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FBMC/OQAM Transceiver for Future Wireless Communication Systems: Inherent Potentials, Recent Advances, Research Challenges

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ABSTRACT The applications and services envisioned for the sixth Generation (6G) Internet of Things (IoT) communication systems will place different requirements on the system design. The current 5G waveform, Orthogonal Frequency Division Multiplexing (OFDM), suffers from a list of drawbacks that questions its suitability and ability to fulfill these prerequisites. Filtered multi-carrier waveforms provide viable alternatives for future mobile networks. Based on the best recent advances including contributions by the authors, this work provides a comprehensive assessment of the current status and future challenges related to the design of a next-generation Filter Bank Multi-Carrier/Offset Quadrature Amplitude Modulation (FBMC/OQAM) transceiver. We start by showing how the next-generation FBMC/OQAM waveform can overcome the drawbacks of OFDM. Furthermore, we highlight the advantages and possibilities of extending the next-generation FBMC/OQAM waveform for massive Multiple-Input-Multiple-Output (mMIMO) in well-identified 6G-IoT scenarios. Results show that the next-generation FBMC/OQAM receivers associated with short prototype filters can unleash appealing properties for 6G-IoT applications. Considered a cornerstone for grant-free spectrum and massive access, asynchronous communications are shown to be achievable. Furthermore, a largely improved robustness is observed compared to OFDM under different channel impairments such as carrier frequency offsets, timing offsets, and multipath channels. Compared to the original FBMC/OQAM associated with long filters, this next-generation transceiver achieves a reduction in complexity down to a comparable level to OFDM. Finally, open research opportunities and challenges for the next-generation FBMC/OQAM waveform are discussed.

INDEX TERMS 6G, Filter-bank multi-carrier (FBMC), Internet of Things (IoT), massive MIMO (mMIMO), orthogonal frequency-division multiplexing (OFDM).

I. INTRODUCTION

Wireless data traffic has significantly expanded due to the rapid advancement of smart terminals, and the emergence of new applications [1]. Moreover, with the increasing number of connected devices, the sixth Generation (6G) Internet of Things (IoT) is expected to set the foundations of future interactions within our society [2]. Indeed, it defines the technical enablers of a simple and seamless interconnection among sensors, computing capabilities, and

machines, through communications and data transfers for a target application providing a service [3], as depicted in Fig. 1.

The current fifth Generation (5G) cellular network cannot fully support the demanding corresponding technical constraints [4]. 6G is expected to offer enhanced services [5] to tackle these challenges. Ultra-Reliable Low-Latency Communications (URLLC) in 6G (6G-URLLC) will bring features such as 10 times less latency [6] and increased reliability by at

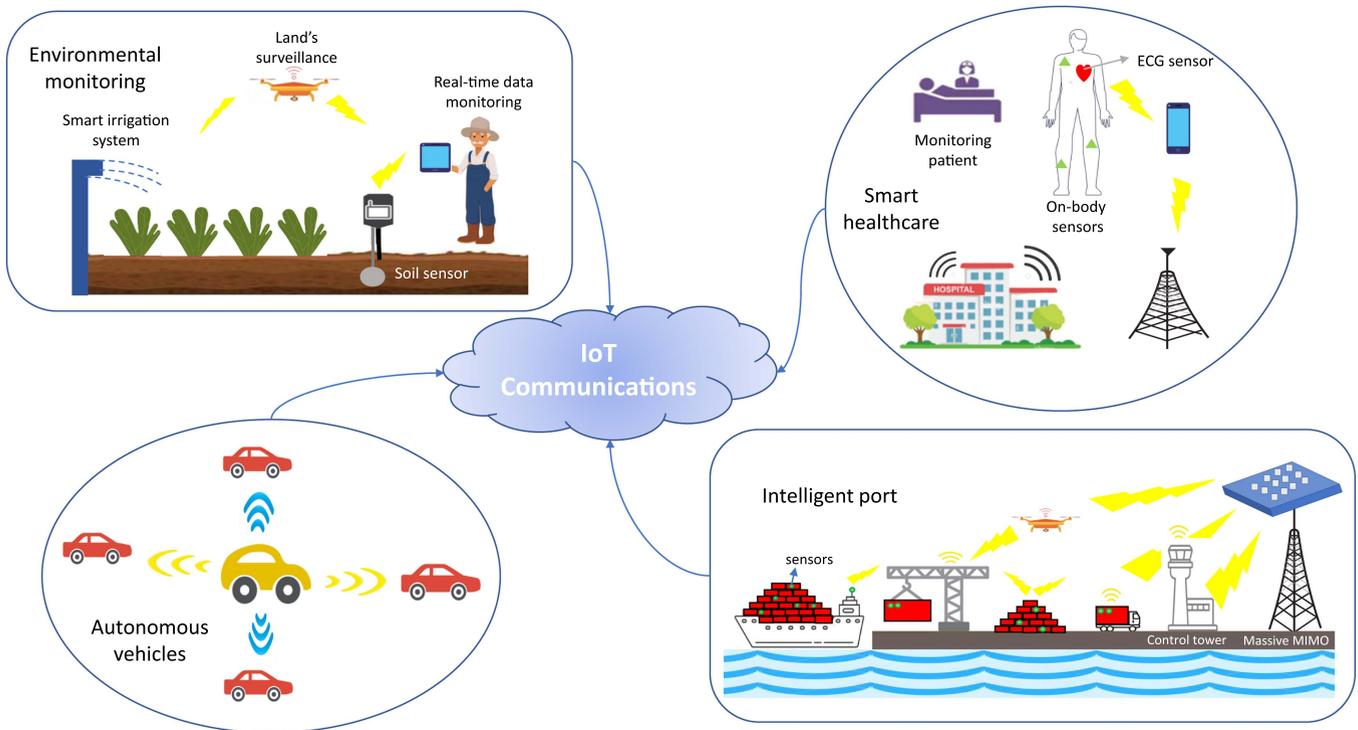


FIGURE 1. Illustration of some 6G-IoT applications: environmental monitoring, smart healthcare, autonomous vehicles, and intelligent ports.

least two orders of magnitude compared with existing cellular networks [7].

Furthermore, the 6G network is anticipated to provide 10 times higher system capacity and user density [5] for supporting services like surveillance cameras and high-resolution video streaming, which require continuous transmission and relatively high throughput [8]. Therefore, massive Multiple-Input-Multiple-Output (mMIMO) can be considered as a promising solution for scenarios where there is no major constraint on power consumption and where several devices must be controlled simultaneously, including the aforementioned scenarios, remote factories, and intelligent ports [9] as shown in Fig. 1.

Special emphasis on the battery life of mobile devices and some service classes is included in the 6G vision and requirements proposed in [10]. For instance, some costumers might be willing to pay a higher price for a device with a battery life that lasts for one week or even longer [10].

Therefore, in some 6G-IoT applications such as environmental monitoring depicted in Fig. 1, the signaling overhead due to hand-shaking in the synchronization procedure, and for setting up the transmission must be minimized. This is a key requirement prior to serving a large number of energy-constrained connected devices. As potential solutions, relaxed synchronization and asynchronous communications were considered [11]. The first corresponds to users transmitting simultaneously. However, since each user is positioned at a different distance from the Base Station (BS), the associated signal is impacted by a distinct propagation delay. A receiver

must compensate for the introduced Timing Offset (TO) in order to have an energy-efficient network. The second case corresponds to users transmitting with an independent time reference. Therefore, scheduled users are not synchronized in time. Consequently, the time difference between users can be greater than the symbol duration.

However, supporting the aforementioned scenarios with Orthogonal Frequency Division Multiplexing (OFDM) is a challenging task since it degrades the performance and increases receiver complexity. This reduces the spectral efficiency since the Cyclic Prefix (CP) duration must be greater than the relative TO between users. Nevertheless, despite being adopted in 5G thanks to its simplicity and robustness to multipath, OFDM presents several drawbacks: high sensitivity to Carrier Frequency Offsets (CFO) coupled with a high Out-Of-Band-Power-Leakage (OOBPL) [12], [13], [14]. Fine synchronization and guard bands are required to avoid compromising multiple access and for the co-existence of multiple services. However, this comes with a non-negligible impact on system requirements in terms of spectral and energy efficiency, throughput, and latency. To provide such flexibility, the waveform design plays a major role [15].

Thanks to its robustness to the aforementioned impairments, Filter Bank Multi-Carrier using Offset Quadrature Amplitude Modulation (FBMC/OQAM abbreviated as FBMC for simplicity) was widely studied in the literature as a candidate waveform for 5G [16], [17], [18], [19]. However, at that time FBMC had its share of challenges, such as increased complexity due to the PHYDYAS long Prototype

Filter (PF) [20], and the lack of complex orthogonality, penalizing the support of certain widely used OFDM techniques for MIMO [21]. Therefore, the original FBMC was not maturely studied in the literature to be rendered as the waveform for the current 5G wireless communication systems.

In recent years, several innovative contributions have been proposed for enhancing the original FBMC at the transmitter and receiver side. The authors in [22] proposed a novel short PF that considerably reduces hardware complexity and energy consumption when combined with original receiver techniques. A novel FBMC receiver technique was proposed in [23]. The resulting receiver significantly improves the robustness against doubly dispersive channels, reduces computational complexity, and supports asynchronous communications. Some of the aforementioned advantages were highlighted in the context of mMIMO systems in [24].

Therefore, the objective of this paper is first to provide an assessment of the current status of the FBMC/OQAM waveform based on compiling the best recent contributions. Then, guidelines for future research endeavors are described in the aim of designing a next generation transceiver tailored for 6G applications. Particularly, we investigate and exploit the advantages of incorporating the new findings of [22], [23], and [24] for the design of a flexible Next-Generation (NG)-FBMC transceiver mainly for the uplink and its corresponding stringent requirements. We also analyze the advantages of extending the NG-FBMC to mMIMO systems. We show how the joint application of several recent innovative solutions largely improves the suitability of the FBMC waveform for 6G-IoT applications and discuss the open research possibilities and future challenges.

