Implementation and measurement of Power Adapted-OFDM using OpenAirInterface

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***Abstract*—The Fifth Generation of mobile communications (5G) is being standardized in order to reach higher data rates and deploy new services. In this frame, researches are looking at possible waveforms to improve the air interface. Orthogonal Frequency Division Multiplexing (OFDM) has high Out-of-Band Emissions (OBE) which force us to leave wider guard bands, reducing so the spectral efficiency. Recently, we have proposed the Power Adapted-OFDM which is capable of fulfilling the requirements of 5G and avoids the main issues of other proposed candidates. OpenAirInterface (OAI) is a powerful and flexible wireless technology platform based on the Long-Term Evolution (LTE) ecosystem, which offers the possibility of evaluating the effects of introducing a new technology on the entire mobile communication system. In this paper, we will evaluate and show the performance of the proposed technique using the OAI.**

I. Introduction

Data rates have significantly grown in the last years and this increase will even be higher in the future in order to support new data-hungry services demanded by the society. Moreover, an unprecedented number of different machine-type devices will be also connected to the network, known as Internet of Things (IoT). This new network will coexist with the cellular broadband communication systems, either Fourth Generation (4G) or the future Fifth Generation (5G). Therefore, it is crucial to analyze how to efficiently make this integration.

Recently, the Third Generation Partnership Project (3GPP) has proposed to integrate Machine Type Communications (MTC) in the existing Long Term Evolution (LTE) network keeping the same waveforms and reusing as far as possible the current configuration, known as NarrowBand-IoT (NB-IoT) [1]. Additionally, a New Radio (NR) for 5G is being standardized, which will be based on Orthogonal Frequency Division Multiplexing (OFDM) [2]. Among others, 5G should be able to provide massive MTC (mMTC) which will coexist with enhanced Mobile Broad-Band services (eMBB).

OFDM has been adopted as the transmission waveform in several communication standards. Despite its advantages such as robustness against multi-path fading and ease of implementation, it also has severe drawbacks, such as high Peak-to-Average Power Ratio (PAPR) and high Out-of-Band Emissions (OBE), among others. Focusing on the high OBE, OFDM requires to leave a guard-band at both edges in order to avoid interfering adjacent bands, reducing the spectral efficiency. For example, in LTE the guard-band wastes 10% of the bandwidth. Therefore, there exists a need to define a new waveform which is capable of solving the mentioned drawback, and keep the backward compatibility, as far as possible.

The scientific community has already proposed several new waveforms capable of reducing the OBE. In the particular case of downlink, a strong technique is filtered-OFDM (f-OFDM) [3] due to its similarity to the traditional OFDM, even though the digital filters increase the Inter-symbol Interference (ISI). In order to avoid this ISI, we have proposed a new technique named as Power Adapted-OFDM (PA-OFDM) [4], which consists on using a spectral mask to give an extra attenuation to the edge subcarriers reducing the undesirable OBE. Furthermore, this technique does not increase ISI, and it also has very reduced complexity and keeps the backward compatibility.

OpenAirInterface (OAI) [5] is a powerful and flexible wireless technology platform based on the 4G ecosystem. This platform offers an open-source software-based implementation of the LTE system spanning the full protocol stack of the Evolved Universal Terrestrial Radio Access (E-UTRA) and the Evolved Core Network (EPC), defined in the 3GPP standard. Therefore, we can deploy an LTE Evolved Node B (eNB), a User Equipment (UE) and the EPC using some conventional PCs. Additionally, we can also connect Commercial Off-The-Shelf (COTS) UEs to the platform.

In the literature, there are already testbeds in order to evaluate the performance of several waveforms [6] [7], some using OAI [8]. In our case, we will deeply evaluate the new proposed technique using the OAI through some measurements. We will deploy PA-OFDM in the downlink creating what we denote as the evolved-LTE (e-LTE) signal, and we will check that the COTS UEs keep working perfectly without any issues. Moreover, we will place a NB-IoT signal in the guard-band of an e-LTE signal in order to verify that the performance of the NB-IoT signal is not compromised when the OBE of the e-LTE is reduced.

