Universal Filtered Multicarrier for Machine type communications in 5G

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***Abstract*—Machine to machine (M2M) and Internet of things (IoT) communication systems are characterized by short and bursty communication cycles. Devices may also have very low duty cycles to increase battery lifetime. Current 4G systems are not adapted to these kind of traffic characteristics. Even to send just a short packet, a user equipment (UE) first needs to synchronize to the network, establish a connection through a random access procedure, and further requires some higher layer signaling to establish end-to-end connectivity. The reduction of latency and the reduction of energy consumption are some of the key requirements for 5G communication systems. In order to achieve these requirements changes to several elements of the protocol stack are required. In this paper we are going to discuss several possible solutions for the PHY and the MAC layer. We focus on the experimental evaluation of these solutions based on the OpenAirInterface platform.**

I. Introduction

Recently emerging trends are changing traffic characteristics of mobile communication technology: Internet of Things (IoT) focuses on increasing spectral efficiency for sporadic short packet transmission in the meanwhile Tactile Internet targets to low latency communications, both foreseeing coarse synchronization procedure in order to prevent wasting of energy and saving battery duration. On the other hand, Gigabit wireless connectivity requests quick downloads of great amount of data, needing of very high data rate [2]. These applications represent the main drivers of new fifth-generation (5G) mobile wireless communications. In fact actual technology, such as Long-Term Evolution (LTE), provides wireless data connectivity accomplishing with important quality in terms of high rate and reliability but it is not designed to manage large amount of data, typical of HD video, or sporadic short packet, due to hundreds of entities placed on the same device [3]. Especially its architecture, based on Cyclic Prefix-Orthogonal Frequency Division Multiplexing (CP-OFDM), provides an optimal fading robustness combining with an easy FFT-based receiver but it doesn't fulfill certain 5G requirements. In fact its spectral efficiency is limited by cyclic prefix length, showing moreover an high spectral side lobe level. Furthermore a strictly synchronization procedure is required.

In order to overcome these drawbacks, satisfying 5G requirements, new architectures are introduced. Universal Filtered MultiCarrier (UFMC) was proposed in [4]. This waveform is based on the idea that a certain number of subcarriers can be grouped together into subbands, performing IFFT and tuned filtering operation per subband. In this way, UFMC allows to exploit coarse synchronization procedure increasing robustness against both time and frequency misalignment at the same time, having a good spectral efficiency due to the absence of cyclic prefix and decreasing out-of-band emission thanks to filtering operation. This paper is an extension of [5], where we have shown some results of real-time experiments of UFMC and Generalized Frequency Division Multiplexing (GFDM) compared to OFDM and Single Carrier-Frequency Division Multiple Access (SC-FDMA) in a cognitive radio setting, highlighting benefits of new waveforms usage for a secondary system that opportunistically exploits spectrum holes in a primary LTE system. In this paper, we focus on UFMC real-time SDR implementation, emphasizing its low computational complexity implementation of the transmitter.

II. Application Scenario

First 5G deployments will need to be backward compatible with existing 4G systems, i.e., a 5G eNB also needs to support 4G UEs. UFMC can be easily integrated into the uplink (UL) of existing 4G systems by simply replacing the last step of the SC-FDMA signal generation with an UFMC modulator (see Fig. 1). The receiver of the eNB can remain unchanged and will function normally if the UE is fully synchronized to the network. The advantage of using UFMC however is that the synchronization requirements on UE are loosened. As we will see later, the additional filtering in the UFMC signal generation results in the fact that small timing offsets do not create any interference to transmissions from other UEs in neighboring resource blocks. However, an additional timing estimation step is needed at the eNB.

UFMC thus enables the transmission of short packets without the requirement of going through the full attachment procedure. When a UE wakes up, it just needs to synchronize the cell on the DL in both frequency and time, but instead of transmitting a preamble on the physical random access channel (PRACH) to initiate the connection and allow the eNB to estimate and signal the timing advance to the UE, it simply transmits its data using the proposed UFMC transmitter on the same PRACH resources. This could be seen as a super-PRACH since it operates in the same way as the classical PRACH but at the same time allows the transmission of more information.