The rest of the paper is organized as follows. Based on prior art, Section II provides the transceiver architecture of the original FBMC waveform along with its advantages and drawbacks. Then, NG-FBMC transceivers and their corresponding features are detailed in Section III. Their extension to mMIMO systems is described in Section IV. Section V evaluates the performance of the NG-FBMC waveform for Single Input Single Output (SISO) transmissions and mMIMO systems under different channel impairments. This is followed in Section VI by a brief survey of the research opportunities regarding NG-FBMC transceivers. Finally, Section VII concludes the paper.

II. ORIGINAL FBMC WAVEFORM: DESCRIPTION, ADVANTAGES, DRAWBACKS

FBMC emerged as a candidate waveform to OFDM largely thanks to the results provided by the PHYDYAS project [20]. In FBMC waveform, a filter-bank applying a PF is introduced to effectively pulse-shape the transmitted signal over each subcarrier. It plays a significant role in controlling the amount of transmit power carried by the secondary pulse lobes. This provides greater flexibility for managing the OOBPL at the cost of added complexity at the transmitter and receiver sides. Also, this represents a major difference with respect to the rectangular pulse-shaping of OFDM [25]. The absence of a

CP is another difference to OFDM that can lead to improved spectral efficiency at the cost of more complex equalizer schemes.

Traditionally, two distinct FBMC transceiver implementation types with different levels of complexity and performance were proposed in the literature: *PolyPhase Network* (PPN)-based [26] and *Frequency Spread* (FS)-based [27]. The first is usually employed at the transmitter side due to its lower complexity [28]. On the other hand, the FS implementation is mostly adopted at the receiver side thanks to its low-complexity equalization process [29], [30].

Fig. 2(a) depicts the PPN-based implementation. To support orthogonality in the real domain, OQAM processing is introduced [31]. First, the real and imaginary components of the QAM signal must be separated as shown in Fig. 2(a). After phase rotation, the imaginary component is time delayed by half of the duration of a FBMC symbol. This is followed by a size- M Inverse Fast Fourier Transform (IFFT). A PPN processing is implemented next, where the IFFT output is replicated $K - 1$ times, with K being the overlapping factor. After, a windowing operation is applied using the impulse response of the PF having a length of $L = KM$. Finally, the resulting components are summed up to provide the transmit signal. As shown in Fig. 2(a), the transmitted FBMC symbols overlap in time, hence the FBMC signal is not made up of successive and separate block symbols.

To use a low-complexity subcarrier-based equalizer at the receiver side, the filtering stage was moved into the frequency domain for the FS implementation. As depicted in Fig. 2(b), both receiver-side implementations apply dual operations with respect to the ones performed by the transmitter. For the PPN-based implementation, the operations must be performed in the following order: PPN, FFT of size M , and OQAM demapper. The FS-FBMC receiver first applies an FFT of size KM on the received signal containing the FBMC symbol to demodulate, comparatively increasing its complexity. This is followed by a filtering stage in the frequency domain. Finally, the recovered pulse amplitude modulated symbols are obtained by extracting the real part of quadrature phase rotated and down-sampled signal.

It is worth noting that the overlapping factor K of the PF has a significant impact on the complexity of the FBMC transceiver. The most known PFs are the long Isotropic Orthogonal Transform Algorithm [32], [33], [34], and the long Martin, Mirabassi, Bellange (MMB4) PFs. The latter has an overlapping factor of $K = 4$ times larger than an OFDM symbol and is the most adopted in the literature [35], [36], [37], [38]. The MMB4 PF is highly localized in the frequency domain since the interference is limited to only one adjacent subcarrier.

Fig. 3 summarizes Key Performance Indicators (KPIs) for the original FBMC with long and short filters ($K = 1$) and for OFDM. At a first glance, it may seem that the long-filtered FBMC is complementary to OFDM in terms of the selected KPIs. Due to its simple implementation and robustness to multipath, OFDM has been adopted in multiple standards,

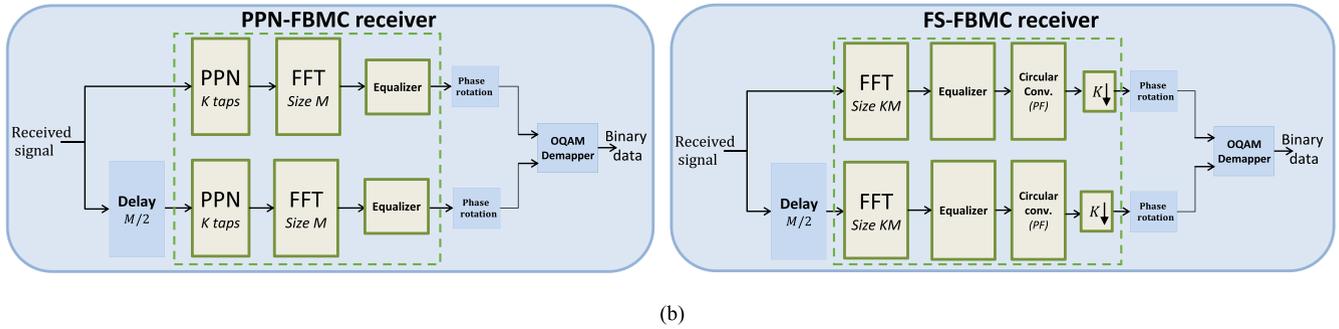
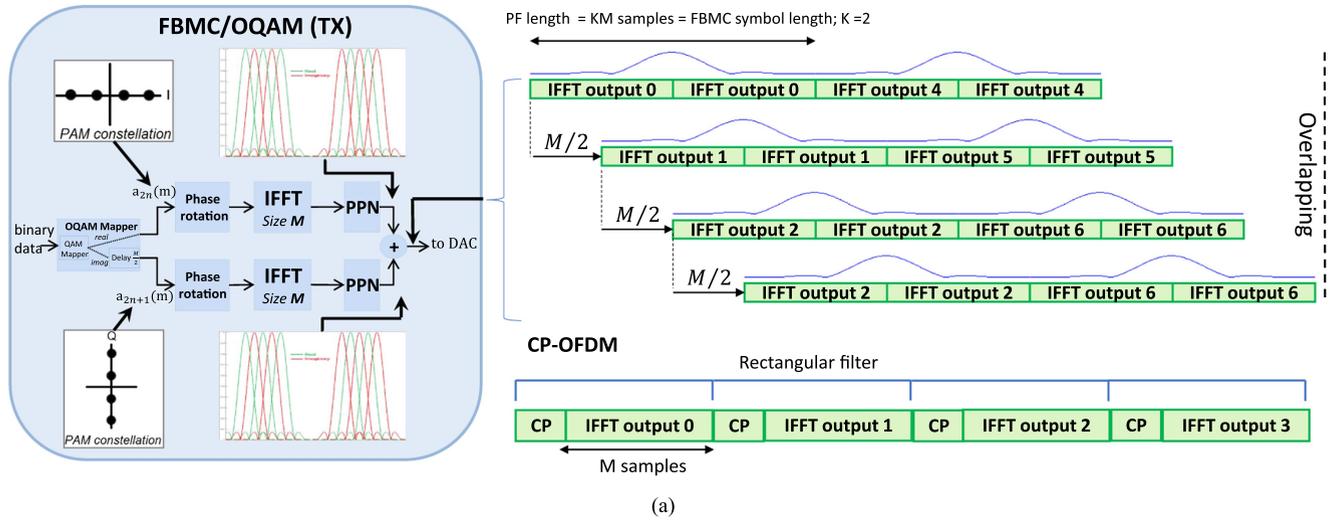


FIGURE 2. Overall original FBMC system illustration. (a) PPN-based FBMC transmitter implementation. (b) PPN and FS-based receiver implementations.

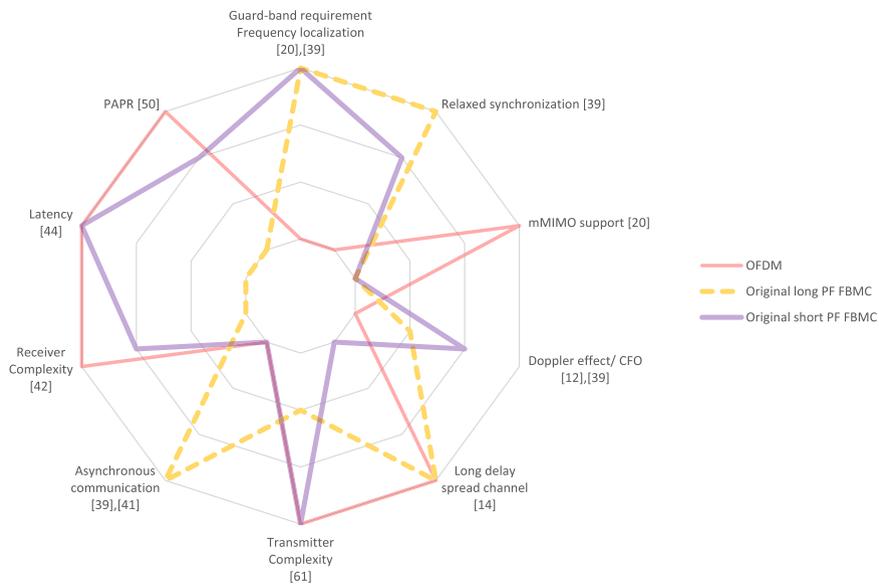


FIGURE 3. Comparison of different properties between original FBMC and OFDM waveforms. A larger circle radius represents a better system performance.

including 5G. Despite the aforementioned advantages, OFDM still suffers from several drawbacks, including a slightly lower spectral efficiency and a high sensitivity to imperfect synchronization due to its low-frequency localization [39].