The remainder of the paper is organized as follows. Section II provides a detailed explanation of the different waveform candidates under study. In section III, we will provide the details of the deployment and configuration of the testbed. In section IV, some measurements will be shown. Finally, in Section V some conclusions will be pointed out.

Notation: x denotes a scalar value, $\mathbf{x}$ denotes a vector whose first element is $x[0]$. $\mod(x, y)$ is the modulo operation which retrieves the remainder of dividing x/y. $*$ denotes the convolution operation. $\circ$ denotes the component wise product of two vectors.

II. Description of the Waveforms

In this section, we provide a summary of the different waveforms under study.

A. OFDM

Given a continuous transmission of complex symbols belonging to an N-QAM or QPSK constellation, we split them into groups of K symbols, where each set is defined by vector $\mathbf{s}$ of size $(K \times 1)$. The modulated signal is obtained in blocks of K samples according to the following expression

$$x[m] = \sum_{k=0}^{K-1} s[k] e^{j\frac{2\pi k m}{K}}, m = 0 \cdots K-1. \tag{1}$$

Before sending each block of K samples, a cyclic prefix (CP) is added, so that the expression of the signal to be transmitted is

$$x_{cp}[m] = \left\{ \begin{array}{cc} x[m] & m = 0 \ldots K-1 \\ x[m+K] & m = -M \ldots -1 \end{array} \right\}, \tag{2}$$

where M is the length of the CP.

At the OFDM receiver, we only need to remove the CP, and perform a Discrete Fourier Transform (DFT) to each block in order to demodulate the entire signal. Thanks to the orthogonality we can process the signal as K independent subchannels.

B. Filtered-OFDM

f-OFDM is one of the proposed waveforms for the evolution towards 5G [3]. Its main feature is its simplicity and its similarity to the well-known OFDM makes it appealing to the mobile operators. The main idea is filtering the OFDM signal (see Fig. 1a) as

$$x_p[m] = p[m] * x_{cp}[m] = \sum_{n=-\infty}^{\infty} p[n-m] x_{cp}[n], \tag{3}$$

where $p[m]$ represents the filter coefficients. Thanks to this filter, the OBE will be reduced making adjacent bands available and easier to use for other purposes.

The use of this additional filter to reduce the OBE has some consequences. If we want to have an ideal filter, the order of the filter will be very high, and a strong ISI will appear compromising the performance of the system. However, if we reduce the order of the filter, not only the ISI will not completely disappear, but also the filter is no longer ideal and a transient band will show up attenuating the edge subcarriers. Therefore, it is required to increase the length of the CP in order to mitigate this additional ISI, which implies a reduction of the efficiency.

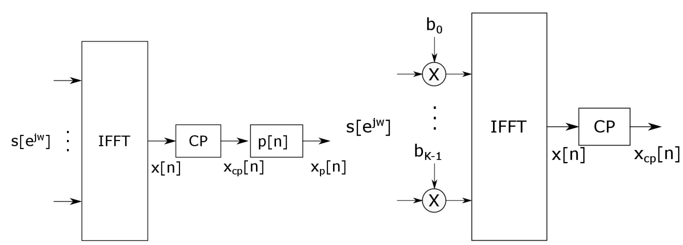
C. Power Adapted-OFDM

Given the drawbacks of f-OFDM that we mentioned before, PA-OFDM attempts to reduce the OBE without increasing the ISI. It consists in keeping the basic structure of the well-know OFDM and applying an amplitude mask to the subcarriers in order to reduce the OBE (see Fig. 1b). Before performing the IDFT operation in (1), we apply a mask to the complex symbols $\mathbf{s}$ giving

$$\mathbf{s_b} = \mathbf{b} \circ \mathbf{s}, \tag{4}$$

where $\mathbf{b}$ is the vector of coefficients of the mask specifying the attenuation of each complex symbol and $\mathbf{s_b}$ is the vector of the pre-processed symbols. Then we follow the same processing steps as for OFDM, applying (1) and (2), where $s[k]$ is substituted by $s_b[k]$ in (1).

