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Abstract

In METIS framework, a test-bed activity is conducted in order to provide a proof-of-concept of few selected key technology components illustrating some of the numerous new challenges and functionalities defined. Another objective of this activity is to show-case the system concept and to complement the theoretical work and numerical system level evaluations through real hardware measurements, e.g. processing delays, control signalling, and hardware implementation complexity and impairments. For this activity, two hardware/software platforms are available from Aalto University and Telecom Bretagne, with associated development resources. One platform is suitable for investigating radio resource management algorithms in realistic radio environments, and the other one is suited for investigation of digital baseband algorithms and related hardware complexity.

In this context, this deliverable provides the detailed descriptions of the realized demonstrations that can be categorized into three areas: device-to-device (D2D) communications, massive machine communications (MMC), and waveform design. For each demonstration, the devised storyline is illustrated together with the proposed hardware implementation, its integration into the test-bed environment, and the obtained results.

Keywords

Test-bed, technology components, D2D, M2M, MMC, vehicular communications, interference cancellation, mode selection, HetNet, compressed sensing, waveform, FBMC, OQAM, OFDM, spectrum access, air interface, software-defined radio, hardware resources, USRP, host computers, FPGA, Xilinx Zynq-7000 SoC, RF front-end, hardware/software development environment, communication software development framework, digital design methodologies, design tools, hardware complexity, KPIs.
Executive summary

METIS project envisions a future where access to information and sharing of data is available anywhere and anytime to anyone and anything. This vision has been described in terms of more concrete technical goals, and METIS 5G system concept has been developed towards the fulfillment of these goals. In order to complement the theoretical work and numerical system level evaluations, METIS has developed two hardware test-beds; one is dedicated to radio resource management algorithms investigation in realistic radio environments, while the other one aims at investigating digital baseband algorithms and related hardware complexity.

The objective of the test-beds is to demonstrate key technology components of the METIS 5G system concept, using hardware platforms, and to show-case the system concept. The test-beds are useful to evaluate aspects that are overlooked in the theoretical studies or hard to verify through software simulations, e.g., processing delays, control signalling, and hardware implementation complexity and impairments. The test-beds have been presented in several conferences and tradeshows; during Information and Communication Technologies (ICT) 2013, European Conference on Networks and Communications (EuCNC) 2014, and Mobile World Congress (MWC) 2015.

As only the two test-beds are available, some technical components have been selected for the test-bed implementation according to good publicity (i.e. appealing to audience via public demonstration), technology impacts, and high implementation feasibility according to the available test-bed resources and tight time-schedule. The selected technology components can be categorized into three areas: device-to-device (D2D) communications, massive machine communications (MMC), and waveform design; technical components in all of these areas are considered to play important key roles for the envisioned future and are part of the METIS 5G system concept. For each demonstration, the devised storyline is illustrated together with the proposed hardware implementation, its integration into the test-bed environment, and the obtained results.

Three D2D related test-beds have been implemented: “Direct network controlled D2D with IC”, “D2D with mode selection”, and “D2D in Heterogeneous Network (HetNet)”. The first test-bed demonstrates the impact of interference cancellation (IC) when it is applied to the reception of the uplink transmission, which is interfered by D2D transmission using the same uplink resources for better spectral utilization. Several practical issues of applying IC to the LTE system are studied. The second test-bed illustrates how direct D2D communication, when degraded, can fall back to communication through base station. An emphasis is on the link control and signalling aspects that are often overlooked in simple physical layer simulations. The third test-bed demonstrates how D2D link can reuse one of the time-frequency resources that are orthogonal between a Macro cell and Pico cells based on the measurements of reference signal receive power (RSRP).

One MMC-related test bed, “Multi-user detection based on compressed sensing for massive machine communications”, has been implemented to show how a large number of machine-to-machine (M2M) type nodes with short packets of data can efficiently communicate over shared channel with non-orthogonal signals.

One test-bed related to waveform design, “FBMC/OQAM waveform”, has been implemented and demonstrated in two different contexts: vehicular communications and MMC. The former is to illustrate the robustness of FBMC/OQAM against high Doppler shift in highly mobile scenarios as compared to cyclic prefix (CP)-OFDM. The latter is to demonstrate the robustness of FBMC/OQAM against asynchronous access as compared to CP-OFDM where close-loop synchronization may be avoided for simple devices like sensors to lower battery consumption.
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<tbody>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>ARM</td>
<td>Advanced RISC Machine</td>
</tr>
<tr>
<td>AXI</td>
<td>Advanced eXtensible Interface</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BLER</td>
<td>Block Error Rate</td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CFO</td>
<td>Carrier Frequency Offset</td>
</tr>
<tr>
<td>CP</td>
<td>Cyclic Prefix</td>
</tr>
<tr>
<td>CP-OFDM</td>
<td>Orthogonal Frequency-Division Multiplexing with Cyclic Prefix</td>
</tr>
<tr>
<td>CS</td>
<td>Compressive Sensing</td>
</tr>
<tr>
<td>D2D</td>
<td>Device-to-Device</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital to Analog Converter</td>
</tr>
<tr>
<td>DDR</td>
<td>Double Data Rate</td>
</tr>
<tr>
<td>DIF</td>
<td>Decimation In Frequency</td>
</tr>
<tr>
<td>DL</td>
<td>Downlink</td>
</tr>
<tr>
<td>DMA</td>
<td>Direct Memory Access</td>
</tr>
<tr>
<td>eNB</td>
<td>Evolved Node B</td>
</tr>
<tr>
<td>EuCNC</td>
<td>European Conference on Networks and Communications</td>
</tr>
<tr>
<td>FBMC</td>
<td>Filter Bank Multicarrier</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward Error Correction</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field-Programmable Gate Array</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>HetNet</td>
<td>Heterogeneous Network</td>
</tr>
<tr>
<td>IAM-R</td>
<td>Interference Approximation Method with Real pilots</td>
</tr>
<tr>
<td>IC</td>
<td>Interference Cancellation</td>
</tr>
<tr>
<td>IOTA</td>
<td>Isotropic Orthogonal Transform Algorithm</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
</tr>
<tr>
<td>LO</td>
<td>Local Oscillators</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-Of-Sight</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>LUT</td>
<td>Look-Up Table</td>
</tr>
<tr>
<td>LVDS</td>
<td>Low Voltage Differential Signal</td>
</tr>
<tr>
<td>M2M</td>
<td>Machine to Machine</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium-access Control</td>
</tr>
<tr>
<td>MCS</td>
<td>Modulation and Coding Schemes</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MMC</td>
<td>Massive Machine Communication</td>
</tr>
<tr>
<td>MU-MIMO</td>
<td>Multiuser Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MWC</td>
<td>Mobile World Congress</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency-Division Multiplexing</td>
</tr>
<tr>
<td>OQAM</td>
<td>Offset Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>PAM</td>
<td>Pulse-Amplitude Modulation</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PPN</td>
<td>PolyPhase Network</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>RACH</td>
<td>Random Access CHannel</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RSRP</td>
<td>Reference Signal Receive Power</td>
</tr>
<tr>
<td>RX</td>
<td>Receiver</td>
</tr>
<tr>
<td>SC</td>
<td>Single-Carrier</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single-Carrier Frequency Division Multiple Access</td>
</tr>
<tr>
<td>SiC</td>
<td>Successive Interference Cancellation</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference-plus-Noise Ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SoTA</td>
<td>State-of-the-art</td>
</tr>
<tr>
<td>SQNR</td>
<td>Signal-To-Noise Ratio</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TD-LTE</td>
<td>Time-Division Long-Term Evolution</td>
</tr>
<tr>
<td>TFL</td>
<td>Time Frequency Localization</td>
</tr>
<tr>
<td>TPC</td>
<td>Transmission Power Control</td>
</tr>
<tr>
<td>TX</td>
<td>Transmitter</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal Software Radio Peripheral</td>
</tr>
</tbody>
</table>

**List of Abbreviations**

- ADC: Analog to Digital Converter
- ARM: Advanced RISC Machine
- AXI: Advanced eXtensible Interface
- BER: Bit Error Rate
- BLER: Block Error Rate
- BS: Base Station
- CDMA: Code Division Multiple Access
- CFO: Carrier Frequency Offset
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- DL: Downlink
- DMA: Direct Memory Access
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- FFT: Fast Fourier Transform
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- IC: Interference Cancellation
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- MAC: Medium-access Control
- MCS: Modulation and Coding Schemes
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- MMC: Massive Machine Communication
- MU-MIMO: Multiuser Multiple-Input Multiple-Output
- MWC: Mobile World Congress
- OFDM: Orthogonal Frequency-Division Multiplexing
- OQAM: Offset Quadrature Amplitude Modulation
- PAM: Pulse-Amplitude Modulation
- PC: Personal Computer
- PPN: PolyPhase Network
- PSD: Power Spectral Density
- QAM: Quadrature Amplitude Modulation
- RACH: Random Access CHannel
- RF: Radio Frequency
- RSRP: Reference Signal Receive Power
- RX: Receiver
- SC: Single-Carrier
- SC-FDMA: Single-Carrier Frequency Division Multiple Access
- SiC: Successive Interference Cancellation
- SINR: Signal-to-Interference-plus-Noise Ratio
- SNR: Signal-to-Noise Ratio
- SoTA: State-of-the-art
- SQNR: Signal-To-Noise Ratio
- TDD: Time Division Duplex
- TD-LTE: Time-Division Long-Term Evolution
- TFL: Time Frequency Localization
- TPC: Transmission Power Control
- TX: Transmitter
- UE: User Equipment
- UL: Uplink
- USRP: Universal Software Radio Peripheral
1 Introduction

1.1 Objective of the document

METIS (Mobile and wireless communications Enablers for the Twenty-twenty Information Society) project envisions a future where access to information and sharing of data is available anywhere and anytime to anyone and anything. The overall technical goal is then to provide a system concept that supports 1000 times higher mobile data volume per area (10 to 100 times higher number of connected devices and 10 to 100 times higher user data rate), 10 times longer battery life for low power massive machine communication (MMC), and 5 times reduced end-to-end latency, all of them at a similar cost and energy dissipation levels as today’s networks [MET13-D11].

Towards the fulfilment of these goals, the METIS 5G system concept has been developed and system evaluations have been performed [MET15-D64; MET15-D65; MET15-D66]. In order to complement the theoretical work and numerical system level evaluations, METIS has developed two hardware test-beds; one is suitable for investigating radio resource management algorithms in realistic radio environments and the other is suited for investigation of digital baseband algorithms and corresponding hardware complexity. The purpose of the test-beds is to demonstrate key technology components using hardware platforms and to show-case the system concept. The test-beds are useful to evaluate aspects that are hard to verify through software simulations, e.g., processing delays, control signalling, and hardware implementation complexity and impairments.

As only the two test-beds are available, some technical components (out of many that were developed in METIS, e.g. [MET15-D24; MET15-D33; MET15-D43; MET15-D53; MET15-D66]) have been selected for the test-bed implementation. The selection process considered the viewpoints of good publicity (i.e. appealing to audience via public demonstration), technology impacts, and high implementation feasibility according to the available test-bed resources and tight time-schedule. The selected technology components can be categorized into three areas: device-to-device (D2D) communications, massive machine communications (MMC), and waveform design; technical components in all of these areas are considered to play important roles for the envisioned future and are part of the METIS 5G system concept [MET15-D64; MET15-D66].

The objective of this document is to provide the detailed descriptions of the test-bed specification and final test-bed results of the implemented technology components.

1.2 Structure of the document

The main part of the document is structured as follows. Sections 2, 3, 4, 5 and 6 describe each of the implemented technology components followed by conclusions and perspectives in Section 7. In particular, Sections 2, 3, and 4 describe the three D2D related test-beds: “Direct network controlled D2D with IC”, “D2D with mode selection”, and “D2D in Heterogeneous Network (HetNet)”. One MMC related test bed, “Multi-user detection based on compressed sensing for massive machine communications” is described in Section 5. Section 6 describes one test-bed related to waveform design, “FBMC/OQAM waveform”. This technical component has been implemented and demonstrated in two different contexts: vehicular communications and MMC.

The main part of the document is supplemented by four annexes that contain the details of the test-bed hardware that are used for the implementations.