TO impairments occur when the processing windows at the transmitter and receiver are not aligned in time, yielding residual interference. Concerning OFDM, the TO at the receiver must be within the CP length to guarantee a reliable communication. However, the propagation delay of the transmitted signal will be constantly changing due to the user and/or transmitter mobility, introducing time-variant TOs. A closed loop time advance mechanism is implemented to overcome such variable timing misalignment in current 5G systems [40]. In this case, the BS monitors each user's uplink timing, requiring additional hand-shake rounds. However, for massive Machine-Type Communications (mMTC), it is desirable to establish a simplified access procedure that enables Grant-Free (GF) communication. Therefore, the first requirement derived from the aforementioned problem is asynchronous communication. Yet, the latter cannot be supported by OFDM, which may hinder its adoption in future communication systems requiring ultra-low latency and reliability, such as autonomous vehicles.

The original FBMC associated with long PFs is robust to long-delay spread channels [17]. It also supports asynchronous communications when utilizing a FS-FBMC receiver [41], which is crucial for some 6G-IoT applications, including driver attention monitoring. However, the combined use of a long PF and a FS implementation comes at the cost of a high transceiver complexity [42]. Indeed, on one hand, the computation of a larger FFT is required for the FS-based implementation, and on the other hand, higher processing capabilities are required for the PPN implementation.

Another well-known drawback of the original FBMC resides in its difficulty to support efficient mMIMO systems due to intrinsic interference [20]. Furthermore, a significant drawback of FBMC employing long PFs resides in the introduction of a ramp-up and ramp-down at the beginning and end of each transmitted frame. Consequently, this results in a higher Peak-to-Average Power Ratio (PAPR) level compared to OFDM [43] and compromises the support of short-frame sizes for low-latency communications [44]. Few solutions have been investigated to address the latency problem [45], [46] that came at the cost of an increased transmitter complexity and a higher OOBPL. Therefore, further progress is needed in order to effectively support short frame sizes and low latency with long PFs.

To address complexity problems, short PFs ($K = 1$) including the Time Frequency Localization 1 (TFL1) [47] and the Quadrature Mirror Filter 1 (QMF1) [48] have been previously proposed. Additionally, FBMC with short PFs is more robust against CFO than with long PFs [39]. However, the use of short filters comes with its share of drawbacks, namely a reduced robustness against long-delay spread channels and a lack of support for asynchronous communications [39] which are crucial for low latency applications requiring GF access.

In summary, the introduction of short filters achieves a different KPI tradeoff, especially in terms of performance/complexity, as seen in Fig. 3. Therefore, the ability to devise a flexible FBMC transceiver capable of striking different KPI tradeoffs becomes particularly appealing in the quest for addressing major FBMC drawbacks while retaining its advantages.

III. NEXT-GENERATION FBMC TRANSCEIVERS

Motivated by the advantages related to the use of a short PF, we compiled recent works that target the design of such a filter coupled with advanced receiver techniques to fully benefit from the inherent advantages of filtered waveforms while largely alleviating corresponding complexity.

A. NEAR PERFECT RECONSTRUCTION SHORT PF

When using a 4 times shorter PF (i.e. $K = 1$), the PPN processing performed on the IFFT output in Fig. 2(a) becomes a windowing operation. Moreover, the FFT of the FS implementation becomes of the same size as for OFDM, added to the advantage of applying equalization before the receiver side, hence avoiding the spreading of potential channel impairment effects due to filtering. Therefore, the usage of short PFs highly addresses the complexity problem for both FBMC transceiver types. Consequently, it is expected that a reduction in power consumption can be achieved when compared to the use of long PFs for the corresponding hardware implementations.

As mentioned in Section II, the extended symbol duration of original FBMC employing long PFs is a serious drawback for low-latency requirements. As a result, the original FBMC cannot efficiently support 6G scenarios that require low-latency communications like smart healthcare monitoring. Alternatively, this is not the case with short PFs thanks to a corresponding FBMC symbol duration equivalent to OFDM. Furthermore, it was evaluated that PAPR reduction techniques are more efficient for FBMC with short PFs [50].

Lately, by inverting the time and frequency axes of the filter-bank impulse response of the MMB4 PF, the Near Perfect Reconstruction (NPR1) short PF was proposed in [22] with a high time localization since the interference is limited to only adjacent FBMC symbols (see Fig. 4(a)).

Therefore, the obtained Signal to Interference Ratio (SIR) for the proposed NPR1 PF is 73 dB [22], which is of the same order of magnitude as for the MMB4 PF (70 dB) [20] corroborating the near-perfect reconstruction property of the NPR1 PF.

To improve the appeal of the original short PF-based FBMC for IoT applications, the complexity of the FS receiver should be further reduced. Truncating the PF frequency response is one way to achieve this aim. However, this aggravates the penalty of the non-perfect reconstruction at the receiver side, degrading performance. Therefore, a suitable compromise between complexity and performance should be targeted.

The 5G system error vector magnitude requirement for a reliable communication is 3.5% for a 256-QAM [40], which

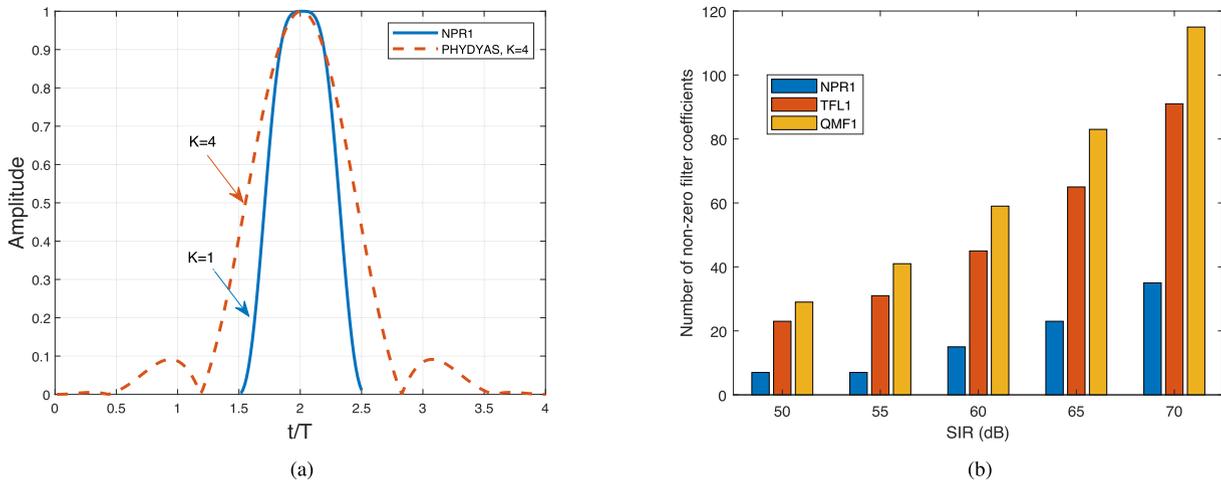


FIGURE 4. Comparison of considered PFs. (a) Impulse response. (b) Truncation impact on near-perfect reconstruction property.

corresponds to a SIR of 30 dB. Therefore, each system block should achieve a larger SIR to adhere to the aforementioned overall system requirement. A residual SIR of 55 dB after truncation should be sufficient to avoid further degradation stemming from channel and hardware impairments. Fig. 4(b) evaluates the effect of the number of non-zero filter coefficients on the SIR for various short PFs. The NPR1 filter requires only 7 non-zero coefficients for a target SIR of 55 dB, as opposed to the 31 and 41 required coefficients by the other short PFs. It is important to note that, an alternative short PF was proposed in [51] to reduce the OOBPL compared to short PFs presented in the literature. However, this came at the expense of reduced robustness to TO and CFO compared to the NPR1 PF. Moreover, if only 7 non-zero coefficients are to be used, the obtained SIR level is 36.26 dB which is less than the target SIR (55 dB). Hence, the NPR1 filter offers a better compromise between complexity and performance. Furthermore, it shows improved robustness to CFOs and TOs [22]. These advantages advocate for the use of the NPR1 PF for NG-FBMC.

Despite the aforementioned advantages, several open issues still need to be addressed. The first resides in lower robustness to TOs since, for long PFs, the signal information is replicated and transmitted during a longer time period. The second is lower robustness to long delay spread channels [14]. In fact, system performance is highly dependent upon the ratio between the channel delay spread and the PF length [22]. Hence, long PFs offer improved robustness in this regard. However, all these problems can be tackled through advanced receiver techniques as shown in the next section.

B. OVERLAP-SAVE FBMC RECEIVERS

Two main advantages motivate the introduction of advanced receiver techniques: improved robustness to long delay spread channels and TOs up to the support of asynchronous communications.

Improved robustness is achieved by the introduction of a time-domain equalizer prior to the original FBMC receiver [49] as shown in Fig. 5(a). Although system performance is improved compared to a conventional FS-FBMC receiver, the resulting complexity is prohibitive for practical applications due to the required computation of several FFT blocks.

Nevertheless, when coupled with a short PF and a FS implementation, it is possible to significantly reduce its complexity [23]. The Overlap-Save (OS) algorithm can be used to decompose and simplify the time-domain equalizer, efficiently performing fast convolution. First, the IFFT of size N is decomposed by its decimation in time to obtain several IFFTs of size $L = KM$ followed by a radix-2 stage as shown in Fig. 5(b). The number of IFFTs is equal to $N_{UF} = N/L$. Next, the summation of the selected radix-2 stage is moved after the FBMC receiver to obtain N_{UF} FBMC receivers before the final summation stage. In fact, the linear-phase-rotation terms of the radix-2 stage can be seen as a frequency shift and can be incorporated into the PF coefficients. Thus, both are shifted to the frequency domain after the FFT. As a result, the multiplications before FFT become circular convolutions. Hence, all IFFTs and FFTs of size L can be simplified as marked by the red-dotted lines. Fig. 5(c) shows the final structure of the NG-OS-FBMC receiver for SISO transmissions, where the equalizer is directly integrated into the FBMC receiver, largely reducing complexity.

