Waveform contenders for 5G – suitability for short packet and low latency transmissions

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Abstract— **In this paper we compare three candidate multicarrier waveforms for the air interface of 5G: filtered CP-OFDM – the choice for 4G, FBMC – heavily discussed in recent years, and Universal Filtered Multi-Carrier (UFMC) – a new contender making its appearance recently. We judge their time-frequency efficiency when transmitting very small bursts (e.g. for machine to machine communications) and under very tight response time requirements (e.g. for car-to-car communications). While FBMC is very efficient when transmitting long sequences, it suffers when having to transmit short bursts/frames. Due to the cyclic prefix and wide frequency guards, OFDM is rather inefficient. UFMC proofs to be the best choice, here, outperforming OFDM by about 10% in any case and FBMC in case of very short packets while performing similar for long sequences.**

Keywords—5G; air interface; FBMC; OFDM; UFMC

I. INTRODUCTION

This article compares filtered CP-OFDM, Filter Bank Multicarrier (FBMC) - we focus on staggered multitone, SMT [1] – and Universal Filtered Multicarrier (UFMC) [2-6] with respect to their capability to meet the huge requirement space a 5G wireless air interface will involve [7]. With the Internet of Things (IoT) being served by a 5G system, the characteristics of the bursts to be transported and of the nodes connected to the network are much more varying in various aspects: Packet size, required response time, packet frequentness (from regular to sporadic), device capabilities (from high end device with easy access to the power grid to low end sensors/actors with simple batteries) and number of devices just to name a few. In the following we focus on the first two aspects: packet size and required response time. Though, the bulk of transmissions will show similar characteristics as today, there will be a class of sensor devices (e.g. temperature sensors) and smartphone functionalities (e.g. incremental updates for stock exchange apps) sporadically transmitting very small packets. This has to be taken into account when designing the air interface to avoid wastage. Additionally, there will be services (e.g. gaming, car-to-car and car-to-infrastructure communication, respectively) requiring fast response times. Naturally, the air interface is only one component, however, very short radio frames are a prerequisite for achieving this. So, 5G will potentially require a transmission mode with very low air interface latency enabled by very short frames. As a summary the main reasons for a waveform to be suited to short burst transmissions are:

- To enable fast TDD switching for fast and flexible UL/DL switching.
- To enable low latency transmissions very short Transmission Time Intervals (TTIs) are to be employed.
- To enable energy efficient communications by minimizing on times of low-cost devices.
- To support very small packet transmissions efficiently.
- To support small signaling messages, downlink (DL) synchronization symbols and uplink (UL) sounding with high efficiency.

In this paper we analyze and compare the three waveform contenders in the light of this.

The paper is structured as follows: The next section introduces the three contenders – filtered CP-OFDM, FBMC and UFMC. Then we describe the metric (time-frequency efficiency) used for comparing them, followed by the results and comparison section. The paper ends with a conclusion.

II. WAVEFORM CONTENDERS

Filtered CP-OFDM is the most commonly known and applied multicarrier format (e.g. in 3GPP LTE and IEEE 802.11). Modulation is IFFT based. Symbols are separated with the help of a Cyclic Prefix (CP). To meet spectral specifications the complete frequency band is digitally filtered as a whole. The single subcarriers are sinc-shaped in frequency domain. Due to the cyclic prefix and required frequency guards, the time-frequency efficiency r_{TF} of filtered CP-OFDM is clearly below 1 (with 1 being the theoretic maximum in case of single antenna transmission).

FBMC has gained high attraction in the last years as potential candidate for 5G. Indeed, FBMC has some advantageous characteristics rendering it a promising contender. Instead of digitally filtering the complete band, the modulator includes a filtering functionality on a per subcarrier basis. So, instead of sinc-pulses the subcarriers have a more suitable shape according to the filter design with reduced side-lobe levels (e.g. [8]). FBMC does not apply a CP and thus is able to approach a time-frequency efficiency r_{TF} of 1 in theory (if the number of symbols to be transmitted goes towards infinity and no spectral mask has to be fulfilled). The subcarrier filters are very narrow in frequency and thus require rather long filter lengths (typically up to 4 times the basic multicarrier symbol length, indicated by the overlapping factor K – a key design parameter of FBMC) and thus the single symbols are overlapping in time accordingly. For achieving orthogonality, offset-QAM (OQAM) is to be applied. So, FBMC is not orthogonal with respect to the complex plane.

