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Performance of a FilterBank MultiCarrier (FBMC) Physical Layer in the WiMAX Context

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Abstract: This paper describes some of the outcome of the FP7 project PHYDYAS, whose main objective was to propose a new physical layer that will enable introduction of cognitive radios and dynamic access spectrum management. During the project both a software simulator and a demonstrator have been developed. A description of the demonstrator and some simulation results that show the differences in spectral efficiency and the sensititvity to synchronisation errors between OFDM and FBMC are given.

The simulator, which is written in Matlab, was used to evaluate the performance of both OFDM and FBMC in a WiMAX context, i.e. the frame format is kept as close as possible to WiMAX. From the simulation results it has been possible to analyze the performance differences between the two systems. In addition to that the simulator was used as a reference in the validation of the demonstrator. The transmitter in the demonstrator is implemented in hardware and operates in real time. The channel emulation and up-conversion to RF is done using commercially available instruments from Agilent which have been modified to fit to the task. In the demonstrator receiver the hardware front-end converts the signal to baseband and digitizes it. The OFDM/FBMC signal processing is done in near real time on a general purpose computer connected to the front- end hardware.

Keywords: Cognitive radio, Filter bank, Physical layer

1. Introduction

The objective of the FP7 project PHYDYAS is to propose a physical layer for future radio systems that is more efficient than present OFDM based solutions and better suited to the new concepts of DASM (Dynamic Access Spectrum Management) and cognitive radio. Increased capacity is achieved using this new physical layer compared to OFDM. This is due to better exploitation both in the time and frequency dimensions. In frequency direction the increase in efficiency for FBMC is due to reduced out of band leakage such that a higher number of carriers can be used within the allocated bandwidth. To allow for synchronization and to manage the frequency selective behaviour of multipath channels, OFDM based systems introduce a cyclic prefix to the signal. With the new physical layer investigated in PHYDYAS the cyclic prefix is removed, again increasing the capacity. Additionally, and maybe more important, the new physical layer is more suited for efficient and reliable spectrum sensing as well as dynamic access spectrum management for cognitive radios

The filter bank introduced into the transmission chain is the heart of the project. A basic solution was provided at the beginning of the project, which was optimised further taking into account different degradation mechanisms. Other aspects of the transmission chain, such as synchronization and initialization, channel estimation and tracking, equalization, demodulation and MIMO processing are also addressed. To gain acceptance within the community the physical layer proposed in PHYDYAS needs to be compared with the state of the art with respect to performance and complexity. To get performance measurements, a physical layer simulator was developed reproducing the complete wireless transmission chain including the algorithms produced during the project. A software simulator developed in the project is based on IEEE 802.16e [1], a worldwide accepted standard which is the basis for WiMAX [2]. In addition a demonstrator was implemented, partly in hardware and partly in software. It shall be emphasized that the principles investigated in PHYDYAS are not limited to WiMAX. With minor modifications they can easily be translated to other OFDM based transmission systems such as LTE (Long Term Evolution). The paper is organised as follows. In Section 2 simulated comparisons regarding spectral efficiency and synchronization sensitivity are analysed. Section 3 gives a description of the implementation of the demonstrator developed in the project. In Section 4 the conclusions that can be drawn so far are given.

2. Simulation results

2.1 Spectral efficiency

FBMC is a way to address the inherent inefficiencies of OFDM (using the example of WiMAX):

- Cyclic prefix (1/8) → ~ 11.1 % spectral efficiency wasted
- Frequency guards → ~ 8 % spectral efficiency wasted