The design of the mask $\mathbf{b}$ is crucial to reduce the OBE [4]. The idea is to reduce the amplitude value of those subcarriers which are placed at the edges of the signal band, close to the MTC signals, and increase the power of the middle subcarriers. The reason is that ICI decays linearly with the frequency separation so the edge subcarriers are mainly the ones to rise the OBE interfering to the MTC, while the middle ones of the band are insignificant in terms of OBE.



(a) Implementation of f-OFDM. (b) Implementation of PA-OFDM.

Fig. 1. Comparative of the architectures.

III. Description of the Testbed

The testbed consists of two independent systems creating two signals: a broadband signal (denoted as e-LTE) and a narroband signal (denoted as NB-IoT) (see Fig. 2). Both signals are placed contiguously in the frequency domain according to [1]. Due to the frequency misalignments (ϵ) caused by the channel effects and the imperfections of the RF chains of the transmitter and receiver, both signals will produce an Inter-Carrier Interference (ICI) to each other. The parameter ϵ is given by

$$\epsilon = \frac{\mod (D, \Delta f)}{\Delta f}, \tag{5}$$

where D is the distance of the two signals measured in Hz and Δf is the subcarrier spacing that, without loss of generality, is the same for both signals.

A. Set-up of the e-LTE signal

Due to the flexibility of OAI, it brings to the users different configurations. In our case, we have selected the most modular one, which consists on deploying the EPC and the eNB in

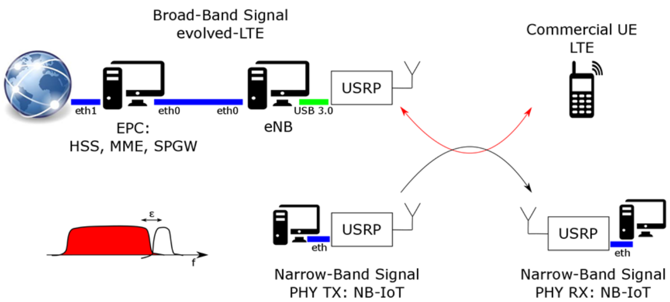


Fig. 2. Diagram of the testbed.

different PCs (see Fig. 2). The reason of this choice is to make easier the integration of commercial EPC or eNB in the future. Additionally, we have selected a COTS UE for our testbed in order to verify that PA-OFDM is fully backward compatible.

OAI also supports different hardware, in our case, we have used the following components:

- Two host PCs Intel Core-i5@3.5 GHz with UBUNTU 14.03.02 and the proper low-latency kernels in order to achieve real time processing.
- Universal Software Radio Peripheral (USRP) B210 by Ettus. This board has two independent radio-frequency (RF) chains which cover from 70 MHz to 6 GHz. OAI highly recommends the use of this terminal due to the quality of its RF chain.
- Omnidirectional antenna of 3 dBi and duplexer.
- Commercial 4G Android cell-phone.
- Programmable SIM cards for testing: sysmoUSIM-SJS1.
- Card reader: Omnikey CardMan 3121 USB CCID reader.

In order to evaluate the performance of PA-OFDM and ease the implementation, the coefficients $\mathbf{b}$ are set manually instead of implementing a full scheduler, which is out of the scope of this paper. We have followed the following steps:

- In order to configure the values of $\mathbf{b}$, we defined two additional input arguments: *N_ATT_PRB* and *ATT_VALUE* which correspond to the number of attenuated Physical Resource Blocks (PRB) at each edge of the band and the attenuation values in dB respectively.
- Added the additional multiplication of $\mathbf{b}$ to the data before calling the IDFT function, described in (4), placed at OFDM modulator function in *openair1/PHY*.
- Modified the functions of the top-level (both for the emulator and soft-modem), located in the *targets* directory, in order to add the two additional input arguments that we have defined.
- Integrated the initialization of the two defined parameters of the main data structures, placed at the directory *openair1/INIT*.

B. Set-up of the NB-IoT signal

We have used the following components in order to transmit the NB-IoT signal:

- Two host PCs Intel Core-i5@3.5 GHz with Windows 7 and LabVIEW 2015.
- USRP NI-USRP-2920 by National Instruments. This board has two independent RF chains which cover from 50 MHz to 2.2 GHz.
- Omnidirectional antenna of 3 dBi and duplexer.