Filtered CP-OFDM and FBMC may be seen as the two extreme cases of a more general modulation paradigm. While the former filters the complete band, the latter applies filtering on a per subcarrier basis. In [2-6] UFMC has been introduced as a new waveform design representing a generalization of this principle targeting to collect the advantages while avoiding the disadvantages. With UFMC, filtering is applied on a per sub-band basis. Fig. 1 depicts the block diagram of the whole transceiver chain in UL.

The time domain transmit vector x_k for a particular multi-carrier symbol of user k is the superposition of the sub-band-wise filtered components, with filter length L and FFT length N (for simplicity we drop the time index m):

$$\underset{[(N+L-1)\times 1]}{\boldsymbol{x}_k} = \sum_{i=1}^{B} \underset{[(N+L-1)\times N]}{\boldsymbol{F}_{ik}} \underset{[N\times n_i]}{\boldsymbol{V}_{ik}} \underset{[n_i\times 1]}{\boldsymbol{s}_{ik}} \tag{1}$$

For each of the B sub-bands, indexed i, the n_i complex QAM symbols - gathered in s_{ik} - are transformed to time domain by the IDFT-matrix V_{ik}. V_{ik} includes the relevant columns of the inverse Fourier matrix according to the respective sub-band position within the overall available frequency range. F_{ik} is a Toeplitz matrix, composed of the filter impulse response, performing the linear convolution. After superposition the sum signal is up-converted and RF processed. The detector receives the noisy superposition of all user transmissions. After conversion to baseband the received signal vector may optionally be processed in time domain, e.g. windowing may be applied to suppress multi-user interference, and after FFT conversion in frequency domain (any procedure known for CP-OFDM is applicable here – e.g. related to channel estimation and equalization) to improve the signal quality. In general UFMC is an enhancement of classical CP-OFDM with the latter being a special case of the former (with L = 1). Therefore, the terminology UF-OFDM (universal filtered OFDM) is used synonymously to UFMC. Within a single sub-band, spectral properties for UFMC are alike filtered CP-OFDM, while different sub-bands are spectrally separated as FBMC separates single subcarriers. UFMC does not use a cyclic prefix (but still is able to do so to further improve on intersymbol-interference protection). The filter lengths depend on the sub-band widths. So far we typically have combined 12 subcarriers into a single sub-band, requiring filter lengths being in the range of the CP (with length L_{CP}) used in LTE (about 7% overhead). We have applied Dolph-Chebyshev filters with design parameters L (filter length) and α_{SLA} (side-lobe-attenuation). Fig. 2 depicts the impulse and frequency response for an exemplary setting.

Fig. 3 shows a single sub-band (i.e. 12 subcarriers) carrying data comparing the spectral behavior of UFMC and OFDM. Fig. 4 depicts the multiplex of 6 sub-bands applying UFMC highlighting the sub-band separation.

