication to product lines and to technical directors | J61.2 - Wireless telecommunications activities | Few months for internal communciation | None | Owner: Thales Communications and Security |

| Type of Exploitable Foreground[7] | Description of exploitable foreground | Confiden-tial Click on YES/NO | Foreseen embargo date dd/mm/yyyy | Exploitable product(s) or measure(s) | Sector(s) of application[8] | Timetable, commercial or any other use | Patents or other IPR exploitation (licences) | Owner & Other Beneficiary(s) involved |
|---|---|---|---|---|---|---|---|---|
| | or multi-antenna application | | | | | | | |
| General advancement of knowledge | Assessment of two-way relaying performance for SC-FDMA PHY layer with respect to decode-and-forward relaying | No | not applicable | Internal communication to product lines and to technical directors | J61.2 - Wireless telecommunications activities | Few months for internal communciation | None | Owner: Thales Communications and Security |
| General advancement of knowledge | Fast-convolution filter bank based waveform processing methods | No | | Simulation models for developed algorithms | J61.2 - Wireless telecommunications activities | | | Owner: Tampere University of Technology |

Below, we include some more detailed explanation about the exploitable background items listed above, classified according to the applicable owner institution:

CASSIDIAN/AIRBUS Defence and Space

The exploitable foreground for AIRBUS Defence and space in the frame of EMPhAtiC project consists of different subjects related to Physical Layer techniques for radiocommunication purpose.

A part of this exploitable foreground has been the subject of patents listed in Section 2.2.1 above. This concerns: narrowband/broadband (NB/BB) coexistence, antenna processing techniques, and channel estimation. This part of the foreground is already exploited by AIRBUS Defence and Space or is intended to be exploited by them in the next future. A part of this foreground has been elaborated with CNAM de Paris and the corresponding patents were filed by both applicants. Later on AIRBUS Defence and Space (ex-Cassidian) did buy all the patent rights. CNAM de Paris is continuing to have some rights on the usage of this foreground in the frame of particular agreement. The NB/BB Coexistence is the exploitable foreground considered as potentially the most important. It is partly protected by a patent.

Another part of the exploitable foreground is not fully finalized. This concerns notably the channel estimation techniques for FBMC signals with embedded pilots. It is expected to do a publication jointly with CNAM de Paris on the subject in 2015. There is no intention for the moment to protect it with a patent.

Bitgear Wireless Design Services:

Some of the implementation work carried out in WP9 is seen as a useful base to initiate the efforts on creation of FBMC FPGA based IP core. This product as such can then be licensed or modified and/or evolved additionally to create derivatives. In order to be able to create this product additional efforts are needed and the cost/benefit analysis will be studied internally in the period after project completion. The foreground has been generated by Bitgear and as such is to be further evolved by the same Party. This being said, the product (FPGA IP) could become available on the market in next 12 to 24 months. Upon full product creation, it is expected that it could generate a yearly income for Bitgear of approximately 100.000€.

Magister:

The described exploitable foreground mainly consists of system level simulations and models for wideband PMR systems. Nowadays development of any new technology is closely related to simulations at every stage: initial study, standardisation, optimization, etc. Therefore Magister’s purpose is to provide means and related R&D services and tools in order to make development process efficient and fast. The foreground might be exploited to provide services to equipment manufacturers: to study new algorithms, support their standardization activities, model large scale realistic scenarios, etc. IRPs in from of patents might be expected as a result of common research projects with equipment vendors.

Further research is needed to develop the results of the project. In particular, current link to system interface was developed only in SISO case, therefore further study of MIMO transmission is needed; other wireless systems can be added to system-level scenarios, etc. Implementation of full-function system level simulator for wideband PMR system will still require time and effort in future. The main impacts are new knowledge/expertise and simulation platform/tools for wideband PMR system. This is the background for new services which Magister can provide to the customers. This will support further study and implementation of evolving PMR systems

<u>SINTEF:</u>

The foreground obtained within the EMPhAtiC project is added to our general knowledge and is important for acquirement of new projects. The main activity for SINTEF is contract research. Our customers are companies both national and international, public sector and EU-funded projects. A large part of our revenue comes from companies. The knowledge and experience gained through projects like EMPhAtiC is a valuable resource that will be exploited in both on-going and future projects. In particular our hands-on experience from the demonstrator was essential.