- Annex A describes the test-bed platform for network level demonstrations.
- Annex B describes the test-bed platform for digital baseband demonstrations.
- Annex C describes the development flow related to the digital baseband platform.
• Annex D complements the document with further details about the proposed optimized architecture for FBMC/OQAM transmitter.
2 Test-bed related to direct network controlled D2D with IC

One solution to the predicted network densification is to offload traffic from BS to direct device to device link. In METIS, it is shown that direct D2D operations can boost the network performance indicators (latency, power dissipation, spectral efficiency) with no or little impact to the ongoing cellular transmissions [MET15-D43].

This demonstration illustrates post-decoding interference cancellation (IC). IC is an effective method that allows multiple users to use same time-frequency resources. In current cellular systems the same cell resource reuse is dominated by multiuser MIMO (MU-MIMO) techniques. The MU-MIMO operates well if the multiplexed users experience sufficiently different channel responses. In practice it means that they are spatially separated. For nearby located users the spatial separation based methods are relatively inefficient. Such users can still use the same time-frequency resources if the receiver is able to decode signals from both transmitters. It is possible if the code rates and powers of the signals are suitably selected. In this demonstration we utilize the BS ability to control transmission of all the user equipment. The BS makes the resource allocations and sets modulation and coding schemes (MCS) for all the users. For performing the IC the BS needs to know MCS of the D2D connection. For simplifying the implementation in this demonstration the BS fixes MCS of all the transmissions.

We explore the D2D and IC connections by integrating two different demonstrations “direct network controlled D2D with IC” and “D2D with mode selection”. These two demonstrations were implemented and demonstrated in MWC 2015 [MWC2015]. In this section we describe IC related aspects of the integrated demo. In the next section we describe the D2D mode selection and the common aspects of both demonstrations.

This demonstration shows the feasibility of IC in BS, identifies what are the implementation related limitations and how the radio interface specification could support better IC implementation. The demonstration has two aspects: (i) visualization aspect that illustrates the benefits of the IC that are easy to grasp in conference demonstration settings and (ii) technical aspects that identify the IC performance related issues.

2.1 Component description

The implementation illustrates two technical components: D2D mode selection and IC. In order to cover both technical components the demonstration has storyline that combines two video connections. One video connection is between D2D nodes, the other connection is from User Equipment (UE) to BS. The storyline contains not only technical components but stresses also visual aspects that makes the message easier to understandable in the conference settings. The attenuations are set up such that we are able to show intended functionality during a short demonstration. The storyline is the following:

1. In the initial state we have video connection between two D2D nodes. The connection is conventional data connection where the BS receives data in uplink and forwards it to other node in downlink. That is illustrated in Figure 2.1 which is based on the LTE TDD configuration 2. The special subframes are not used. The data transmission uses all the uplink subframes (yellow) and the BS maps the data to downlink subframes 4. In demonstration we illustrate this connection by sending video from one D2D node to the other one.

2. The forwarded connections can be switched to direct D2D mode. In direct mode the transmitter continues to send in uplink subframes but the D2D receiver switches from receiving BS’s downlink to receive D2D transmitter's UL transmission. Due to the broadcast nature of the radio transmission these same subframes will also be received by the BS, as illustrated in Figure 2.2.
3. After switching the D2D connection to direct mode the BS instructs the UE node to start transmitting. This transmission contains video signal from the attached surveillance camera. As a result we have two simultaneous transmissions: D2D transmission and UE transmission. Both of these transmissions use the same uplink time-frequency resources. In the demonstration set up the D2D signal is set stronger than UE signal. Since these two connections overlap without IC the BS is not able to decode the UE video stream.

4. BS switches on the IC mode. Then, BS decodes the D2D video, re-encodes it and subtracts the re-encoded signals from the received signal. After the subtraction the BS is able to decode the UE signal.

5. In the final stage of the demonstration the user sees two active connections using the same time-frequency resources. One video connection between D2D nodes and other video connection from UE to BS. Here we assume that the UE is far enough from the D2D RX and will not interfere with it.

Figure 2.1: Initial state in IC demonstration. The BS forwards D2D data. The colours indicate which subframes are used in uplink and downlink. The BS makes mapping from uplink subframes to downlink subframes.

Figure 2.2: BS with IC on. The UE and D2D transmissions overlap in the uplink subframes. The colours indicate which subframes are used.
2.2 Test-bed implementation

The demonstration uses TD-LTE software radio test-bed provided by Aalto University. The test-bed is composed of general purpose Personal Computers (PCs) and Universal Software Radio Peripheral (USRP) units. All the baseband processing is implemented in C++ code that is running in PC. The PC uses Ubuntu Linux 14.04. The code is compiled with g++4.8 and uses C++11 version. In the demonstrations the USRP units are used as remote radio heads. They convert baseband signals to and from Radio Frequency (RF) signals. The platform provides functionality for data transmission. The demonstration can operate in any frequency supported by USRP frontends (0.4 – 4 GHz). In conference settings the demonstrations use 2.4 GHz carrier frequency. However, for avoiding interference to other systems the setup is configured over cables. The SNR and SINR measurements are done over cables and attenuators.

The implemented parts follow Time Division Duplex (TDD)-LTE Release 8 specifications. The implementation details of physical and Medium-Access Control (MAC) layer functionalities can be found in 3GPP specifications. The relevant physical layer functionality is described in references [3GPP08-36211; 3GPP08-36212; 3GPP08-36213]. The current platform supports only transmission mode 1 [3GPP08-36213]. The links in demonstration use one transmit antenna and one receive antenna.

The demonstration relies on the TD-LTE frame structure provided by the platform: physical layer mapping, physical and logical channels, transport block segmentation, and turbo coding/decoding. The demonstration adds to the platform: IC functionality, D2D transmission and reception, methods for configuring platform to operate in D2D mode, in IC mode or non IC mode and the user interface.

The implementation uses DL UL subframe configuration 1 [3GPP08-36211]. In this allocation TDD up- and down-link have roughly the same amount of resources. This feature helps in D2D demonstration where the BS forwards data from the uplink subframes to downlink subframes.

The IC demonstration operates on BS side with received uplink subframes. The control of the user data rates and resource allocation are handled at the BS. The BS knows the allocated resources and MCS of all the transmitters. In order to simplify the IC decoding process we fix the used resource blocks and MCS of the D2D transmitter. That defines also how many bits the D2D transport block will contain. If D2D transmitter has less data to be transmitted the MAC multiplexer pads zero bits.

![Figure 2.3: Computation flow of a successive interference cancellation.](image-url)
In our implementation we use successive interference cancellation (SIC). While it is known that SIC is not the optimal decoding approach, its simplicity makes it attractive for many practical systems. In this demonstration we exploit the SIC. For simplifying the implementation we fix the decoding order. At the BS the D2D signal is stronger than UE signal. For receiving the UE signal the BS has first to decode and cancel the D2D signal. The block diagram of the implementation is seen in Figure 2.3. The processing flow is as follows. The BS first estimates and equalizes the D2D signal that is interfering the UE signal. Because the signals use the same resources, also their pilots are overlapping as well. However, they are selected to have different LTE pilot sequences. In channel estimation stage, we average pilots over one resource block. After averaging, the impact of the UE pilots on the D2D pilots is reduced and we get sufficiently good channel estimate. After decoding of the D2D signal, we encode it again and construct an estimate of the received D2D symbols. These estimated symbols are then subtracted from the received symbols. The remaining signal contains UE signal that is equalized and decoded. After this decoding the receiver has UE signal s(t), (..., b1, b2, b3, ... in Figure 2.3).

2.3 Results

The main target of this demonstration is to illustrate and visualize the LTE system ability to use IC. The demonstration has been developed continuously during the project period. Different stages of the demonstration have been shown in various exhibitions in ICT13 [KBG+13], CrownCom 2014 [RMK+14a], EuCNC 2014 [RMK+14b], MWC 2015 [ZMB+15].

Thanks to this implementation, we also measured the system performance. Figure 2.4 illustrates the measured system throughput with different MCS schemes. The measurements are done at 2.4 GHz and connections between the transmitters and receivers are over the cable and attenuators. The SINR is measured from the received pilots. The D2D measures the transmitter pilot strengths. The SINR is estimated from the mean and variance of the received pilot powers.

![Figure 2.4: Test-bed throughput for different MCS schemes. Shannon limit is indicated by the dashed line.](image)

Relatively large difference between the measured throughput and the Shannon limit can be partly explained by the high noise floor of the USRP frontends, partly by non-optimal implementation (Max-log approximation) of the turbo decoding algorithm.

We are also interested in the SIC performance. Particularly of interest is how many dB the interfering signal could be stronger than the useful signal. We measure this ratio by setting the UE signal level and identifying the SINR required for decoding the D2D signal and then the UE signal with BLock error rate (BLER) target of 0.1.
In Figure 2.5 we present the required SINR for successful decoding of D2D signal as a function of the relative UE signal level. The performance is evaluated from cellular users UE with MCS values 1 and 13. The D2D MCS is fixed to 11. The relative level in the x-axis is computed with respect to SNR for which the non-interfered UE signal can be decoded with BLER target of 0.1. This level is evaluated by measuring the non-interfered UE signal BLER curve. In x-axis we increase the UE signal level and in y-axis we indicate at what SINR level the D2D signal can be decoded. In y-axis the D2D signal level is represented as how many dB it is stronger than the UE signal. The signal levels are measured from pilots of the received signals. The levels are controlled by adjusting attenuations between the transmitters and receivers.

As a reference we measured that non-interfered MCS 11 can be decoded with BLER=0.1 at SNR = 7dB. One could expect that for SIC to be successful the D2D signal with MCS 11 should be 7 dB higher than the UE signal. As one can see when UE power increases the target SINR for D2D decreases. The D2D needs relatively less power increase over UE power. This effect can be explained by the non-Gaussian nature of the D2D's SINR distribution. The interfering UE signal has uniform distribution over the QAM constellation. When the UE signal dominates the interference plus noise distribution, the target SINR for D2D can be reduced. For instance for UE with MCS 1, the low UE power is in the order of the noise power and the target D2D SINR is in the order of 7 dB. When UE power is increased, the UE signal distribution starts to dominate interference plus noise distribution and the D2D's target SINR can be decreased. MSC 13 shows far less dependence than MCS 1. For MCS 1 the signal and interference seen by D2D contains relatively higher amount of thermal noise. Therefore the sum interference and noise signal for MCS 1 is closer to Gaussian distribution. Only when the cellular user signal power is increased the interference starts to be closer to uniform distribution. For successful decoding MCS 13 requires higher SNR level. Because of that the cellular user interference dominates the D2D user SINR.

In Figure 2.6 we illustrate how the interfering D2D impacts the UE BLER after successive interference cancellation. For high SINR we can decode the D2D signal, compensate it and then decode the UE signal. When the D2D signal power is very low, the reception of the UE signal does not require IC and the UE SINR is sufficient for directly decoding the UE signal. If the D2D power is in the same order as the UE power, the SIC cannot be applied. The interference from D2D does not allow decoding of UE signal. One has to notice that, in this
power ratio range, SIC algorithm cannot be applied; however the decoding could still be carried out by a decoder that decodes D2D and UE signals together (not sequentially). For instance the decoder could combine D2D and UE turbo decoding processes. However, LTE block segmentation and encoding does not support such decoder. Both systems could have independent data block segmentation and therefore the combined decoder cannot decode the segments independently. The combined decoder has to decode multiple code block segments in parallel. That makes the decoding very complex and one would lose the benefits of simplifying the decoder that the LTE code segmentation offers.

Figure 2.6: BLER of UE signal after IC as a function of the interfering D2D signal power relative to the UE signal power.
3 Test-bed related to D2D with mode selection

This component demonstrates how D2D communication can be maintained in case when direct connection between D2D is degraded. The connection is maintained by redirecting data from low quality direct D2D link to BS that starts to relay the data. End user sees this demonstration as uninterrupted connection between D2D devices.

The D2D mode selection helps to offload the cellular data traffic to direct D2D link. Such configuration increases spectrum utilization by requiring radio resources only for one (direct) link and not for two (one link from D2D transmitter to BS and another from BS to D2D receiver). By avoiding two hops the direct link will reduce latency and if the D2D nodes are located close to each other the transmitter can reduce its transmission power.

