Abstract — 5G will have to cope with a high degree of heterogeneity in terms of services and requirements. Among these latter, flexible and efficient use of all available non-contiguous spectrums for different network deployment scenarios is one challenge for the future 5G. To maximize spectrum efficiency, the 5G air interface technology will also need to be flexible and capable of mapping various services to the best suitable combinations of frequency and radio resources. In this work, a fair comparison of several 5G waveform candidates (UFMC, FBMC, and GFDM) has been proposed under a common framework. Spectral efficiency, power spectral density, peak to average power ratio and robustness to asynchronous multi-user uplink transmission are assessed. The benefits of these new waveforms for the foreseen 5G use cases are clearly highlighted and it is also underlined that some concepts still need to be improved to achieve the full range of expected benefits of 5G.

Keywords — waveform; spectral efficiency; PAPR; multi—user access scheme; GFDM; UFMC; FBMC

I. INTRODUCTION

The fourth generation of wireless network (4G) is currently massively rolled-out but it is also known that it will quickly reach its limits. To face this issue, 3GPPP started to discuss 5G requirement during the RAN 5G workshop held in September 2015 leading to an emerging consensus that there will be a new, non-backward compatible, radio access technology as part of 5G [1].

As the availability of large amount of contiguous spectrum is getting more and more difficult to guarantee, the aggregation of non-contiguous frequency bands is considered for future generations of wireless networks (a.k.a. 5G) to meet higher data rates and/or improve access flexibility [2]. This requirement of spectrum agility has encouraged the study for alternative multicarrier waveforms to provide better adjacent channel leakage performance without compromising spectral efficiency. On the other hand, sporadic access has been identified as one of the significant challenges future mobile access networks have to face. In order to reduce battery power, a mobile node may be configured to enter a dormant state as rapidly as possible after a data transaction. This feature, called fast dormancy has been identified as the root cause of significant signaling overhead on the cellular network [3]. Consequently, relaxed synchronization schemes have been considered to limit the amount of required signaling. This is the case for instance when the mobile node carries only a coarse knowledge of time synchronization. In the expected 5G, the massive number of devices and the support of multi-point transmissions will thus imply the use of relaxed synchronization, potentially leading to strong inter-user interference.

Even though Orthogonal Frequency Division Multiplexing (OFDM) is the most prominent multi-carrier modulation technique in wireless standards for below 6GHz transmission, it also exhibits some intrinsic drawbacks. An important frequency leakage is caused by its rectangular pulse shape; the cyclic prefix insertion drives to a spectral efficiency loss; and fine time and frequency synchronization is required to preserve the subcarrier orthogonality that guarantees a low level of intra and inter-cell interferences. To overcome these limitations, several alternative candidates have been intensively studied in the literature in the past few years, such as Universal Filtered Multi Carrier (UFMC) [4], Generalized Frequency Division Multiplexing (GFDM) [5] and Filter Bank Multicarrier (FBMC) [6]. Multiple references in the literature focus on different receiver architectures and scenarios for these waveform candidates. However, to the best of our knowledge, a fair comparison between the different waveforms in the context of an asynchronous multi-user scenario is lacking.

In this work, the multi-user interference is modelled by a bandwidth shared between two users. The user of interest is assumed to be perfectly synchronized (in both time and frequency domains) with its serving base station whereas the second user suffers both from timing and carrier frequency offsets. The performance of the candidate waveforms (GFDM, UFMC, FBMC) are compared and discussed for several delays and carrier frequency offsets, for different number of guard carriers, and according to different waveform parameters. We also discuss the possible variants for UFMC and GFDM to optimize the performance for the multi-user access scheme by selecting the appropriate parametrization of the waveforms. The baselines for comparison are the LTE waveforms, namely Cyclic Prefix OFDM and SC-FDMA (Single-Carrier Frequency Division Multiple Access).

We also compare the spectral efficiency (SE), the power spectral density (PSD) and the peak to average power ratio
(PAPR) for each waveform candidate in this study. This paper thus proposes a fair comparison regarding different criteria that are representative for benchmarking 5G waveforms.

