IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 26, 2018, accepted December 18, 2018, date of publication January 7, 2019, date of current version January 29, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2891312

Green Coexistence for 5G Waveform Candidates: A Review

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This work was supported in part by the Ministry of Higher Education Malaysia through the Fundamental Research Grant Scheme and the Universiti Tun Hussein Onn Malaysia under Grant 1627.

ABSTRACT There is a growing demand for 5G applications in all fields of knowledge. Current applications, such as the Internet of Things, smart homes, and clean energy, require sophisticated forms of 5G waveforms. Researchers and developers are investigating the requirements of 5G networks for better waveform types, which will result in high spectrum efficiency and lower latency with less complexity in systems. This paper proposes an assessment of various 5G waveform candidates [filtered orthogonal frequency-division multiplexing (OFDM), universal filtered multicarrier (UFMC), filter bank multicarrier (FBMC), and generalized frequency-division multiplexing] under the key performance indicators (KPIs). This paper assesses the main KPI factors (computational complexity, peak-to-average-power ratio, spectral efficiency, filter length, and latency). Moreover, this paper compares and evaluates all KPI factors in various 5G waveforms. Finally, this paper highlights the strengths and weaknesses of each waveform candidate based on the KPI factors for better outcomes in the industry. In conclusion, the current review suggests the use of optimized waveforms (FBMC and UFMC) for better flexibility to overcome the drawbacks encountered by previous works. Regarding coexistence, FBMC and UFMC showed better coexistence with CP-OFDM in 4G networks with a new radio spectrum. The rapprochement between the above-mentioned waveforms has been called green coexistence and is due to the mix between one waveform in 4G networks and two waveforms in 5G networks based on the subcarrier and subband shaping (FBMC and UFMC).

INDEX TERMS 5G, FBMC, F−OFDM, GFDM, KPI, UFMC, waveform.

I. INTRODUCTION

The rapid emergence of smart devices, mobile computing and the Internet, data has become a vital resource in human society and our daily activities and lifestyles. No longer are there physical boundaries restricting the flow of data. However, while there are many advantages of free-flowing data between users, businesses and government, stringent measures must be adopted to safeguard and protect these data. This is one of the initial challenges of fifth generation (5G) wireless broadband technology [1] as it synchronizes various online services and can investigate mobility levels, as well as the deployment of environment categories [2], [3]. In this study, Key Performance Indicators (KPIs) are used to measure the different technical approaches for Air Interface Components for Mobile Broadband (MBB), Massive Machine Communications (MMC), Mission Critical Communications (MCC), Broadcast/Multicast Services (BMS) and Vehicle-to-vehicle and vehicle-to-infrastructure communications (V2X) and to identify which are the most suitable waveforms used in 5G in covering all these applications.

Orthogonal frequency division multiplexing (OFDM) is one of the most widely used and adopted groups and has been used extensively for previous technology generations of waveforms, such as Long Term Evolution (LTE) and Long Term Evolution-Advanced (LTE-A). Indeed, OFDM have solved many of the problems experienced by these previous systems. One interesting finding have been towards selecting selectivity, improving spectrum efficiency and reducing inter-symbol interference (ISI) and inter-carrier interference (ICI) using a cyclic prefix (CP), but some weaknesses, however, could not be addressed. Therefore, the application of the fifth generation (5G) needs to improve these weaknesses, which

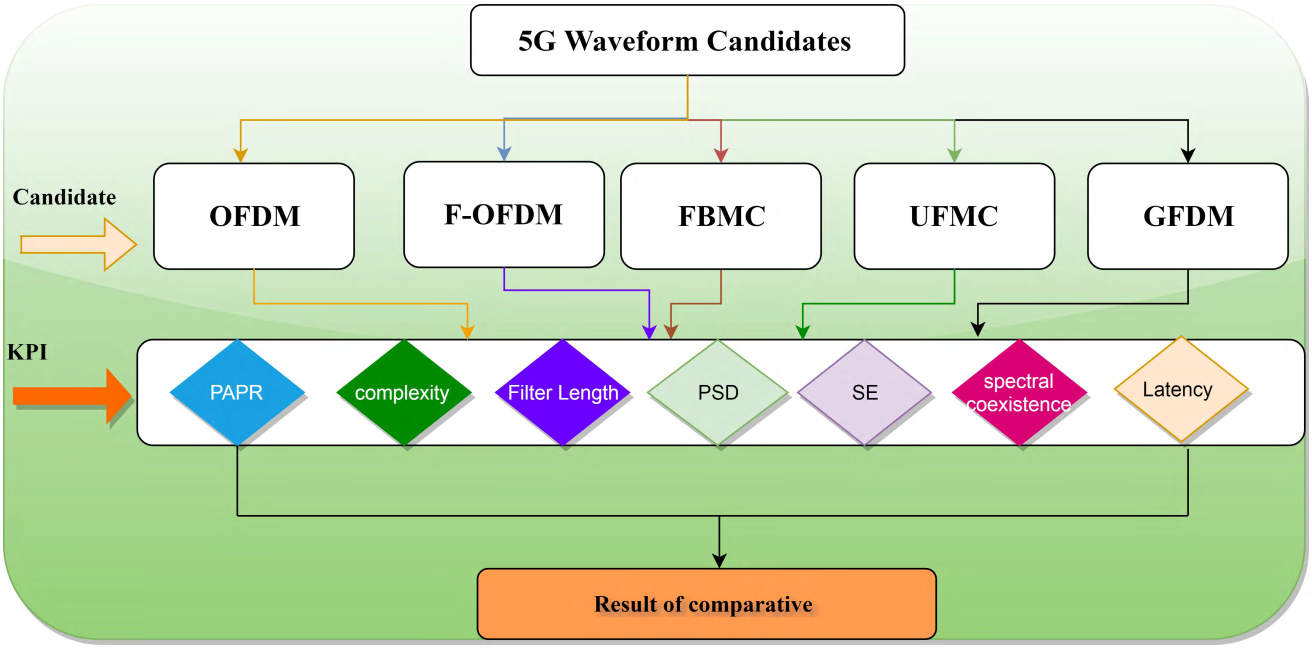

FIGURE 1. Process of the comparison of waveform candidates.

include:

1) High spectral leakage, it should be used pulse shaping to improved [4],
2) Stringent synchronization requirements [5],
3) Sensitivity to multiple carrier frequency offsets (CFOs) [6], whereas it need so many techniques to solve this problem as shown in this studies [8], [9],
4) The need to introduce a cyclic prefix to avoid multipath fading,
5) The peak to average power ratio (PAPR), which is very high, and out-of-band emission (OOBE),the overall power emitted at the frequencies of the out-of-band spectrum, because the OFDM uses square waves as the baseband waveform [7], [10].
6) The bandwidths of the subcarriers that should have the same bandwidth [11].
7) The OFDM loss of 10% of the total bandwidth, spent as a guard band [12].
8) The inferior performance and high bit error rate (BER) of OFDM with the higher modulation scheme.