3.1 Component description

The demonstration shows that data connection between D2D nodes can be maintained even when direct link between the nodes becomes unavailable. We use the setup with three software radio nodes as shown in Figure 3.1 and Figure 3.2. One node operates as BS and the other two nodes represent D2D nodes. The D2D nodes operate under control of the BS. The demonstration follows the following storyline:

1. D2D nodes communicate directly over the air. The data plane uses direct D2D link. In this mode the signalling is split between the direct link and the link to BS. The BS maintains some of the control signalling. In this demonstration, the BS uses the control signalling only for switching between direct D2D link and relaying the data over the BS.

2. In this step of the demonstration we reduce D2D link quality by blocking the line-of-sight (LOS) path. The D2D measures the SINR of the received signal. When the link quality falls below certain threshold, the D2D receiver starts the mode switching process.

3. The BS starts to receive the signal from D2D transmitter and forwards it to the D2D receiver. The forwarding is done by mapping the received data packets from the UL subframes to the downlink subframes as illustrated in Figure 3.2. It also depicts the UL and downlink signals are transmitted using the TD-LTE slots.

4. D2D receiver starts to listen the downlink subframes.

![Figure 3.1: D2D connection where the data plane connection is established directly, and some of the signalling is still controlled by BS.](image-url)
3.2 Test-bed implementation

The test-bed uses the demo platforms based on TD-LTE frame structure. The D2D link operates in uplink subframes. The handover from the direct link to relaying over the BS is implemented at the D2D receiver as switching from listening on UL subframes to listening on DL subframes.

In a practical system the D2D receiver reports low SINR to the network, which then starts relaying traffic in the classical manner from the D2D TX. However, for demonstration purposes, we simplify these steps by bringing the decision process into D2D node. In order to simplify the signalling, the decision process about the mode switching is implemented in the D2D receiver. The receiver continuously measures the direct D2D link quality in terms of SINR. If the measured SINR falls below a given target level, the D2D receiver initiates the mode switching process. In this demo we avoid mode switching signalling by continuously forwarding the data at the base station. The D2D receiver sees two data streams; one in UL subframes from D2D transmitter and other in DL subframes from BS. The mode switching is simply switching the receiver between these two. The implementation illustrates how the mode switching can benefit from TD-LTE frame structure.

Combination of D2D with mode selection and IC

We have combined the D2D with mode selection and demonstration of IC. For carrying out IC, the BS needs to know the D2D link’s MCS and resource allocation. In practice it means the D2D link has to maintain signalling connection to the BS. This corresponds to the D2D communication mode 1 discussed currently in 3GPP standardisation process. In our demonstration we use fixed resource usages by D2D. And this allocation is known to the BS. When the UE starts to transmit, the BS can decode the D2D signal with known MCS and resource allocation. In the demonstration the successive interference cancellation is carried out as described in the previous section.

3.3 Results

The demonstration illustrates how the TDD frame format enables an easy implementation of the mode selection feature. In TD-LTE the transmitter and receiver operate on the same frequency. Mode selection is realized by simply changing which subframes are used for reception. Direct D2D link is implemented by setting D2D receiver to listen on the uplink subframes. A side effect of this is that the D2D receiver cannot use those uplink subframes for
communication with BS. In order to maintain signalling channel towards BS the subframe allocation has to be carefully designed. A practical system using TDD frame structure for D2D mode selection should reserve some of the UL subframes for signalling channels towards BS.

**Combination of D2D with mode selection and IC**

Demonstrations in ICT13 [KBG+13], EuCNC 2014 [RMK+14b], and MWC 2015 [ZMB+15] were showing the feasibility of combined mode selection and IC reception in a 5G system. It has been demonstrated in a real-time radio transmission that IC can be performed in a BS, in combination with mode selection, cancelling an interfering D2D signal. In the D2D IC work clear operational regions were observed in terms of the required SIR of the interfering signal in Figure 2.6. In the demonstration, the D2D signal was controlled to be stronger than the cellular UE signal.

In a conventional underlay D2D scenario, the D2D Tx powers would be controlled to cause negligible interference to the cellular system. In such situation cellular UE transmits relatively strong signal compared to D2D signal. The D2D nodes could benefit from UE interference cancellation. The potential gains from IC if performed by multiple D2D nodes have been assessed by simulation in such a scenario. Such D2D nodes could be for instance mode selecting UE. The results are depicted in Figure 3.3.

An uplink cellular system with 16 three-sector cells has been modelled. The system bandwidth is 20MHz. One cellular UE may be served per resource block. Cellular traffic may be offloaded to D2D by mode selection. Cellular Transmission Power Control (TPC) compensating path loss is used. In addition, following [MET15-D43, Section 5.11], an upper transmit power boundary is determined to minimize severe interference from underlay D2D to cellular UE. The D2D Tx power is upper bounded by the cellular TPC value minus a margin. The system keeps aggregate interference from all D2D nodes under this margin, so that irrespectively of the number of offloaded UEs, the cellular UE performance is kept constant. D2D users that are offloaded have a requirement of 5 Mbps data rate. Once they meet this data rate, they reduce the Tx power. IC is used in the network on a cooperative basis. On the left hand side of Figure 3.3, the outage probability of an offloading D2D user to reach its target data rate is depicted, with and without IC. IC reduces outage of D2D communication to one quarter, when there are few offloading D2D users, 0.5-1 per cell, or by a quarter, when there are many, 10 D2Ds per cell. That is, outage is reduced between 75% and 25%. It can be explained by D2D users’ locations. Without IC only the D2D users who are located far from cellular UEs (UEs connected to BS) can have reliable communication. With IC reliable
communication is possible also for D2D users who are far from all but one cellular UE. On the right hand side of Figure 3.3, the mean spectral efficiency per cell is depicted. When there are 10 offloaded D2Ds without IC capability per cell, the cell throughput increases by a factor of 2.27, i.e. more than 100%. For 10 offloading D2D users with IC the system spectral efficiency increases from 2.27 to 2.73 bits/s/Hz. Combined with the results from “Test-bed related to direct network controlled D2D with IC” in Section 2, we conclude that IC combined with mode-selection based offloading of cellular traffic to D2D has potential to be a very effective method of boosting system performance.
4 Test-bed related to D2D with HetNet

The target of this demonstration is to show how D2D link can reuse frequency radio resources by simply detecting the BS signal levels in a heterogeneous network (HetNet). We consider a scenario where the time-frequency resources are split between a macro cell (Macro eNB) and picocells (Pico eNBs). The D2D transmitters could be located anywhere in the cells’ coverage areas. If D2D transmitter uses low enough power, its signal does not disturb the UEs communicating with eNBs. In macro cell where UEs use relatively high power, this assumption holds most of the time. However, in picocell the UE power could be comparable to D2D transmitter power. In order to protect picocell communication the D2D link can’t use picocell’s resources nearby. In this demonstration the D2D decides whether to use the resources by measuring RSRP values from both eNBs illustrated in Figure 4.1.

4.1 Component description

We consider a HetNet with macrocell and picocell. The Pico eNB is located within the coverage area of the Macro eNB as illustrated in Figure 4.1. The Macro eNB has a larger coverage area due to higher transmit power compared to the Pico eNB. The resources are distributed between the eNBs by splitting the TD-LTE frame to Macro eNB part and Pico eNB part. The LTE fame contains 10 subframes. Except second and fifth subframes the first five of these subframes are allocated to Macro eNB and the last five to Pico eNB. This is illustrated in Figure 4.2. The system is synchronized to Macro eNB. The synchronization sequences are transmitted in the second and fifth subframe and therefore they are used by Macro eNB.

If D2D transmitters want to use spectrum they transmit using either Macro cell’s resources or Pico cell’s resources. The Pico cell resource usage is regulated by comparing the Pico cell’s signal strength (RSRP) value with a predefined threshold.

The demonstration presents scenario where D2D link reuses network’s resources by detecting the signal RSRP levels in both cells. The D2D transmitter continuously measures the RSRP level from both cells and we show visually at each moment which resources are in use. The viewer can physically change the antenna location of the D2D transmitter. The change of used resources is visible in graphical user interface.
4.2 Test-bed implementation

This demonstration uses the USRP and PC based software radio TD-LTE test-bed. We modified the test-bed software stack to reflect Macrocell and Picocell resource allocations. One frame is 10 ms in time and consists of 10 subframes. Both cells are allocated half of the subframes according to Figure 4.2. In the demonstration the BS does not transmit in non-allocated subframes except that Macro eNB is sending synchronization signal in the special subframe allocated to Pico eNB. Pico cell does not send any synchronization sequence.

All the nodes are synchronized to the Macro eNB synchronization signals. For synchronizing the Pico eNB, we have modified the base station code to listen to other eNB synchronization sequence. The D2D communication is implemented as modified UE node. It uses the same code as UE for synchronization with Macro eNB. It transmits by using LTE uplink SC-FDMA. The transmission however is continuous and does not need BS signalling channel.

The Macro cell and Pico cell do not transmit data. However, they continuously transmit pilots and synchronization signal. In LTE the pilots are used for estimating the RSRP. The D2D node measures the transmitter signal strengths as defined in the LTE specification [3GPP08-36214]. The measured values are mapped to RSRP as defined in the LTE specification [3GPP08-36133]. The decision for using the resources are made by first averaging RSRP values over a certain time interval and then comparing the result with the threshold.

4.3 Results

Performance of the proposed algorithm depends on the RSRP measurements. We tested how the D2D node can estimate the resource selection from the measured RSRP trace. For that we set up Macro cell and Pico cell transmitters and move D2D nodes around. The outdoor Macro eNB was located on the rooftop and the indoor Pico in one room in the same floor where the D2D node is moved. The network set up is illustrated in Figure 4.3.
The D2D transmitter was moving along the corridor and it recorded the signal RSRP values from both eNBs. The measured Pico eNodeB’s RSRP values along the corridor are shown in Figure 4.4. The corridor was measured four times back and forth. We started from the right end of the corridor and moved the receiver with speed 1.5 m/s to the left end. After that we moved back towards right. While moving the receiver we passed a room where Pico cell was located. This is seen in Figure 4.4 as a rise in the RSRP value.

The decision of the channel usage is done based on the signal level. As one can see in Figure 4.4 the signal strength varies significantly. The D2D spectrum reuse is not only impacted by the threshold but also how the decision variable is computed and therefore it is not clear how to set the signal threshold. We consider two different computation algorithms:

**Algorithm 1: Mean and hysteresis based algorithm**

The decision to use or avoid Pico cell resources is based on the level comparison. We have two threshold levels that are located around the mean value:
• D2D can use the Pico cell resources till next decision moment if
  Mean < threshold - hysteresis;
• D2D will not use the Pico cell resources till next decision moment if
  Mean > threshold + hysteresis,
where the hysteresis is a user defined value. We study the algorithm by selecting various
threshold values

Algorithm 2: Percentile based algorithm
We use margins similarly as in previous algorithm. In this algorithm the margins are computed
by assuming that signal has Gaussian distribution around the mean value and the threshold is
set such that the signal exceeding some level is bounded by probability
• D2D can use the Pico cell resources till next decision moment if
  percentile (e.g. 80%) < threshold ;
• D2D will not use the Pico cell resources till next decision moment if
  percentile (e.g. 20%) > threshold.

Both of these algorithms base their decision on a function operating on the measured signal
mean value. It should be noted that Algorithm 1 with 0 dB hysteresis is the same as Algorithm
2 with percentiles 50/50. Due to the large variation of the RSRP values and for getting better
estimate, we would like to average the signal over longer time. In specification [3GPP09-36331]
it is suggested to use a moving average filter. The mean value computation window is a critical
averaging parameter. The signal is not stationary, and over long time the mean value itself is
changing and the computed mean does not reflect any more the instantaneous channel state.
In measurement analysis section we evaluate the impact of the averaging window on the
system performance.