This paper is organized as follows: the main 5G waveforms candidates are presented in section II. A comparison in terms of spectral efficiency, power spectral density and PAPR is described in section III. The simulated results for multi-user access scheme scenario are eventually discussed in section IV.

II. WAVEFORMS

In this section, we briefly introduce the main 5G waveform candidates that will be compared and studied in section III and IV.

a) Cyclic Prefix- Orthogonal Frequency Division multiplexing (CP-OFDM)

CP-OFDM is a well-known multi-carrier modulation (which serves as the physical layer for 3GPP-LTE or 802.11.a/g/n) where a block of complex symbols is mapped onto a set of orthogonal subcarriers. The OFDM transceiver scheme is depicted in Figure 1. The important characteristic of OFDM is that the frequency to time (resp. time to frequency) transform can be done with an Inverse Fast Fourier Transform (IFFT) (resp. FFT) process of size \( N_{FFT} \) and thus allows a Tx (resp. Rx) architecture with low complexity. Besides, as the total bandwidth is divided into \( N_{FFT} \) subcarriers, the channel equalization can be reduced as a one tap coefficient per subcarrier if the coherence bandwidth of the channel is large enough. Finally, as the subcarrier orthogonality can be broken by the channel effect (leading to strong inter-carrier interference), a cyclic prefix (CP) is inserted, i.e. the end of the symbol is appended to its beginning. The CP guarantees circularity of the OFDM symbol (and thus no inter-carrier interference) if the delay spread of the channel is lower than the CP length. It however leads to a loss of spectral efficiency, as the CP is used to transmit redundant data.

b) Single Carrier- Frequency Division Multiple Access (SC-FDMA)

SC-FDMA mode is used for the uplink of 3GPP-LTE; it is also called Discrete Fourier Transform (DFT)-Spread OFDM. It is indeed a modulation based on the previously introduced CP-OFDM, with an additional stage of precoding before the IFFT. This precoding is used to limit the PAPR of the transmitted signal. It is implemented by a DFT applied before the IFFT at the transmitter (and an IDFT at the reception stage after the FFT). A synopsis of the transceiver is depicted in Figure 2.

The transmitted signal, due to the concatenation of the DFT-IFFT scheme, can be approximated by a single carrier signal, and therefore achieves a lower PAPR compared to a classical multicarrier modulation. SC-FDMA has the same spectral efficiency as CP-OFDM due to the same CP insertion. PSDs of SC-FDMA and CP-OFDM are also the same as carrier mapping stages are the same.

c) Filter Bank Multicarrier (FBMC)

FBMC consists in a set of parallel data that are transmitted through a bank of modulated filters. It is parameterized by the prototype filter that controls the time and frequency localization of each carrier. The choice of the filter can lead to a lower Adjacent Channel Leakage (ACL) but introduces interference between consecutive carriers and between successive symbols. This issue can be solved by the use of Offset Quadrature Amplitude Modulation (OQAM) modulation that (asymptotically) maximizes spectral efficiency [6].

The classical architecture for FBMC is based on polyphase network, but an alternative architecture, called Frequency Spreading (FS) FBMC, has been proposed, based on the frequency sampling technique [7]. The prototype filter is defined in the frequency domain. The overlapping factor \( K \) defines the \( 2K − 1 \) non-null points of the filter in the frequency domain. For \( K = 4 \), the filter parameters are defined as

\[
H_0 = 1, \quad H_1 = H_{−1} = 0.971960, \quad H_2 = H_{−2} = \frac{\sqrt{2}}{2}, \quad H_3 = H_{−3} = \sqrt{1 − H_1^2}
\]

The complex modulated data is first transformed into OQAM data: real and pure imaginary alternate in the time-frequency lattice, guaranteeing orthogonality. Then, the OQAM symbols are filtered in the frequency domain. The result then feeds an IFFT of size \( KN_{FFT} \). The final step is a parallel to serial converter, which performs an overlap and sum operation [8]. The transmitter is depicted on Figure 3.