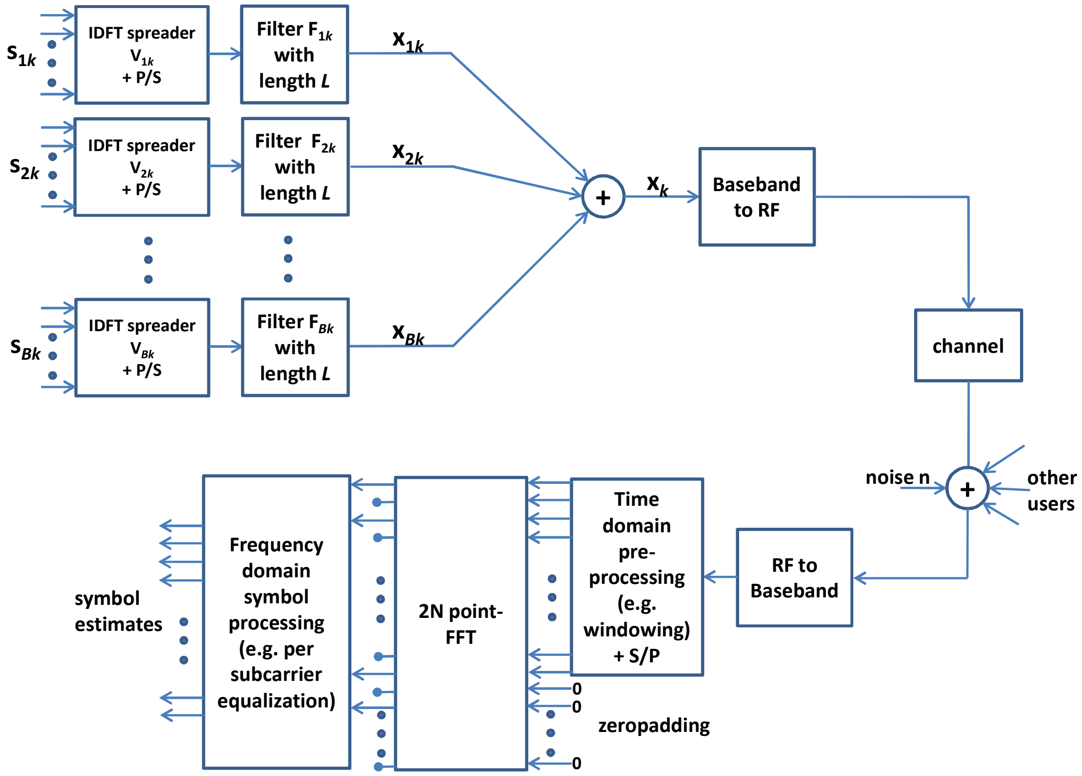

Fig. 1: UFMC transceiver (UL).

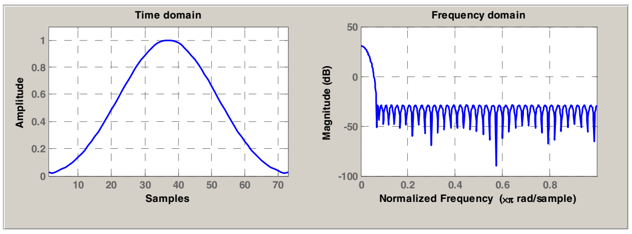

Fig. 2: Dolph-Chebyshev filter (L = 73, α_{SLA} = 60 dB).

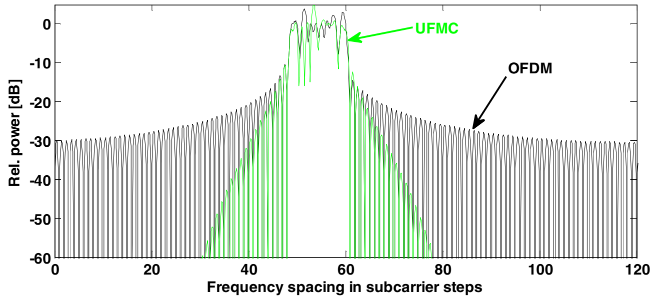

Fig. 3: Side-lobe behavior of OFDM and UFMC (subcarriers per sub-band).

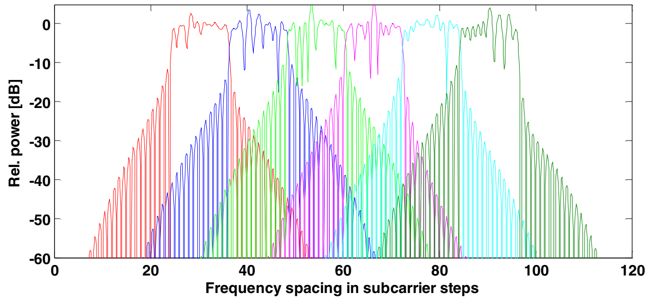

Fig. 4: UFMC - multiplex of 6 sub-bands.

The spectral behavior at the band edges is similar as with FBMC and thus UFMC is able to utilize the available spectrum as efficiently as FBMC does. As shown in Fig. 5, the single time domain symbols do not overlap in case of UFMC and thus QAM may be used for modulating the single subcarriers.

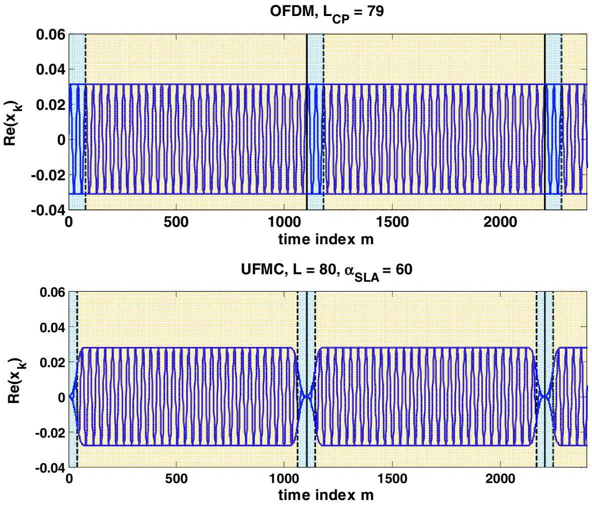

Fig. 5: Symbol trains of CP-OFDM (top) and UFMC (bottom), exemplified by a single subcarrier (real part and envelope). Light blue areas: CP and filter ramps, respectively. Light orange areas: data carrying part.