The choice of suitable and acceptable waveforms has long been a question of significant interest in a wide range of physical layers, which are specified in the design of 5G. Therefore, the objective of this Systematic Literature Review is to present the limitations, challenges and comparisons with other types of waveforms, including OFDM, FBMC, UFMC, GFDM, and F-OFDM. These depend on KPIs such as Peak-to-Average-Power-Ratio (PAPR), computational complexity, filtering type, latency, spectrum efficiency, power spectral density and Spectral coexistence to create a clear image for researchers, academia and industry in making proper decisions for 5G waveforms. Fig. 1 shows the process of the comparison of waveform candidates. This paper introduces the academic literature published with a focus on 5G waveform candidates.

This paper includes three primary objectives. First is a systematic review of 5G waveforms based on their KPI. The purpose of this systematic review is to classify the literature that is related to 5G waveforms to create a taxonomy and identify gaps in the research in this area. In addition, challenges and obstacles that were reported in the selected list of articles are classified to identify the problems of the current 5G waveforms, as well as to show which waveforms will achieve the demands of 5G requirements.

The rest of this paper is organized as follows: in the section Second, a systematic review method is provided. Section III, dedicated to wave filters in 5G and offer the idea in each candidate, we suggest studying them. In section IV, waveform summary. Accordingly, we explained the reason for searching for criteria for shape candidates, and the presentation of the different wave patterns we see in Section V. In Section VI. We suggest a new KPI for evaluating performance in each candidates, which is common used to study these waveforms in 5G. In Section VII, We offer the new idea of previse coexistence studies. We have therefore explained the reason for the search and we suggest for green coexistence 5G waveform and the presentation of the different wave patterns we see in Section VIII. Finally, section IX concludes this article.

II. METHOD OF SYSTEMATIC REVIEW

It is very useful to understand the significant databases used in this paper and the type of data collected. Four databases

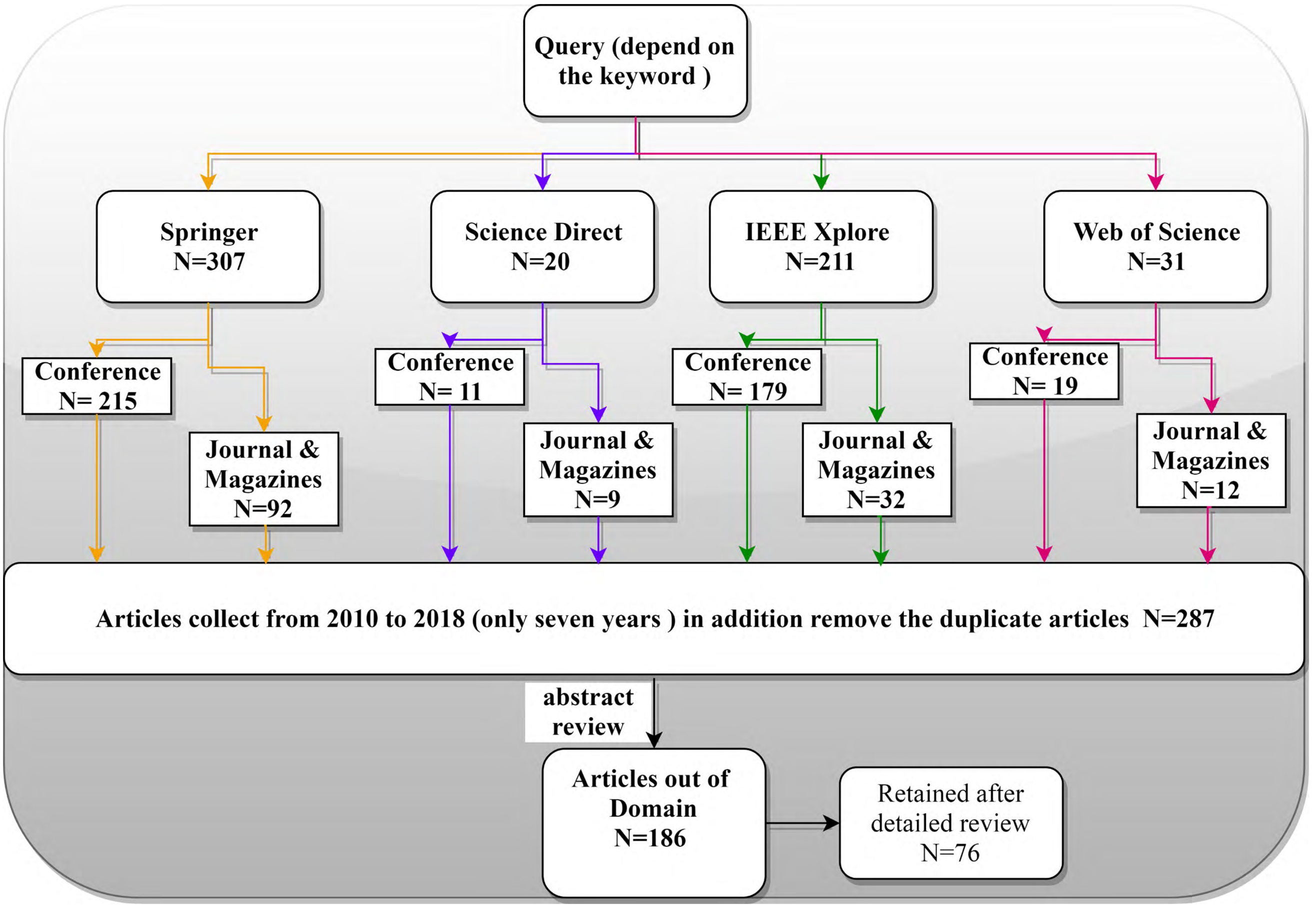

FIGURE 2. Flowchart of the studies collected, including the search query and inclusion criteria.

are utilized: the Springer, Science Direct, IEEE Xplore, and Web of Science (WOS) databases. The query depends on the keyword used in the search of all databases, as shown in Fig. 2. The search was limited to journal and conference articles, as well as some reports specific to 3GPP. We considered these two venues to be the most likely to include all relevant scientific works/trends regarding 5G waveform candidates and KPI.