Each OQAM symbol is transmitted every \( N_{FFT}/2 \) samples, and has a length of \( KN_{FFT} \) samples [9]. A frame structure for FBMC is depicted on Figure 4, and is compared to classic CP-OFDM.

At the receiver side, the dual operation of the overlap-and-sum operation of the transmitter is a sliding window in the time domain.

Figure 3. FBMC Tx stage

Figure 4. CP-OFDM (top) and FBMC (bottom) frames
domain that selects $K N_{\text{FFT}}$ points every $N_{\text{FFT}}/2$ samples. A FFT is then applied every block of $K N_{\text{FFT}}$ selected points. Equalization is applied using a single tap equalizer and is followed by filtering by the prototype matched filter. Because the size of the FFT is $K$-times larger than the multicarrier symbol time period, the signal at the output of the FFT is oversampled by a factor of $K$ with respect to the carrier spacing. This property gives a significant advantage to FS-FBMC receiver when the channel is exhibiting large delay spread [10].

d) Universal Filtered Multicarrier (UFMC)

UFMC is a derivative of OFDM where a group of subcarriers is filtered in the frequency domain. It has been introduced by Alcatel-Lucent [11]. The subband filtering has been motivated by the fact that the smallest frequency element in 3GPP-LTE is a resource block (RB), which is a group of 12 subcarriers. The filtering operation leads to an ACL lower than for OFDM.

The UFMC transmitter depicted in Figure 5 [12] is composed of $B$ subband filtering operations (combined with frequency mapping), that modulate the $B$ data blocks. The $B$ signals are then summed. The transmitted signal uses no CP, but a spectral efficiency loss is due to the transient state of the shaping filter (of length $L$) introduced by the convolution. The filter is also defined by the stop-band attenuation; in the rest of the paper a 40dB attenuation filter was chosen, as it is widely used in the literature [4] [12].

The Rx stage is composed of a $2N_{\text{FFT}}$ point FFT receiver (the initial received signal length is $N_{\text{FFT}} + L - 1$ so zero-padding is applied before the FFT), which is next decimated by a factor 2 to recover the data [13]. It is also possible to insert before the receive FFT a windowing stage. This stage introduces interference between carriers but could be interesting to consider when asynchronous uplink transmission is considered (we will see this effect hereafter). It indeed helps to separate contiguous users and therefore leads to an overall gain of performance (see section IV).

e) Generalized Frequency Division Multiplexing (GFDM)

GFDM was introduced in 2009 by Vodafone Chair Mobile Communications Systems [5] and is based on the time-frequency filtering of a data block, which leads to a flexible but non-orthogonal waveform. A data block is composed of $K$ subcarriers and $M$ time slots, and transmit $N = KM$ complex modulated data. Each data is filtered by a filter that is translated into both frequency and time domains. Thus, as the symbols overlap both in frequency and in time, interference (between sub-symbols and between symbols) occurs.

To avoid inter-symbol interference, a CP is added at the end of each symbol of size $KM$. The GFDM waveform is parametrized by its shaping filter, which is usually chosen to be a Root Raised Cosine (RRC) filter [14]. To further lower the ACL, a windowing process can be added in the transmission stage. It however increases the interference level, that can be mitigated at the receiver stage with a tail-biting approach [5]. Several receiver architectures can be used. In this paper we consider two receivers: the matched filter (MF) and the zero forcing (ZF) schemes. In the MF approach, each received block is filtered by the same time and frequency translated filters as in the transmission stage. This approach has a low complexity but, as the modulation is non-orthogonal, offers poor performance due to inter-symbol interference. It is thus necessary to implement an interference cancellation scheme [15], which improves the performance but severely increases the complexity of the receiver (as the IC scheme is based on the reconstruction of the $a$-priori transmitted GFDM signal). In the ZF approach, the signal is decoded with the pseudo-inverse of the transmitter matrix. The ZF-receiver does not introduce self-interference but suffers from noise amplification and its performance depends on the properties of the transmitter matrix [14]. The GFDM transceiver is described in Figure 6.