The developed software is based on the source code of OFDM provided by National Instruments. Several modifications that we have done are:

- Integrated the model of the selected USRP to the source code, and set the internal gain of the USRP to 10dB, which is the recommended value.
- Developed a synchronization algorithm based on [9].
- Modified the parameters of the OFDM according to [1], such as: length of CP, size of FFT, number of used subcarriers, pilot position, etc.
- Added a Zero-Forcing equalizer at the receiver to compensate the channel.

C. Parameters of the Testbed

As we mentioned before, we are deploying our testbed with signals that are compliant with the 3GPP standards, hence all physical parameters are defined in [1]. The numerology that we have chosen for the e-LTE signal, deployed using OAI, is defined in Table I.

TABLE I
PHYSICAL PARAMETERS OF THE E-LTE SIGNAL.

Bandwidth	5 MHz	**Cyclic Prefix**	Normal
Duplexing	FDD	**Trans. Mode**	1
DL Carrier Freq.	2122.5 MHz	**UL Carrier Freq.**	1932.5 MHz

The NB-IoT signal is transmitted in the guard-band of the e-LTE signal in the downlink, and it has only one PRB. Additionally, the constellation of symbols in NB-IoT is QPSK.

IV. MEASUREMENTS

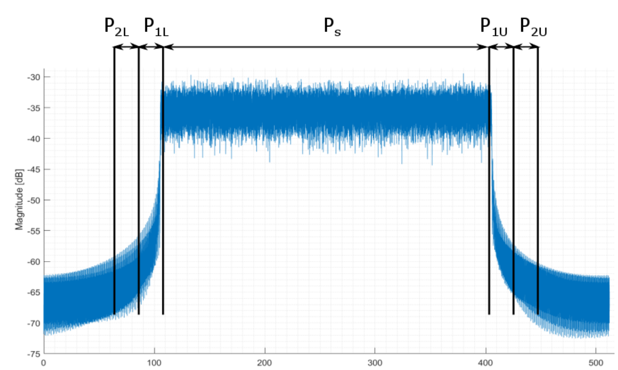


Fig. 3. Procedure of the measurement of OBE.

In this section, we will provide all the measurement results obtained with our testbed. First, we show the performance of the e-LTE signal using PA-OFDM, checking that it is capable of reducing the OBE according to our analysis. Then, we verify if the performance of NB-IoT is compromised with the presence of an e-LTE signal. Note that, this case is precisely the most critical situation due to the fact that e-LTE is a broadband signal which is capable of rising a strong ICI to its guard-bands.

A. Performance of PA-OFDM

We measure the OBE at both edges of the e-LTE signal. Specifically, we will focus on the interference power introduced on the two contiguous 200KHz bands. The reason of the choice of 200KHz is due to the fact that mMTC will occupy this bandwidth and it will be placed in the guard-bands of LTE, according to [1].

According to Fig. 3, we will measure several power values of an OFDM symbol, where P_s is the mean power of the subcarriers, P_{vL} and P_{vL} are the power of the lower and upper guard-bands respectively for the subindex v, and the subindex v is the number of the adjacent guard-band. Finally, we will compute the ratio R_{vL} and R_{vU} as

$$R_{vL} = 10\log\left(\frac{P_{vL}}{P_s}\right), \;\; R_{vU} = 10\log\left(\frac{P_{vU}}{P_s}\right). \qquad (6)$$

For the sake of space, we provide the measured OBE in Table II for all the different configuration options that we have measured. We can see that attenuating only 1PRB by 3dB (see Fig. 4a) we are achieving 3dB of improvement in the first 200KHz band. However, this improvement will be reduced as we move away from the e-LTE signal, which is not a big issue due to the low magnitude of the OBE. When the number of attenuated PRB is increased to 3 (see Fig. 4b), it shows that the improvement is the same as before. This means that the edge PRBs are the main responsible of the OBE, so attenuating only one PRB at both edges is enough to reduce the undesirable OBE. We have also attenuated 1PRB by 6dB. We can see clearly that the improvement in the adjacent 200KHz band is also 6dB.