Despite this major step forward, the complexity of the proposed OS receiver is still dominated by the FFT size N . The latter depends on the up-sampling factor N_{UF} which provides a compromise between system performance and complexity. Indeed, the factor N_{UF} represents the number of FBMC symbols considered for processing only one FBMC symbol. As means to achieve several tradeoff levels between performance and complexity, we propose to flexibly modify the number of FBMC symbols N_s to be processed simultaneously by the receiver as shown in Fig. 5(d). The newly introduced parameter

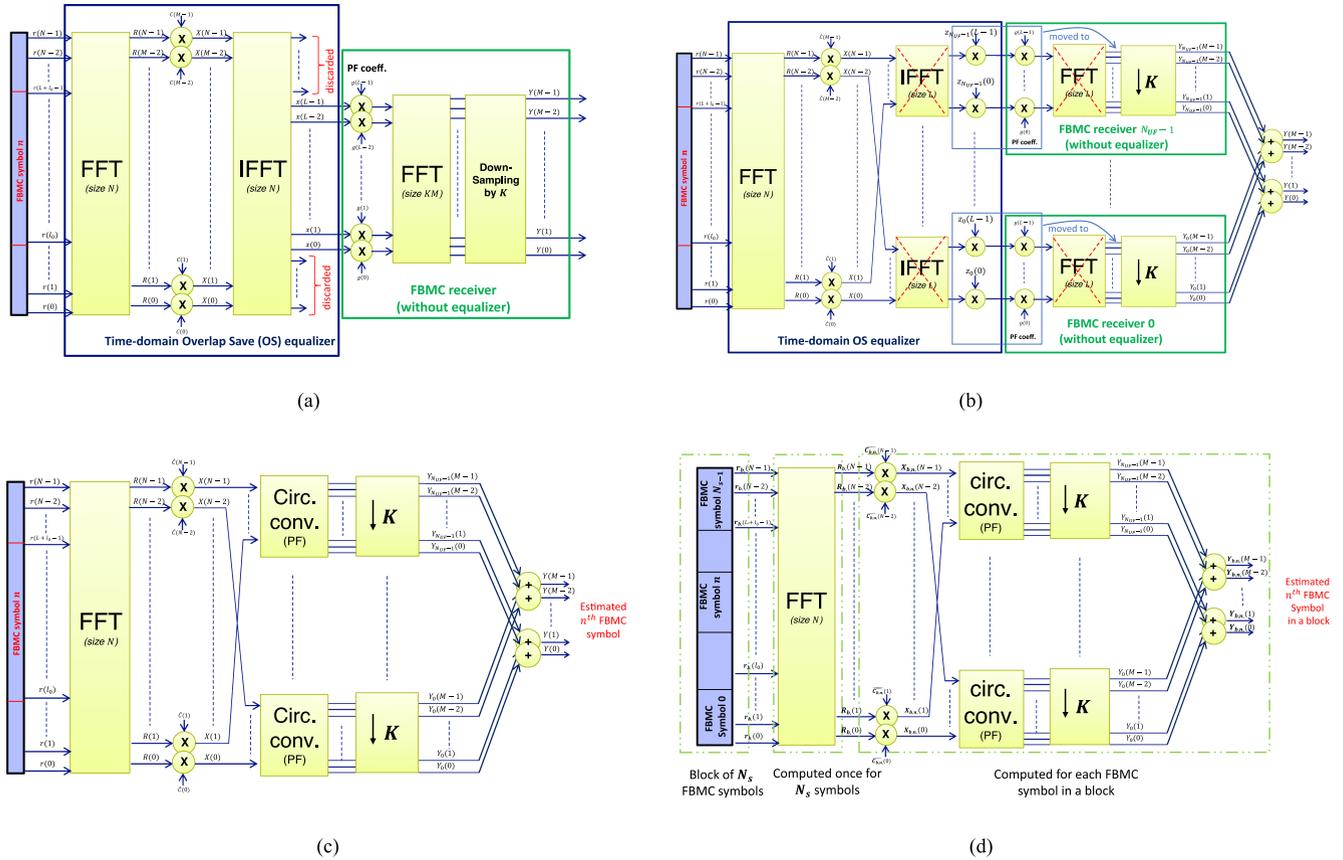


FIGURE 5. Next-generation overlap-save FBMC receiver development. (a) Original FBMC receiver augmented with the time-domain equalizer [49]. (b) Intermediate stage of the NG-FBMC receiver development. (c) NG-OS-FBMC receiver. (d) NG-OSB-FBMC receiver.

N_s is related to the upsampling factor N_{UF} as follows

$$N_{UF} = \frac{N_s + 1}{2}.$$

Indeed, an FFT of size $N = N_{UF}M$ is computed only once per block regardless of the value of N_s , which significantly reduces complexity. The rest, however, is computed for each FBMC symbol as depicted in Fig. 5(d). This receiver type is denoted by Overlap-Save Block (OSB).

IV. NG-FBMC TRANSCIVERS: EXTENSION TO mMIMO

New transmission techniques are now being researched in order to fulfill the challenging requirements of URLLC use cases. In particular, GF transmissions, which have been incorporated into the 5G standard, have the potential to reduce latency in comparison to conventional grant-based techniques. In this case, several URLLC devices may become active simultaneously and share the same time transmission interval for data transmissions with high access loads. The GF potential, however, may be hindered due to preamble collision occurrences. In fact, even when there is no preamble collision in non-GF conventional systems with few antennas on the BSs, the data decoding may still fail. Due to the influence of multi-user interference and noise, their reliability scarcely

meets requirements [52]. This inevitably leads to additional re-transmission attempts and access failures, increasing latency, and deteriorating transmission reliability.

As a potential solution for a reliable communication, mMIMO can improve reliability and throughput, thanks to its large array, diversity, and multiplexing benefits. This is one of the most significant enhancements to GF URLLC required in applications such as automated car driving and near real-time robotics [53]. Furthermore, the capacity increase provided by mMIMO systems is a key feature for enabling massive device connectivity in mMTC.

In fact, the use of FBMC in mMIMO systems was widely investigated with the PPN and FS structures in [54], [55], [56], [57], [58], [59]. However, thanks to the advantages brought on by the NG-OS-FBMC receivers compared to the FS and PPN structures, extending their usage to the context of mMIMO becomes particularly interesting. In this section, the NG-FBMC solution applying the NPR1 short PF and advanced receivers is extended to mMIMO systems.

A. mMIMO: OS-BASED RECEIVERS

The received signal represents a combination of all signals coming from different users. It consists of several FBMC symbols. The receiver processing starts with the computation of a

FFT of size $N = N_{UF}M$ applied on the received signal of each antenna. Similarly to OFDM, FBMC mMIMO equalization is performed directly after the FFT using a zero-forcing equalizer in order to separate user signals. Next, each user's signal will be processed independently by the remaining receiver blocks shown in Fig. 5(c).

Similarly to the SISO case, the complexity of the NG-OS-FBMC mMIMO receiver can be reduced thanks to the proposed OSB design. Nevertheless, it can be sufficiently accurate to assume that the channel response remains static over a given block in the particular scenario of low mobility. This assumption reduces the equalization complexity which is particularly interesting in mMIMO systems given the complexity of the equalization step [24]. Indeed, when applying demodulation steps analog to the mMIMO NG-OS-FBMC case, only one FFT of size $N = N_{UF}M$ is computed for a block of N_s FBMC symbols consisting of the received signal per antenna. An equalization stage is then applied to separate the signals of the users. It is performed on each FBMC symbol in the block. For each user, the remaining receiver stages will be performed for each FBMC symbol in a block.

V. PERFORMANCE EVALUATION

To evaluate the efficiency of the proposed NG-FBMC transceivers, it is necessary to compare their performance to that of OFDM and the original FBMC receivers in the context of SISO transmissions and mMIMO systems for well-identified 6G-IoT scenarios.

A. SIMULATION SETUP

The simulation parameters are set to a 5 MHz bandwidth, a FFT size $M = 512$, 300 used subcarriers, a frequency sampling $F_s = 7.68$ MHz, and a CP size of 36. NG-OS $_{N_{UF}}$ -FBMC and NG-OSB $_{N_s}$ -FBMC represent the receiver notations with the corresponding parameters N_{UF} and N_s . In our simulations, N_{UF} and N_s are set to 4 and 7 respectively, representing a good compromise between system performance and complexity. The FS $_4$ -FBMC term refers to the FS receiver with the long MMB4 PF. The channel is assumed to be perfectly estimated at the receiver side. The following 5G multipath channels are considered in our simulations for SISO transmissions and in the context of mMIMO systems respectively.

- *SISO. Tapped Delay Line C*: In the context of the 3GPP 5G standard, the Tapped Delay Line C (TDL-C) multipath 3GPP channel model is defined with a delay spread τ and a Doppler frequency shift ν [40].
- *mMIMO. 5G QuaDRiGa channel*: The 5G QuaDRiGa channel in [60] enables modeling MIMO radio channels for specific network configurations and is used to generate realistic radio channels. The chosen parameters follow the 5 G standard [40], with 4 users, 64 cross-polarized antennas at the BS, a carrier frequency of 3.5 GHz, and considering the 3D urban-macro-cell non-line of sight model. Specific simulation parameters can be found in [24].

B. SISO: NG-FBMC PERFORMANCE

The BER performance of the NG-OS-based FBMC receivers using the NPR1 short PF is compared to that of OFDM and FS $_4$ -FBMC receivers with a 16-QAM constellation under different channel impairments.

1) TIMING OFFSETS

For some application cases like earthquake and rain monitoring having sporadic traffic with short frame duration, the signaling overhead introduced by the synchronization procedure can be considered large, penalizing spectral efficiency. Therefore, when aiming for an energy-efficient network, an appealing transmission scheme in such a scenario avoids the costly signaling procedure. Equivalently, the sensors wake up from sleep mode, directly send the required information to the BS, and switch to sleep mode again, avoiding TO impairments. To be able to apply such a scheme, the robustness of the proposed NG-FBMC receivers to TO impairments must be investigated.