III. SPECTRAL EFFICIENCY, PSD & PAPR COMPARISON

In section II, 5G waveforms candidates have been introduced, and their main parameters and architectures have been described. In this section, we compare the waveforms regarding several criteria: their power spectral density, their spectral efficiency and their peak to average power ratio.

a) Spectral efficiency

First, we compare the waveforms in terms of spectral efficiency (SE) expressed in bit per second per Hertz versus the time duration of the burst. We consider the parameters (based on LTE 10MHz) described in Table 1.

For OFDM, SC-FDMA, GFDM and UFMC, the spectral efficiency does not depend on the burst duration and is a function of the FFT size, the modulation order and the modulation parameters. OFDM and SC-FDMA have the same spectral efficiency defined as
If we compare the spectral efficiencies of GFDM and OFDM:

- **GFDM SE** is higher than OFDM SE if the frequency grid is fixed (i.e., same number of data carrier and same FFT size). Each GFDM symbol contains more modulated complex samples \( (M \times N_x) \) for GFDM versus \( N_x \) for OFDM (and the size of a GFDM subsymbol is equal to the size of an OFDM symbol without the CP insertion). The SE increase for GFDM is due to the use of one CP per \( M \) sub-symbols.

- The GFDM SE is identical to the OFDM SE if we consider a constant data block size (i.e., \( N_x \times M = N_{OFDM}^{OFDM} \) and \( K M = N_{FFT} \)). It means that the frequency grid is modified, and divided by \( M \). In such a case, the GFDM symbol size is the same as the OFDM one (the sub-symbol size is thus \( 1/M \) compared to OFDM symbol size), and the frequency spacing is \( M \) times higher.

In our case, we have fixed the frequency grid, which means that the GFDM SE is thus higher than the OFDM SE.

For FBMC, the SE depends on the frame duration. The SE loss is due to the transient state of the global shaping filter. Thus, there is no constant loss per symbol (compared to other waveforms) and the SE increases with the burst duration to reach an asymptotic level equal to the modulation order. If we denote \( S \) the number of symbols, the SE for FBMC is expressed as:

\[
\eta_{FBMC} = \frac{m \times S \times N_{FFT}}{2N_{FFT} + 1} \frac{K}{S + K - \frac{1}{2}}
\]

We compute the SE of the different waveform candidates, versus the duration of the burst. Results are depicted in Figure 7 with \( m = 2 \). It is shown that UFM has the same SE as OFDM (as the filter length has been defined to this end) and that GFDM has a better SE compared to OFDM and UFM. The SE loss for GFDM is low as the CP is added only once per symbol which means that there is \( M \) times less CP for GFDM compared to OFDM. Besides, FBMC SE depends on the time duration, and is better than OFDM and UFM if the burst duration is longer than 3.5 ms (when \( K = 4 \) and \( m = 2 \)). It asymptotically reaches the modulation spectral efficiency and is comparable to GFDM if the burst duration is higher than 18 ms.

### b) Power Spectral Density

In this section, we compute the power spectral density of the candidates. We consider the parameters described in Table 1,

<table>
<thead>
<tr>
<th>Table 1. Simulation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overall parameters</strong></td>
</tr>
<tr>
<td>FFT size</td>
</tr>
<tr>
<td>Bit per Symbol</td>
</tr>
<tr>
<td>Resource block size</td>
</tr>
<tr>
<td>Number of active RB</td>
</tr>
<tr>
<td>( N_{RB} ), ( N_{RB} )</td>
</tr>
<tr>
<td>72 samples</td>
</tr>
<tr>
<td>Sampling frequency</td>
</tr>
<tr>
<td><strong>OFDM and SC-FDMA parameters</strong></td>
</tr>
<tr>
<td>Cyclic prefix</td>
</tr>
<tr>
<td><strong>UFMC parameters</strong></td>
</tr>
<tr>
<td>Filter length</td>
</tr>
<tr>
<td>Stop band attenuation (db)</td>
</tr>
<tr>
<td><strong>GFDM parameters</strong></td>
</tr>
<tr>
<td>Number of sub-symbols</td>
</tr>
<tr>
<td>FFT size</td>
</tr>
<tr>
<td>Roll Off factor</td>
</tr>
<tr>
<td><strong>FBMC parameters</strong></td>
</tr>
<tr>
<td>Spreading factor</td>
</tr>
<tr>
<td>Asynchronous access parameters</td>
</tr>
<tr>
<td>Guard carriers</td>
</tr>
<tr>
<td>Timing Offset</td>
</tr>
<tr>
<td>Carrier Frequency Offset</td>
</tr>
</tbody>
</table>