The filter ramp-up and -down areas (light blue) at the beginning and end of individual UFMC multi-carrier symbols provide a kind of "soft" inter-symbol-interference (ISI) protection, in the presence of channel delay spreads and timing offsets. With very high delay spreads sophisticated multi-tap equalizers are to be applied.

III. TIME-FREQUENCY EFFICIENCY

The characteristics of the underlying waveform of an air interface needs to be tailored to a multitude of system specifications. As a single publication is not able cover all of them, we concentrate here on the time-frequency efficiency. For further comparisons the interested reader is referred to [5,6] and future publications.

The time-frequency efficiency r_{TF} is defined as follows:

$$r_{TF} = r_T \cdot r_F = \frac{L_D}{L_D + L_T} \cdot \frac{N_u}{N'} \qquad (2)$$

r_T is the efficiency in time direction relating the information carrying body (L_D) of the burst to its overall length including the tails (L_T). Here, the use of a cyclic prefix and the lengths of the filters are of relevance.

r_F is the efficiency in frequency direction relating the number of usable subcarriers N_u (i.e. excluding guards) to the overall number of subcarriers N' within the usable band.

We are concentrating here on the very basic signal characteristics (i.e. how many data symbols may be included into a given time-frequency block). In a later publication the time-frequency efficiency will be extended taking realistic transmission aspects into account (power efficiency, interference tolerance). E.g. in a non-idealistic scenario with multi-user interference due to carrier frequency and timing offsets, the time-frequency efficiency has to be complemented by the spectral efficiency to reflect the actual achievable system throughput and overheads such as pilot symbols need to be taken into account, too. So far we assume back-to-back transmissions within a single-cell setting to compare the very basic characteristics of the analyzed waveforms.

When calculating the respective efficiencies, we rely with filtered CP-OFDM on existing solutions, e.g. LTE, make use of published results with FBMC and provide a more detailed analysis for UFMC.

IV. RESULTS

As indicated in (2) the overall efficiency consists of two elementary coefficients. On the one hand we need to quantify the efficiency degradation due to time domain overheads (e.g. filter ramps, cyclic prefix) on the other hand we need to look at frequency domain overheads (e.g. frequency guards to meet a given spectral window).

A. *Time domain efficiency*

We start with evaluating the time efficiency of CP-OFDM, FMBC and UFMC:

$$r_T = \frac{L_D}{L_D + L_T} \qquad (3)$$

The time efficiency is characterized by the ratio of the length of the information carrying body of the transmitted burst to its overall length. If we assume the burst to contain M multicarrier symbols (each comprising N samples), we get:

$$L_D = MN \tag{4}$$

Regarding the tails the contenders differ as follows:

$$\begin{aligned} L_{T,UFMC} &= M(L-1) \propto M \\ L_{T,CP-OFDM} &= ML_{CP} \propto M \\ L_{T,FBMC} &= \left(K - \frac{1}{2}\right) N \neq f(M) \end{aligned} \tag{5}$$

As indicated in (5) $L_{T,*}$ (with * being a placeholder for CP-OFDM and UFMC) are depending on the number of symbols the burst is constituted of (obvious, as here, each single symbol has tail(s)), i.e. the overall length is proportional to M. This is different for FBMC. Here, the overlapping factor K and the number of samples per multicarrier symbol are the relevant quantities. While being advantageous for long bursts, this feature is unfavorable for very short burst transmissions. A means to improve on this aspect is e.g. burst truncation [9].