III. UFMC System Model

A. Transmitter

UFMC is a multicarrier system based on filtered version of OFDM. In order to have a comparison with LTE standard with 10MHz channelization, we assume to have same nomenclature and same parameters. As depicted from classical scheme of

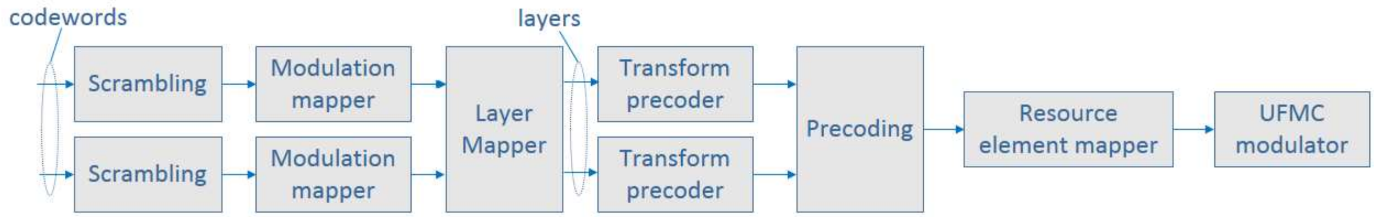

Fig. 1. Architecture of the UFMC transmitter

Fig. 2 proposed in [4], input vector $\mathbf{X} = [\mathbf{X}_0, ..., \mathbf{X}_{B-1}]^{\mathrm{T}} = [X_0, ..., X_{12B-1}]^{\mathrm{T}}$ of complex modulated samples is generated by our OAI source, also including a 12B-DFT operation performed in case of SC-UFMC. UFMC collects together a certain number of subcarriers in a block, called Physical Resource Block (PRB) for affinity with LTE. Each PRB is composed by 12 subcarriers and it is represented by $\mathbf{X}_i$. Each $\mathbf{X}_i$ is zeropadded with N-12 zeros, in order to perform a N-IDFT, obtaining $\mathbf{x}_i$, and filtered by a Dolph-Chebyshev FIR filter with sidelobe level attenuation of 60 dB, tuned to properly subband with impulsive response $\mathbf{q}_i$. Output vector of each subband branch $\mathbf{z}_i$ is finally summed with others, obtaining $\mathbf{z}$, which has the following expression:

$$z(u) = \sum_{i=0}^{B-1} z_i(u) = \sum_{i=0}^{B-1} \sum_{m=0}^{N-1} x_i(m) q_i(u-m). \quad (1)$$

where $u = 0, ..., N+L-1$ and filter length $L = L_{CP}-1$ where L_{CP} is the cyclic prefix length of LTE system, in order to get same output length of OFDM transmitter. If only a few (e.g., 1–3) PRBs shall be generated (which is the case of interest here), some optimizations with respect to scheme proposed in [4] can be applied. The classical scheme doesn't show good computational performance because a N-IDFT operation is performed on 12 complex samples, producing N complex samples that will be filtered entirely. Furthermore using a shifted version of the filter, convolution operation is performed using complex filter coefficients, redoubling the amount of operations. For the previous reason, we proposed a modified UFMC transmitter scheme, decreasing IDFT dimension using a correct upsampling and moving frequency shift operation to the end of transmission chain, as depicted in Fig. 3.

The IDFT dimension, which is indicated with *N'*, represents the heart of our computational complexity reduction process, because a value too small leads to have an high upsampling factor thus overlapping of replicated signals in frequency domain, while a value too high leads to have a small upsampling rate wasting useful computational resources. For the transmission of only one PRB, we show the UFMC spectrum (blue) shape in comparison with an OFDM spectrum (red) for different values of *N'* in Fig. 4. Using 16-IDFT and upsampling factor of 64, we can find spurious repetitions within filter bandwidth that create heavy out-of-band (OOB) emissions and therefore the quality of our signal was found to be not good. Employing 32-IDFT and upsampling factor of 32, we can find contributions of spurious repetition at the edges of filter bandwidth and it damages the spectrum in terms of OOB emission because they are not attenuated enough (around 30dB). Using 64-IDFT and upsampling factor of 16, finally we have not in-band spurious repetition and only one contribute at -60db out of band, much lower than OFDM OOB emission. Comparing 64-IDFT with 1024-IDFT, we can note that the spectrums have more or less the same shape and features but saving a lot of computational resources on IDFT operation and filtering. For this reason, we use N' = 64 improving computational performance of our scheme without losing spectrum features. System parameters are summarized in Tab. I, in according with LTE 10Mhz channelization.