SINTEF has been responsible for WP9 and in particular the receiver part of the demonstrator. The knowledge and experience acquired in EMPhAtiC has already been used in an on-going project for an international company. In this project, which is a non-PMR application, we replace older, less efficient communication techniques with FBMC in order to improve quality, capacity and robustness in a commercial product. Due to non-disclosure agreements we cannot yet disclose any details about this activity.

Filterbank techniques can be used in a wide variety of communication systems. New application areas require adoptions and new added features. The impact of our involvement with the commercial product mentioned above is that the product owner is still competitive with this new product and will thus contribute to the overall revenue. Quantifiable numbers are not available yet.

<u>Thales Communications and Security:</u>

As far as TCS is concerned, besides the FBMC competence accumulated during the project, three main results (foregrounds) have been obtained. A resource allocation algorithm for ad-hoc networks based on the back-pressure algorithm approach adapted for the distributed problem was obtained during the project. Its purpose is to deal with traffic without stringent delay constraints in order to better use the energy of the equipment over the medium term, while stabilizing the size of the buffer queues, which is an important practical problem.

This foreground may be exploited in PMR systems with partial coordination between them, or in other wireless systems with similar characteristics, like proprietary security systems. The result may be exploited by TCS on the medium or long term. It may be exploited also as a basis for further research. On the short term, internal dissemination of the results to technical management will be done. Since the results were published in public deliverables, no patent submission is possible. Further research can be necessary for better characterizing the behaviour of the algorithm over a scope broader than the one of the project. Moreover, interactions of the algorithms with all the other procedures running over a real MAC must still be investigated. This algorithm has low technological readiness level; hence the expectation is improving its readiness level in the near future or helping in improve the readiness level of similar algorithm. Its impact if also in strengthening the knowledge about the behaviour of FBMC and OFDM in resource allocation context, which can help in taking strategic technical choices.

On the other hand, a channel estimation algorithm for SC-FDMA multi-user or multi-antenna applications was obtained during the project. Its purpose is to have a channel estimation method adapted to PMR parameters and which can be used in the multiple access phase of a two-way relaying protocol. This foreground may be exploited in clusterized PMR system, where multiple hops are necessary, or in other context were multiple communications on the same time and frequency resources are needed. The result may be exploited by TCS on the medium or long term. It may be exploited also as a basis for further research. On the short term, internal dissemination of the results to technical management will be done. Since the results were published in public deliverables, no patent submission is possible. Originally a patent submission was planned but then dropped for lack of time. Further research is necessary for better characterizing the behaviour of two-way relaying in presence of error correcting codes and this channel estimation algorithm. This algorithm has low technological readiness level; hence the expectation is improving its readiness level in the near future. Since the technique is quite generic, it can be applied in a multitude of systems and possible products which have either a SC-FDMA or a SC-FDE physical layer.

Finally, an assessment of two-way relaying performance for SC-FDMA PHY layer with respect to decode-and-forward relaying was obtained during the project. Its purpose is to have a comparison, in a case adapted to PMR, of a two-way relaying protocol and the traditional decode and forward protocol. It was also the occasion to study scheduling constraint at MAC and propose an adaptive TWR protocol which joins part of the benefits of TWR and decode-and-forward. This foreground may be exploited in clusterized PMR system, where multiple hops are necessary, or in other context were multiple communications on the same time and frequency resources are needed. The result may be exploited by TCS on the medium or long term. It may be exploited also as a basis for further research. On the short term, internal dissemination of the results to technical management will be done. Since the results were published in public deliverables, no patent submission is possible. Moreover, the work on comparison of performance has an aim of improving knowledge and understanding of the behaviour of such algorithms and cannot be the object of any patent. Further research is necessary for better characterizing the behaviour of two-way relaying in presence of a more complete system, with multiple users, for instance, and taking more realistic propagation assumptions. The impact here is a finer understanding of the mechanisms of TWR and of the cases in which it can have a realistic advantage over decode and forward. The study done can also help the promotion inside TCS of these new relaying techniques, showing their advantages.