B. Frequency domain efficiency

Next is the efficiency in frequency direction:

$$r_F = \frac{N_u}{N'} \tag{6}$$

Here, the required parameters are the number of subcarriers N' fitting into the given frequency range and the number of subcarriers actually usable for carrying data (so far we do not distinguish between data and pilots). Using LTE as reference and assuming a transmission bandwidth of 10 MHz with subcarrier spacing 15 kHz we get:

$$N' = floor\left(\frac{10MHz}{15kHz}\right) = 666 \tag{7}$$

with *floor(x)* being the closest integer smaller than x. According to the standard the number of subcarriers actually carrying data is:

$$N_{u,OFDM} = 600 \tag{8}$$

For FBMC assuming a design tailored for very low out-of-band radiation (e.g. [8]) one subcarrier guard at each side of the band is sufficient and thus we get:

$$N_{u,FBMC} = 664 - (N_g - 1) \tag{9}$$

N_g reflects the number of users sharing the band: As outlined earlier, FBMC (SMT) is not orthogonal with respect to the complex plane [1]. Therefore, we need an additional guard subcarrier to separate UL transmissions (if complex precoding is applied the same holds for DL transmissions) of users being allocated adjacent in frequency. This is necessary as the transmissions of different users are experiencing different channel gains introducing multi-user interference at the allocation edges. So, N_g equals the number of users sharing the transmission time interval (assuming continuous user allocations).

In case of UFMC $N_{u,UFMC}$ depends on the choice of L and α_{SLA}. Figs. 6 and 7 depict the spectral behavior of the signal envelopes of OFDM and UFMC at the edge of the fully occupied band without additional filtering.

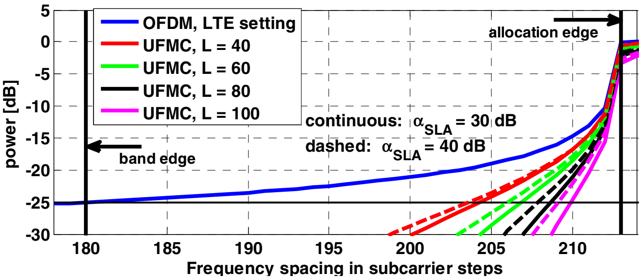

Fig. 6: Band edge behavior of OFDM and UFMC (α_{SLA} = [30, 40] dB).

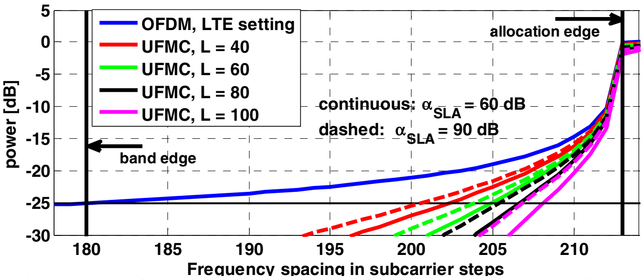

Fig. 7: Band edge behavior of OFDM and UFMC (α_{SLA} = [60, 90] dB).

Obviously, the out-of-band radiation of UFMC arrives at the same power level as OFDM exhibits at the edge of the overall band with less distance to the data carrying block, thanks to the reduced side-lobe. Argumentum e contrario: The data carrying area may be made wider accordingly. So, with applying UFMC we are able to use $N_{u,UFMC}$ subcarriers for transmitting data as given in the following table to meet the same spectral properties at the band edge as with OFDM.

TABLE I. $N_{u,UFMC}$ FOR VARIOUS SYSTEM SETTINGS:

	α_{SLA}=30dB	α_{SLA}=40dB	α_{SLA}=60dB	α_{SLA}=90dB
L=40	650	648	646	642
L=60	654	652	650	648
L=80	658	656	654	652
L=100	660	660	658	654

UFMC is orthogonal with respect to the complex plain. So, we do not need to add additional guard subcarriers between the user transmissions as with FBMC.

C. Overall time-frequency efficiency

Combining the results so far, Fig. 8 compares OFDM and UFMC with respect to their time-frequency efficiency for various system settings. The x-axis corresponds to the length of the filter (L) and the CP-length (L_{CP}), respectively. The black vertical line reflects the design used by LTE (normal CP mode). For UFMC we have computed the time-frequency efficiency for various side-lobe attenuations α_{SLA}. UFMC outperforms CP-OFDM for any setting by about 10 %.

Fig. 9 adds FBMC to the investigation and fixes the side-lobe attenuation of UFMC to 60 dB. We assume a system with N_g = 15 users sharing the available bandwidth. The FFT length N equals 1024. UFMC applies α_{SLA} = 60 dB and various filter lengths L. Overlapping factor K in case of FBMC is 4. M is the number of multicarrier symbols per burst. The black horizontal curve corresponds to a system based on CP-OFDM applying LTE settings. The blue curves depict the performance of a system applying UFMC. The independency of the performance of a system applying OFDM or UFMC on M is obvious.