III. WAVEFORM CANDIDATES

The waveform has long been a question of great interest in a wide range of previous-generation and next-generation contexts. Recently, there has been renewed interest in new Radio Access Technology (NR), and there is a possibility of obtaining a better waveform design to comfortably multiplex various services while making enhancements for the specific demands of each service. The waveforms can be classified into single-carrier waveforms and multi-carrier waveforms.

A. SINGLE CARRIER WAVEFORMS

Single-carrier waveforms have been exceedingly utilized in cellular systems, such as Universal Mobile Telecommunications System (UMTS) and Wideband Code Division Multiple Access (WCDMA). The single-carrier waveform has various features, including time-domain symbol sequencing and low peak-to-average power ratio, which makes the power amplifier work inefficiently. One longitudinal study found that the optimization goals for single-carrier waveforms are extended battery life and coverage extension, such as massive Machine Type Communications (mMTC) [13].However, single-carrier waveforms stick with link degradation under frequency selective channels. Additionally, in the multipath scenario, single-carrier waveforms need an equalizer to enhance spectral efficiency.

B. MULTI CARRIER WAVEFORMS

The best example of multi-carrier waveforms is orthogonal frequency-division multiplexing (OFDM), such as that used in 4G. Several reports have shown that the OFDM waveform have sharp points. One interesting finding is that it makes functional utilization of the spectrum by allowing overlap. Additionally, the complexity of OFDM is lowest compared with other waveforms due to the use of Fast Fourier Transform/ Inverse Fast Fourier Transform (FFT/IFFT). The current study found that multi-carrier waveforms have simple equalization needs compared with those of single-carrier

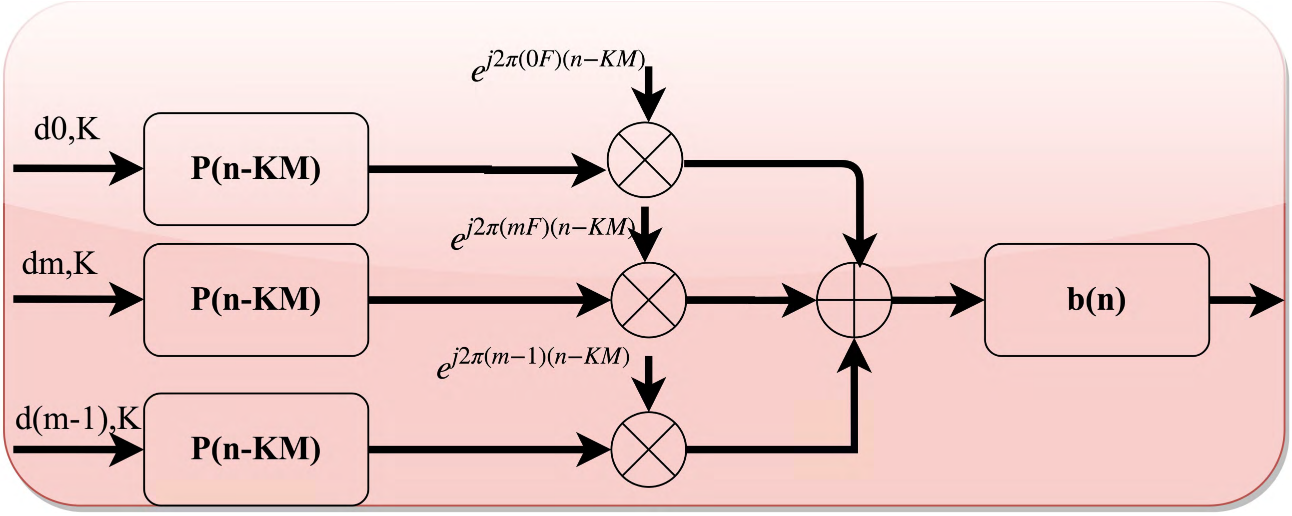

FIGURE 3. Show us general implementation of multi-carrier waveform.

waveforms. The OFDM waveform avoids ISI and ICI by use of a cyclic prefix and is less sensitive to sample timing offsets [14], [15].

Alternately, the PAPR of OFDM is very high as a result of the nonlinear power amplifier work. There are side lobes in frequency (OOB) because OFDM uses a square wave as the baseband waveform; this results in the spectrum of OFDM having reduced power efficiency. Furthermore, it is more sensitive to carrier frequency offset. Additionally, there is greater need for a synchronization system. All of these essential disadvantages block the adoption of OFDM in the 5G waveform.

The multi-carrier waveform should be further appreciated by the inclusion of the band-pass filter b(n) to avoid the weakness of the OFDM waveform and achieve the demands of 5G. Multi-carrier waveforms can be represented by the following expression, (1).

$$y(n) = \sum_{k=-\infty}^{\infty} d_{k,m} \cdot p(n-kM) \cdot e^{j2\pi mF(n-kM)} \tag{1}$$

where $p(n)$ is the prototype filter,$e^{j2\text{ÏĂ}mF(n-kM)}$ represents the frequency shifter corresponding to the $m-th$ subcarrier, k is the data symbol index within each carrier, and n is discrete time index in the digitally domain. Fig. 3 shows a general implementation of a multi-carrier waveform illustrating which parts will be developed to obtain different candidates. $p(n)$ is consistently executed by time-domain windowing, which correlates to manipulating the pulse shaping in the subcarrier in the frequency domain.

Filter Bank Multicarrier (FBMC) can be likewise viewed as utilizing this method. $b(n)$ is consistently executed by time-domain filtering, which depends on applying a frequency-domain band-pass window over a block of contiguous subcarriers, as we will see, the Universal Filtered Multicarrier (UFMC).

1) CYCLIC PREFIX OFDM (CP-OFDM) WAVEFORM

The cyclic prefix OFDM (CP-OFDM) waveform is the most used multi-carrier waveform specified with an LTE \ LTE-A system because it has attractive features. The first feature is high spectrum efficiency, as well as the application of MIMO technology. Another possible feature is straightforward frequency-domain equalization per subcarrier for the non-flat channel. Moreover, bandwidth can be dynamically specify to users [16].