Fig. 6(a) depicts the BER performance of the considered receivers under the effect of TO as a function of the symbol duration over the static TDL-C channel with $\tau = 2.6 \mu s$ and $\nu = 0$ Hz. It can be observed that the NG-OSB $_7$ -FBMC can support a TO corresponding to 13% of the symbol duration. Note that, OFDM shows severe performance degradation for this TO value since it suffers from an irreducible error floor. In fact, OFDM cannot support any TO value larger than half of its CP duration, confirming its high sensitivity to TO impairments. Applying higher TO values (25%), the BER performance is highly degraded for the NG-OSB $_7$ -FBMC receiver, implying that this FBMC transceiver structure cannot support asynchronous communications.

The NG-OS $_4$ -FBMC is suitable for asynchronous communications since it can tolerate a TO value of 50% of the symbol duration without any BER performance degradation. Considering that the TO is perfectly known at the receiver side, TOs larger than 50% of the symbol duration can also be fully compensated since this value is larger than the OQAM delay, and the intended information to be demodulated is still within the processing window of the receiver.

In summary, NG-OS-based FBMC receivers unleash the full potential of the original FBMC when associated with the NPR1 short PF. The robustness to TOs is largely improved, enabling asynchronous communications, an essential feature for power-constrained 6G-IoT devices.

2) MULTIPATH CHANNEL

Frequency-selective fading can cause inter-symbol interference, hence resulting in an irreducible BER and imposing an upper limit on the symbol rate. OFDM is said to be robust to multipath channels thanks to the insertion of a CP. However, the multipath channel may become highly frequency selective for some transmission cases, resulting in a long channel delay spread that may exceed the OFDM CP duration.

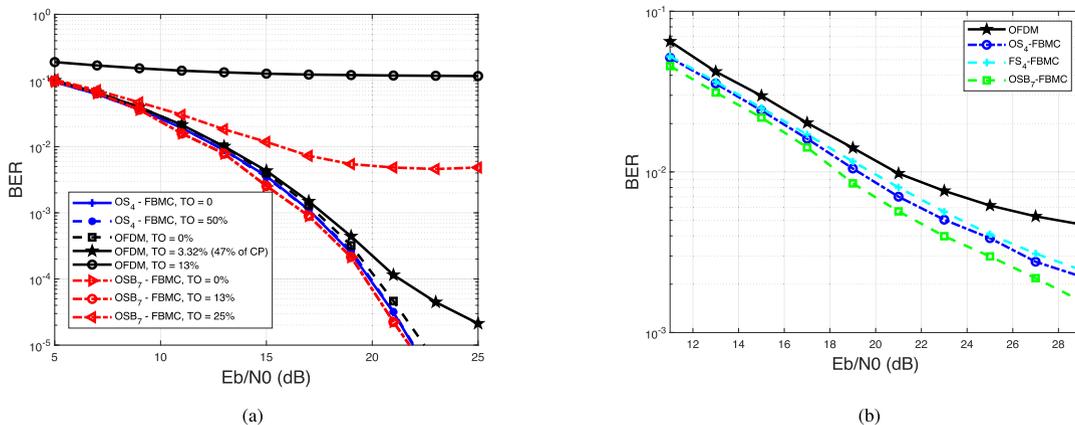


FIGURE 6. Performance comparison of all considered receivers under different channel impairments. (a) Timing offsets. (b) Multipath channel.

A straightforward solution to combat the corresponding consequences is to increase the CP length. In a multi-user uplink scenario, users face different channels, hence experience different effects of frequency selectivity. Therefore, the user suffering the most from selectivity determines the required target CP length for all users sharing the same received OFDM symbol slot. However, this yields a spectral efficiency loss since the other users do not require such a long CP length. Furthermore, any attempt to adapt the CP length to each user’s channel condition leads to interference and performance degradation for the subset of users suffering from longer delay spread channels. Therefore, a compromise between interference-limited performance and spectral efficiency needs to be set for OFDM.

The inherent capabilities of each waveform determine its robustness to such channel impairments. To evaluate the effect of such impairments for FBMC, we show in Fig. 6(b) the performance of all considered receivers over the non-static TDL-C channel characterized by a long delay spread ($\tau = 5 \mu s$) slightly larger than the OFDM CP duration ($4.7 \mu s$) with a Doppler shift $\nu = 300$ Hz. Although the difference between the CP and the channel delay spread is small, it is sufficient to introduce an error floor for OFDM. Meanwhile, the benefits of NG-OS-FBMC and NG-OSB-FBMC receivers are clearly visible since they enable NG-FBMC to outperform OFDM.

3) PEAK-TO-AVERAGE POWER RATIO

Multi-carrier modulations are typically susceptible to non-linear distortions as a result of their PAPR. For instance, the distortion caused by the non-linearity of the high-power amplifier can degrade the BER performance. To reduce the PAPR in OFDM systems, a precoder applying the Discrete Fourier Transform to QAM symbols can be used before their allocation to subcarriers. However, since orthogonality is restricted to the real domain for FBMC/OQAM, a different precoder is required. In this case, the Discrete Cosine Transform (DCT) can be employed. Nevertheless, other precoding techniques are available [61].

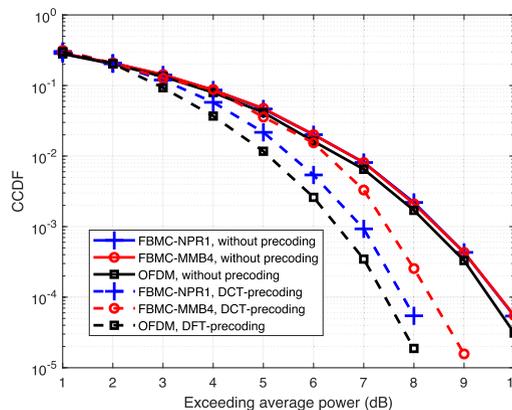


FIGURE 7. CCDF comparison between the considered receivers with and without precoding.

Fig. 7 depicts the Complementary Cumulative Distribution Function (CCDF) of OFDM and FBMC/OQAM signals with and without precoding. The choice of the PF has a negligible impact on the PAPR for FBMC/OQAM systems without precoding, as shown in the figure. However, compared to OFDM, the PAPR of the FBMC/OQAM signal is slightly increased due to the presence of a ramp-up and ramp-down at the beginning and end of the frame [50].

All precoded signals exhibit a significant reduction in PAPR compared to their non precoded counterparts. However, the efficiency of the precoding technique in FBMC/OQAM depends on the choice of the PF. Employing a long PF results in a larger PAPR than a short one, even when the same precoder is used. This is because precoding techniques are typically applied to each FBMC symbol independently, while the FBMC symbols overlap before transmission through the channel and the number of overlapping symbols increases with the filter length.

C. mMIMO: NG-FBMC PERFORMANCE

Synchronization errors greatly affect the performance of mMIMO systems. To evaluate the effects of such errors, the

TABLE 1. BER Performance Comparison for the Considered Receivers in the Presence of CFO in (%) With QPSK and 16QAM Modulation Schemes

Rx \ CFO (%)	QPSK		16QAM	
	10	26	4	10
NG-OS ₄ -FBMC	0	1.23×10^{-5}	0	1.49×10^{-5}
NG-OSB ₇ -FBMC	2.01×10^{-5}	1.21×10^{-1}	2.01×10^{-5}	3.34×10^{-4}
PPN-FBMC	2.07×10^{-4}	3.25×10^{-1}	3.52×10^{-3}	1.03×10^{-1}
FS-FBMC	1.98×10^{-4}	3.23×10^{-1}	3.31×10^{-3}	9.86×10^{-2}
OFDM	4.86×10^{-1}	4.88×10^{-1}	2.61×10^{-1}	4.71×10^{-1}

BER of the NG-OS-based FBMC receivers using the NPR1 short PF is evaluated for QPSK and 16QAM and compared to OFDM.

1) CARRIER FREQUENCY AND TIMING OFFSETS

The features, solutions, and conclusions detailed for SISO in the previous Section V-B and related to the performance under TO impairments still apply for mMIMO. Indeed, the impact of TO impairments is critical for mMIMO performance. As TO aspects have been already discussed previously, we will focus on CFO aspects. In fact, the benefits of mMIMO significantly depend on the accuracy of frequency synchronization. Hence, the impact of CFOs is assessed in terms of BER for typical simulation conditions of an IoT-like scenario [24]. No noise was included in this simulation to illustrate better the CFO effect.

Table 1 compares the BER performance of PPN and FS structures used for FBMC-mMIMO systems in [58] to that of OS-based FBMC and OFDM receivers at different CFOs. OFDM shows the worst performance among all considered receivers due to its low frequency localization. The PPN and FS receivers exhibit nearly identical performance, which can be attributed to the fact that the phase compensation term solely relies on the FBMC symbol index.

For the NG-OSB-FBMC receiver, equalization is performed for each FBMC symbol in a block. This improves equalization for fast varying channels at the cost of an increased complexity compared to OFDM. Hence, with QPSK, the NG-OSB₇-FBMC receiver can tolerate a CFO of 10% of the subcarrier spacing denoted by Δf for a target BER of around 10^{-5} , and 4% with 16-QAM. The NG-OS₄-FBMC receiver offers the best performance, where it can support a CFO of 26% and 10% of Δf with QPSK and 16QAM respectively for an error floor around 10^{-5} of BER. Therefore, NG-FBMC with OS-based receivers successfully alleviates OFDM, PPN, and FS-FBMC drawbacks by reducing the required signaling overhead while enabling the usage of low-cost oscillators.

D. IMPLEMENTATION ASPECTS AND COMPARATIVE PERFORMANCE

Complexity aspects highly depend on the application and its corresponding system parameters. When considering a typical uplink 6G-IoT scenario, the complexity at the transmitter is a priority. Following the PPN transmitter shown in

Fig. 2(a), additional IFFT and filtering modules are required when compared to OFDM. However, thanks to the pruned FFT algorithm [62], the usage of two IFFT blocks at the transmitter can be avoided. Moreover, a short PF can considerably reduce the complexity. When coupled, these techniques lead to NG transceivers with a complexity level comparable to that of OFDM [62].