Centre Tecnològic de Telecomunicacions de Catalunya:

The foreground of CTTC consisted of multiple aspects related to physical layer and demonstration of filterbank based multicarrier solutions. More specifically, as a result of the project, CTTC gained some important knowledge on computationally efficient equalization methods for filterbank multicarrier signals that could be exploited by any future communication system transmitting with this technology over highly frequency selective channels (e.g. wired and wireless communications). In order to protect this invention, a patent application was submitted and granted, both in USA and in Europe. Current research involves the generalization of the proposed approach to time selective scenarios, in order to guarantee its efficiency in high mobility scenarios. The potential impact can be significant, especially if filterbank technology is finally adopted as physical layer support of 5G Communications.

On the other hand, CTTC has also been involved in demonstration activities of the project, and as a consequence of this, a valuable know-how on implementation strategies for fiterbank multicarrier modulations has been gained. In the future, we plan to exploit this foreground by developing transceiver solutions for the industrial sector. At the moment, CTTC is in contact with a powerline modem manufacturer in order to develop a filterbank multicarrier modulation modem for this application. We hope to be able to complete a fully commercial solution by the end of the year.

Tampere University of Technology:

The main contributions of TUT in EMPhAtiC were related to the application of fast-convolution (FC) techniques for advanced waveform processing and channelization filtering in wireless communication systems. Before EMPhAtiC, the core ideas of FC were known and a few scientific SDR-oriented publications existed, but FC technique was not considered as a useful tool for waveform processing. FC-FB is also closely connected to (and potential implementation scheme for) certain recent advanced waveform proposals, such as frequency-spread implementation of FBMC/OQAM (CNAM, CEA/LETI), GFDM (TU Dresden), and WCP-COQAM (Orange). The results of the work can be exploited by wireless equipment vendors in the development of flexible and effective waveform solutions for future radio communication systems, as well as for SDR-oriented implementations of legacy systems.

## *2.3 Report on societal implications*

| | |
|---|---|
| **A General Information** *(completed automatically when **Grant Agreement number** is entered.* | |
| **Grant Agreement Number:** | 318362 |
| **Title of Project:** | EMPhAtiC |
| **Name and Title of Coordinator:** | Dr. Xavier Mestre |

| | |
|---|---|
| **B Ethics** | |
| **1. Did your project undergo an Ethics Review (and/or Screening)?**<br><br>• If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports?<br><br>Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'* | ***No*** |
| **2. Please indicate whether your project involved any of the following issues (tick box) :** | ***YES*** |
| **RESEARCH ON HUMANS** | |
| • Did the project involve children? | |
| • Did the project involve patients? | |
| • Did the project involve persons not able to give consent? | |
| • Did the project involve adult healthy volunteers? | |
| • Did the project involve Human genetic material? | |
| • Did the project involve Human biological samples? | |
| • Did the project involve Human data collection? | |
| **RESEARCH ON HUMAN EMBRYO/FOETUS** | |
| • Did the project involve Human Embryos? | |
| • Did the project involve Human Foetal Tissue / Cells? | |
| • Did the project involve Human Embryonic Stem Cells (hESCs)? | |
| • Did the project on human Embryonic Stem Cells involve cells in culture? | |
| • Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos? | |
| **PRIVACY** | |
| • Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)? | |
| • Did the project involve tracking the location or observation of people? | |
| **RESEARCH ON ANIMALS** | |
| • Did the project involve research on animals? | |
| • Were those animals transgenic small laboratory animals? | |
| • Were those animals transgenic farm animals? | |
| • Were those animals cloned farm animals? | |
| • Were those animals non-human primates? | |
| **RESEARCH INVOLVING DEVELOPING COUNTRIES** | |
| • Did the project involve the use of local resources (genetic, animal, plant etc)? | |
| • Was the project of benefit to local community (capacity building, access to healthcare, education etc)? | |
| **DUAL USE** | |
| • Research having direct military use | 0 Yes 0 No |