FBMC does not apply a cyclic prefix and due to the low out-of-band leakage much lower guards may be applied. Hence, FBMC does not introduce these inefficiencies. In the following the spectral efficiencies achievable with FBMC and OFDM within the context of WiMAX are compared. We have calculated the spectral efficiency as follows:

$$c = c_{\max} r R_T R_G R_p$$

with

$$c_{\max} = R_{CTC} ld(B) \quad \text{and} \quad r = 1 - PER$$

$c_{\max}$ is the maximal achievable spectral efficiency depending on the modulation order B and the code rate R_{CTC}. We have based the normalized throughput r on the packet error rate (PER), i.e. a bit is treated as erroneous if any of the bits within its packet (64 Bytes) is received erroneous. R_T reflects the efficiency in time direction, i.e. it is the ratio of time duration used for data transmission and the time duration of the complete subframe:

$$R_T = \frac{N_S T_S}{T_{SF}}$$

N_S is the number of multicarrier symbols within the subframe used for data transmission, T_S the useful symbol length. T_{SF} is the sub frame length. R_G R_P reflects the efficiency in frequency direction, i.e. the overhead due to the guard bands and the pilot symbols is accounted for here.

$$R_G = \frac{N_{SC} - N_G - 1}{N_{SC}} \qquad R_P = \frac{N_{SC} - N_G - 1 - N_P}{N_{SC} - N_G - 1}$$

N_{SC} is the number of subcarriers, N_G the number of subcarriers used as guard and N_P the number of pilots per multi carrier symbol.
In downlink we have adopted PUSC, in uplink AMC permutation schemes. We use convolutional turbo coding (CTC, code rate 1/2) as channel coding scheme. We have chosen a transform size of 1024, out of which the active subcarriers cover a bandwidth of approximately 10 MHz.
The channel is modelled as Pedestrian B (Ped-B) at 3 km/h. The receiver estimates the channel at the pilot locations. Then 2-D linear interpolation over time and frequency yield the channel estimate at each subcarrier and at each time instant. Perfect synchronization is assumed. In the OFDM-based WiMAX system, the length of the cyclic prefix is sensibly chosen to cover most channel delay spreads, so that single tap equalization can be performed. This is the case for scenarios with delay spreads similar to Ped-B and a CP with a normalized length of 1/8. For the FBMC case 3-tap equalization is performed.
At the CTC decoding stage four iterations are performed before the bits are decided and fed into the bit sink. The general parameter settings are summarized in Table 1:

Table 1. Simulation parameters.

Parameter	chosen value	Parameter	chosen value
Number of subcarriers	1024	Number of symbols per frame	47 (WiMAX) 53 (FBMC)
Carrier frequency	2.5 GHz	Packet size	64 Bytes
Bandwidth	10 MHz	Pilot boost	2.5 dB
Sampling rate	11.2 MHz	Coding scheme	CTC
Subcarrier spacing	10.94 kHz	Code rate	1/2
Overlapping factor	4	Number of turbo iterations	4
Permutation scheme	PUSC (DL) AMC (UL)	Channel model	Ped-B 3 km/h

The distribution of the usable multicarrier symbols to the sub frames is (one symbol is used as preamble):

Downlink subframe	WiMAX: 31, FBMC: 35
Uplink subframe	WiMAX: 15, FBMC: 17

For more detailed descriptions and results the reader is referred to [3]

2.2 DL PUSC:

Due to the broadcast nature of the downlink and in the case that the coherence bandwidth of the channel exceeds two subcarriers, there is no need for guards between the users. Otherwise the PUSC permutation would not be applicable efficiently anyway. The following figures compare the spectral efficiency of the WiMAX reference (applying OFDM) and the FBMC system. First perfect channel knowledge, then real channel estimation is applied. Perfect synchronization is assumed. The increased efficiency due to the usage of the filter bank is apparent.