Moreover, in Table III, we provide the simulation results for the same cases defined in Table II. Note that the absolute values of the simulation and the measurement results do not match, because in the simulation we are showing the transmitted base band signal, and for our measurements we are showing the RF demodulated signal. However the relative values of the improvement match perfectly for all cases.

TABLE II
MEASUREMENTS RESULTS

	OFDM	**PA-OFDM 1PRB, 3dB**	**PA-OFDM 3PRB, 3dB**	**PA-OFDM 1PRB, 6dB**
$\mathbf{R_{1L}}$	-30.40	-33.57dB	-33.31dB	-36.04dB
$\mathbf{R_{1U}}$	-29.12	-33.51dB	-34.63dB	-37.86dB
$\mathbf{R_{2L}}$	-45.32	-47.43dB	-46.67dB	-49.06dB
$\mathbf{R_{2U}}$	-44.88	-46.96dB	-47.20dB	-47.94dB

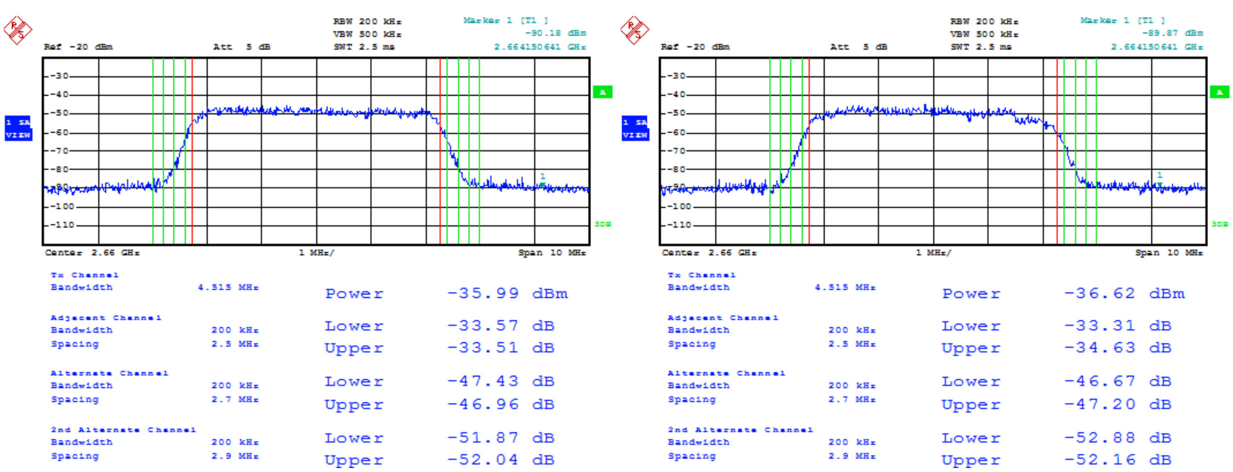
TABLE III
SIMULATION RESULTS

	OFDM	**PA-OFDM 1PRB, 3dB**	**PA-OFDM 3PRB, 3dB**	**PA-OFDM 1PRB, 6dB**
$\mathbf{R_{1L}}$	-17.66	-19.79dB	-19.86dB	-21.71dB
$\mathbf{R_{1U}}$	-17.68	-19.89dB	-19.91dB	-21.65dB
$\mathbf{R_{2L}}$	-25.57	-26.75dB	-27.16dB	-27.05dB
$\mathbf{R_{2U}}$	-25.78	-26.91dB	-27.06dB	-27.02dB

B. Performance of NB-IoT signal in the presence of e-LTE signal

We measure the performance of the NB-IoT signal in the presence of e-LTE (see Fig. 5), where the e-LTE signal could be either OFDM or PA-OFDM.

In Table IV, we show the EVM performance of the NB-IoT signal for three different cases. The first case is when there is not any e-LTE signal close to the NB-IoT signal, which is our reference case. In the second case, an e-LTE signal using OFDM is placed contiguously to the NB-IoT signal. Obviously, the performance of the NB-IoT is worse than before due to the high OBE caused by OFDM. In the third case, we use the PA-OFDM (1PRB attenuated by 3dB) instead of the standard OFDM, and we can see that the performance



(a) OBE of PA-OFDM with 1PRB attenuated by 3dB. (b) OBE of PA-OFDM with 3PRB attenuated by 3dB.