| | |
|---|---|
| • Research having the potential for terrorist abuse | |

## C Workforce Statistics

**3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).**

| **Type of Position** | **Number of Women** | **Number of Men** |
|---|---|---|
| Scientific Coordinator | 0 | 2 |
| Work package leaders | 0 | 7 |
| Experienced researchers (i.e. PhD holders) | 2 | 26 |
| PhD Students | 3 | 12 |
| Other | 1 | 11 |

| | |
|---|---|
| **4. How many additional researchers (in companies and universities) were recruited specifically for this project?** | **9** |
| Of which, indicate the number of men: | 8 |

## D Gender Aspects

| | | | |
|---|---|---|---|
| 5. | **Did you carry out specific Gender Equality Actions under the project?** | O<br>x | Yes<br>No |

**6. Which of the following actions did you carry out and how effective were they?**

| | Not at all effective | | | | Very effective |
|---|---|---|---|---|---|
| ❑ Design and implement an equal opportunity policy | O | O | O | O | O |
| ❑ Set targets to achieve a gender balance in the workforce | O | O | O | O | O |
| ❑ Organise conferences and workshops on gender | O | O | O | O | O |
| ❑ Actions to improve work-life balance | O | O | O | O | O |

O Other:

**7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?**

O Yes- please specify

x No

## E Synergies with Science Education

**8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?**

X Yes- please specify: Seasonal Schools, Workshops, University Lecctures, Ms Theses

O No

**9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?**

X Yes- please specify: Tutorials, Lecture notes, demos, lab exercises and the EMPhAtiC website

O No

## F Interdisciplinarity

**10. Which disciplines (see list below) are involved in your project?**

X Main discipline[9]: Engineering and Technology

X Associated discipline[9]: Electrical engineering, electronics

O Associated discipline[9]:

## G Engaging with Civil society and policy makers

| | | | |
|---|---|---|---|
| 11a | **Did your project engage with societal actors beyond the research community?** *(if 'No', go to Question 14)* | X<br>O | Yes<br>No |

**11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?**

X No

O Yes- in determining what research should be performed

O Yes - in implementing the research

O Yes, in communicating /disseminating / using the results of the project

[9] Insert number from list below (Frascati Manual).

| | | |
|---|---|---|
| **11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?** | O<br>X | Yes<br>No |
| **12. Did you engage with government / public bodies or policy makers (including international organisations)** | | |
| O No<br>O Yes- in framing the research agenda<br>O Yes - in implementing the research agenda<br>X Yes, in communicating /disseminating / using the results of the project | | |
| **13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?**<br>O Yes – as a **primary** objective (please indicate areas below- multiple answers possible)<br>X Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)<br>O No | | |
| **13b If Yes, in which fields?** Information Society, Research and Innovation | | |

| | | | | | |
|---|---|---|---|---|---|
| Agriculture<br>Audiovisual and Media<br>Budget<br>Competition<br>Consumers<br>Culture<br>Customs<br>Development Economic and Monetary Affairs<br>Education, Training, Youth<br>Employment and Social Affairs | | Energy<br>Enlargement<br>Enterprise<br>Environment<br>External Relations<br>External Trade<br>Fisheries and Maritime Affairs<br>Food Safety<br>Foreign and Security Policy<br>Fraud<br>Humanitarian aid | | Human rights<br>Information Society<br>Institutional affairs<br>Internal Market<br>Justice, freedom and security<br>Public Health<br>Regional Policy<br>Research and Innovation<br>Space<br>Taxation<br>Transport | |