The CP-OFDM waveform can be incorporated as a particular straightforward situation of Fig. 3 by just setting out the prototype filter $p(n)$ as a rectangular pulse. In addition, pass $b(n)$ and $K = 1$ as show in (2).A major disadvantage of the CP-OFDM waveform is poor frequency localization because of the rectangular prototype filter $p(n)$ [17]. Interference of the adjacent band is due to slowly decaying OOB leakage, as well as the frequency offset between users. Another major disadvantage of the CP-OFDM waveform is that the CP length is set to be approximately 10% of the OFDM symbol length, as well as higher PAPR [18].

$$y(n) = \sum_{k=-\infty}^{\infty} \sum_{m=0}^{M} d_{k,m} \cdot e^{j2\pi mk/M} \; K \subset \left[-L_{cp}, M-1\right] \tag{2}$$

In CP-OFDM with weighted overlap, add (WOLA) [19] as show in Fig. 4. The main point is that, different from previous waveforms (CP-OFDM without WOLA), the rectangular prototype filter is changed to pulse with soft edges at both sides (raised-cosine prototype filter). The excellent achievement in this point will be much sharper sidelope decay in the frequency domain. The soft edges at the outset and end of the filter response entirely bear the best guarantee prototype filter in the frequency domain.

This method is particularly useful in studying trade-offs between the width of the main lobe and repression of the side

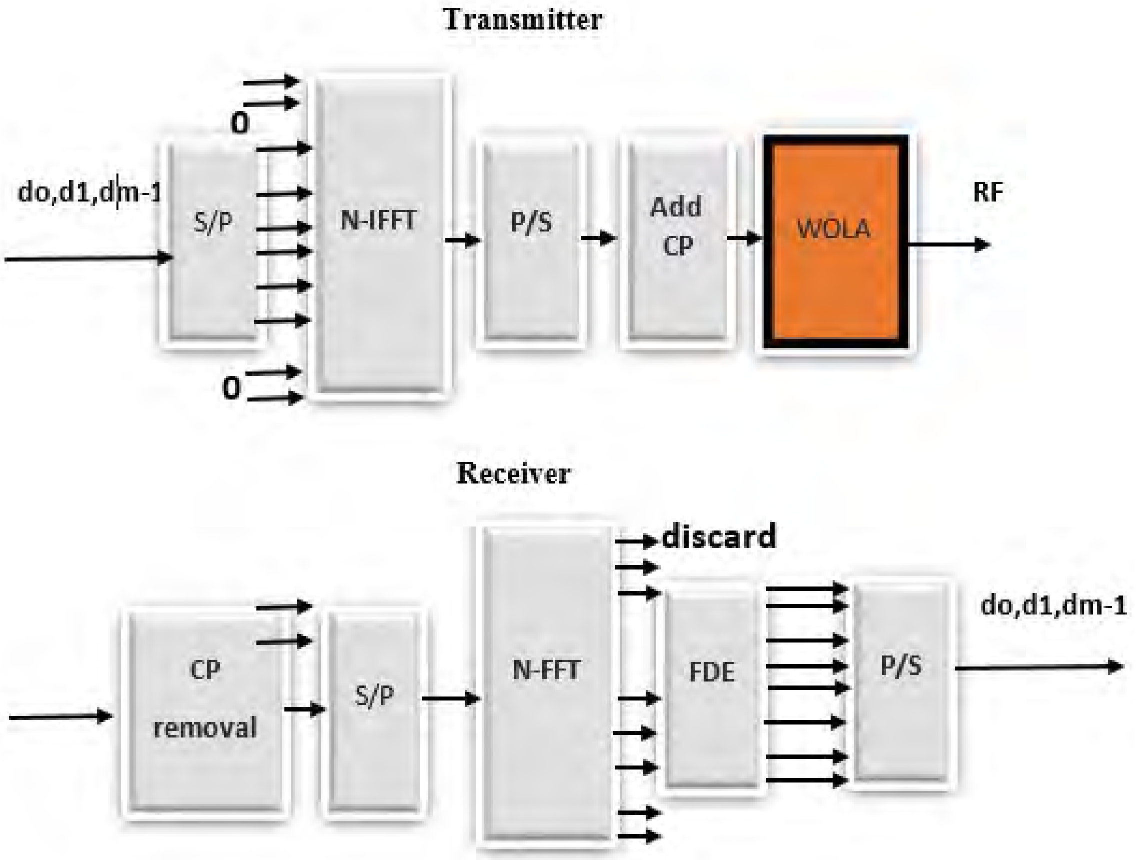

FIGURE 4. Transmitter and receiver of the CP-OFDM-WOLA.

lobes, and various types of windowing have been investigated in the literature [20].The WOLA is applied in the transmitter to limit the OOB leakage of the signal. Additionally, if applied, the WOLA in the receiver will avoid the users interference, specifically when users are asynchronous. Fig. 5 show us the idea of CP-OFDM-WOLA in the transmitter and receiver side. The CP-OFDM-WOLA is used in the LTE downlink. Alternately, several questions remain unanswered at present and should be investigated for this waveform. The main disadvantage of CP-OFDM-WOLA are high Adjacent Channel Leakage Ratio (*ACLR*) side and the need for more synchronous multiplexing.

2) UNIVERSAL FILTERED MULTICARRIER (UFMC) WAVEFORM

UFMC, as shown in Fig. 6 [21], [22] attempts to decrease the *OOB* leakage from the signal like WOLA. However, the UFMC uses a non-trivial band-pass filter $b(n)$.The apparent difference between CP-OFDM and UFMC is that UFMC does not use the CP, but a guard interval (GI) padded with zeros is introduced between the IFFT symbols to avoid ISI due to transmitter filter delay. In the last step, the symbols pass through filter b (n) shows the process of UFMC at the transmitter. Generally, the length of the filter is set the same as the length of the guard interval duration. Fig. 7 shows the modulation and demodulation of the UEMC waveform. The filter design (band-pass filter) passes the assigned RB.

The current study found that UFMC does not use cyclic convolution, whereas CP-OFDM does use it. Another significant finding was that the receiver structure of UFMC is using the entire symbol, adding GI comprehensively, and using two ×size of FFT at the receiver to recover the signal. Fig. 8 shows the process of the receiver of UFMC. Additionally, the receiver avoids the odd tone of the 2×size FFT, and uses just the even tones to recover the signal.

Another proposal is for the same UFMC method but differs in one point regarding the filter cyclic prefix OFDM (FCP-OFDM). UFMC uses just the ZP, whereas FCP-OFDM uses the mixed CP and ZP with flexible partition, as shown in Fig. 9. The encouragement is to offer an undemanding trade-off between multipath processing and OOB emission repression.