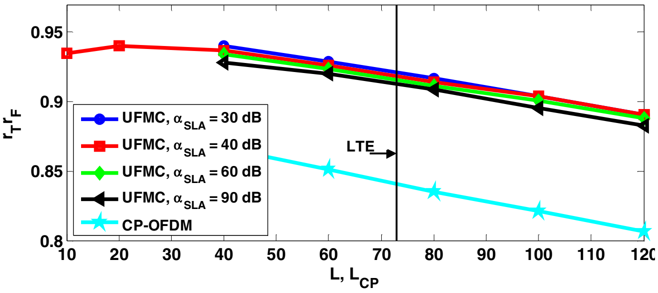

Fig. 8: Time-frequency efficiency of filtered OFDM and UFMC. L and L_{CP} are filter length and CP length, respectively.

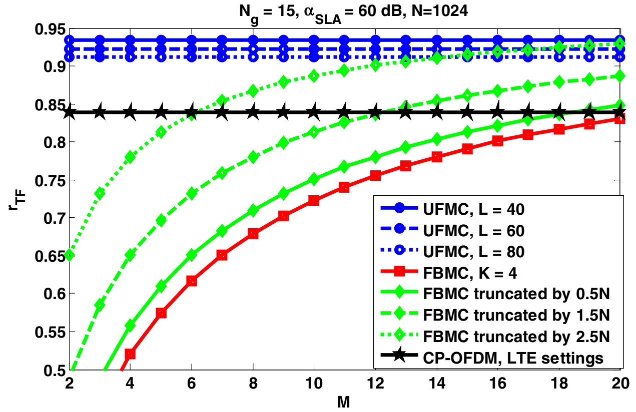

Fig. 9: Time-frequency efficiency of FBMC, CP-OFDM and UFMC. M is the length of the respective burst.

UFMC outperforms OFDM of about 10 % and brings additional benefits such as higher robustness to time and frequency misalignments and improves spectral properties (e.g. for supporting fragmented spectrum scenarios). FBMC is very efficient with long bursts (high M). However, the time-frequency efficiency degrades significantly in case of small M as L_T does not scale with M for FBMC in contrast to UFMC and CP-OFDM. With burst truncation [9] the efficiency loss may be reduced at the cost of added intercarrier interference and increased out-of-band radiation hitting the edge symbols of the burst. Thus, burst truncation is able to fit FBMC better to short burst transmissions, however, infringing the original design targets. Fig. 10 compares UFMC, FBMC and truncated FBMC (truncated by 2.5 symbol lengths) in terms of overall burst lengths ($M = 5$).

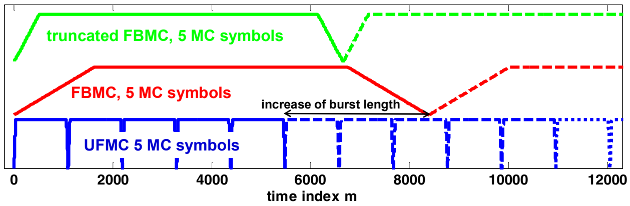

Fig. 10: Effective burst lengths for UFMC, FMBC and truncated FBMC.

Note that M not only refers to the TTI length, but additionally to the length of further control and data elements required for the system, which are to be inserted into the overall frame, such as DL synchronization and UL sounding symbols, UL random access preamble, UL ACK/NACK messages etc. This significantly adds overhead to an FBMC based system.

V. CONCLUSIONS

While UFMC is able to make use of the available spectrum with similar efficiency as FBMC (both outperforming OFDM), it does not suffer from high time domain overheads as FBMC does, unless burst truncation is applied increasing interference and introducing spectral regrowth.

So, UFMC is the best choice for a system targeting to include an option for short burst transmissions into the overall design. This is required to support fast TDD switching, enable low latency modes, support small packet transmissions (e.g. from machine type devices and UL control messages) with low energy consumption (on-time of the device) and with high efficiency. Additionally, the added overhead introduced by FBMC makes the integration of DL synchronization, UL sounding symbols and small UL control messages (ACK/NACK) very inefficient. These problems are avoided if UFMC is applied.

ACKNOWLEDGMENT

Part of this work has been performed in the framework of the FP7 project ICT-317669 METIS, which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues in METIS, although the views expressed are those of the authors and do not necessarily represent the project.

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