**13c If Yes, at which level?**

- ○ Local / regional levels
- ○ National level
- X European level
- X International level

## H Use and dissemination

| | |
|---|---|
| **14. How many Articles were published/accepted for publication in peer-reviewed journals?** | **17** |
| **To how many of these is open access[10] provided?** | **11** |
| **How many of these are published in open access journals?** | **11** |
| **How many of these are published in open repositories?** | **11** |
| **To how many of these is open access not provided?** | **6** |
| **Please check all applicable reasons for not providing open access:** | |
| X publisher's licensing agreement would not permit publishing in a repository<br>❑ no suitable repository available<br>X no suitable open access journal available<br>X no funds available to publish in an open access journal<br>❑ lack of time and resources<br>❑ lack of information on open access<br>❑ other[11]: …………… | |

| | |
|---|---|
| **15. How many new patent applications ('priority filings') have been made?** *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).* | **2** |

| | | |
|---|---|---|
| **16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).** | Trademark | |
| | Registered design | |
| | Other | **4** |

| | |
|---|---|
| **17. How many spin-off companies were created / are planned as a direct result of the project?** | **0** |
| ***Indicate the approximate number of additional jobs in these companies:*** | |

**18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:**

| | | | |
|---|---|---|---|
| X | Increase in employment, or | X | In small & medium-sized enterprises |
| X | Safeguard employment, or | ❑ | In large companies |
| ❑ | Decrease in employment, | ❑ | None of the above / not relevant to the project |
| ❑ | Difficult to estimate / not possible to quantify | | |

| | |
|---|---|
| **19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:** | *Indicate figure:* |
| Difficult to estimate / not possible to quantify | ❑ |

## I Media and Communication to the general public

**20. As part of the project, were any of the beneficiaries professionals in communication or media relations?**

○ Yes X No

**21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?**

○ Yes X No

**22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?**

| | | | |
|---|---|---|---|
| ❑ | Press Release | X | Coverage in specialist press |
| ❑ | Media briefing | ❑ | Coverage in general (non-specialist) press |
| ❑ | TV coverage / report | ❑ | Coverage in national press |
| ❑ | Radio coverage / report | ❑ | Coverage in international press |
| X | Brochures /posters / flyers | X | Website for the general public / internet |
| ❑ | DVD /Film /Multimedia | ❑ | Event targeting general public (festival, conference, exhibition, science café) |

**23 In which languages are the information products for the general public produced?**

| | | | |
|---|---|---|---|
| ❑ | Language of the coordinator | X | English |
| ❑ | Other language(s) | | |

[10] Open Access is defined as free of charge access for anyone via Internet.
[11] For instance: classification for security project.

# 3. Final report on the distribution of the European Financial Contribution

This report shall be submitted to the Commission within 30 days after receipt of the final payment of the European Union financial contribution.

## Report on the distribution of the European Union financial contribution between beneficiaries

| Name of beneficiary | Final amount of EU contribution per beneficiary in Euros |
|---|---|
| 1. CENTRE TECNOLOGIC DE TELECOMUNICACIONS DE CATALUNYA | TBC |
| 2. CONSERVATOIRE NATIONAL DES ARTS ET METIERS | TBC |
| 3. TTY-SAATIO | TBC |
| 4. TECHNISCHE UNIVERSITAET MUENCHEN | TBC |
| 5. UNIVERSITE CATHOLIQUE DE LOUVAIN | TBC |
| 6. COMPUTER TECHNOLOGY INSTITUTE & PRESS DIOPHANTUS | TBC |
| 7. TECHNISCHE UNIVERSITAET ILMENAU | TBC |
| 8. STIFTELSEN SINTEF | TBC |
| 9. UNIVERZITET U NOVOM SADU FAKULTET TEHNICKIH NAUKA | TBC |
| 10. CASSIDIAN SAS | TBC |
| 11. THALES COMMUNICATIONS & SECURITY SA | TBC |
| 12. BITGEAR WIRELESS DESIGN SERVICES DOO | TBC |
| 13. MAGISTER SOLUTIONS OY | TBC |
| **Total** | |