In Figure 4.5 and Figure 4.6 we report measurement results when the RSRP threshold is set
to 28. The mapping between the measured RSRP values in dB and different levels is given in
[3GPP08-36133]. This is set arbitrarily with the target to have reasonable coverage area.
Optimization of the RSRP threshold is left for further measurement campaigns. The threshold
means that below this threshold Pico’s resources should be used by D2D node and above this
threshold only Macro’s resources should be used. In Figure 4.5 we present how many mode
changes occur during the measurement period shown in Figure 4.4 when these algorithms are
used. In this figure different groups correspond to different hysteresis values. Mode change
means that the D2D node would start or stop of using Picocell’s UL subframes. Longer
averaging sequences and larger hysteresis margins naturally reduce the number of mode
changes. Figure 4.6 shows the inaccuracy of the algorithms. The inaccuracy is presented as
the probability that the actual RSRP value is not matching the algorithm’s decision. It can be
seen that both algorithms have similar performance. Long sequences with large margins
decrease the switching moment accuracy significantly. The reason being that longer
averaging interval delays the decision moment. Because of that the decision is not made
exactly at the cell border but away from optimal decision moment. Figure 4.7 shows how
efficiently the algorithms use Pico cell’s resources, i.e. in how many locations the D2D node
decides to use Pico cell’s resources. The averaging impacts the Pico cell less than Macro cell.
The Pico cell was located at the same floor where the measurement was made. The Pico cell
signal amplitude changes much more than far located Macro cell signal amplitude. The larger
amplitude change allows better cell border identification.
Based on the instantaneous measurements, the actual RSRP was below the threshold with probability 0.4 where the instantaneous measurement means that the D2D node makes decision at each sample without averaging.

Figure 4.5: Number of D2D resource mode changes (between cases A and B) during measurement shown in Figure 4.4.

Figure 4.6: Probability that instantaneous RSRP is not matching selected resource usage mode.
Figure 4.7: Portion of time that D2D is using Pico cell’s resources.
5 Test-bed related to multi-user detection based on compressed sensing for massive machine communications

This test-bed demonstrates advanced physical layer processing for M2M MAC [MET14-D23]. The key aspect of this demonstration is to show how M2M nodes can communicate over shared channel with non-orthogonal signals. Many M2M services are characterized by large number of users which send short/small packets of data. Such traffic is difficult to serve with current LTE radio interface since the LTE random access channel does not allow data transmission. The described M2M traffic is best served with low overhead random access channel (RACH) where M2M nodes can transmit small amount of data as illustrated in Figure 5.1. We use compressive sensing (CS) algorithm and compose a random access channel that can be used for short data packet transmission in LTE system. The LTE BS provides the frame structure to which all the M2M nodes are synchronized. The designed system uses and modifies results proposed in [SCH13]. The proposed MAC allows to separate overlapping signals from different users. The receiver uses CS and detects which users are active. After that it detects the channels of the active users and proceeds with data decoding. In this demonstration the CDMA based algorithm proposed in [SCH13] is adapted for Single-Carrier (SC)-OFDM type subframe.

5.1 Component description

The demonstration corresponds to the system with extremely large number of nodes that have low activity. The nodes produce short packets. Each node has identification code that it uses for informing BS about its transmission. At each time slot only very few nodes are active. However, transmissions from active nodes overlap. Challenge of the BS is to identify which nodes are active and to estimate the channel coefficients for each active node.

One candidate algorithm for serving such RACH is Compressive Sensing or Compressive Sampling (CS) based Multi-User detection (CS-MUD). CS is an alternative approach to Shannon/Nyquist sampling where a sparse or compressible signal can be sampled with a rate much less than the Nyquist rate [CAN08; BAR07]. The proposed component contains CS based user identification algorithm used in [SCH13]. The algorithm identifies the users one by one. It iteratively removes stronger, already identified users’ signals from the received signal.

![Figure 5.1: 12 M2M RACH burst transmissions.](image)

In order to apply M2M random access channel in LTE we propose to use new type of channel in uplink subframes. We assume large amount of user identification codes. At the same time there are only few active users. As in [SCH13] we use block sparse channel estimation and detect user activity and data. We adapt CS to frequency domain pilots and data. We analyse the system performance in frequency selective radio channel.
5.2 Test-bed implementation

This demonstration uses the test platform’s TD-LTE stack. The new random access channel uses LTE uplink (UL) subframes. As in LTE UL the centre OFDM symbol contains pilot symbols. Pilots are user specific and are used also for user identification. The M2M packet is half a millisecond long which fits into one LTE time slot. There are three nodes that send random access burst in one uplink time slot. Each node is configured to generate traffic for four M2M transmitters. In each transmission moment, the node selects one out of four user IDs for transmission. The activity probability of nodes is less than 1. This implies that there are only few bursts (less than or equal to 3) that are transmitted simultaneously.

The random access burst follows LTE uplink frame structure. An LTE frame is divided into twenty slots each having seven OFDM symbols. The fourth OFDM symbol in a slot is fully allocated for the pilot sequence as shown in Figure 5.2. The pilots of all users are overlapping and serve as signal to identify the active users.

![Figure 5.2: RACH burst mapping to LTE time slot.](image)

5.3 Results

In this section we present simulations based observations related to this implementation. In order to fit the proposed algorithm from [SCH13] into LTE framework we had to develop an OFDM version of it. We adapted the CDMA based algorithm to make user activity estimation, channel estimation and data estimation in the frequency domain.

In order to validate the modified user detection and channel estimation algorithm, we have conducted simulations with a large number of users and frequency-selective channels. All users have identical and constant three tap channel profile [0.873 0.436 0.218]. The taps locations are randomly selected in interval 0...2 samples. In the simulations we consider 64 users of which only 4 are active at the same time. All the users are synchronized to the BS pilot signal and that gives the slot level synchronization.

The random access packet is transmitted in LTE uplink slots. The slot contains seven OFDM symbols of which the fourth is a pilot symbol. We assume the pilot symbol size to be 196 resource elements. The detection process contains two different steps: firstly user pilot based ID and channel estimation and then user data detection. In Figure 5.3 we illustrate the detection performance for 4 active users. We compare two different ID sequence generation methods: (i) random code and (ii) highly structured code packed into Grassmanian space [PIT14]. The left figure in Figure 5.3 shows that the highly structured code packed in Grassmanian space has similar detection performance as fully random code. As such the proposed codebook is a good candidate for users’ activity and channel detection.

On the right hand side of Figure 5.3 we illustrate how the CS algorithm performs in user data detection. The users’ data are spread with 16 sample spreading code over frequency. The
data is detected by least square (LS) detector. Both used codebooks indicate the error floor. However, for the structured code this floor is higher. The main difference between the random and structured codes is that the structured code has only finite number of distance values between the codewords. The code spectrum is far from being random. The simulation results indicate that while the structured code suits for user identification it is not good for user data spreading.

Figure 5.3: Left: Miss detection as a function of Signal-to-Noise Ratio (SNR). Right: Symbol error rate as a function of SNR.
6 Test-bed related to FBMC/OQAM waveform

This section presents the test-bed related to Filter Bank Multicarrier/Offset-QAM (FBMC/OQAM) waveform proposed in [MET13-D22] and selected for hardware implementation and proof-of-concept. After a brief introduction on the proposed waveform and related advantages with respect to state-of-the-art Orthogonal Frequency-Division Multiplexing with Cyclic Prefix (CP-OFDM) multicarrier modulation, two developed demonstrations are presented in detail. The first demonstration is related to vehicular communications, while the second one targets MMC. For both demonstrations, the devised storyline is illustrated together with the proposed hardware implementation and its integration into the test-bed environment. Finally, this section provides a summary of measured results in terms of hardware complexity, power consumption, power-spectral density, error rates, and throughput. These results have been partially presented in the following dissemination events: [NAB14; NAB+14a; NAB+14b; NAB+15].

6.1 Component description

FBMC/OQAM is a multicarrier transmission scheme that introduces a filter-bank to enable efficient pulse shaping for the signal conveyed on each individual subcarrier [MET13-D22]. This additional element represents an array of band-pass filters that separate the input signal into multiple components or subcarriers, each one carrying a single frequency sub-band of the original signal. The decomposition process performed by the filter bank is called analysis (meaning analysis of the signal in terms of its components in each sub-band); the output of analysis is referred to as a sub-band signal with as many sub-bands as there are filters in the filter bank. The reconstruction process is called synthesis, meaning reconstitution of a complete signal resulting from the filtering process. Such a transceiver structure usually requires a higher implementation complexity related not only to the filtering steps but also to the applied modifications to the modulator/demodulator architecture. However, the usage of digital polyphase filter bank structures [CEO+00; SSL02], together with the rapid growth of digital processing capabilities in recent years have made FBMC a practically feasible approach.

As a promising variant of filtered modulation schemes, FBMC/OQAM can usually achieve a higher spectral efficiency than CP-OFDM since it does not require the insertion of a Guard Interval (GI) generally represented by a Cyclic-Prefix (CP). Additional advantages include the robustness against highly variant fading channel conditions and imperfect synchronizations by selecting the appropriate prototype filter type and coefficients [MET13-D22].

In fact, 3GPP LTE/LTE-A is based on CP-OFDM multicarrier modulation. According to Balian-Low theorem (BLT) [FS98], CP-OFDM:

1. respects the complex orthogonality,
2. is poorly localized in frequency domain by adopting a rectangular waveform, and
3. wastes part of the available bandwidth due to the addition of a CP.

The property in 2) results into a high out-of-band power leakage (therefore, large guard-bands have to be inserted) and into a poor robustness against Doppler spread. Further possible disadvantages of the corresponding CP-OFDM system (including LTE/LTE-A) are related to flexible spectrum usage scenarios, where spectrum sharing and fragmented usage are not efficiently supported [PWK+13].

To overcome the shortcomings 2) and 3) of CP-OFDM, FBMC/OQAM:

a) relaxes to the real field orthogonality,
b) is better localized in time and frequency (depending on the prototype filter type and coefficients), and
c) uses efficiently available bandwidth to achieve a higher spectral efficiency.
Property a) is obtained by changing the way QAM symbols are mapped onto each subcarrier. Instead of sending a complex symbol (I and Q) of duration T like in classical CP-OFDM, the real and imaginary parts are separated and sent with an offset of T/2 (hence the name Offset-QAM).

Improvement b) comes from the introduction of the filter-bank and therefore highly depends on its type and coefficients. Property c) is the consequence of the absence of a CP [Far11].

Previous published works have identified two major design criteria for a FBMC/OQAM system:

- **Time Frequency Localization (TFL) criterion:** for a better localized waveform in time and frequency domains thanks to the prototype filter, it is foreseeable that FBMC systems exhibit better robustness than CP-OFDM in doubly-dispersive channels [FAB95] and in the case of communications with synchronization errors [LGS14]. To this purpose, filter designs with the optimized TFL criterion have been proposed, such as Isotropic Orthogonal Transform Algorithm (IOTA) [FAB95] and TFL1 [PS13].
- **Lower sideband criterion:** for achieving low out-of-band power leakage in the frequency domain and for improving spectrum coexistence with other systems. To this purpose, particular filter types should be used such as PHYDYAS [PHYD; MM02] and Frequency Selective [PSS04].

State-of-the-art low complexity FBMC/OQAM modulator structure using PolyPhase Network filter (PPN) is illustrated in Figure 6.1. The incoming binary data are translated into QAM symbols (I and Q) for each selected subcarrier. Then, I and Q are separated in the block “OQAM Mapper” to become two independent Pulse-Amplitude Modulation (PAM) symbols. Afterwards, two adjacent symbols are phased by $e^{j\pi/2}$. The filter bank is decomposed as a stage of multipliers for filter reconstruction, an $M$-points IDFT (inverse discrete Fourier transform, as for the OFDM modulator) and a polyphase network [Hir81].

**Figure 6.1:** CP-OFDM and FBMC/OQAM system description.

FBMC/OQAM constitutes an enabler to several METIS scenarios as it enhances system robustness to different types of impairments. Therefore, it was logical to provide a proof-of-concept of the cases for which system performance benefits best from FBMC/OQAM. Several
comparisons have been performed in the context of METIS and the following two demos have been chosen to be developed:

- **FBMC Demo 1**: Resilience to Doppler shift. This corresponds to the establishment of communication links in mobile environments such as between the classical infrastructure and a moving vehicle, or communication between vehicles. Using a short filter like TFL1 improves the robustness against this particular type of impairment as shown in [LGS14]. This aspect has been the subject of in-depth study leading to the design of a hardware prototype. The demonstration and details about this implementation are provided in Section 6.2.