Fig. 4. OBE of different configurations.

of NB-IoT is improved compared to the second case. In Fig. 6, we also provide the constellation obtained in the three cases.

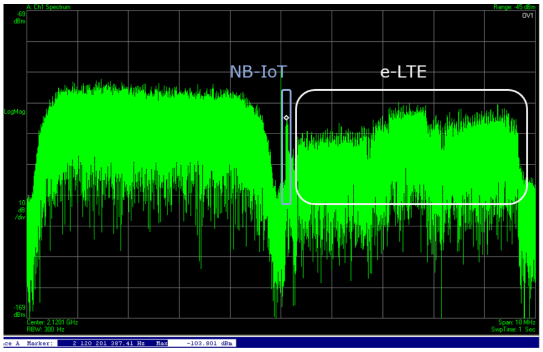


Fig. 5. Spectrum-sharing among NB-IoT, e-LTE and other signals.

TABLE IV
COMPARISON IN TERMS OF EVM OF NB-IOT SIGNAL FOR DIFFERENT CASES

Case	without e-LTE	with e-LTE OFDM	with e-LTE PA-OFDM
EVM	13.56%	29.64%	19.39%

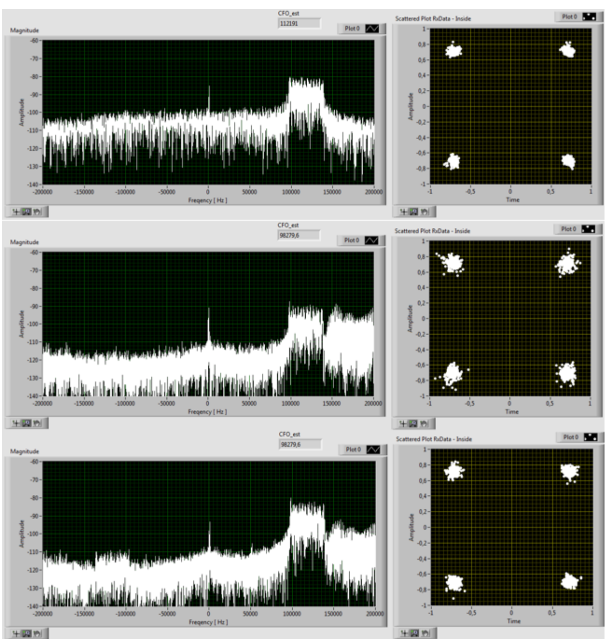


Fig. 6. Constellation of NB-IoT signal without e-LTE signal (top), with e-LTE signal using OFDM (medium) and e-LTE signal with PA-OFDM (bottom).

V. CONCLUSIONS

In this work, we have developed a testbed based on the numerology of 3GPP standards in order to evaluate PA-OFDM as a good option to allow the integration of eMBB and mMTC signals.

The implementation of the testbed shows that OAI is a powerful tool in order to do testing and verification tasks for research in the area of mobile communication systems. Its flexibility has allowed to evaluate new concepts in a realistic environment, giving us a better understanding of the behavior of the proposed system.

The measurements have shown that PA-OFDM can reduce the undesirable OBE without increasing ISI and keeping the backward compatibility. Moreover, thanks to this OBE reduction, we have also shown that deploying other services in the guard-band is possible.

In order to maximize the benefit of this new waveform, either for 5G or to improve the current 4G, some modifications should be considered. Currently, in LTE, UEs only support one Modulation and Coding Scheme (MCS) for all the allocated PRBs. However, PA-OFDM will provide PRBs with different power values in order to reduce OBE. Therefore, in order to leverage this flexibility, UEs should support different MCSs adapting to the power of the allocated PRB.

Moreover, some control channels defined in LTE, such as: Physical Control Format Indicator Channel (PCFICH) Physical Hybrid ARQ (Automatic Repeat reQuest) Indicator Channel (PHICH) are spread over several PRBs, where one of them is precisely the first PRB which corresponds to the left edge of the band. In order to ensure that control channels are transmitted with the lowest error probability, all of them should avoid the edge bands Hence, the control channels should be shifted to the middle bands, as far as possible.

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