# Glossary and definitions

| Acronym | Meaning |
|---|---|
| AF | Amplify and Forward |
| AFB | Analysis Filter Bank |
| AWGN | Additive White Gaussian Noise |
| B-PMR | Broadband PMR |
| C2R | Complex to Real |
| CF | Compute and Forward |
| CFO | Carrier Frequency Offset |
| CoF | Compute and Forward |
| CoMP | Coordinated Multi-Point |
| COTS | Commercial Off-The-Shelf |
| CP-OFDM | Cyclic Prefix based Orthogonal Frequency Division Multiplexing |
| CQI | Channel Quality Indicator |
| CRS | Cell Specific Reference Signal |
| CSD | Canonical signed digit |
| DF | Decode & Forward |
| DFE | Decision Feedback Equalizer |
| DMO | Direct Mode Operation |
| DoW | Description of Work |
| DWHT | Discrete Walsh-Hadamard Transform |
| ED | Energy Detector |
| ELT | Extended lapped transform |
| EM | Expectation-Maximization |
| FB | Filterbank |
| FBMC | Filterbank Multicarrier |
| FBSC | Filterbank Single Carrier |
| FC | Fast Convolution |
| FC-FB | Fast-Convolution based Filter Banks |
| FLO | Frequency Limited Orthogonal |
| GA | General Assembly |

| | |
|---|---|
| HO | Hand Over |
| HPA | High Power Amplifiers |
| IAM | Interference Approximation Method |
| ICI | Inter Carrier Interference |
| IIM | Intrinsic Interference Mitigating |
| ISI | Inter Symbol Interference |
| LS | Least Squares |
| MA | Margin Adaptive |
| MAP | Maximum a Posteriori |
| MC | Multicarrier |
| MCS | Modulation and Coding Scheme |
| MIMO | Multiple Input Multiple Output |
| ML | Maximum Likelihood |
| MMSE | Minimum Mean Square Error |
| NEF | Network Event File |
| PAPR | Peak to Average Power Ratio |
| PER | Packet Error Rate |
| PF | Proportional Fair |
| PMR | Professional Mobile Radio |
| PPDR | Public Protection and Disaster Relief |
| PSD | Power Spectral Density |
| PTS | Partial Transmit Sequence |
| QAM | Quadrature Amplitude Modulation |
| QMR | Quarterly Management Report |
| R2C | Real to Complex |
| RC | Raised Cosine |
| RLF | Radio Link Failure |
| ROC | Receiver Operating Characteristics |
| RRC | Root-raised Cosine |
| RRM | Radio Resource Management |
| SAS | Subcarrier Asignment Scheme |

| | |
|---|---|
| SC | Single Carrier |
| SDR | Software Defined Radio |
| SED | Subband Energy Detector |
| SFB | Synthesis Filter Bank |
| SFBC | Space-Frequency Block Coding |
| SIC | Successive Interference Cancellation |
| SINR | Signal-to-Interference-and-Noise Ratio |
| SLF | Strictly-Linear Filtering |
| SLM | Selective Mapping |
| SM | Spatial Multiplexing |
| SNR | Signal-to-Noise Ratio |
| SSPA | Solid State Power Amplifiers |
| STBC | Space Time Block Coding |
| TLO | Time Limited Orthogonal |
| TWR | Two-Way Relaying |
| TWTA | Traveling Wave Tube Amplifiers |
| WLF | Widely Linear Filtering |
| WP | Work Package |
| WSSUS | Wide-Sense Stationary Uncorrelated Scattering |
| STBC | Space Time Block Coding |
| TLO | Time Limited Orthogonal |
| TWR | Two-Way Relaying |
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