- **FBMC Demo 2**: Robustness against narrowband interference. In a dense network, cellular users may coexist with MMC-type users such as sensors; for example by sharing the same spectrum resources. Under power and signalling overhead constraints, perfect synchronization may not be easily ensured. Therefore, interference is created between subcarriers allocated to different services or even allocated to the same type of services but to different UE or sensors. FBMC/OQAM applying a long filter has been proven to be particularly well suited to cope with the impairments resulting from this scenario. In particular, PHYDYAS filter [PHYD: MM02] has been demonstrated to show good robustness in this context thanks to its improved frequency localization. This particular scenario is covered by this test-bed and details about the corresponding implementation are provided in Section 6.3.

### 6.2 Test-bed implementation: context of vehicular communications

The purpose of this FBMC Demo 1 is to illustrate the robustness of FBMC/OQAM against Doppler shift compared to CP-OFDM. Such impairments appear in a situation where users are subject to high Doppler, for instance in a high speed vehicle, or in a train. This demonstration describes a situation where a user in a high speed vehicle uploads an image to the base-station (uplink communication). Other possible scenarios for such impairment include transmissions using millimeter waves where high Doppler shifts can be encountered.

The test-bed environment for this demonstration, provided by Telecom Bretagne, is presented in Figure 6.2 where one board (ZedBoard) emulates an UE physical layer (transmitter side), and a second board is used to emulate the base station (receiver side). Both boards are extended by an RF interface (AD-FMCOMMS1-EBZ) to enable on-air transmission. The compared modulation techniques, OFDM and FBMC/OQAM, are implemented on the Field-Programmable Gate Array (FPGA) part of the Zynq-7000 SoC. The control and interface are ensured by a dual-core Advanced RISC Machines (ARM) cortex A9 processor embedded in the Zynq SoC and through the development of a dedicated MATLAB Graphical User Interface (GUI). Details about the characteristics of these boards (ZedBoard and FMCOMMS1) are provided in Annex B. The effect of high mobility is simulated directly in hardware. The GUI at the transmitter side is used to select mapping and modulation parameters like the QAM constellation order, the Fast Fourier Transform (FFT) and the CP sizes, the number of active subcarriers, etc. The GUI at the receiver side only displays KPIs.

The numbered storyline of this demonstration is provided in Figure 6.2 and applies the following steps:

1. User selects appropriate parameters on the GUI. Transmission with OFDM or FBMC/OQAM component is chosen along with or without the presence of the mobility (10% of Doppler shift). Only TFL1 filter is considered in this scenario. The image to send can be selected. The demonstration begins when the user pushes the “Start” button of the corresponding scenario.

2. UE board receives the image from the computer, and transmits it to the channel through the RF interface.
3. BS board receives the image impaired with Doppler shift due to UE in high mobility situation.

4. Measurements of KPIs are displayed on the GUI at the receiver side. Resulting image and constellation of the demodulated signals are displayed for both OFDM and FBMC/OQAM to show the differences in terms of transmission quality. Measured BER is also displayed to have quantitative results. Hardware complexity is provided in terms of, logic and memory usage.

The following LTE parameters are used for this demonstration: FFT of length 512, 16-QAM modulation, sampling frequency of 7.68 MHz, using 25 RBs (300 active subcarriers). Uncoded results are presented with uncompressed image format. However, the LTE turbo coding and decoding have been implemented in hardware and they are currently being tested on the platform.

The sub-section 6.2.1 details the hardware implementation of the corresponding system for the two considered waveforms (FBMC/OQAM and CP-OFDM). Sub-section 6.2.2 presents how these technical components are integrated into the test-bed, in other words, this section is where the hardware architecture is detailed.

6.2.1 Hardware implementation of the FBMC/OQAM and CP-OFDM transceiver

In order to validate the described algorithm of Section 6.1 and to propose more efficient numeric representation, a first floating-point MATLAB reference model has been provided by Orange Labs. Then, quantization issues have been studied in order to propose efficient fixed-point software model while preserving signal representation accuracy. The number of quantization bits, the fixed-point representation, the shift to apply for re-scaling after multiplication, and the type of approximation (floor or round) have been specified for each unit. Round approximation is chosen due to its reduced impact on the spectrum shape. In order to obtain a power spectrum density without significant quantization error, the following fixed-point
representation has been devised enabling less than -70 dB Signal-to-Quantization-Noise Ratio (SQNR) for all specified constellation sizes in LTE (4, 16 and 64-QAM):

- All samples at input and output of each unit have 16-bit quantization. This also applies for each stage of the FFTs.
- All coefficients are quantized and stored with a precision of 12 bits. This includes the fractional part of the twiddle factors (related to inverse FFT (IFFT) computations), and PPN filter coefficients.

After architecture exploration and optimization by successively refining the fixed point model [NAB+14a], the final architecture of the CP-OFDM and FBMC/OQAM transceiver is designed. More detail about the development flow is presented in Annex C. The resulting architecture is illustrated in Figure 6.3. For the purpose of fair comparison, same architectural choices and optimisation techniques are devised for both transceivers.

The first unit of the proposed OFDM modulator architecture is the QAM mapper which is implemented through the use of Look-Up Tables (LUT), one for each constellation order (4 to 256-QAM). A multiplexer selects the LUT corresponding to the desired QAM order. The QAM mapper of FBMC/OQAM uses a QAM mapper identical to OFDM. In addition, a delay element implemented as a FIFO module is inserted at the imaginary output to introduce the corresponding offset. Subcarrier allocation is also performed at this stage, where the output of the QAM mapper is forced to zero if it corresponds to a non-active subcarrier.

The second unit is the IFFT, which represents the core element of the OFDM and FBMC/OQAM transceiver architecture. In both systems, the Radix-2² Single-path Delay Feedback (R2²SDF) architecture [ST96] was implemented for the FFT/IFFT modules. This solution allows for a fully pipelined architecture and a minimum memory requirement with efficient resources (multipliers, adders, and registers) utilisation. The corresponding design exploits the fact that an M-point IFFT can be recursively decomposed into four IFFTs of length...
\( M/4 \) and can be implemented by \( \log_4(M) \) stages of an elementary IFFT module of length 4, called radix-4 butterfly. Instead of computing all butterflies iteratively stage by stage, all stages are computed at the same time, in a pipelined way. The devised architecture for the IFFT uses the Decimation In Frequency (DIF) decomposition which results in output samples in bit reversal order. Concerning FBMC/OQAM, we manage to optimize the design of the receiver by using only one FFT at the same processing rate as OFDM, thanks to the pruned FFT algorithm [DS11; NAB15]. The details on the modifications of the architecture are presented in Annex D.

Concerning the last block of the OFDM transmitter, the insertion of the cyclic prefix and the bit reversal reordering operations are done jointly to avoid additional memory usage and latency overhead. In the case of FBMC/OQAM, the PPN implementation is based on the horizontally folded design proposed in [DMO11]. It represents a pipelined architecture suitable for low complexity and low memory usage designs. In addition, it enables the introduction of filters with a flexible length thanks to its repetitive structure. In case of a short filter like TFL1 (length \( M \)), only 2 real multipliers are required per PPN block.

For the two considered FBMC demo cases, an over-the-air transmission is performed by going through the RF modules. Therefore, the corresponding channel may introduce alterations to the transmitted signal such as fading, phase rotation and carrier frequency offset. These impairments need to be estimated and compensated for at the receiver side. To this end, a channel estimation technique based on block-type pilot patterns was implemented for the two compared modulation techniques. Because of OQAM processing, the classical channel estimation techniques used for CP-OFDM cannot be directly applied to FBMC/OQAM. Instead, block-type Interference Approximation Method with Real pilots (IAM-R) channel estimation method was implemented. It has the advantage of offering an improved performance when compared to OFDM at low SNRs [LSL08].

If \( H \) denotes the channel frequency response (at one subcarrier), and \( \tilde{H} \) represents its least square estimation, then:

\[
\tilde{H} = H + \frac{w}{P + ju}
\]

where \( P \) is the pilot value (real valued), \( u \) designates the intrinsic interference, and \( w \) a noise term. The idea behind IAM channel estimation is to choose \( P \) in order to control and maximize the intrinsic interference to improve the SNR, since the resulting noise term has less power when \( u \) increases. For both CP-OFDM and FBMC/OQAM, the preamble is repeated every 6 OFDM symbols (12 OQAM symbols) like in uplink frame format, to track any eventual channel variation. The implemented equalization is based on the classic zero forcing algorithm which consists in dividing the received impaired symbol by the estimated channel frequency response for each subcarrier. To enable a fair comparison, the same type of equalization technique and hardware implementation is used for FBMC/OQAM and for CP-OFDM.

### 6.2.2 Integration into the test-bed environment.

The hardware design presented in section 6.2.1 was integrated between a Direct Memory Access (DMA) block and the AD9122/AD9643 interface block on the FPGA, as presented in Figure 6.4. The AD9122 interface adapts the modulator output signals, including clocks, to the 16 bits Digital to Analog Converter (DAC) with Low Voltage Differential Signal (LVDS) and Double Data Rate (DDR) modules of the AD-FMCOMMS1-EBZ board, whereas the AD9643 interface has the same function for the 14 bits Analog to Digital Converter (ADC). The DMA ensures the transition of the data from a DDR memory (embedded in the ZedBoard) to the (O)QAM mapper input, without the intervention of the Advanced Extensible Interface (AXI) bus dedicated to the ARM processor.
System parameters are configured dynamically by the ARM processor. The transmitter receives its configuration over Ethernet while the receiver receives its configuration over the air. At the transmitter side, the selected parameters from TX GUI are sent via the Ethernet link to the processor, using Transmission Control Protocol/Internet Protocol TCP/IP Application Program Interface (API) (in Mathworks MATLAB) and lightweight IP (lwIP) library (from ARM). After parsing and interpreting the received command, it configures, via the AXI bus, the appropriate slave register on the FPGA which holds the test-bed configuration (reset, start transmission, enables the Carrier Frequency Offset (CFO)) and parameters of the components (FBMC or OFDM mode, QAM order). Since the RX GUI is used only for display, the receiver cannot be configured by the Ethernet link. Instead, a short frame containing the information of the selected parameters from the TX GUI is sent to the receiver board. Two bytes are enough to hold this information. However, it is repeated 2048 times and recovered by majority vote at the RX to be sure that channel impairments do not alter the configuration. This short frame is always sent using the same configuration for both TX and RX (OFDM with 16-QAM on 25 RBs), and the receiver side always expects this short frame before receiving classical data content.

Figure 6.4: Demonstration setup with front end interface.
The Doppler shift is emulated in hardware at the receiver side by generating a fractional CFO. If $s(k)$ represents the received time domain sample at sampling index $k$, the resulting signal with Doppler shift impairment is:

$$r(k) = s(k)e^{j2\pi rCFOM}$$

where $rCFO$ denotes the carrier frequency offset relative to the subcarrier spacing. For instance, in LTE, the subcarrier spacing is defined at 15 kHz independently of the considered bandwidth, thus an $rCFO$ of 10% corresponds to a Doppler shift of $F_d = 1.5$ kHz. The maximum corresponding relative mobility speed is:

$$v_r = \frac{c*F_d}{F_c}$$

where $F_c$ is the carrier frequency and $c$ is the speed of light. In our case, $F_c = 2.4$ GHz, meaning that 10% of CFO is equivalent to a speed of 674 km/h. Other values are also possible. It was preferred for demonstration purposes and was chosen in such a way to degrade enough the BER performance to clearly observe resulting errors on user data.

Because the Doppler shift is a parameter of the demonstration, it has to be controlled accurately. The CFO induced by the frequency difference between the Local Oscillators (LO) of both boards need to be cancelled properly. The most straightforward and precise way to solve this problem is to synchronize both LO by a common clock. Thus, in our test-bed, the LO clock of the receiver is connected by wire to the clock of the transmitter LO.

The timing synchronization is also resolved by connecting the two boards with a wire carrying a synchronization signal (denoted by ‘sync’ in the rest of this document). The synchronization process starts by sending at the same time the sync signal and an impulse through the RF interface. When the sync signal is received, a counter starts and the number of clock cycles is counted until the impulse signal is received. Thus, the latency induced by the propagation channel is estimated, the sync signal is then delayed accordingly by a configurable shift register and set as a validation signal for the OFDM and FBMC/OQAM receiver.