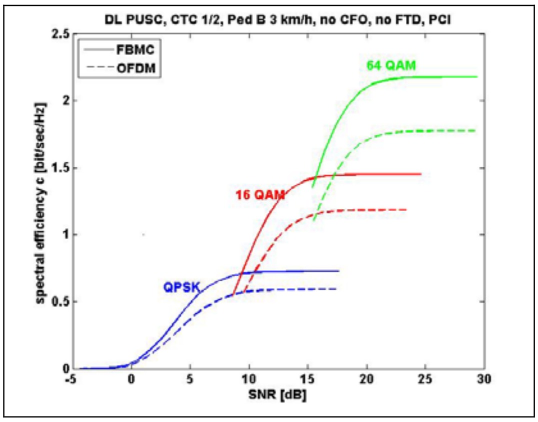

Figure 1: DL PUSC, perfect channel knowledge

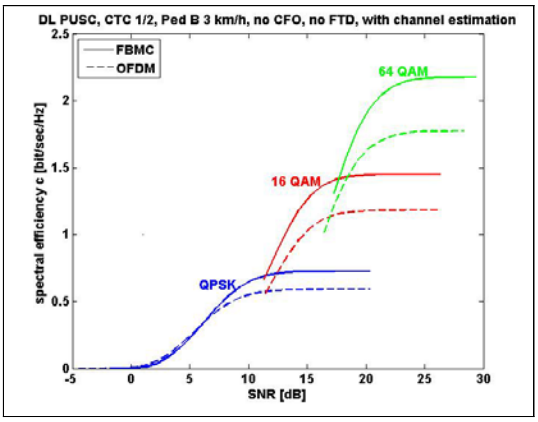

Figure 2: DL PUSC, real channel estimation.

2.3 UL AMC:

Contrary to the downlink the uplink is a multiple access channel. Different users access the channel separately. Thus, adjacent subcarriers may encounter different complex channel gains (if they are transmitted by different users), orthogonality is destroyed. Therefore time and frequency guards to separate the users are necessary, reducing the spectral efficiency. The following figures depict the single user case (upper bounds), thus no subcarriers are left empty as guards. Due to the lack of space multi user case is shifted to a later publication, however, first results show that FBMC outperforms ODFM even in the multi user case. Again first perfect channel knowledge is assumed, afterwards real channel estimation is applied:

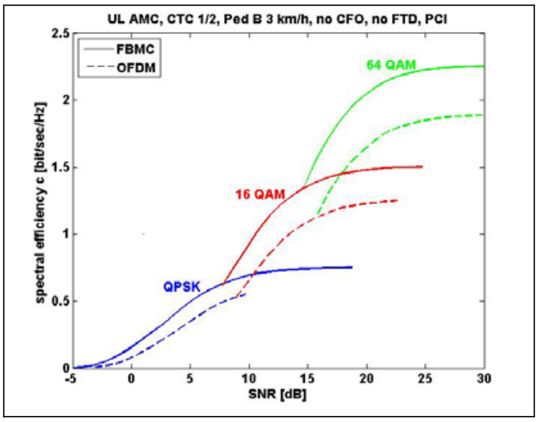

Figure 3: UL AMC (upper bound), perfect channel knowledge available.

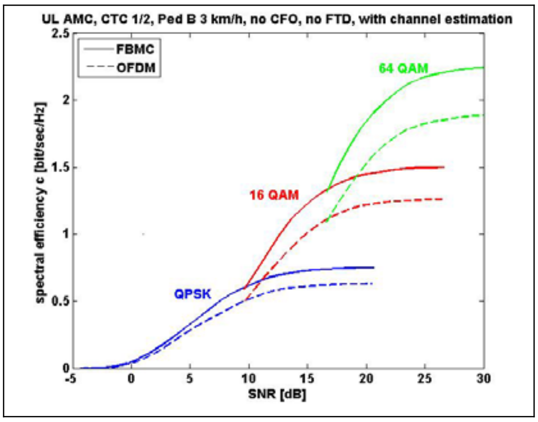

Figure 4: UL AMC (upper bound), real channel Estimation.

2.4 Synchronization

Both symbol timing and carrier frequency have to be adjusted. Pilot based estimation of fractional time delay (FTD, normalized to the length of a single symbol) and carrier frequency offset (CFO, normalized to the subcarrier spacing) are applied here. A timing offset adds a linear phase ramp in frequency direction, a frequency offset adds a linear phase ramp in time direction. With the estimates at the pilot positions as supporting points and linear regression the slopes of these phase ramps are estimated and accordingly compensated.