3) FILTERED OFDM (F-OFDM) WAVEFORM

The filtered-OFDM (F-OFDM) [15] is other spectrum shaping mechanism using the filtering process. The prototype filter $p(t)$ used in this candidate is a rectangular pulse mask of the OFDM symbol, as well as a cyclic prefix. Additionally,

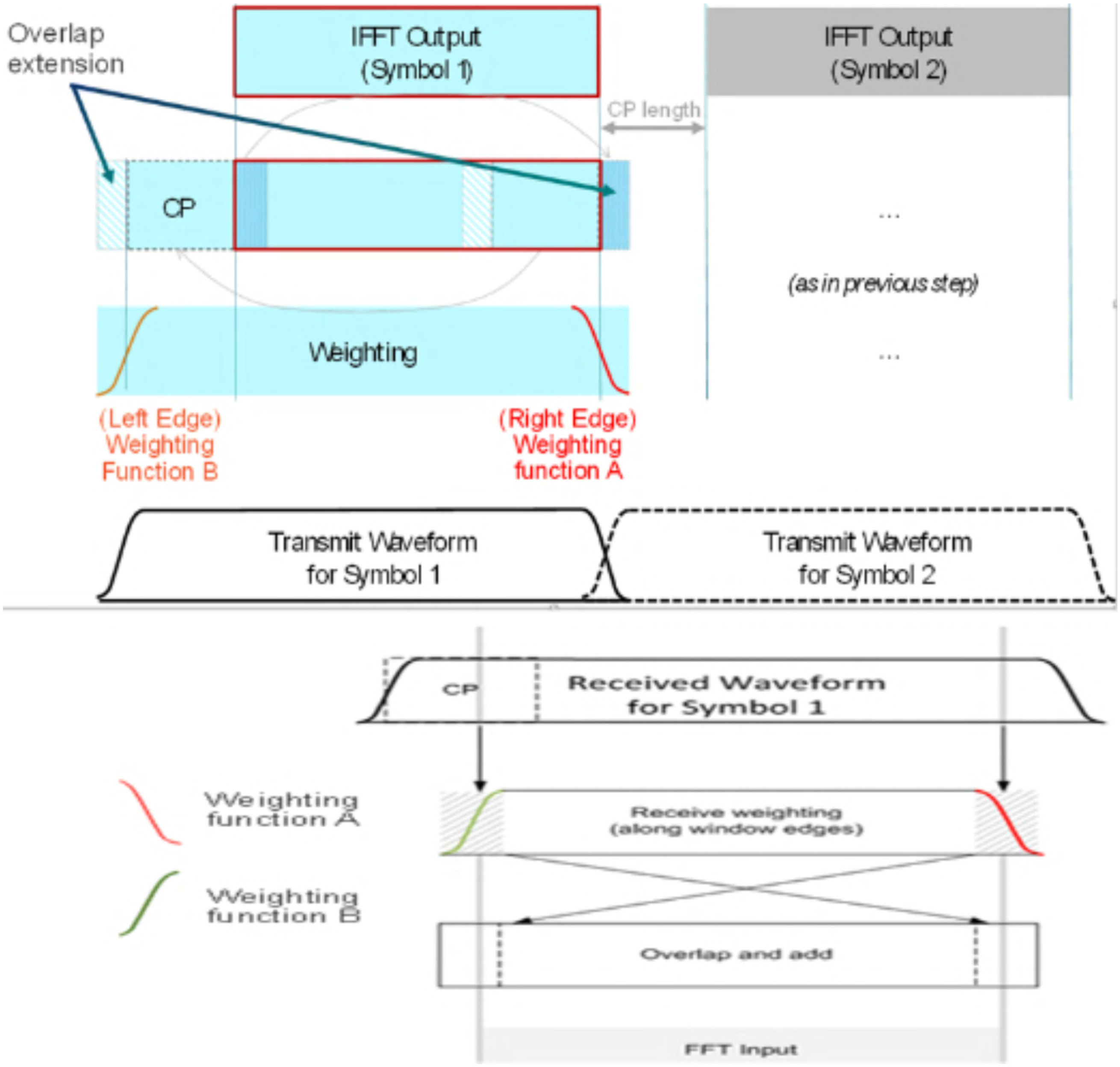

FIGURE 5. The idea of CP-OFDM-WOLA on the transmitter and receiver side.

the filter $b(t)$ is carefully intended to avoid OOB interference. The length of filter should be set to $1/2$ of the OFDM symbol, as well as the band pass filter depend on the (3) in time domain. $p_i(n)$: is ideal band pass filter and $w(n)$ is the Hanning window.

$$f(n) = p_i \cdot w(n) \tag{3}$$

The main weakness with this waveform (F-OFDM) is the long filter length. The second limitation is that the filters should be dynamically constructed depending on the tone allocation. Additionally, this is challenging for low-latency service due to the filter length.

4) FILTER BANK MULTI-CARRIER (FBMC) WAVEFORM

The Filter bank multi-carrier (FBMC) waveform was primarily suggested in the 1960s [20], [23]. Recently, this waveform has been redrawn to be more suitable for cognitive radio and excellent for spectral containment [24]. The shape of the prototype filter $p(n)$ can achieve the correct spectral property due to oversampled coefficients in the frequency domain. The one interesting finding is that the FBMC waveform is commensurate to time-domain windowing. Alternately, the transmitter and receiver are of high complexity. Additionally, the FBMC wave should use the offset-QAM to avoid ISI, which will increase the complexity. One limitation of FBMC is that deployment with MIMO specific features with high