To summarize, when a user starts the transmission of useful data, the test-bed follows 5 steps:

1. Receiver is waiting to receive the synchronization signal to start the demodulation.
2. Before sending useful data, a short frame is sent from the TX containing selected demo parameters to the receiver board. This set of parameters is used to configure the receiver.
3. Uncompressed image data are formatted in MATLAB and sent through the Ethernet link to the ARM processor of the Zynq. Bits of the image are randomized in MATLAB to avoid high Peak to Average Power Ratio (PAPR) and the resulting clipping of the quantized signals.
4. When the image is stored in the DDR3 memory, the ARM processor initiates the DMA transfer from DDR3 to the digital base-band FPGA, directly to the input of the QAM mapper.
5. The receiver starts processing when receiving the sync signal. The demodulated binary data and the received constellation are continuously transferred to the DDR3 using the 64 bits DMA, then read and sent to the computer through Ethernet link.

### 6.3 Test-bed implementation: context of massive machine communications

The key aspect of this demonstration is to assess the behaviour of FBMC/OQAM and State-of-The-Art (SoTA) OFDM in the context of asynchronous links foreseen in MMC, as described in Section 6.1. This demonstration emulates a situation where a massive number of sensors...
send short packets of information to the base station. To avoid close-loop synchronization and lower the power consumption of the sensors, asynchronous communication is considered in this demonstration. The sensors do not share the time-base of the base station: they wake-up from sleep mode, directly transmit the required few bits of information to the base station, and switch to sleep mode again. In this context, four sensors send an image file to the base station for simulating the transmission of a few bits of information at low data rate. These sensors are allocated on different subcarriers and experience different levels of synchronization misalignment with respect to the existing, already occupied, fragmented spectrum. The fragmented spectrum can be the result of the transmissions of other sensors or broadband users. Due to this lack of synchronization, the fragmented spectrum acts as interference for the four considered sensors. A configurable guard-band of 1 to 3 subcarriers is inserted around the subcarriers allocated to the four sensors. Several levels of interference can be illustrated by controlling the timing offset. The effect of the prototype filter is evaluated for PHYDYAS, TFL1 and the rectangular (CP-OFDM) cases.

The test-bed environment for this demonstration is presented in Figure 6.5. One ZedBoard is used to simulate 4 sensors at the transmitter side, and the second ZedBoard at receiver side simulates the base station. Both boards are extended by an RF interface to enable over-the-air transmission. The main difference with the previous demonstration setup is the use of the TX antenna on the receiver board to generate the existing occupied fragmented spectrum (acting as interference for the four sensors). A GUI at the transmitter side is used to select system parameters like QAM constellation order, number of subcarriers in the guard-band, number of active subcarriers, etc. The GUI at the receiver side only displays KPIs.

CP-OFDM and FBMC/OQAM transceivers are implemented in the FPGA part of the Zynq SoC for both boards. A dual-core ARM cortex A9 processor embedded in the Zynq is used for communicating with the computer through an Ethernet link. It also configures system parameters selected by the transmitter GUI.
The storyline of this demonstration is described as follows:

1. User selects appropriate parameters on the GUI. Transmission with OFDM or FBMC/OQAM is chosen, along with the number of subcarriers in the guard band. PHYDYAS and TFL1 prototype filters can be considered in this scenario.
2. Transmitter boards receive image file from computer through an Ethernet link, and transmit it over the channel by the RF interface, in 4 separate subcarriers corresponding to 1 sensor each.
3. The board at the receiver side uses its TX antenna to transmit the interfering fragmented spectrum. In parallel, it receives and demodulates the signal of the 4 sensors, and sends the resulting digital data corresponding to the image and to the shape of the transmitted constellation to the host computer.
4. Performance measurements are displayed on the GUI of the receiver. For every sensor, the image and the corresponding received constellations illustrate one level of interference and are displayed for OFDM and FBMC/OQAM to enable a comparison in terms of transmission quality. BER and gross data rate are also calculated and displayed to have quantitative results, along with hardware complexity.

The hardware implementation presented in Section 6.2.1 remains the same. The corresponding system is flexible concerning subcarrier allocation. Therefore, any kind of spectrum fragmented or not, can be generated. A memory which can be written using the AXI bus stores the position of the active subcarrier, and the output of the QAM mapper is forced to zero at the clock cycle corresponding to a non-active subcarrier. The implemented PPN hardware design [DM011] allows flexible and configurable filter length (multiple of FFT length). The use of the longer filter like PHYDYAS increases the number of applied multipliers and memory requirements.

The test-bed environment described in details at Subsection 6.2.1 and shown in Figure 6.4 is reused for this demonstration. The major difference is the addition of a transmitter in the receiver board to simulate the fragmented spectrum acting as interference since the AD-FMCOMMS1-EBZ RF board has one antenna for transmitting and another one for receiving. Interfering sensors do not have coherent data since they are discarded during the demodulation process, so data is generated randomly using a linear feedback shift register. The timing offset can be adjusted to control the interference level of the synchronization misalignment by precisely delaying the signal to start a transmission with a configurable shift register.

### 6.4 Results

This section presents the results of the test-bed related to the FBMC/OQAM waveform. It is divided in three parts. First, the common results about the hardware complexity and the power consumption are presented in Subsection 6.4.1. Second, the results relative to the vehicular communication demonstration detailed in Section 6.2 are illustrated in Subsection 6.4.2. Response of both systems when applying a high Doppler shift is evaluated in terms of transmission quality, BER and gross data rate. The spectrum shape of the RF front end interface is displayed. Finally, the third part in Subsection 6.4.3 concerns the results related to massive machine communication scenario presented in Section 6.3.

#### 6.4.1 Hardware complexity and power consumption

The hardware complexity and measured power consumption of OFDM and FBMC/OQAM modulators are summarized in Table 6.1. For FBMC/OQAM, the table includes results related to typical SoTA implementation and to the proposed optimized architecture. The targeted FPGA is the XC7z020-1 Xilinx Zynq SoC device. These results correspond to an IFFT of length 512, TFL1 prototype filter and 16-QAM constellation. Concerning the quantization, all
samples at input and output of each stage have 16-bit quantization, as presented in Section 6.2. This also applies to each stage of the IFFT. All coefficients stored in LUT are quantized and stored with a precision of 12 bits. This includes the fractional part of twiddle factors (related to IFFT computations) and the PPN filter coefficients.

As expected, the pruned IFFT based FBMC/OQAM is almost twice less complex than typical SoTA implementation. This constitutes one of the major contributions of this work. Using a short filter and the proposed optimized architecture, the FBMC/OQAM modulator is comparable to OFDM in term of registers (6% less), LUT (10% more), and memories (15% more). As for the number of multipliers, they are increased by 25% because of the one tap PPN unit, but when the IFFT increases in length, it becomes negligible with respect to the total complexity. Regarding the latency, it is reduced by approximately 256 clock cycles compared to OFDM and the classical (non-optimized) FBMC/OQAM. The reason is the bit reversal reordering operation which is performed for only half of the total number of samples compared to OFDM. Thus, the resulting latency for this unit is only 256 clock cycles for the proposed FBMC/OQAM architecture instead of 512 clock cycles for OFDM.

The PPN units represent the real problem concerning the increase in complexity in terms of memory requirements when the prototype filter has a length larger than one tap. Indeed, the overall complexity is greatly increased in the case of the 4-tap PHYDYAS prototype filter. The two PPNs require more than twice the memory needed for the complete OFDM. It also requires 16 multipliers, the same number as the OFDM transmitter. However, the optimized FBMC/OQAM architecture offers an overall complexity reduction of 40% compared to SoTA implementation, which is clearly not negligible.

<table>
<thead>
<tr>
<th>Block</th>
<th>Transmitter</th>
<th>Registers</th>
<th>LUTs (as logic)</th>
<th>LUTs (as RAM)</th>
<th>DSP multiplier</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QAM mapper</td>
<td>OFDM</td>
<td>20</td>
<td>109</td>
<td>16</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>FBMC/OQAM (SoTA)</td>
<td>51</td>
<td>254</td>
<td>104</td>
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<td>6</td>
</tr>
<tr>
<td></td>
<td>FBMC/OQAM (Optimized)</td>
<td>108</td>
<td>300</td>
<td>192</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Pre-process</td>
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<td>546</td>
<td>0</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>FBMC/OQAM (Optimized)</td>
<td>106</td>
<td>426</td>
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<td>4</td>
<td>11</td>
</tr>
<tr>
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<td>FBMC/OQAM (SoTA &amp; Optimized)</td>
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<td>300</td>
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<td>4</td>
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<td>1846</td>
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<td>912</td>
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<td>109</td>
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<td>8952</td>
<td>3744</td>
<td>52</td>
<td>359</td>
</tr>
<tr>
<td></td>
<td>FBMC/OQAM PHYDYAS (Optimized)</td>
<td>3788</td>
<td>5585</td>
<td>3180</td>
<td>32</td>
<td>252</td>
</tr>
</tbody>
</table>

The critical path is related to the real multiplier, so there is no difference in terms of reachable clock frequency which is (220 MHz on the XC7z020-1 target). Regarding the reachable throughput, the devised architecture is fully pipelined allowing continuous stream processing.
of one complex sample in baseband discrete time domain per clock cycle. It is worth to note that the baseband processing can be done at a higher rate than the sampling frequency (maximum 30.72 MHz for LTE) if a high latency constraint is imposed.

Power consumption was measured block by block for the CP-OFDM and FBMC/OQAM transmitters. It is measured and calculated from a current sense resistor of 10 mΩ available on the ZedBoard. A dedicated top-level test-bench was set up to conduct these measures as shown in Figure 6.6. These exclude the contribution of the RF board and the ARM processor. A first measure is realized by running the test-bench, with the OFDM and FBMC/OQAM modulator disabled (asynchronous reset activated). This way, we can deduce the power consumption of the unwanted activities and the static power of the board. Thus, by a simple subtraction, the dynamic power consumption of the desired component can be deduced. The developed test-bench must ensure that the component run in continuous, in the most realistic condition. To do so, a Linear Feedback Shift Register (LFSR) is used to simulate uniform random binary data, and a simple Finite State Machine (FSM) is added for control purposes. A final register is present to "force" the synthesis tool to avoid optimizing the design.

Measured results indicate a total increase in 27% of the power consumption for the proposed FBMC/OQAM architecture using a TFL1 filter with respect to OFDM. This is due to the additional required memories in the OQAM mapper and the reorder stage. The 4 multipliers in the PPN unit also contribute to this increase in power consumption.

Using the PHYDYAS filter and a SoTA implementation, the increase in power consumption is around 250% when compared to OFDM. However, in the case of the proposed architecture, this increase is scaled down to only around 140%.

Figure 6.6: Hardware configuration for measuring the dynamic power consumption.

Concerning the hardware complexity of the receiver components, the results are depicted in Table 6.2. The pruned FFT being not directly applicable for the FBMC/OQAM demodulator, the FFT has to be duplicated, leading to a non-negligible increase in complexity. Further studies are envisaged in this context. For a one tap filter implementation, the complexity is almost doubled in terms of number of registers (+91%), LUTs (+84%), memory requirements (+93%) and number of multipliers (+100%). However, in the case of the uplink, the power consumption and the complexity is less critical than the UE since the receiver is located at the base station. This increase in complexity can be considered acceptable given the advantage of FBMC/OQAM in term of spectral usage and when it is compared to the total system complexity including the Forward Error Correction (FEC) decoder.
### Table 6.2: Synthesis results for OFDM and FBMC/OQAM receiver.