B. Receiver

At receiver side, classical UFMC receiver is composed by FFT of size 2N, followed by a downsampler with a factor of 2 and by an equalizer, a Zero-Forcing(ZF) for simplicity [7]. Here we proposed to maintain same structure of LTE regular PUSCH receiver, composed by N-FFT followed by an equalizer. We can obtain this structure only if we include a timing synchronization block, which is able to estimate the delay correctly for performing FFT operation, as depicted in Fig. 5. Timing synchronization is achieved exploiting uplink demodulation reference signal (DRS), carried as third multicarrier symbol of each slot of an LTE subframe, that we call *DRS1* and *DRS2*. Assuming that the receiver doesn't know the delay of the channel, it takes complex symbols of received vector $\mathbf{r}$ within a window with dimension $2N$ around the position of the third multicarrier symbol of each slot calculated in absence of channel delay. So a 2N-FFT is performed, then multiply by the conjugate DRS sequence, already processed in the same way of UFMC signal, obtaining C_1 and C_2 respectively. Absolute square is performed followed by an element-wise sum of the vectors. At the end, a peak detection reveals the exact delay from which is possible to apply regular PUSCH receiver.

IV. Results

In this section, we describe the results of UFMC implementation compared with SC-FDMA. First of all, we focus on evaluation of computational complexity, fundamentals for real-time execution of the waveform. Then we evaluate the

System Parameters	*Value*
Channelization	10 MHz
Subcarriers per PRB	12
PRBs	1
N	1024
N′	64
L	72
Sidelobe attenuation	60 dB
Noise level	-40 dBm

TABLE I. System parameters

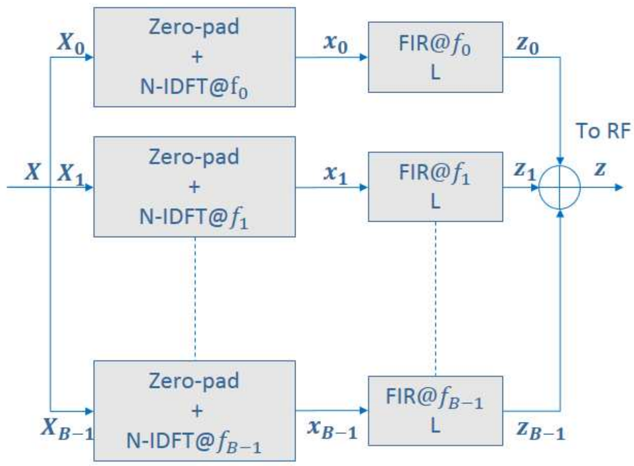

Fig. 2. Architecture of classical UFMC transmitter

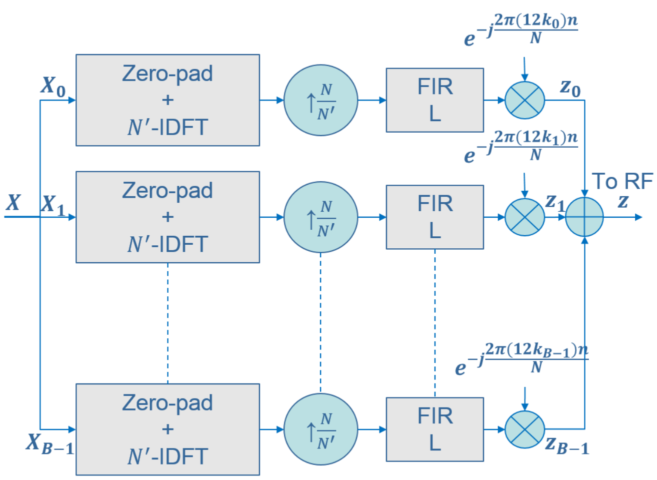

Fig. 3. Architecture of improved UFMC transmitter

performance obtained in the experimental tests using SDR hardware and supported by commercial laptop.

A. Computational Complexity

We compare the complexity of classical and novel schemes of UFMC modulator. In order to have a reference, we have also calculated CP-OFDM modulator complexity. Complexity of SC waveforms is omitted but it can be obtained simply adding the operation amount of initial 12B-DFT. Note that the complexity is evaluated only on the modulator, ignoring the amount of operation performed by encoder, frame adapter and other operations executed before, because these operations are in common with both systems. We assume the total number of real addictions and multiplications as metric of complexity. Furthermore we assume filter coefficients, shifting vectors and DRS sequences as precalculated. The metric is calculated only at the transmitter but an idea of receiver complexity is also given. Radix-3, radix-4 and radix-5 FFT algorithm has been implemented on OpenAirInterface [1]. Using LTE 10Mhz channelization parameters, as we supposed in Section III, we employ only 64 or 1024-FFT, achievable using radix-4