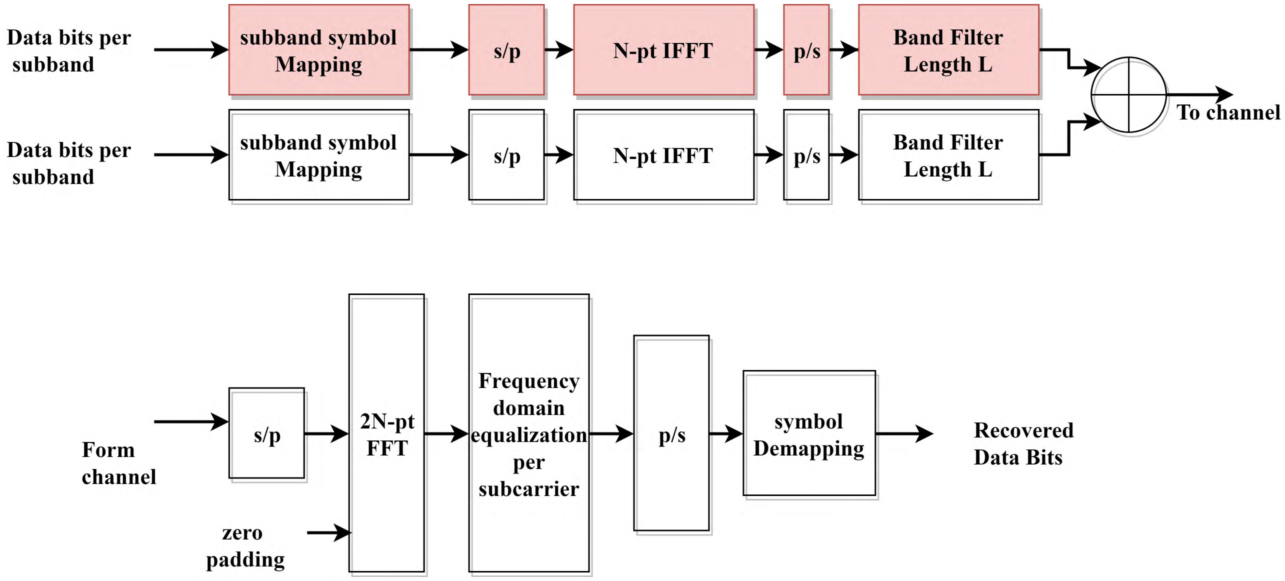

FIGURE 6. Transmitter and receiver of UFMC.

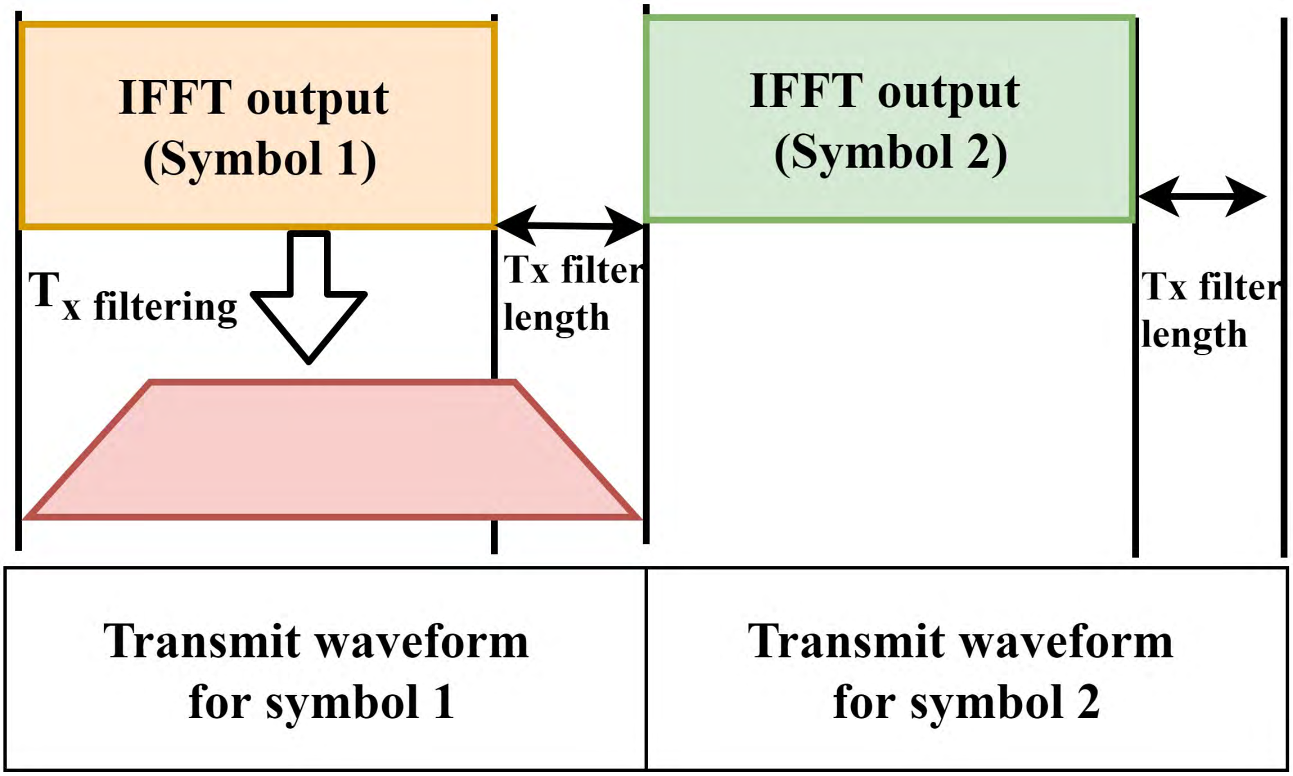

FIGURE 7. Process at the transmitter side.

spectral efficiency should be covered utilizing more degrees of freedom [7].

5) GENERALIZED FREQUENCY DIVISION MULTIPLEXING (GFDM) WAVEFORM

Generalized frequency division multiplexing (GFDM) [25], [26]is performed by investigating OFDM symbols collected into a block and adding a cyclic prefix to the block. Additionally, the prototype filter $g(n)$ ((4)),uses circular convolution in time and will be well localized in the frequency domain. Moreover, it features low out-of-band radiation. The GFDM has flexible allocated bandwidth per user. A block of GFDM waveforms can be represented by (5).Each block is represented by $N = K \cdot M$ samples. Separately, each