<table>
<thead>
<tr>
<th>Block</th>
<th>Receiver</th>
<th>Registers</th>
<th>LUTs (as logic)</th>
<th>LUTs (as RAM)</th>
<th>DSP multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPN TFL1</td>
<td>FBMC/OQAM</td>
<td>276</td>
<td>810</td>
<td>176</td>
<td>4</td>
</tr>
<tr>
<td>PPN PHYDYAS</td>
<td>FBMC/OQAM</td>
<td>1102</td>
<td>1471</td>
<td>2288</td>
<td>16</td>
</tr>
<tr>
<td>FFT</td>
<td>OFDM</td>
<td>2833</td>
<td>3343</td>
<td>544</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>FBMC/OQAM (x2)</td>
<td>5666</td>
<td>6686</td>
<td>1088</td>
<td>32</td>
</tr>
<tr>
<td>Reorder</td>
<td>OFDM</td>
<td>87</td>
<td>98</td>
<td>352</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>FBMC/OQAM (x2)</td>
<td>174</td>
<td>196</td>
<td>704</td>
<td>0</td>
</tr>
<tr>
<td>Chan. estim + equalizer</td>
<td>OFDM</td>
<td>346</td>
<td>1555</td>
<td>306</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>FBMC/OQAM</td>
<td>728</td>
<td>1965</td>
<td>355</td>
<td>10</td>
</tr>
<tr>
<td>QAM Demapper</td>
<td>OFDM</td>
<td>0</td>
<td>53</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>FBMC/OQAM</td>
<td>0</td>
<td>53</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>OFDM</strong></td>
<td><strong>3384</strong></td>
<td><strong>5119</strong></td>
<td><strong>1200</strong></td>
<td><strong>23</strong></td>
</tr>
<tr>
<td></td>
<td><strong>FBMC/OQAM TFL1</strong></td>
<td><strong>6467</strong></td>
<td><strong>9453</strong></td>
<td><strong>2320</strong></td>
<td><strong>46</strong></td>
</tr>
<tr>
<td></td>
<td><strong>FBMC/OQAM PHYDYAS</strong></td>
<td><strong>7349</strong></td>
<td><strong>10121</strong></td>
<td><strong>4452</strong></td>
<td><strong>58</strong></td>
</tr>
</tbody>
</table>

#### 6.4.2 Results related to vehicular communication demonstration

The KPIs related to this demonstration and displayed at the receiver GUI are shown in Figure 6.7 and Figure 6.8. The image and constellation points are received in a high mobility condition simulated via the introduction of 10% of Doppler shift for OFDM (left side of the figure) and for FBMC/OQAM (right side). The difference in quality between the received uncompressed images is clearly visible. The corresponding error rates are provided. This demonstrates the improvement in transmission quality that can be offered by the FBMC/OQAM modulation in a scenario related to high mobility when using a short filter. In the case of OFDM, the constellation is very noisy while constellation points can be clearly separated and identified for FBMC/OQAM. The BER shows in a more quantitative ways the performance gap separating the two modulations: the BER difference in order of magnitude is three. BER is simply calculated in MATLAB by comparing bitwise the received image with the reference one stored locally, each picture containing 6.3 Mb of data. Finally, it is observed that the gross data rate is a little higher for FBMC/OQAM since the insertion of a CP is not needed, resulting in a gain in spectral efficiency of around 7% (when a CP length of 7% is considered for OFDM).

![Figure 6.7: Results for FBMC/OQAM (TFL1 filter) on the right and CP-OFDM on the left with 10% Doppler shift.](image)

Measures using PHYDYAS filter were also conducted concerning this demonstration, and results are illustrated in Figure 6.8. Compared to OFDM, FBMC/OQAM using the PHYDYAS...
filter remains better in terms of BER by one order of magnitude, resulting in much better image quality and less noisy constellation points. However, PHYDYAS filter is clearly outperformed by TFL1 in this demonstration (two orders of magnitude worse). Even if PHYDYAS filter offers a good time and frequency localization which limits the inter-carrier interference induced by Doppler shift, the filter length is 4 times longer than an OFDM and a TFL1-based FBMC/OQAM symbol, making it more sensitive to channel variations. These results are coherent with [LGS14].

Figure 6.8: Results for FBMC/OQAM (PHYDYAS filter) on the right and CP-OFDM on the left with 10% Doppler shift.

The Power Spectral Density (PSD) at the output of the transmitter RF board was measured with a spectrum analyser to confirm the advantage in spectral shape of FBMC/OQAM when compared to OFDM. Figure 6.9 depicts the results of this measure conducted with the following LTE parameters:

- FFT size of 512 points.
- Sampling frequency of 7.68 MHz, carrier frequency at 2.4 GHz.
- 300 active subcarriers (25 RBs), giving a total bandwidth of 4.5 MHz.
- 16-QAM constellation is considered, and the TFL1 prototype filter is used for FBMC/OQAM.

Even with a short filter like TFL1, which is not the most frequency localized filter, the out-of-band leakage is noticeably decreased by 20 dB of difference when compared to OFDM.

Figure 6.9: Power Spectral Density of FBMC/OQAM and CP-OFDM.
6.4.3 Results related to massive machine communication demonstration

Current results for the massive machine communication demonstration focus on the transmission of an uncompressed image file with only 1 sensor instead of 4. This sensor uses 1 RB in terms of spectral resource. Only one subcarrier, considered as a guard band is inserted between each sensor band and the fragmented band acting as interference. The synchronization misalignment is controlled and four different levels are investigated. Figure 6.10 and Figure 6.11 depict the results in terms of quality of received image/constellation, BER and gross data rate for a timing offset of 0%, 25%, 50% and 75% relatively to an OFDM symbol length. In the case of OFDM, the image and the constellation are particularly noisy except for the case of 0% timing offset implying that the system is synchronized. For higher timing offset values, the lack of synchronization generates interference for each sensor. This is due to the high out-of-band leakage of OFDM, implying a high level of interference when compared to FBMC/OQAM. Indeed, the effect of OFDM seems to have a threshold beyond which the level of interference is increased drastically.

In the FBMC/OQAM case, it appears that the results are slightly dependent on the synchronization misalignment. At a first glance, this seems mainly due to the filter shape and its corresponding impulse response or equivalently due to its localization properties in frequency when an overlap occurs.

Therefore, even when perfectly synchronized (0% timing offset), FBMC/OQAM using TFL1 filter still suffers from a performance degradation when applying only one sub-carrier as guard band (due to the intrinsic interference). In the case of 50% of misalignment representing the worst case scenario, measured experiments show at least three orders of magnitude of difference in BER between OFDM and TFL1-based FBMC/OQAM ($5 \times 10^{-2}$ versus $5 \times 10^{-5}$). For 25% and 75% of misalignment, the improvement over OFDM reaches up to 5 orders of magnitude. Increasing the number of sub-carriers acting as guard band to 2 greatly reduces the resulting interference allowing a close-to interference-free behaviour for a TFL1 filter.

![Figure 6.10: Results for TFL1-based FBMC/OQAM and CP-OFDM for asynchronous communication with four sensors each having a different misalignment value of 0%, 25%, 50% and 75% of the duration of one OFDM symbol.](image)

When using the PHYDYAS filter, results are presented in Figure 6.11. Regardless the level of synchronization misalignment, using only one subcarrier as a guard band is enough to be isolated from interfering sensors. Indeed, the intrinsic interference of this type of filter spans only the closest neighbouring sample. Therefore, with one sub-carrier as a guard band, no intrinsic interference is experienced in this case: BER reaches zero, and the constellation points are clean. This illustrates the particular suitability of PHYDYAS prototype filter in case of asynchronous communication.
Figure 6.11: Results for PHYDYAS-based FBMC/OQAM and CP-OFDM for asynchronous communication with four sensors each having a different misalignment value of 0%, 25%, 50% and 75% of the duration of one OFDM symbol.

It is worth to note that the increase in gross data rate of the FBMC/OQAM solution is due to the absence of a cyclic prefix.

Figure 6.12 illustrates a comparison of the power spectral densities related to one sensor in a MMC context. OFDM, TFL1-based FBMC/OQAM and PHYDYAS-based FBMC/OQAM are considered. The continuous lines correspond to the power spectral densities of the sensor occupying a band of 1 RB for the modulation scheme with the corresponding colour (red = OFDM, blue = TFL1-based FBMC/OQAM and green = PHYDYAS-based FBMC/OQAM).

Figure 6.12: Comparison of the spectrum shapes for the case of one sensor for MMC of OFDM, TFL1-based FBMC/OQAM and PHYDYAS-based FBMC/OQAM.
The dotted lines correspond to the power spectral densities of the rest of the considered 5 MHz bandwidth corresponding to other sensors or to classical mobile terminal services acting as interference. A reduction of 55 dB in the power spectral density leakage for the sensor band and for the rest of the considered 5 MHz band is observed for the TFL1-based FBMC/OQAM when compared to OFDM. This reduction reaches 90 dB when the PHYDYAS filter is used. These results are coherent with the measured error rate results and observed image qualities provided earlier.

To conclude, the results concerning MMC demonstration illustrate that:

- OFDM is clearly not adapted for asynchronous communication and by extension for MMC.
- FBMC/OQAM using short filter like TFL1 is more adapted than OFDM for MMC, but requires more than one subcarrier as guard band to reduce the interference.
- When using PHYDYAS filter, FBMC/OQAM is best suited for MMC, and one subcarrier as guard band is enough to separate each sensor without experiencing any interference.
7 Conclusion and perspectives

In this document, detailed description of the test-bed specification and final test-bed results of the implemented technology components were provided. The conducted hardware prototyping activity constitutes valuable proof-of-concept and implementation guidelines. It allowed to analyse and to evaluate aspects that are overlooked in the theoretical studies or hard to verify through software simulations, such as processing delays, control signalling, and hardware implementation complexity and impairments. Furthermore, the developed test-beds allowed to show-case the METIS 5G system concept in several conferences and tradeshows. As only two test-bed platforms were available, some technical components have been selected for the test-bed implementation based on the criteria of good publicity, technology impacts, and high implementation feasibility according to the available test-bed resources and tight timeline.

In this context, three D2D related test-beds have been implemented. The first one demonstrates the impact of interference cancellation (IC) in direct network controlled D2D. The document provided an overview of a system using successive interference cancellation at the BS. While implementing the demonstration, it has been noticed that the LTE segmentation and encoding does not support simple implementation of the IC.

The second D2D related test-bed enriched the first one with the mode selection, and was presented in MWC 2015. Based on our observation from the implemented demonstrations, we studied also the system gain with D2D and IC at the D2D nodes. By using such IC in D2D, the studies suggest that the system could double its capacity.

The third D2D related test-bed concerns D2D in HetNet which uses the resources based on RSRP measurements. The demonstration was assisted with an initial measurement campaign. It was noticed that subframe level RSRP values vary a lot. We investigated how to average these values such that we can control interference probability at both macro and picocells.

Using this same test-bed platform, an additional MMC demonstration has been developed to show how a large number of M2M type nodes with short packets of data can efficiently communicate over shared channel with non-orthogonal signals. In this demonstration, we first had to modify the proposed algorithm such that it could be ported to LTE test-bed. We designed the algorithm that uses SC-FDMA frame structure and can be inserted into LTE uplink subframes. In this document we reported the performance of this modified algorithm. We use a structured code that provides same transmitter activity detection performance as a random sequence. The analysis shows that simple least square receiver is capable to decode data from multiple simultaneous active nodes. However, the simultaneously active M2M transmitters create an interference environment where least square detector presents error floor as it is not an optimal receiver.

Regarding the test-bed activities related to the selected FBMC/OQAM waveform, the objective was to illustrate its key advantages compared to state-of-the-art CP-OFDM, in terms of spectrum usage, resilience to imperfect synchronization and high robustness to mobility (Doppler). Such advantages are key elements, with respect to 5G challenges resulting from the extension of asynchronous dense networks (including device-to-device and massive deployment of machines) and vehicular communications. Towards this objective, two demonstrations have been developed. The first one targets to show-case related advantages in the context of vehicular communications, while the second demonstration targets the context of massive machine communications. For both demonstrations, the devised storyline was illustrated together with the proposed hardware implementation and its integration into the test-bed environment. Furthermore, a summary of measured results was provided in terms of hardware complexity, power consumption, power-spectral density, error rates, and throughput. The obtained results confirm the superiority of FBMC/OQAM compared to CP-OFDM in these contexts. At least a gain of 3 decades in BER has been observed for the two demonstrations.
Regarding the hardware complexity, a novel optimized architecture was proposed at the transmitter side. This architecture is based on the use of a short localized filter and a pruned IFFT algorithm, which avoids any redundancy in OQAM processing.