---

**Figure 6. GFDM transceiver**

\[ \eta_{OFDM} = \eta_{SC-FDMA} = m \times \frac{N_{FFT}}{N_{FFT} + N_{CP}} \]

Where \( m \) is the modulation order. For UFM, a SE loss is due to the transient state of the shaping filter. The SE is expressed as:

\[ \eta_{UFMC} = m \times \frac{N_{FFT}}{N_{FFT} + L - 1} \]

In the rest of the paper, we choose \( L = N_{CP} + 1 \), in order to have the same SE between UFM and OFDM. The obtained filter length is then very similar to filter lengths used in the literature [12].

For GFDM, the CP insertion is done per symbol and the SE is expressed as:

\[ \eta_{GFDM} = \frac{m \times K \times M}{M \times K + N_{CP}} \]

**Figure 7. Spectral efficiency vs burst duration for QPSK**
except for the carrier allocation. To better stress the impact of the ACL, we consider 2 users that occupy 36 subcarriers (3 RBs), with 12 guard subcarriers (1 RB) as guard band. The PSD is depicted in Figure 8. The PSD of SC-FDMA is the same as OFDM and thus has not been plotted.

The best spectral location is obtained with FBMC (here with an overlapping factor of 4). GFDM has a slightly lower ACL compared to OFDM but is clearly outperformed by UFMC. With the addition of the windowing process, GFDM PSD becomes comparable to the UFMC PSD.

c) **PAPR comparison**

We compute the CCDF of the PAPR for the considered waveforms, for a burst duration of 3ms and with the parameters described in Table 1 with QPSK modulation. The PAPR is defined as

\[
PAPR = \frac{\max(|y[k]|^2)}{E[|y[k]|^2]}\]

Results are depicted in Figure 9. SC-FDMA, due to its (quasi) single carrier property, offers the best performance. The other modulations, which are multicarrier, have a higher PAPR and none of the multicarrier candidate with the chosen parametrization offers better performance than OFDM. However the gap is small, ~0.5dB.

It should be noted that the PAPR can be reduced by changing the waveform parameters or by the addition of specific reduction method. It is however beyond the scope of this paper, and should be addressed jointly with other criteria (such as PSD, SE …).

IV. **MULTI-USER ACCESS SCHEME**

a) **Principle and parameters**

In this section, we compare the performance of the waveform candidates in a typical multi-user asynchronous access scheme [2].

We consider 2 users, User Equipment (UE) 1 and UE 2. The first user is assumed to be perfectly synchronized in time and frequency domains (i.e. no timing offset, and no frequency offset) with its serving base station. The secondary user suffers from a delay error (i.e. a timing offset) and a potential frequency offset (a synchronization mismatch with downlink channel). Figure 10 illustrates this scenario.

Due to the timing and frequency errors, the secondary user interferes with the first one. The first user is decoded (assuming a perfect channel with no noise), and the performance in terms of Mean Square Error (MSE) on the decoded constellation is evaluated. This MSE gives information about the interference level introduced by the secondary user.

Part of these results have been presented for UFMC and OFDM in [2], [4] and [16] and for GFDM in [17]. However, to the best of our knowledge, no comparison results have been made, and the influence of architectures (Rx stage, presence ofwindowing …) and CFO have not been intensively studied.

We consider the 5G waveforms candidates presented in the previous section

- OFDM and SC-FDMA, which serve as references: these two waveforms have the same performance, so only OFDM curves are plotted on the next figures.
- UFMC: the classical UFMC and UFMC with windowing at the receiver stage are studied. The windowing process introduces self-interference for UE 1, but limits the
interference level from the secondary user, which improves the MSE performance if the delay error does not belong to the CP interval.