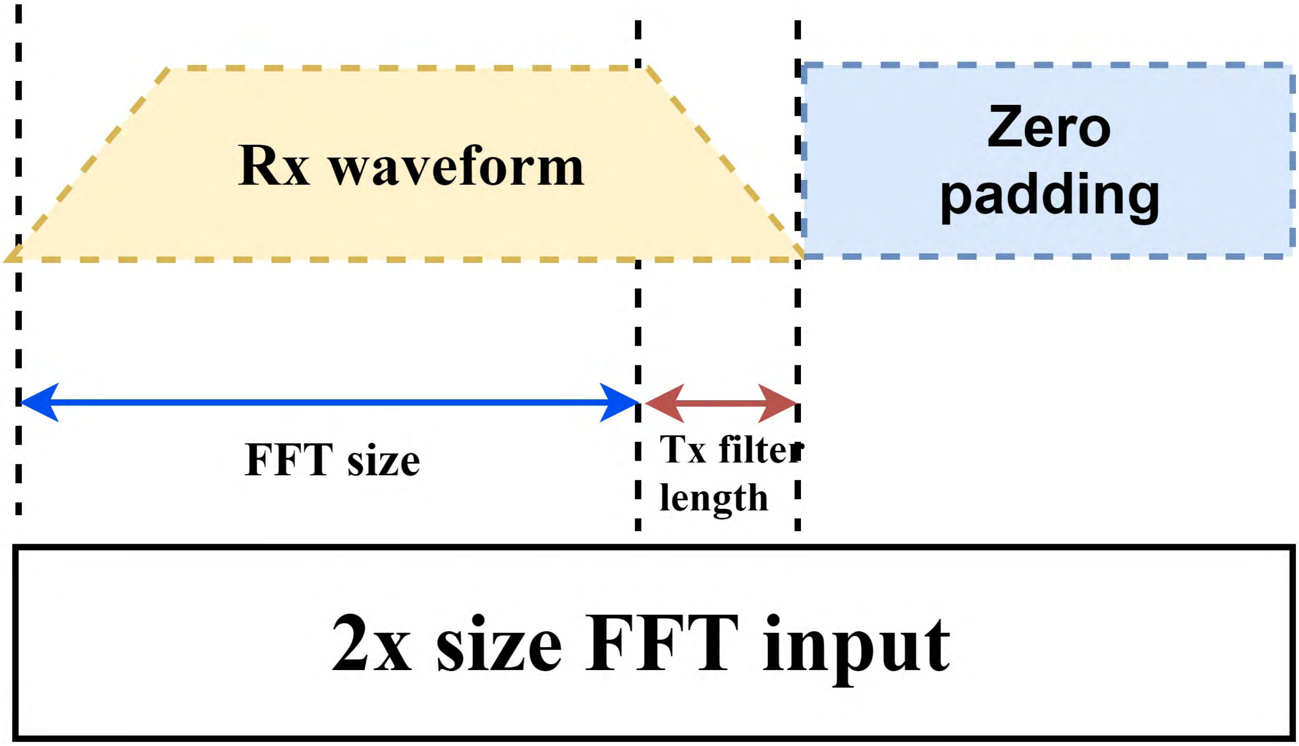

FIGURE 8. Process at the receiver side.

FIGURE 9. The difference between FCP-OFDM and UFMC.

subsymbol contains $K = BT/M$ subchannels and spacing of M/T (Hz). Fig. 10 shows the division of resource in GFDM.

$$g_{k,m}(n) = g[(n-mK)modN]\cdot e^{j2\pi k\frac{n}{K}} \tag{4}$$

$$x(n) = \sum_{k=0}^{K-1}\sum_{m=0}^{M-1} g_{k,m}(n)\cdot d_{k,m} \quad for\ n = 0, 1\cdots, N-1 \tag{5}$$

Alternately, the receiver of GFDM has more complexity. Furthermore, GFDM should use the Mach filter to recover and avoid the ISI and ICI. The GFDM needs a high filter order to avoid the ICI and tail biting [27].Another limitation of GFDM is that it is more sensitive to Symbol time offset (STO) and Carrier frequency offset (CFO). Pre-cancellation should be in demand to relieve the ICI that as yet occurs after filtering.

IV. SUMMARY OF WAVEFORMS

Although this study focuses on waveform candidates in 5G and previous generations, the findings may well have a bearing on how to evaluate the waveforms and find what the main differences between them are. All waveforms use FFT/IFFT. In addition, CP, zero-guard or GI should be used in the waveform to avoid the ISI and ICI. The findings reported here shed new light on the primary factor that the design of any waveform depends on. The type of shaping of data (subband or subcarrier) that is used to design the waveform will be limited by the criteria of the waveform. Table 1 shows a comparison of the implementations of different waveforms depending on waveform synthesis.

V. CRITERIA FOR WAVEFORMS CANDIDATES

A. OFDM WAVEFORMS CRITERIA

OFDM broadband for both wired and wireless communications has been a recognized field of research for several

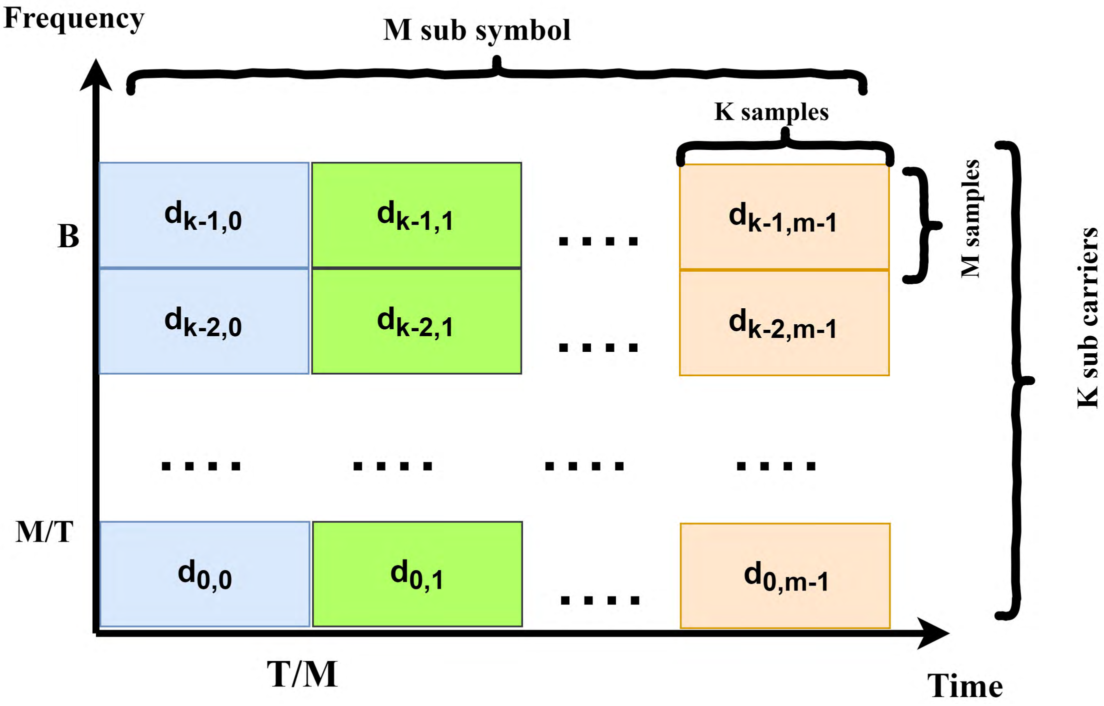

FIGURE 10. Division of resources in GFDM.

TABLE 1. Comparison of the implementations of the different waveforms.