Results showed that the proposed implementation is twice less complex than typical state-of-the-art one, leading to a comparable hardware complexity to CP-OFDM. Regarding the receiver side, further studies are required in order to reduce its complexity which represents typically twice that of CP-OFDM for the considered system parameters. In addition, future studies can consider other candidate waveforms and their combination with other proposed techniques at the physical and MAC layers.

Finally, the developed test-beds have been presented in several conferences and tradeshows, in particular during ICT 2013, EuCNC 2014, and MWC 2015.
8 References


**[MET15-D53]** ICT-317669-METIS, Deliverable 5.3 “Description of the spectrum needs and usage principles”, August 2014.


**[NAB14]** J. Nadal, C. Abdel Nour, and A. Baghdadi, “METIS DBB key component: FBMC/OQAM-related new waveform,” European Conference on Networks and Communications (EuCNC), Exhibition stand 18, June 2014.


Annex A
A. Test-bed platform for network level demonstrations

The software radio test-bed developed in Aalto University consist PC and USRP based remote radio head. The software defined radio encompasses the part of TD-LTE software stack that is required for data transmission. The software environment is using Ubuntu Linux 14.04 and is compiled with g++4.8. The code is written in C++11.

Baseband processing

The baseband processing in the test-bed is geared towards efficient implementation of TD-LTE type physical layer. The implementation renders its functionalities, as much as possible, from 3GPP LTE specification Release 8. As such it is not designed to be a flexible platform for studying alternative signal processing algorithms but rather to provide basic transceiver functionalities.

The baseband processing is split into two parts (Figure A.1): TxRx implementation and local RRM (L-RRM) functionality. The main interference control logic is to be located in the RRM modules. The TxRx layer is designed to provide resources that RRM controls. In its current form it is constructed to support TD-LTE type radio frames. The implementation follows LTE Release 8 specifications.
Functions in Tx chain

The Tx thread constructs the LTE TDD frame. It selects the TDD format, assembles resource blocks structure, inserts the primary and secondary synchronization sequences and users data.

Turbo encoder and decoder: the code implements turbo coding according to the LTE specification 3GPP TS 36.212 V8.8.0. The implementation is bit exact according to standard: it has input data segmentation, CRC construction, padding etc.

Convolutional code encoder and decoder: the code implements the convolution code according to the LTE specification 3GPP TS 36.212 V8.8.0.

TDD resource blocks construction as specified by 3GPP TS 36.211 V8.9.0.

Pilot allocation: the pilot carriers are allocated as specified in 3GPP TS 36.211 V8.9.0.

Sub-frame structure format selection: TDD sub-frame formats can be generated as defined in the LTE specification 3GPP TS 36.211 V8.9.0.

Primary and secondary synchronization sequence generation and allocation into sub-frame as specified in 3GPP TS 36.211 V8.9.0.

Functions in Rx Chain

The Rx thread handles the reception of radio frames. The Rx processing depends on its location, whether it is in a BS and or in a user equipment. In the user equipment, the Rx process has two stages: the synchronisation stage where the receiver synchronizes to the transmitter and the reception stage where the bit stream is received. In BS, the receiver knows the user data location and it simply attempts to decode it.

Synchronization to the synchronization sequence: This operation adjusts the sampling moment at the receiver. After the synchronization the receiver goes into the reception mode and the synchronization function starts tracking the time of the transmitter.

Channel estimation and equalization: The channel equalization is based on the pilot signals inserted into the TDD frame.

Functions handling connections towards USRP

Communication between the PC and USRP is handled by UHD driver from Ettus Research (Figure A.3). The UHD driver handles the transmission and reception of samples of the USRP unit. It contains API for communicating with USRP. The transmission and reception moments are controlled by time stamps. The transmission timing is synchronized by using the clock in USRP unit. We have prepared the functions that synchronise the UHD driver and Tx and Rx threads.

Radio head hardware platform

The signal conversion to and from radio frequencies are done by USRP units provided by Ettus Research. A USRP unit contains the main unit and the daughter board. In the testbed, we have 20 N200 type main units and four N210 type main units. The radio connection is provided by a SBX radio attachment board.

The USRP unit main board contains the Gigabit Ethernet connector, FPGA (Field Programmable Gate Array) circuit and AD/DA converters.

Both boards are capable of transmitting 25 Msps (Mega-samples per second). This speed is supported if the main PC and the USRP unit communicate by using complex samples with 16 bit precision. 50 Msps transmission is possible if the precision is dropped to 8 bits per sample.
The FPGA is responsible for handling responses UHD driver commands, it controls data streaming and it also handles the signal interpolation and decimation. The decimation and interpolation rate has to be integer division of the sample rate.

The radio performance of the system is defined by the stability of the USRP units and the daughterboard characteristics. The used SBX daughterboard has independent voltage-controlled oscillator (VCO) for transmitter and receiver chain and it supports full duplex transmission.

Figure A.3: USRP front view and internals.
Annex B
B. Test-bed platform for digital baseband demonstrations

The test-bed platform for FBMC/OQAM demonstrations was provided by Telecom Bretagne. The digital processing is handled by the ZedBoard which integrates the very recent (2012) Xilinx device: Zynq-7000 All Programmable SoC (System on Chip). This device, which belongs to the latest series 7 Xilinx programmable circuits, integrates a dual-core ARM Cortex-A9 processing system clocked at 677 MHz. Its block diagram is illustrated in Figure B.1. The processing system integrates in addition several peripheral controllers for communication (including 2 instantiations of tri-mode gigabit Ethernet and USB2.0) and external memory management.

The ZedBoard can be programmed through two integrated interfaces: a USB-JTAG interface available through a Micro-B USB connector and a traditional Platform Cable JTAG connector. Once programmed, it runs typically in a standalone mode. Other executions modes (e.g. a hardware-in-the-loop system prototyping) can be built by the system designer using the onboard available communication interface (e.g. 10M/100M/1G Ethernet and USB 2.0). Furthermore, an embedded Linux kernel is included for running on the ARM dual-core Cortex-A9 with all required device drivers. This configuration opens interesting perspectives for a target demonstration where the software part is executed on-board rather than on a host computer.

Table B.1 summarizes the available programmable logic in the Xilinx Zynq-7020 device integrated in the ZedBoard.

Table B.1: Available programmable logic per Zynq-7020 All Programmable SoC.

<table>
<thead>
<tr>
<th>Logic Cells(^{(1)})</th>
<th>LUTs</th>
<th>Flip-Flops</th>
<th>DSP Slices</th>
<th>Block RAM (# 36 Kb Blocks)</th>
<th>Peak DSP Performance (Symmetric FIR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xilinx Zynq-7020 (Artix-7 FPGA)</td>
<td>85K</td>
<td>53,200</td>
<td>106,400</td>
<td>220</td>
<td>560 KB (140)</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Approximate ASIC Gates for this 85K Logic Cell is around 1.3M, with the assumption of 1 Logic Cell = around 15 ASIC Gates.
The ZedBoard can further be connected to an Analog Devices AD-FMCOMMS1-EBZ daughterboard to obtain an RF interface. The RF interface is software-tunable across a wide range (400MHz to 4GHz) with 125MHz channel bandwidth. The transmitter chain integrates 16-bit dual-DAC allowing a sample rate of 1200 MSps, while the receiver is integrating 14-bit dual-ADC able to achieve 250 MSps. Regarding the software development aspect, full Linux support is provided by Analog Devices. Furthermore, a dedicated application-programming interface is available and can be used without an operating system to interact with the AD-FMCOMMS1-EBZ board, like we did to implement our test-bed. The possibility to connect the AD-FMCOMMS1-EBZ RF board to high-capacity FPGA boards opens interesting perspectives on the demonstration of a wide range of compute-intensive FPGA-based radio applications.
C. Development flow related to the digital baseband platform

The different development phases, from algorithm specification to on-board validation and demonstration, are summarized in Figure C.1.

The development framework entry consists of the description of the technical component to be demonstrated and the related aspects of usage scenarios and estimated performances. In the presented design and prototyping experience, these inputs have been made available by the company Orange Labs. The description of the technical component includes the following: (1) a detailed description of the proposed algorithm/technique, which has been summarized in the previous section, (2) a reference software model, including a reference software testbench, and (3) supported system parameters, including those related to the target channel models.

![Figure C.1: Development framework for DBB test-bed.](image-url)

The first phase in the development framework starts by analysing the selected technical component considering an implementation/demonstration perspective. The objective in this phase is to achieve simplified algorithms which are suitable for hardware implementation. It also targets the exploration of inherent properties of the algorithm which can be exploited for low power implementations (as one of the main targets of METIS). In this context, quantization issues are studied in order to propose efficient numeric representation of the processed data.
algorithm. Impact of the proposed optimisations is assessed and compared against the MATLAB reference model and the target/estimated KPIs. Algorithm parallelisation techniques are proposed and their efficiency is characterised. Furthermore, besides the computation complexity, communication and memory requirements (size and access rates) are analysed in this phase and optimisation techniques are proposed. Results comparison considering both OFDM and FBMC transmission techniques are conducted at this phase and at all the subsequent development phases.

The second phase concerns the digital hardware architecture exploration. The objective is to exploit efficiently the proposed algorithm optimisation techniques by selecting the most suitable hardware architectural choices in order to fulfil the target KPIs. Combined algorithm/architecture optimisation techniques is explored and proposed in this context with emphasis on parallelism techniques and architecture efficiency. The outcome of this phase consists of an original architecture fully specified and ready for the hardware implementation phase. The attainable performances are also fully characterized and compared to the reference ones from the MATLAB reference models. This phase includes also the refinement of the reference software model (including the test-bench) into a bit-true model for validation and to be used as a reference for the hardware implementation.

The third phase in the development framework concerns the hardware implementation using the adequate design methodologies and tools for the devised architecture. Besides the traditional digital hardware design approaches, the DBB test-bed environment includes recent design methodologies and tools related to system-level design. The required design tools and expertise are available to evaluate and compare the implementation results at this level in terms of throughput, latency, area (complexity), energy consumption, and error rate performance. Validation and comparison with the reference software model are conducted at this level through behavioural and post-synthesis simulations.

The last phase concerns the on-board implementation and the development of the final demonstrator environment. Typically, a complete communication system which integrates the considered technical component is developed and prototyped on the target FPGA-based platform. This includes simplified models of the transmitter, the channel model, the receiver, a performance evaluation module, and a global controller.
D. Low-complexity architecture for FBMC/OQAM transmitter

FBMC/OQAM was considered to be two to three times more complex than OFDM in terms of computational and hardware complexity. This is mainly due to the OQAM processing scheme and the addition of a filtering stage. These lead to an important increase in the number of performed operations, in particular the duplication of the costly iFFT processing. In this context, we propose a low complexity design for a FBMC/OQAM transceiver requiring only one iFFT processing and running at the same data rate as in the case of an OFDM [NAB15].

The corresponding proposed architecture is based on a novel pruned IFFT algorithm proposed in [DS11] to divide the computational complexity of the FBMC/OQAM transmitter by almost a factor of two. The main idea is to exploit the relation between the iFFT outputs to only calculate half of them and deduce the remaining samples. Such a relation can be exploited thanks to the use of real valued \( a_n(m) \) PAM symbols. They introduce redundancy in the computation of the complex valued iFFT, and the outputs are symmetrical in case of real valued inputs. Figure D.1 illustrates the output sample relation for an iFFT of length \( M = 8 \) with Decimation In Frequency (DIF) decomposition (input sample in normal order, output in bit reversed order). This decomposition is obtained by a stage of radix-2 butterfly connected to two iFFTs of length \( M/2 \). In case of a filter with length \( qM \), with \( q \) being a natural number, this relation exists between even and odd index samples at the output of iFFT as demonstrated in [DS11]. Thus, one of the two iFFTs in the DIF decomposition can be removed, and \( x_n(m) \) and \( x_n(m + M/2) \) are sent in parallel, one iFFT of length \( M/2 \) can be used without increasing the clock frequency by two.

All the processing blocks except the two PPNs are modified to support the pruned iFFT implementation, as shown in Figure D.2. Concerning the receiver side, such optimization is difficult to realize in practice as the channel introduces complex coefficients which need to be equalized to recover the real orthogonality, and this step is generally achieved in frequency domain after the FFT computation.
Figure D.2: Typical FBMC/OQAM and its optimized version with pruned IFFT.