- GFDM, with and without the windowing. With windowing, tail-biting procedure is added. Besides, for GFDM without windowing, two architectures are considered for the Rx stage: Matched Filter and Zero-Forcing (denoted as GFDM for MF, and GFDM-ZF for ZF),

- And FBMC.

The first user has 3 RBs allocated and 9 RBs are allocated for the second user as in [4]. The spacing in terms of guard carriers (GC) between the 2 users is variable: no guard carrier (contiguous allocation), 1 guard carrier, 2 guard carriers, and 5 guard carriers.

The timing offset between the 2 users is expressed as the ratio between the effective delay and the FFT size (here set to 1024). Besides, the Carrier Frequency Offset (CFO) $\Delta$ is expressed in percent of the subcarrier spacing. The rotation factor introduced by the CFO on time sample $n$ is

$$\phi_{\text{CFO}}(n) = e^{-\frac{2i\Delta n}{N_{	ext{FFT}}}}$$

We describe in Table 1 the parameters used for the asynchronous access scheme simulation.

b) Performance without CFO

In this section, we consider the impact of the time delay error without CFO. We first consider different variants for GFDM to extract the most suitable configuration for the waveform. We do the same for UFMC and we finally compare GFDM, UFMC and FBMC in their best cases.

- GFDM: influence of receiver architecture

As described in section II-e, we consider 2 GFDM receivers, one based on the MF filtering (with interference cancellation scheme on the receiver side), and one based on the ZF architecture. We illustrate in Figure 11 the MSE for the two receivers, versus the delay error, for several number of GC. It is shown that for negligible delay errors, the ZF receiver has better performance than the MF one. It is also shown that ZF, due to the noise increase, does not preserve the performance within the CP. If the delay error increases, the MF approach exhibits better performance. In the rest of the paper, we thus consider the MF receiver for GFDM, as it has more consistent performance and because the receiver is less complex.

- GFDM: influence of windowing

We have depicted in Figure 8 that windowing for GFDM greatly improves the ACL, as it improves the spectral isolation between users. We plot in Figure 12 the performance with and without windowing for GFDM. It is shown that the performance without windowing are better in case of low delay error value (as the interference introduced by the windowing effect is non negligible), but that the performance are increased as soon as the error delay does not belong to the CP interval anymore. This is due to the trade-off between the self-interference introduced by the windowing process (loss of performance when inter-user interference is low) and the isolation gain between users offered by the windowing (which is noticeable when the delay error increases).

- UFMC: influence of windowing

The windowing effect for UFMC is different from GFDM as the windowing is applied on the receiver side, and thus has no consequence on the ACL of the transmitted signal. It however also increases the performance in the multi-user scenario as shown on Figure 13. These results are very similar to the results presented in [4] and [16] and validate the positive impact of the windowing scheme for UFMC in the multi-user asynchronous access scenario.

- Performance of FBMC

The performance of FBMC is displayed in Figure 14. Due to the very good spectral location of the FBMC prototype filter, the MSE reaches its lower bound at soon as a guard carrier is inserted. The performance is besides independent from the delay error value. If no GC is added the MSE is around -26dB which means that the interference level is not negligible.

- Comparison between waveforms

We now compare the different waveforms. Results are depicted in Figure 15, in which UFMC with windowing (on the receiver side) has been considered. Concerning GFDM, we have
applied windowing, and chosen the MF receiver, as it leads to better global behaviour for both waveforms.

We also compute the performance of CP-OFDM for comparison. First we show that all the waveforms outperform CP-OFDM if the delay error does not belong to the CP interval. On the contrary, if the delay is in the CP interval, OFDM is the best modulation (as the CP prevents from the interference). We show that GFDM always exhibits better performance than UFMC, excepting however when both the delay is very small and no GC is inserted. If there is at least one GC, FBMC outperforms all the candidates as the interference introduced by the secondary user is null.