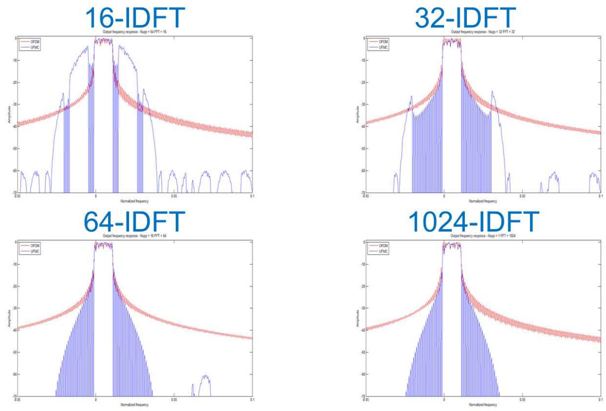

Fig. 4. UFMC spectrum(blue) and OFDM spectrum(red) versus IDFT size

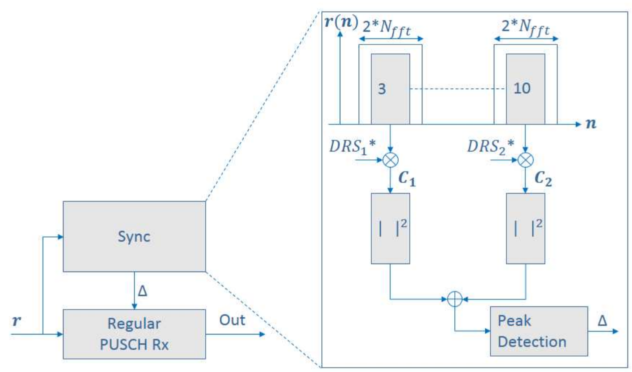

Fig. 5. Structure of proposed UFMC receiver

algorithm. Its total number of operations is evaluated in [6] and it is represented by $(\frac{3N}{8})log_2(N)$ complex multiplications and $(\frac{3N}{2})log_2(N)$ complex additions. Talking in terms of real operations, we obtain:

$$N_{FFT}(N) = 6(\frac{3N}{8})log_2(N) + 3Nlog_2(N) \tag{2}$$

The results of our comparison is depicted in Fig.6.

1) CP-OFDM Complexity: One of the best advantages of CP-OFDM waveform is represented by simplicity of its waveform based on FFT algorithm. At the transmitter, only a N-IFFT operation is performed, therefore the overall complexity is:

$$C_{OFDM} = N_{FFT}(N) \tag{3}$$

At the receiver, a N-FFT is applied for an amount of $N_{FFT}(N)$ operations, synchronization procedure excluded.

2) Classical UFMC Complexity: We calculate the complexity of classical UFMC waveform starting from the transmitter depicted in Fig. 2. We take into accounts two main operations for each subband: N-IDFT and filtering by complex tuned FIR filter. The filtering is a linear convolution over all samples outgoing from IDFT and its complexity is $6LN + 2(L-1)(N-1)$. At the end of the transmitter, the contributes of B subbands are summed for an amount of

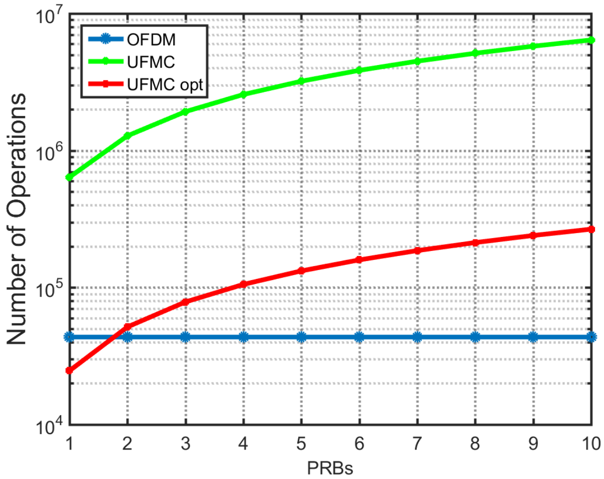

Fig. 6. Complexity of OFDM(blue), classical(green) and proposed(red) UFMC modulators

$2(B-1)(N+L-1)$ real operations. Therefore the overall complexity at the transmitter is:

$$C_{UFMC,Class} = B[N_{FFT}(N) + 6LN + 2(L-1)(N-1)] + 2(B-1)(N+L) \quad (4)$$

For completeness, at receiver side a 2N-FFT is used in [7], for a further amount of $N_{FFT}(2N)$ operations.