The following diagram shows the range of acceptable FTD and CFO if the communication system spends 3 dB link budget to this matter, i.e. all combinations of FTD and CFO below and to the left of the lines within the following diagram are degrading the performance less than 3 dB (actually the combinations lying on the lines are degrading the performance exactly by 3 dB) with respect to the required SNR to achieve a PER of 1%. Due to the lack of space just DL PUSC is presented here:

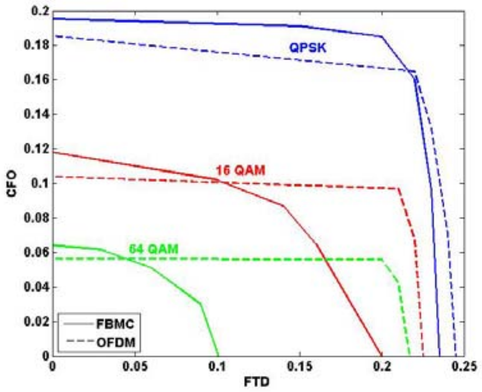

Figure 5: 3 dB tolerance with respect to FTD and CFO.

As to be expected FBMC is less sensitive to carrier offsets, OFM less sensitive to timing offsets due to the cyclic prefix.

3. OFDM – FBMC demonstrator

One of the objectives of the laboratory setup is to test, measure and demonstrate the advantages of an FBMC-based approach as compared to an OFDM-based approach. It will try to bring additional insight on top of the simulation results. Realistic performance expectations can only be checked if we can evaluate the impact of large time scale channel effects in a repeatable way. The figure below shows the demonstrator setup that is built during the PHYDYAS project. A more detailed description of the demonstrator is given in [3]

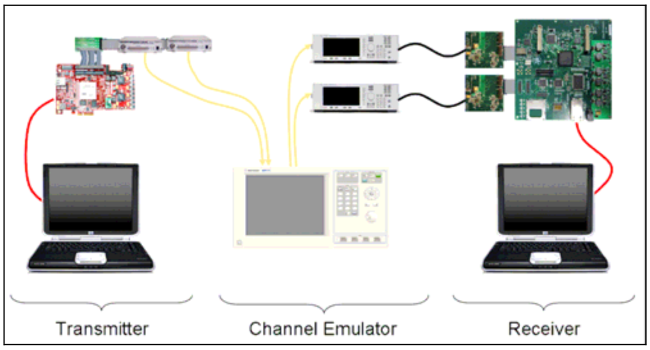

Figure 6: Demonstrator setup.

3.1 Transmitter

The real time transmitter is implemented in hardware on an FPGA board (HTG-V5-DDR3-PCIE) from HiTech Global. It is implemented as a dual mode terminal that can operate both in OFDM mode in a WiMAX context and in FBMC mode. Two instances of the transmitter can run simultaneously on the same physical board. The second transmitter can be used for MIMO or for generation of interference. The FPGA board's main component is a Virtex-5 SX 95 FPGA from Xilinx which is programmed in VHDL.

The transmitter implements the physical layer only. A block diagram is shown in Figure 7. Tables that are static for a given setup are calculated offline on the connected computer and loaded upon start-up. These tables include the content of the Frame Table, the subcarrier randomization, the instruction RAM for the auxiliary pilot calculation as well as other configuration parameters. The majority of the modules in the transmitter are equal for OFDM and FBMC mode, and in the following description we will focus only on the modules that are different.

