EMPhAtiC: Contributions to Filter Bank-Based Multicarrier MIMO, Cooperative communications and relaying

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I INTRODUCTION

The EMPhAtiC project has explored the technical solutions based on Filter-Bank approach with application to the domain of Professional Mobile Radio (PMR). Within the project a lot of techniques related to the use of MIMO schemes, cooperative and coordinated communications and relaying have been proposed and developed to achieve this target. The present white paper will summarize the main contributions of the EMPhAtiC project in this field.

In chapter II we will mainly focus on point to point MIMO transmission and reception both without and with channel state information at the transmitter and on the problem of MIMO channel estimation using preamble or pilots.

The chapter III will present the main contributions of the project EMPhAtiC on cooperative and coordinated communications and on relaying.

II MIMO TRANSMISSION AND RECEPTION

A. *MIMO transmission and reception without channel state information at the transmitter*

This section tackles the techniques that have been specifically designed for MIMO-FBMC/OQAM systems when channel state information (CSI) is solely available at the receiver. The emphasis is put on schemes that achieve spatial multiplexing gains, where the streams are mapped onto the transmit antennas.

Due to the intrinsic interference inherent to the FBMC signal, the classical MIMO transmission and reception schemes developed for single carrier or OFDM cannot be directly applied for FBMC. In this project, we have proposed different SM/FBMC-OQAM partial or full interference cancellation schemes. A first approach is 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 (PaIC) [22]. The interference cancellation scheme (MMSE-ML) has also been studied. This scheme has been also evaluated when associated with channel code in an iterative framework. Another interesting line of research is to use QAM symbols instead of OQAM symbols [23]. It can be shown that in this case, the energy of the intrinsic interference can be significantly reduced using FBMC-QAM.

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 interference cancellation and widely linear processing are combined (IC-WL) [5]. 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.

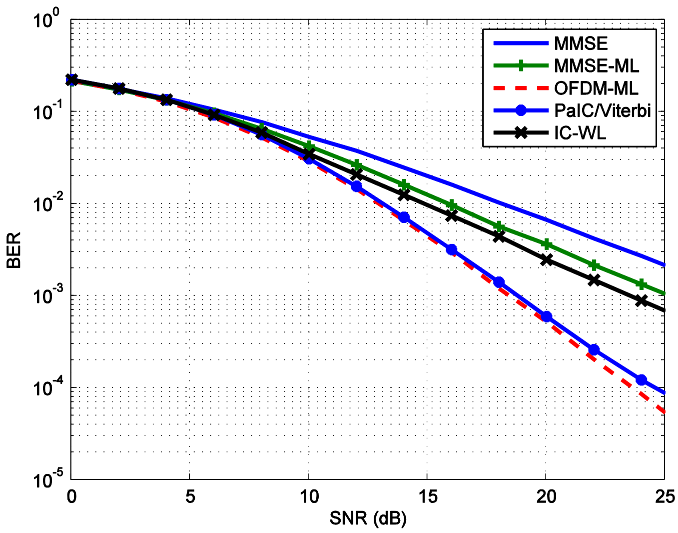

Fig. 1: BER performance comparison of different interference cancellation receivers

In figure 1, we have compared the BER performance of the different receivers in a 2x2 SM system with M=1024 subcarriers, 4- OQAM and assuming perfect channel state information at the receiver. The considered receivers are the linear MMSE, the MMSE-ML, the widely IC-WL and the PaIC. It is shown the IC-WL receiver outperforms both MMSE and MMSE-ML receivers but is still far from the performance of OFDM-ML. This performance limitation is due to the reliability level of the MMSE equalizer. On the other hand, the PaIC/Viterbi scheme outperforms the other studied schemes and achieves the same diversity gain as OFDM-ML.

When CSI is only exploited by the receiver, diversity gains can be achieved using space-time-block-coding (STBC). Nevertheless, since the perfect reconstruction property is satisfied in the real domain, whereas STBC is constructed by using orthogonal structures in the complex field, the application of STBC to FBMC/OQAM results in ISI and ICI.

In this project, the combination of STBC and SFBC with FBMC-OQAM has been 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 [24]. We have shown that after several iterations, the intrinsic interference is removed and we can reach the Genie-Aided performance. We have also shown that the best performance is achieved by using QAM symbols with the conventional lattice structure of OFDM.

B. MIMO channel estimation and tracking

The problem of MIMO-FBMC/OQAM channel estimation was addressed both in its preamble based and pilot based versions.

We have considered preambles of the shortest possible duration since it 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 [17] as shown in figure 2. 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.

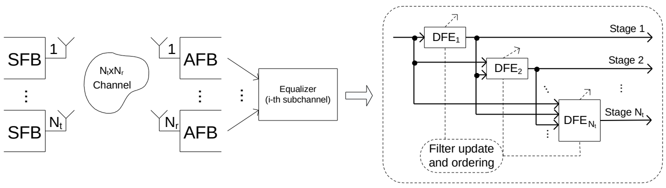

Fig. 2: proposed adaptive equalization of MIMO FBMC systems

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 this project, 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 is 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.