3) Proposed UFMC Complexity: Proposed UFMC scheme employs a N'-IDFT, followed by an upsampler with an upsampling factor $\alpha = \frac{N}{N'}$. Filter impulsive response is real and filtering is performed only on samples different to zero, obtaining a complexity of $2LN' + 2N'(L-\alpha) - (L-1)$. Then filtered signal is multiplied to complex shifting vector for moving signal in the proper subband, requiring further $6(N+L-1)$ operations. At the end, output of each subband is summed, achieving the overall complexity of:

$$C_{UFMC,opt} = B[N_{FFT}(N') + (2LN' + 2N'(L-\alpha) - (L-1)) + 6(N+L-1)] + 2(B-1)(N+L) \quad (5)$$

About receiver and its timing-synchronization block complexity, it is given by 2N-FFT performed on symbol 3 of each slot, multiplied to precalculated conjugate DRS sequence. Absolute square is performed on outputs, followed by an element-wise sum of the vectors, and finding the sample where the signal is maximum. After finding channel delay, a N-FFT operation is performed. Therefore the operation amount is $2[N_{FFT}(2N) + 6(2N) + 6(2N)]$. As depicted in 6, the proposed modulator scheme shows a constant and notable gain in terms of complexity with the increasing of the PRBs number.

B. Performance Results

In Fig. 8, we compare the performance of the UFMC with SC-FDMA receiver in terms of BLER over SNR for different modulation and coding schemes (MCS) in an AWGN channel. It can be seen that UFMC performs actually sligthly better than SC-FDMA for the same SNR, due to the absence of the cyclic prefix (therefore the total energy of one packet is less). As we

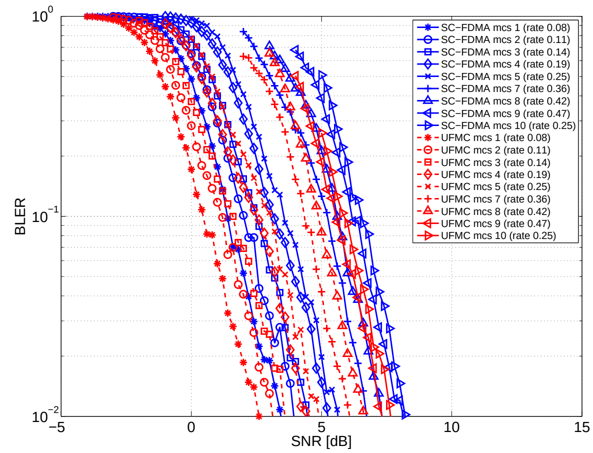

Fig. 7. Performance evaluation (BLER vs SNR) of the UFMC receiver in an AWGN channel.

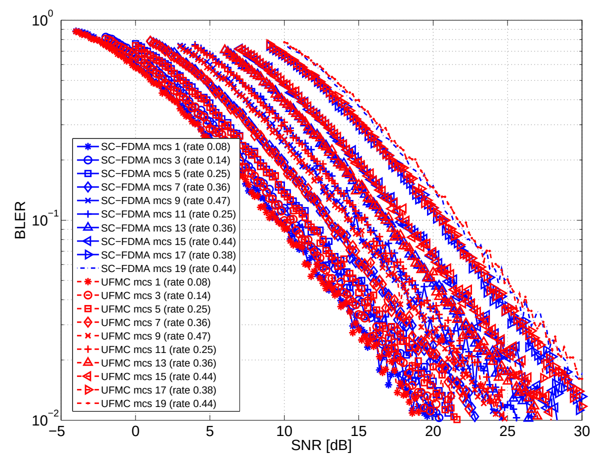

Fig. 8. Performance evaluation (BLER vs SNR) of the UFMC receiver in a Rayleigh fading channel

depicted in Fig.7, in a flat Rayleigh fading channel, UFMC shows almost the same performance than SC-FDMA. Note that these results have been obtained with perfect synchronization.

V. Conclusion

Motivated by applications such as the Internet of Things and others involving machine-to-machine communication we studied the performance of universal filtered multi-carrier (UFMC) waveforms for sporadic short packet transmissions. We have seen that UFMC can be used in a way that is backward compatible to 4G systems and does re-use most of the existing transceiver architecture. The advantage of using UFMC over classical SC-FDMA is that we can transmit data in a single shot without requiring a full attachment procedure. This could be seen as a super-PRACH since it operates in the same way as the classical PRACH but at the same time allows the transmission of more information. We have further implemented the UFMC in the OpenAirInterface platform and proposed a method for UFMC signal generation which is less complex than the original while keeping the same performance.

ACKNOWLEDGMENT

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