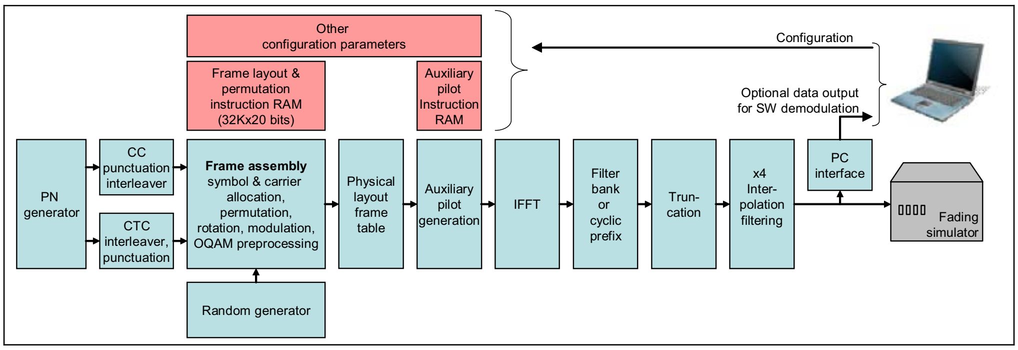

Figure 7. Block diagram transmitter

The frame assembly uses a table driven approach that can be configured to generate almost any configuration of frame, uplink or downlink, both for OFDM and FBMC. It operates like a programmable computer that reads instructions from an instruction RAM. Most instructions generate one encoded subcarrier in the output RAM.

A pilot in FBMC consists of the main pilot and auxiliary pilot, which together correspond to one modulated OQAM symbol. The primary part of the auxiliary pilot is calculated as a weighted sum of the surrounding carriers such that the secondary part of the main pilot is forced to zero. The channel estimation can then be done the same way as for OFDM in the receiver. The calculation of the auxiliary pilots requires 17 or 11 mult/add per pilot depending on required accuracy.

The IFFT is 1024 points and is identical for OFDM and FBMC. The difference is that the IFFT is running at double speed for FBMC due to OQAM modulation

The filter bank is used only in FBMC mode. It is implemented using a small data RAM (32 kbytes) that holds a history of 8 output vectors from the IFFT, a coefficient RAM (8 kbytes) containing 4096 filter coefficients (overlap factor 4) and two multiply/add slices. In OFDM mode the data flows unfiltered through this block but the reading sequence from the data RAM is modified such that the cyclic prefix is added.

The truncation module is used only for FBMC and allows truncation (fading in and out) of the pre and post tails of the FBMC signals. It is applied when signals from different transmitters are concatenated without gap in the time direction.

3.2 Channel emulator

Multiple Input Multiple Output (MIMO) technology holds the promise of higher data rates with increased spectral efficiency. Due to the potential improvement in system performance and advances in digital signal processing, many wireless systems, including IEEE 802.16e based Mobile WiMAX™, have adopted the use of MIMO and multiple antenna technologies.

Developing and testing MIMO components and systems requires advanced channel emulation tools that are easily configured and provide an accurate representation of realistic wireless channels and conditions. Complex channels can be emulated using commercially available instrumentation such as the Agilent N5106A PXB MIMO Receiver Tester, which will be referred to as the PXB.

A channel emulator, such as the PXB, that replicates real-world MIMO conditions using powerful digital signal processing technology provides a quick path for troubleshooting advanced radio components and systems. The channel emulator also has the advantages that it can generate realistic fading scenarios including path and channel correlations. The PXB provides up to 8 faders useful for testing and troubleshooting up to 4x2 MIMO systems. Figure 8 shows a simplified configuration diagram for testing a 2x2 MIMO transmitter and receiver using the PXB. It's internal faders can be independently configured with a standards-compliant fading model, such as a WiMAX ITU Pedestrian B, or custom configured model using a variety of path and fading conditions.