Another approach elaborated within the project has been an extension of the entirely real-domain formulation of the FBMC-OQAM system (which is consistent with the related orthogonality conditions) of the SISO case [1] to the 2x2 MIMO case [21]. Herein the intrinsic intersymbol interference is not treated as ‘annoyance’ , but rather as the part of information bearing samples, in that it leads to two-dimensional subchannels impulse responses (of size 3xL) instead of the one-dimensional (of length L) ones. For example, even for the flat fading channel where for the conventional complex-domain formulation only one complex tap suffices, the real-domain SIC subchannel impulse responses have size of 3 times the length of the filer-bank referent impulse response. The successive interference cancellation framework proceeds in the standard way and includes the outer code soft decoding. The effectiveness of the proposed approach has been shown for the flat fading case.

C. MIMO precoding

When CSI is also available at the transmitter, transceiver architectures robust to the presence of severe channel frequency selectivity can be designed for FBMC/OQAM. In this project, 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 [19]. 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 as shown in the figure above. 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.

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 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 intrinsic interference mitigating coordinated beamforming (IIM-CBF) schemes are effective in mitigating the intrinsic interference that is inherent in FBMC/OQAM based systems [8][9]. 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 figure 3.

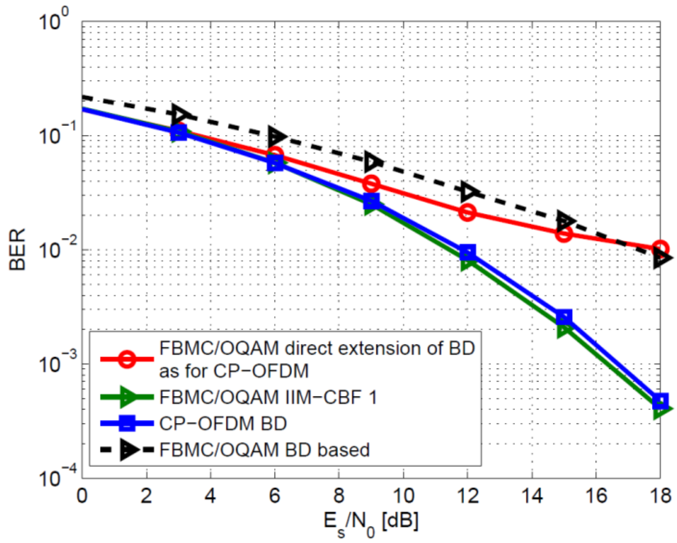

Fig. 3: BER performance comparison

In addition, the performance of the proposed IIM-CBF algorithms has been evaluated in the presence of imperfect channel state information at the transmitter. We have investigated more challenging but more realistic PMR scenarios where the channels are highly frequency selective.

In addition, we have 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 [14].

Finally, 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.

III COOPERATIVE AND COORDINATED COMMUNICATIONS AND RELAYING

A. Cooperative communications

Some of the above proposed solutions have been applied to cooperative communication such as the two-step with widely linear MMSE receiver [5] and channel estimation issue by proposing optimal designs of both sparse and full preambles, where the optimality is in the sense of the minimum Mean Square Error estimation subject to transmit energy constraints [15][16]. By performing extensive simulations considering a variety of asynchronous scenarios with different configurations and settings, we have shown the robustness of FBMC against time and frequency misalignments.

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.

B. Coordinated multipoint and distributed beamforming.

Different coordinated beamforming based transmission strategies were designed for the downlink of FBMC/OQAM based multi-user 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, the IIM-CBF scheme was used to alleviate the classical dimensionality constraint of these systems [4].

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 as shown in figure 4. In this scenario, cell interior users experience only intra-cell interference while cell edge users suffer from intra-cell and inter-cell interference.
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.

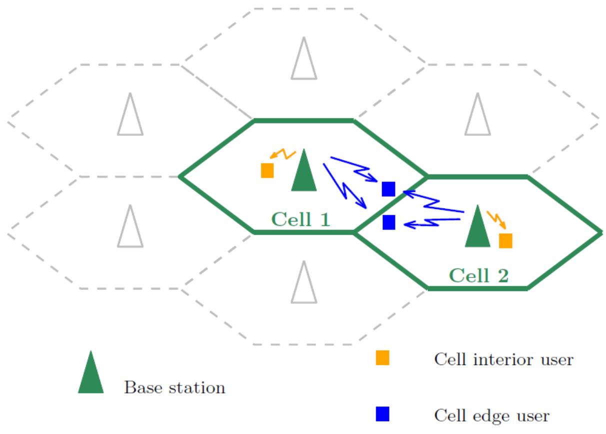

Fig. 4: Downlink of the FBMC/OQAM based coordinated multi-point

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 [7][11. 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.

C. RELAYING

The main objective of this work has been the study of relaying techniques in an ad-hoc and centralized PMR scenario using FBMC.

We have first studied 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.

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 interference of the FBMC scheme can be neglected. Due to the limitation of single tap equalization, further investigations have been 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 5. 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.