As a conclusion, GFDM is a promising candidate for the multi-user asynchronous access scheme. However, without GC, none of the candidate can offer a MSE lower than \(-30\)dB on the whole delay range. At the price of the insertion of one GC, only FBMC can null the interference from the secondary user. In these conditions, FBMC offers the best performance in the multi-user asynchronous access scheme (provided the delay does not belong to the CP).

c) **Influence of CFO**

We now consider the performance with an additional CFO of 10%. We use the same waveform candidates with the same parameters as above (i.e. GFDM with windowing and MF receiver with IC, UFMC with windowing) and performance is compared. Results are illustrated in Figure 16.

Due to the additional interference introduced by the CFO, the MSE is higher for all the waveforms, except for FBMC with at least one GC. For OFDM, the orthogonality cannot be preserved anymore and a strong interference level is present even if the delay error belongs to the CP interval. Besides, without GC, the performance of GFDM and FBMC become very similar, and are slightly better than UFMC out of CP. If the GC number is non-null, FBMC exhibits no interference, and the hierarchy between the other candidates is the same as without CFO. In terms of performance, CFO has thus a non-negligible impact especially when no GC is inserted.

d) **Conclusion and summary**

Flexible and efficient use of all available non-contiguous spectrums for widely different network deployment scenarios are one challenge for the future 5G. To maximize spectrum efficiency, the 5G air interface technologies will need to be flexible and capable of mapping various services to the best suitable combinations of frequency and radio resources. Therefore flexibility and good frequency localization of the waveform are a key requirement. Legacy OFDM/SC-FDMA waveforms could be a good candidate if a filtering process is added. However, as the number of possible configurations is large, the associated complexity will be very high. Therefore the frequency agility is very limited in that case.
UFMC waveform is an interesting option. The spectral efficiency is comparable to the one of OFDM and the pulse shaping function gives robustness to access with loose synchronization compared to OFDM. With UFMC backward compatibility with well-known OFDM algorithms (Channel estimation, MIMO detectors...) is also preserved. New waveforms such as FBMC or GFDM go further. The well localized frequency response entitled the use of fragmented spectrum with minor interference on adjacent bands. Very good performances are demonstrated in non-synchronous access (whatever the time delay between users). However, under the time-frequency localization relationship the time localization is sacrificed making these new waveforms difficult to adapt to short packet size. On the other hand, the absence of guard period gives efficiency gain for larger packet size. One other challenge FBMC waveform need to face is the adaptation to MIMO. It is not straightforward and concepts have to be revisited. Finally, the intrinsic complexity of the transceiver is higher (it is also true for GFDM) compared to OFDM transceivers. However, to be fair, FBMC transceiver complexity need to be compared with an OFDM one with embedded digital or analog filtering functions. In that case, when flexibility is required, the complexity of these new transceivers could be few orders of magnitude below. Finally a synthesis radar chart is depicted in Figure 17 summarizing all these information (where MUAC stands for Multiple User Access Scheme). OFDM is defined as reference. Waveforms parameters are those defined in Table 1.

Flexible and efficient use of all available non-contiguous spectrums for widely different network deployment scenarios are one challenge for the future 5G. To maximize spectrum efficiency, the 5G air interface technologies will need to be flexible and capable of mapping various services to the best suitable combinations of frequency and radio resources. In this work, a fair comparison of several 5G waveform candidates (UFMC, FBMC, GFDM) has been proposed under a common framework. Spectral efficiency, peak to average ratio and robustness to asynchronous multi-user uplink transmission are assessed. The benefits of new waveforms for the 5G use cases have been clearly highlighted. UFMC offers improvements keeping backward compatibility with legacy OFDM. FBMC and GFDM go forward making these waveforms particularly interesting for 5G scenarios. However, we underline that some concepts should be revisited – MIMO, short packet adaptation – for a future deployment.

**ACKNOWLEDGMENT**

This work has been performed in the framework of the Horizon 2020 project FANTASTIC-5G (ICT-671660) receiving funds from the European Union. The authors would like to acknowledge the contributions of their colleagues in the project, although the views expressed in this contribution are those of the authors and do not necessarily represent the project.

**REFERENCES**


non-orthogonal, asynchronous waveforms for future mobile applications," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 97-105, February 2014.