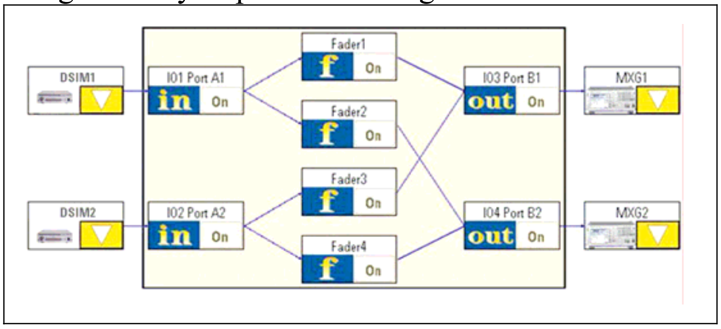

Figure 8. 2 x 2 MIMOBlock diagram

3.3 Receiver

A flexible prototype providing a rapid test environment for PHYDYAS physical layer receiver has been implemented. The implementation of the receiver consists of a combination of hardware and software.

The RF front-end (ADV-3000T from Mercury Computer Systems) is a radio frequency tuner system with programmable gain control. The RF frequency is 2.5GHz. The IF frequency at the output of the front-end is in the range between 3MHz and 40MHz. All the signals that are down converted are fully coherent so that MIMO processing is allowed.

The digital hardware consists of Universal Software Radio Peripheral (USRP2) board attached via a Gigabit Ethernet link to a General Purpose Processor (GPP). The USRP2 has two high-speed ADCs and one Xilinx Spartan 3-2000 FPGA which are used for sampling and digital down conversion of the signal respectively.

The entire OFDM/FBMC processing runs on a general purpose processor with Linux operating system. The programming language is C++.

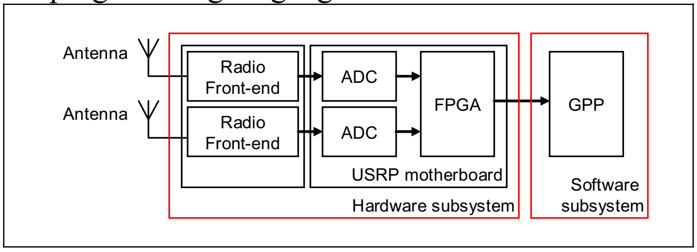

Figure 9. Block diagram of the receiver

4. Conclusions

Perhaps the most important feature for an FBMC system is the properties introduced by the filter bank. Spectrum sensing can be done accurately with low interference from adjacent subcarriers. An intereference-free group of carriers that have been detected can be exploited by an FBMC-based using only one guard carrier to the next group. This enables extremely efficient use of the spectrum for unsynchronized cognitive users.

From the results in section 2 it can be seen that FBMC outperforms OFDM with regard to spectral efficiency. This is due to the fact that efficiency is gained both in the time and frequency directions. In frequency direction the increase in efficiency for FBMC is due to reduced out of band leakage such that a higher number of carriers can be used within the allocated bandwidth. In time direction the gained efficiency is due to omission of the cyclic prefix. For the downlink case the PUSC permutation scheme has been used and due to the broadcast nature of the signal, orthogonality between carriers allocated to different users is maintained. For the uplink case, however, this orthogonality is destroyed due to different complex channel gains from different users. Guards are therefore introduced both in time and frequency for the FBMC case to allow for this, contributing to a reduction in efficiency. On the other hand, this enables operation in an unsynchronised environment, opposed to OFDM that relies on a synchronised network. Even with introduction of these guards the efficiency for FBMC is higher than OFDM.

The vulnerability to synchronisation errors that are analysed in section 2, is found by allocating 3 dB of the link budget to synchronisation errors. The results show that FBMC is less sensitive to carrier frequency offsets. For timing offsets the degradation is in favour for OFDM due to usage of the cyclic prefix.

The project has demonstrated that the complexity increase for a dual mode OFDM/FBMC transmitter is modest compared to a pure OFDM transmitter. The signal processing blocks that are different for OFDM and FBMC can operate in dual mode. This means that some blocks operate differently in OFDM and FBMC mode and some blocks are pass-through for OFDM and something else for FBMC. One way to measure complexity is to count the number of real multiplications needed per output sample. In the transmitter the filter bank and calculation of the auxiliary pilots are the main contributors and they contribute with 16 and 2 real multiplications per output sample respectively for downlink PUSC.

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