In many other 6G-IoT applications such as autonomous vehicles, environmental monitoring, and camera surveillance, a slight increment in the receiver computational complexity is less of an issue since the receiver is located at the BS. For instance, while introducing significant advantages such as the support of asynchronous communications, the NG-OS-FBMC receiver comes at the expense of a higher receiver computational complexity. On the other hand, the NG-OSB-FBMC receiver highly reduces the complexity of the NG-OS-FBMC receiver by processing a block of N_s FBMC symbols simultaneously. Indeed, this compromises the support of asynchronous communication, showing the trade-off existing between these two KPIs.

Furthermore, a limited subset of system parameters can have a considerable impact on certain KPIs for NG-FBMC receivers, including the complexity of the transceiver, latency, and the support of asynchronous communications. We can point out in particular the values of the up-sampling factor N_{UF} and the number of FBMC symbols N_s in a block. Therefore and more generally, the ability to flexibly modify these system parameters (N_s and N_{UF}) enables the system designer to explore KPI tradeoffs in order to set parameter values tailored to the target 6G-IoT application requirements.

Fig. 8 compares the NG-FBMC KPIs to that of OFDM and the original FBMC receiver with a long PF. The shaded region delimited by the KPIs of the NG-OS-FBMC receiver and that of the NG-OSB-FBMC receiver can be explored by the designer to strike tradeoff levels better adjusted for the application requirements and constraints.

Another KPI presented in Fig. 8, which is a constraint for many 6G-IoT applications, is latency. Indeed, it is directly impacted by the system parameters N_{UF} and N_s . It can be approximated if we consider that it is directly related to the time transmission interval regardless of the propagation delay, hardware latency, and retransmission mechanisms. In fact, an iterative forward error correcting code, which is employed at the receiver side in modern communication systems, requires

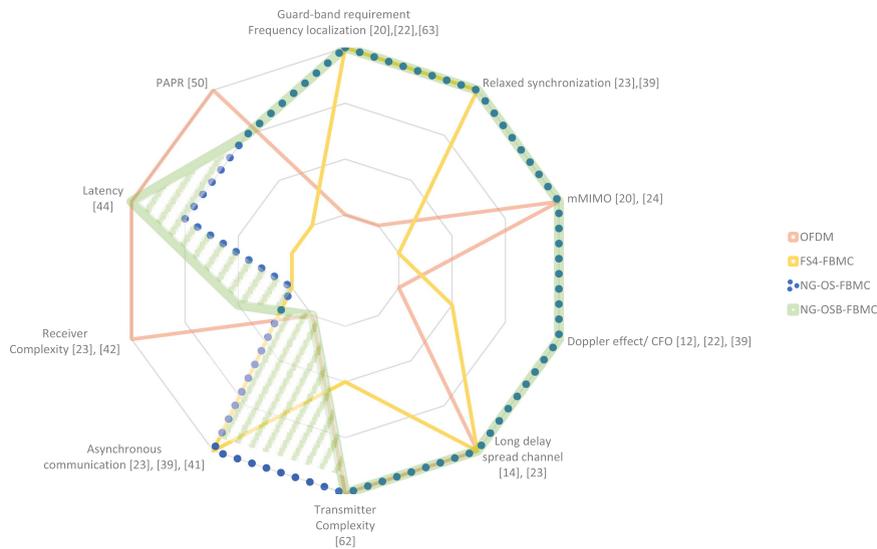


FIGURE 8. Radar chart illustrating the set of 6G-IoT relevant KPI and tradeoffs for OFDM and several variants of the original and NG-FBMC waveforms. A larger circle radius represents a better system performance. The green shaded area corresponds to the flexibility that can be attained by the NG-FBMC receivers, according to the selected parameters N_s and N_{UF} .

receiving the entire frame before decoding. Therefore, the latency of the NG-OSB-FBMC receiver $L_{NG-OSB_{N_s}}$ can be approximated as the number of samples in a frame $(M(N_s + 1)/2)$ divided by the sampling frequency as follows

$$L_{NG-OSB_{N_s}} = \frac{M(N_s + 1)}{2 \times F_s}.$$

On the other hand, the NG-OS-FBMC receiver increases the latency, albeit not to the same extent as the original FS₄-FBMC receiver. This is due to the addition of $M(N_{UF} - 1)/2$ samples to demodulate the last FBMC symbol in each frame.

Furthermore, the frame length impacts the data rate for the NG-OSB_{N_s}-FBMC receiver. Therefore, for a fair comparison, the latency of the such a receiver must be compared to that of OFDM, with both having the same data rate loss. The data rate loss of the NG-OSB_{N_s}-FBMC receiver can be written as follows

$$DR_{loss,FBMC} = \frac{1}{N_s + 1}.$$

This comes from the filter-related ramp-up and ramp-down observed at the beginning and end of each frame. Regarding the OFDM waveform, the addition of a CP for each OFDM symbol consisting of M samples leads to the following data rate loss

$$DR_{loss,OFDM} = \frac{L_{CP}}{M + L_{CP}}.$$

Considering the 5G standard [40], the data rate loss due to a CP size $4.68 \mu s$ is approximately 6.6%. For the same target DR_{loss} , the number of FBMC symbols N_s in a block must be 14 symbols. This corresponds to $N_{UF} = 8$ and a frame composed of $7.5 \times M$ samples. It is worth mentioning that this corresponds to 1 resource block that is composed of 7

OFDM symbols, including the CP [40]. Therefore, the NG-OSB-FBMC receiver with short PFs can achieve the same latency ($L_{NG-OSB_{N_s}} = 7.5 \times M/F_s = 0.535 ms$) as OFDM for the same data rate loss.

Other KPIs might also play a major role in the waveform selection for some 6G-IoT applications. Despite the existing trade-off between receiver complexity and the support for asynchronous communications, all the NG-OS-based FBMC receivers can support relaxed synchronization. Furthermore, all considered receivers are robust to long-delay spread channels, as depicted in Fig. 8. Indeed, the NG-OS-based FBMC receivers outperform the FS₄-FBMC receiver, as shown in Fig. 6(b). Moreover, when the delay spread of the channel is larger than the CP length, NG-OS-FBMC receivers outperform OFDM over long delay spread channels.

Finally, another significant KPI which might hinder the co-existence of multiple services concerns spectral leakage. Indeed, FBMC with long PFs exhibits better spectrum confinement than with short PFs [20], [22]. Nevertheless, the NG-FBMC waveform is able to properly address this problem even with short PFs. OFDM shows the worst spectral confinement of all considered waveforms, requiring a large number of guard-bands to avoid compromising efficient multiple access (or service) support under impairments [63]. In summary, NG-FBMC transceivers are able to overcome the main drawbacks of the original FBMC and OFDM waveforms as depicted in Fig. 8.

VI. RESEARCH OPPORTUNITIES

While considerable improvements were achieved by the proposed NG-FBMC waveform, several research challenges and study item opportunities are still to be tackled for 6G-IoT applications.

A. CHANNEL ESTIMATION

The introduction of OQAM for FBMC complicates the adoption of certain techniques supported by OFDM. We can mention here specific techniques related to channel estimation: the use of scattered pilot patterns and the nature of the pilot values. Indeed, the transmitted pilots should be real-valued to prevent interference with the transmitted data. However, the received signal is still corrupted by imaginary-valued interference due to transmitted data on adjacent subcarriers.

To estimate the Channel Frequency Response (CFR), Successive Interference Cancellation (SIC) methods like those proposed in [64] can be used. This requires the introduction of iterative channel estimation using forward error-correcting techniques in the loop. Hence, the resulting complexity is highly increased. To avoid increasing complexity, the study of alternative methods that consider NG-FBMC represents an interesting future work opportunity.

In fact, FBMC can use complex-valued pilots. These latter should be shielded from interference. This can be done by keeping the neighboring FBMC subcarrier positions vacant or inactive at the cost of a data rate loss. However, for short PFs, where just one FBMC symbol is required as a guard interval to properly shield the pilots, the rate loss is negligible compared to long PFs. For example, it is possible to estimate the CFR at even subcarrier positions and to use interpolation to provide an estimate for the odd positions. Following this suggestion, the Zadoff-Chu sequences considered as pilots for channel estimation in OFDM systems due to their low PAPR, can still be used for FBMC. Further improvements to this channel estimation technique could represent a promising study item for the NG-FBMC waveform.

Given that block-type pilot structures can be used for channel estimation, an efficient frame structure similar to that of OFDM was proposed in [65]. However, scatter-type pilot structures remain an open challenge for FBMC due to the lack of complex orthogonality.

B. PAPR REDUCTION

PAPR is one of the major open problems for FBMC. Regardless of the used PF, the corresponding PAPR is the same as that of OFDM, assuming that an infinite number of FBMC symbols are transmitted [43]. However, since frames are typically limited in duration, the PAPR is slightly increased for FBMC.

Moreover, the OQAM scheme prevents direct use of the pre-coding techniques widely adopted for OFDM, such as the FFT pre-coder. Actually, for these algorithms, the achieved PAPR reduction for FBMC is not as significant as for OFDM. In fact, it is inversely proportional to the overlapping factor. Therefore, NG-FBMC transceivers with short PFs have the potential to further reduce the PAPR.

Alternative approaches based on low-complexity selective mapping techniques were investigated in [61], [66] for original FBMC. Corresponding results show that FBMC using the MMB4 PF can obtain a lower PAPR than OFDM.

Therefore, it can be interesting to investigate the advantages of adopting such techniques for short PFs. This is crucial for some 6G-IoT applications since corresponding devices require energy-efficient transmissions.

C. SENSING

Sensing is a fundamental functionality for IoT [67]. Localization enables many IoT services, such as emergency call localization, area imaging, and personal radar. The advent of the millimeter waves and the availability of even larger bandwidths (in THz ranges) improve localization accuracy boosted by high-definition imaging and frequency spectroscopy.