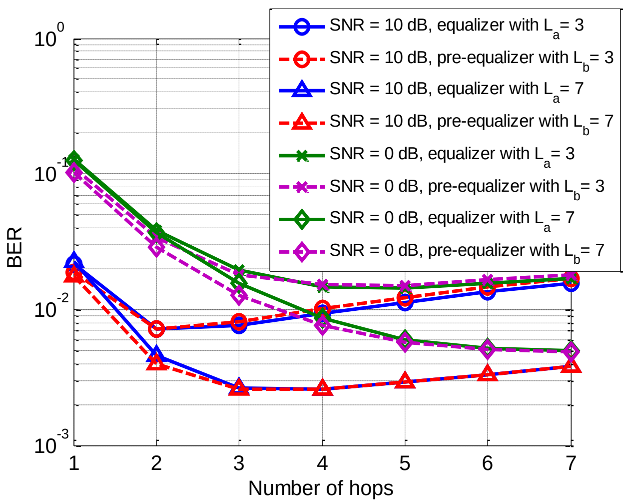

Fig. 5: Comparison of the BER performance in case of SNR = 0 dB and SNR = 10 dB for the FBMC/OQAM based multi-hop relaying network where a multi-tap equalizer or pre-equalizer is employed.

The two-way Decode-and-Forward (DF) relaying architecture was studied [25]. Both fundamental limits and practical implementations have been considered. 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.

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.

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. The key idea of this precoding is to align the intrinsic interferences caused by source transmitters. AF,DF and CoF protocols for Multi-access relaying have been compared in terms of complexity, performance and suitability to the PMR case. In contrast to DF protocol, AF and CoF are demonstrated to be more appropriate to PMR communications.

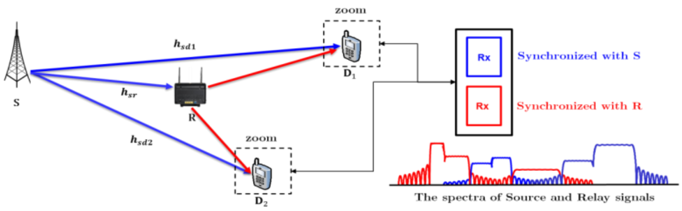

Fig. 7 : structure of the DF-relayed system

Cooperative relays for asynchronous multi-user transmissions were analyzed considering the scenario given in figure 8. The effect of asynchronous interference due to co-channel interference was also analyzed.

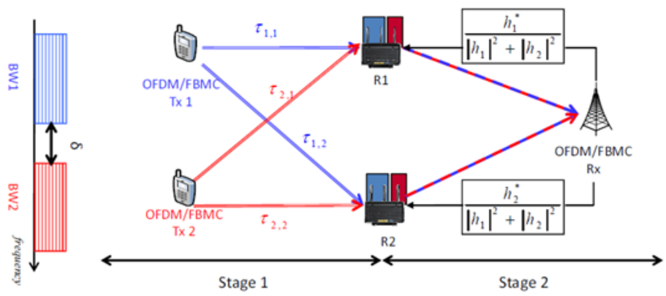

Fig. 8: Cooperative relay for asynchronous multiuser transmission.

As shown in figure 9, simulation and analytical results allowed concluding 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.

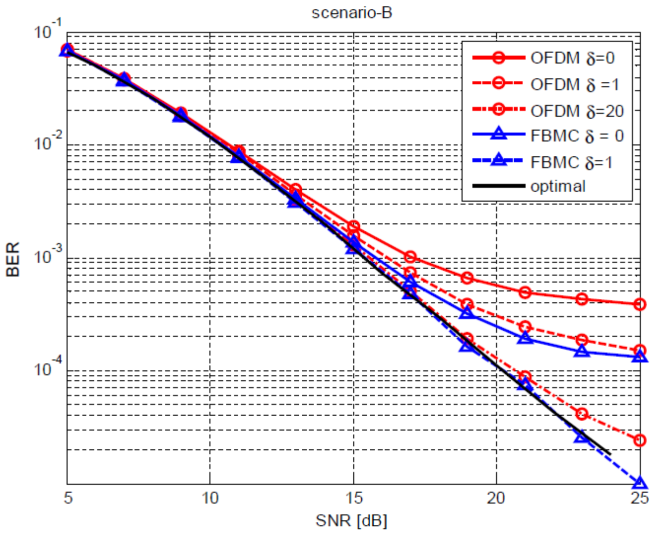

Fig. 9: BER performance comparison

IV CONCLUSION

The EMPhAtiC project has contribute a lot to FBMC-MIMO, cooperative communications and relaying. Many efforts have been made to propose original and practical solutions. Some of them such as the MIMO 2x2 MMSE-ML algorithm have been implemented in the hardware demonstrator of the project. While there is still some work to do before standardization, we believe that FBMC is now a mature solution for coexistence of narrow and broadband PMR systems.

Many works have not been presented in this white paper and we recommend the interested reader to visit the website of the project (http://www.ict-emphatic.eu) for further documentation.

ACKNOWLEGMENT

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