Composed of frequency-modulated continuous waves, chirps signals were generally used for short-range radar systems. However, such modulation schemes cannot provide high data rates. Moreover, the radar signals have to compete for the same spectrum resources as wireless communications waveforms.

For addressing these problems, there is a trend of merging the sensing (radar) and communication systems [67], [68], [69]. Their integration can help decrease power consumption, reduce hardware costs, and improve spectral efficiency. In this case, waveform design plays a central role since it should provide a single waveform capable of performing simultaneous communications and sensing tasks.

Adopted in 5G systems, OFDM cannot be directly used for joint communications and sensing. This leads to a full duplex self-interference problem. This problem can be aggravated by its high OOBPL and any encountered channel impairments due to its high sensitivity to CFOs and TOs.

NG-FBMC waveform is a promising alternative for joint sensing and communications. Indeed, a recent work [70] proposed a joint radar communication transmitter system based on FBMC waveform. Results showed a better performance in radar targeting, and improved BER performance in multipath channels compared to OFDM. However, the introduction of the FS-FBMC receiver associated with MMB4 PF highly increased the computational complexity. Motivated by these excellent results, it may be advantageous to investigate the use of NG-FBMC transceivers in this context.

D. MACHINE LEARNING

In some 6G-IoT applications, system conditions might be regularly changing. For tracking these modifications and adapting accordingly the system parameters, Machine Learning (ML)-based algorithms are expected to be particularly useful.

Indeed, Deep Neural Networks (DNN) can be used to find the most suitable system parameters including the sub-carrier spacing, modulation order, code rate, and FFT size for FBMC-based systems taking into account the transmission channel and the characteristics of the devices/users. For example, considering the NG-FBMC transceivers, a larger FFT size can provide a lower BER at the expense of a higher computational complexity and energy consumption.

DNN can be introduced to learn Fourier series channel geometry representations and exploit some hidden parameters that are not usually considered for channel estimation. This can be helpful for addressing the previously identified pilot pattern structure problem. Moreover, devised solutions can include ML-based algorithms for improving NG-FBMC-based systems when facing non-linear impairments such as high levels of PAPR and any resulting amplifier non-linearities.

The next step beyond the choice of physical layer system parameters concerns ML algorithms for resource allocation in NG-FBMC-based systems. Since this waveform preserves orthogonality only in the real domain, new studies considering this constraint are necessary for improving power and subcarrier allocations for orthogonal and Non-Orthogonal Multiple Access (NOMA) systems. NOMA can be particularly suitable to efficiently support massive access in 6G-IoT networks.

VII. CONCLUSION

In this work, we provided a next-generation FBMC transceiver with flexible and advanced features fully benefiting from recent advances to unleash the inherent potential of such a filtered waveform. The attained level of flexibility enables the system designer to better explore key performance indicators tradeoffs leading to transceiver parameters tailored to target 6G-IoT application requirements. Despite the full range of benefits that the original FBMC was able to provide, it still suffered from several drawbacks that hindered its wider reach. Therefore in this work, we focused on algorithmic and implementation-related proposals that improve its set of advantages while reducing complexity and latency, leading to a new flexible variant.

We started with the target of designing short PFs coupled with advanced receiver techniques to fully benefit from the original FBMC inherent advantages while largely decreasing its complexity. We also showed how a short PF, specifically the NPR1 PF provides a good compromise between system complexity and performance. The next-generation FBMC waveform, which is the association of the NPR1 PF with the OS-based receivers, can alleviate the most impactful limitations of OFDM for some 6G-IoT applications. Indeed, compared to OFDM, a significantly improved robustness is seen under several channel impairments, including carrier frequency offsets, multipath channels, timing offsets, and even enabling asynchronous communications. In addition, the potential of using mMIMO in some 6G-IoT applications was explored.

Moreover, the complexity of the next-generation FBMC advanced receivers was also evaluated jointly with the set of features and performance improvements they bring, particularly for the uplink connection. Indeed, several performance/complexity takeoffs are now achievable depending on the desired system key performance indicators and channel characteristics. Finally, we discussed several research opportunities and challenges relevant to the quest of making the next-generation FBMC waveform an excellent fit for 6G-IoT applications.

REFERENCES

- [1] P. Yang, Y. Xiao, M. Xiao, and S. Li, "6G wireless communications: Vision and potential techniques," *IEEE Netw.*, vol. 33, no. 4, pp. 70–75, Jul./Aug. 2019.
- [2] D. C. Nguyen et al., "6G Internet of Things: A comprehensive survey," *IEEE Internet Things J.*, vol. 9, no. 1, pp. 359–383, Jan. 2022.
- [3] F. Guo, F. R. Yu, H. Zhang, X. Li, H. Ji, and V. C. M. Leung, "Enabling massive IoT toward 6G: A comprehensive survey," *IEEE Internet Things J.*, vol. 8, no. 15, pp. 11891–11915, Aug. 2021.
- [4] I. Tomkos, D. Klionidis, E. Pikasis, and S. Theodoridis, "Toward the 6G network era: Opportunities and challenges," *IT Prof.*, vol. 22, no. 1, pp. 34–38, Jan./Feb. 2020.
- [5] W. Saad, M. Bennis, and M. Chen, "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems," *IEEE Netw.*, vol. 34, no. 3, pp. 134–142, May/June 2020.
- [6] F. Tariq, M. R. A. Khandaker, K.-K. Wong, M. A. Imran, M. Bennis, and M. Debbah, "A speculative study on 6G," *IEEE Wirel. Commun.*, vol. 27, no. 4, pp. 118–125, Aug. 2020.
- [7] C. She et al., "A tutorial on ultrareliable and low-latency communications in 6G: Integrating domain knowledge into deep learning," *Proc. IEEE*, vol. 109, no. 3, pp. 204–246, Mar. 2021.
- [8] K. Shafique, B. A. Khawaja, F. Sabir, S. Qazi, and M. Mustaqim, "Internet of Things (IoT) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5G-IoT scenarios," *IEEE Access*, vol. 8, pp. 23022–23040, 2020.
- [9] A.-S. Bana et al., "Massive MIMO for Internet of Things (IoT) connectivity," *Phys. Commun.*, vol. 37, 2019, Art. no. 100859.
- [10] K. David and H. Berndt, "6G vision and requirements: Is there any need for beyond 5G?," *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 72–80, Sep. 2018.
- [11] D. Passos, H. Balbi, R. Carrano, and C. Albuquerque, "Asynchronous radio duty cycling for green IoT: State of the art and future perspectives," *IEEE Commun. Mag.*, vol. 57, no. 9, pp. 106–111, Sep. 2019.
- [12] A. R. Khedkar and P. Admane, "Estimation and reduction of CFO in OFDM system," in *Proc. Int. Conf. Image Process.*, 2015, pp. 130–134.
- [13] B. Lim and Y.-C. Ko, "SIR analysis of OFDM and GFDM waveforms with timing offset, CFO, and phase noise," *IEEE Trans. Wirel. Commun.*, vol. 16, no. 10, pp. 6979–6990, Oct. 2017.
- [14] B. Farhang-Boroujeny, "OFDM versus filter bank multicarrier," *IEEE Signal Process. Mag.*, vol. 28, no. 3, pp. 92–112, May 2011.
- [15] Y. Medjahdi et al., "On the road to 5G: Comparative study of physical layer in MTC context," *IEEE Access*, vol. 5, pp. 26556–26581, 2017.
- [16] X. Zhang, L. Chen, J. Qiu, and J. Abdoli, "On the waveform for 5G," *IEEE Commun. Mag.*, vol. 54, no. 11, pp. 74–80, Nov. 2016.
- [17] M. Schellmann et al., "FBMC-based air interface for 5G mobile: Challenges and proposed solutions," in *Proc. 9th Int. Conf. Cogn. Radio Oriented Wireless Netw. Commun.*, 2014, pp. 102–107.
- [18] A. Ijaz, L. Zhang, P. Xiao, and R. Tafazolli, "Analysis of candidate waveforms for 5G cellular systems," in *Towards 5G Wireless Netw.*, Rijeka, Croatia: IntechOpen, 2016. [Online]. Available: <https://doi.org/10.5772/66051>
- [19] A. Lizeaga, P. Rodríguez, I. Val, and M. Mendicute, "Evaluation of 5G modulation candidates WCP-COQAM, GFDM-OQAM, and FBMC-OQAM in low-band highly dispersive wireless channels," *J. Comput. Netw. Commun.*, vol. 2017, 2017, pp. 1–11.
- [20] M. Bellanger et al., "FBMC physical layer: A primer" Jan. 2010.
- [21] "FP7 metis 2020 project." 2017. [Online]. Available: <https://www.metis2020.com>
- [22] J. Nadal, C. A. Nour, and A. Baghdadi, "Design and evaluation of a novel short prototype filter for FBMC/OQAM modulation," *IEEE Access*, vol. 6, pp. 19610–19625, 2018.
- [23] J. Nadal, F. Leduc-Primeau, C. A. Nour, and A. Baghdadi, "Overlap-save FBMC receivers," *IEEE Trans. Wirel. Commun.*, vol. 19, no. 8, pp. 5307–5320, Aug. 2020.
- [24] F. Hamdar, J. Nadal, C. A. Nour, and A. Baghdadi, "Overlap-save FBMC receivers for massive MIMO systems under channel impairments," in *Proc. IEEE 95th Veh. Technol. Conf.*, 2022, pp. 1–7.
- [25] R. Nissel, S. Schwarz, and M. Rupp, "Filter bank multicarrier modulation schemes for future mobile communications," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 8, pp. 1768–1782, Aug. 2017.
- [26] B. Hirosaki, "An orthogonally multiplexed QAM system using the discrete Fourier transform," *IEEE Trans. Commun.*, vol. 29, no. 7, pp. 982–989, Jul. 1981.

- [27] M. Bellanger, "FS-FBMC: An alternative scheme for filter bank based multicarrier transmission," in *Proc. 5th Int. Symp. Commun., Control Signal Process.*, 2012, pp. 1–4.
- [28] M. Alrwashdeh and Z. Kollár, "Analysis of quantization noise in FBMC transmitters," *Digit. Signal Process.*, vol. 131, 2022, Art. no. 103760.
- [29] M. Bellanger, "FS-FBMC: A flexible robust scheme for efficient multicarrier broadband wireless access," in *Proc. Globecom Workshops*, 2012, pp. 192–196.
- [30] V. Berg, J.-B. Doré, and D. Noguét, "A flexible FS-FBMC receiver for dynamic access in the TVWS," in *Proc. 9th Int. Conf. Cogn. Radio Oriented Wireless Netw. Commun.*, 2014, pp. 285–290.
- [31] C. Kim, Y. H. Yun, K. Kim, and J.-Y. Seol, "Introduction to QAM-FBMC: From waveform optimization to system design," *IEEE Commun. Mag.*, vol. 54, no. 11, pp. 66–73, Nov. 2016.
- [32] B. L. Floch, M. Alard, and C. Berrou, "Coded orthogonal frequency division multiplex," *Proc. IEEE*, vol. 83, no. 6, pp. 982–996, Jun. 1995.
- [33] M. E. Tabach, J.-P. Javaudin, and M. Helard, "Spatial data multiplexing over OFDM/OQAM modulations," in *Proc. IEEE Int. Conf. Commun.*, 2007, pp. 4201–4206.
- [34] R. Zakaria and D. L. Ruyet, "A novel filter-bank multicarrier scheme to mitigate the intrinsic interference: Application to MIMO systems," *IEEE Trans. Wirel. Commun.*, vol. 11, no. 3, pp. 1112–1123, Mar. 2012.
- [35] S. Taheri, M. Ghoraishi, P. Xiao, and L. Zhang, "Efficient implementation of filter bank multicarrier systems using circular fast convolution," *IEEE Access*, vol. 5, pp. 2855–2869, 2017.
- [36] C. Le, S. Moghaddamnia, and J. Peissig, "On the performance of Alamouti scheme in 2 x 2 MIMO-FBMC systems," in *19th Int. Conf. OFDM Freq. Domain Techn.*, 2016, pp. 1–6.
- [37] M. Renfors, T. Ihalainen, and T. H. Stitz, "A block-Alamouti scheme for filter bank based multicarrier transmission," in *Proc. Eur. Wireless Conf.*, 2010, pp. 1031–1037.
- [38] H. Zhang, D. Le Ruyet, and M. Terre, "Spectral efficiency analysis in OFDM and OFDM/OQAM based cognitive radio networks," in *Proc. IEEE 69th Veh. Technol. Conf.*, 2009, pp. 1–5.
- [39] H. Lin, M. Gharba, and P. Siohan, "Impact of time and carrier frequency offsets on the FBMC/OQAM modulation scheme," *Signal Process.*, vol. 102, pp. 151–162, 2014.
- [40] 3GPP TS 38 104 v17.7.0, "Base Station (BS) radio transmission and reception," 2022.
- [41] D. Mattered, M. Tanda, and M. Bellanger, "Analysis of an FBMC/OQAM scheme for asynchronous access in wireless communications," *EURASIP J. Adv. Signal Process.*, vol. 2015, no. 1, pp. 1–22, 2015.
- [42] D. Dasalukunte, S. Mehmood, and V. Öwall, "Complexity analysis of IOTA filter architectures in faster-than-Nyquist multicarrier systems," in *Proc. NORCHIP*, 2011, pp. 1–4.
- [43] D. Qu, F. Wang, Y. Wang, T. Jiang, and B. Farhang-Boroujeny, "Improving spectral efficiency of FBMC-OQAM through virtual symbols," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4204–4215, Jul. 2017.
- [44] S. Eldessoki, D. Wieruch, and B. Holfeld, "Impact of waveforms on coexistence of mixed numerologies in 5G URLLC networks," in *Proc. 21th Int. ITG Workshop Smart Antennas*, 2017, pp. 1–6.
- [45] F. Wang, D. Qu, T. Jiang, and B. Farhang-Boroujeny, "Tail shortening by virtual symbols in FBMC-OQAM signals," in *Proc. IEEE Signal Process. Educ. Workshop*, 2015, pp. 157–161.
- [46] M. Bellanger, "Efficiency of filter bank multicarrier techniques in burst radio transmission," in *Proc. IEEE Glob. Telecommun. Conf.*, 2010, pp. 1–4.
- [47] D. Pinchon, P. Siohan, and C. Siclet, "Design techniques for orthogonal modulated filterbanks based on a compact representation," *IEEE Trans. Signal Process.*, vol. 52, no. 6, pp. 1682–1692, Jun. 2004.
- [48] H. Malvar, "Modulated QMF filter banks with perfect reconstruction," *Electron. Lett.*, vol. 26, pp. 906–907, 1990.
- [49] D. Mattered, M. Tanda, and M. Bellanger, "Filter bank multicarrier with PAM modulation for future wireless systems," *Signal Process.*, vol. 120, pp. 594–606, 2016.
- [50] B. Elmaroud, M. Faqih, M. Abbad, and D. Aboutajdine, "On the impact of prototype filter length on the PAPR reduction of FBMC signals," *Int. J. Eng. Technol.*, vol. 6, pp. 1951–1960, 2014.
- [51] I. Galdino, R. Zakaria, D. L. Ruyet, and M. L. R. d. Campos, "Short prototype filter design for OQAM-FBMC modulation," *IEEE Trans. Veh. Technol.*, vol. 69, no. 8, pp. 9163–9167, Aug. 2020.
- [52] T. Jacobsen et al., "System level analysis of uplink grant-free transmission for URLLC," in *Proc. IEEE Globecom Workshops*, 2017, pp. 1–6.
- [53] P. Popovski et al., "Wireless access for ultra-reliable low-latency communication: Principles and building blocks," *IEEE Netw.*, vol. 32, no. 2, pp. 16–23, Mar./Apr. 2018.
- [54] F. Rottenberg, X. Mestre, F. Horlin, and J. Louveaux, "Performance analysis of linear receivers for uplink massive MIMO FBMC-OQAM systems," *IEEE Trans. Signal Process.*, vol. 66, no. 3, pp. 830–842, Feb. 2018.
- [55] A. Aminjavaheri, A. Farhang, L. E. Doyle, and B. Farhang-Boroujeny, "Prototype filter design for FBMC in massive MIMO channels," in *Proc. IEEE Int. Conf. Commun.*, 2017, pp. 1–6.
- [56] N. E. Tunalı, M. Wu, C. Dick, and C. Studer, "Linear large-scale MIMO data detection for 5G multi-carrier waveform candidates," in *Proc. 49th Asilomar Conf. Signals, Syst. Comput.*, 2015, pp. 1149–1153.
- [57] A. Farhang, N. Marchetti, L. E. Doyle, and B. Farhang-Boroujeny, "Filter bank multicarrier for massive MIMO," in *Proc. IEEE 80th Veh. Technol. Conf.*, 2014, pp. 1–7.
- [58] A. Aminjavaheri, A. Farhang, N. Marchetti, L. E. Doyle, and B. Farhang-Boroujeny, "Frequency spreading equalization in multicarrier massive MIMO," in *Proc. IEEE Int. Conf. Commun. Workshop*, 2015, pp. 1292–1297.
- [59] A. Aminjavaheri, A. Farhang, and B. Farhang-Boroujeny, "Filter bank multicarrier in massive MIMO: Analysis and channel equalization," *IEEE Trans. Signal Process.*, vol. 66, no. 15, pp. 3987–4000, Aug. 2018.
- [60] [Online]. Available: <https://quadriga-channel-model.de/>
- [61] D. Na and K. Choi, "Low PAPR FBMC," *IEEE Trans. Wireless Commun.*, vol. 17, no. 1, pp. 182–193, Jan. 2018.
- [62] Y. Dandach and P. Siohan, "FBMC/OQAM modulators with half complexity," in *Proc. IEEE Glob. Telecommun. Conf.*, 2011, pp. 1–5.
- [63] Y. Medjahdi, D. L. Ruyet, D. Roviras, H. Shaiek, and R. Zakaria, "On the impact of the prototype filter on FBMC sensitivity to time asynchronism," in *Proc. Int. Symp. Wireless Commun. Syst.*, 2012, pp. 939–943.
- [64] C. Lele, R. Legouable, and P. Siohan, "Iterative scattered pilot channel estimation in OFDM/OQAM," in *Proc. IEEE 10th Int. Workshop Signal Process. Adv. Wireless Commun.*, 2009, pp. 176–180.
- [65] J. Nadal, F. Leduc-Primeau, C. A. Nour, and A. Baghdadi, "A block FBMC receiver designed for short filters," in *Proc. IEEE Int. Conf. Commun.*, 2018, pp. 1–6.
- [66] R. Bäuml, R. F. H. Fischer, and J. B. Huber, "Reducing the peak-to-average power ratio of multicarrier modulation by selected mapping," *Electron. Lett.*, vol. 32, pp. 2056–2057, 1996.
- [67] Y. Cui, F. Liu, X. Jing, and J. Mu, "Integrating sensing and communications for ubiquitous IoT: Applications, trends, and challenges," *IEEE Netw.*, vol. 35, no. 5, pp. 158–167, Sep./Oct. 2021.
- [68] F. Liu et al., "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728–1767, Jun. 2022.
- [69] Z. Wei, F. Liu, C. Masouros, N. Su, and A. P. Petropulu, "Toward multi-functional 6G wireless networks: Integrating sensing, communication, and security," *IEEE Commun. Mag.*, vol. 60, no. 4, pp. 65–71, Apr. 2022.
- [70] K. Ammar, O. B. H. Belkacem, and R. Bouallegue, "OQAM-FBMC based radar sensing and wireless communication in V2V context," in *Proc. IEEE Symp. Comput. Commun.*, 2021, pp. 1–6.



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