Waveform	IFFT	CP/Zero-guard	Windowing	FIR Filter
OFDM w/o WOLA	Yes	CP	No	No
OFDM w/ WOLA	Yes	CP	Yes	No
UFMC	Yes	ZP	No	Yes
FCP-OFDM	Yes	ZP + CP	No	Yes
FBMC	Yes	No	Yes	No

decades and is widely adopted due to the number of aspects that it can offer for use with different generations. This section is included in the study for several reasons; OFDM uses the IFFT block in the transmission of signals and have FFT block separation of the transmitted data symbols at the receiver, therefore enabling the OFDM to have low complexity compared with other different waveforms. Also important are its simple equalization over a scalar gain per subcarrier and its adoption of multiple-input-multiple-output (MIMO) channels. According to space orthogonal subcarriers, which allow the flexible bandwidth to be divided into a maximum group of narrow subbands, as well as the adaptive modulation scheme that depends on subcarrier bands, the bandwidth efficiency/transmission rate will be higher. Based on synchronization, the OFDM symbol structure is exceptional and simplifies synchronization. These advantages are well recognized and demonstrated in the literature [14], [28]–[30].

However, OFDM deteriorates as a result of several weaknesses. The first weakness is the PAPR, as well as OOB due to the OFDM using a square wave as the baseband waveform. Accordingly, this reduces the power efficiency and performance of the OFDM spectrum, which many researchers have investigated [7], [31], [32].Moreover, the wastage of these radio resources in OFDM results because they use the cyclic prefix to avoid multipath fading. Furthermore, the OFDM, in this case, represented 10%of the allocated bandwidth to prevent ISI and inter-block interference (IBI) from occurring [12].

Further, when increasing the amount of user equipment (UE), the signaling overhead increases in the OFDM-based system. Moreover, the OFDM is more sensitive to CFO as a result and the incongruity between the different devices. Therefore, all these inherent disadvantages block the adoption of OFDM in the 5G waveform. Researchers in this field who have been investigating the 5G waveform have also highlighted the shortcomings of OFDM, such as its use of filtering or windowing with OFDM and signal processing to enhance the OFDM and to make it suitable as a 5G waveform requirement. Notably, the waveform is only one aspect of the configuration for outlining the PHY and MAC layer for fifth-generation mobile communication. In theory, a perfect waveform may satisfy several requirements: increase the spectral efficiency with high data rates and productive utilization of the available spectrum; reduce PAPR, thereby permitting productive power amplifier design; have robustness against the Doppler shift to permit mobility; and support asynchronous transmission and reception.

B. F-OFDM WAVEFORMS CRITERIA

The central concept of F-OFDM (filtered-OFDM) is to completely filter the band in the transmitter and use a

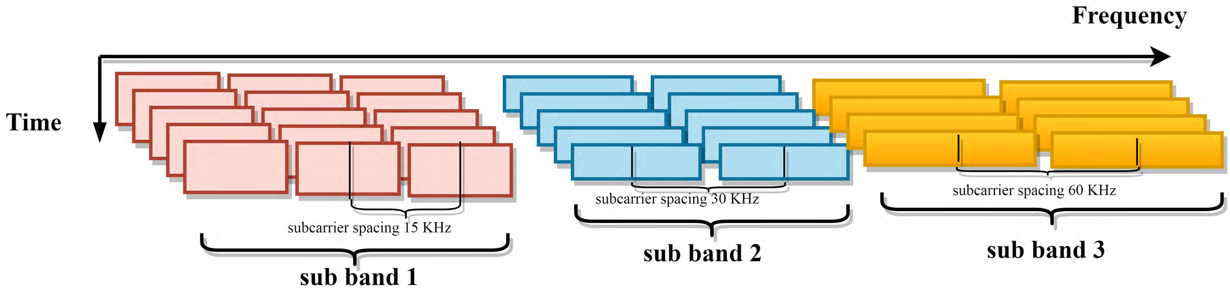

FIGURE 11. Divided the bandwidth into different sub-bands.

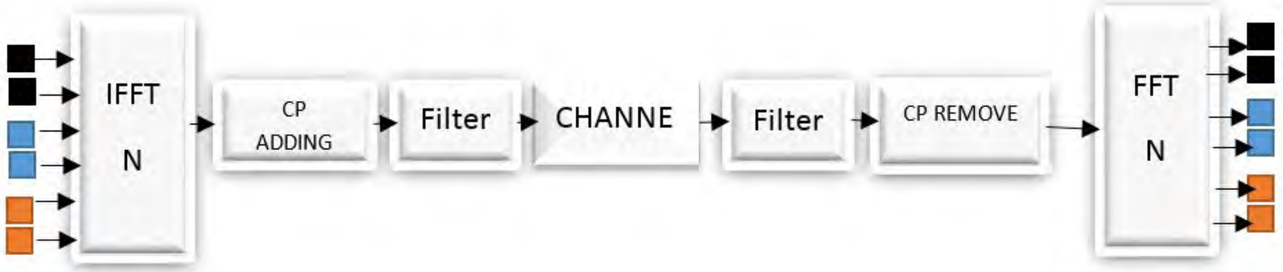

FIGURE 12. F-OFDM candidate.

matched filter in the receiver to receive the same band as shown in Fig. 11. The approach applies a filtering OFDM symbol using time-domain filtering. Further, this candidate (F-OFDM) can be viewed as a windowed frequency domain due to the multiplication process that is used in the frequency domain, which is equal to the convolution process in the time domain [33].Strategies to enhance the power spectral density might include designing the window width to cover the subband (subband window), whereby this band is allocated to only one user to receive this band. However, this pattern for F-OFDM is not regarded as useful compared with the requirements of 5G because it has several limitations; the length of the filter is very long due to the filter covering the entire band and NFFT [34].

The other concept of F-OFDM splits the bandwidth into subbands, such as resource-block-filtered-OFDM (RB-F-OFDM) [35] and filters the bands. Fig. 12 shows the bandwidth divided into different subbands. Additionally, the guard band is shallow between the subband as a result, which reduces the overhead in the waveform. Another significant finding is that each subband constructed for different sets of waveform parameters gives the F-OFDM greater flexibility in different business scenarios [12]. Moreover, the subband F-OFDM can be used for different modulation schemes depending on the service and power. The value of the cyclic prefix is flexible with different subbands, whereby increasing the subband will increase the cyclic prefix. Fig. 13 illustrates the cyclic prefix, as well as that the length of the filter is decreased. Furthermore, the latency will be lower than the spectrum regrowth of the spectral, which aims to employ the available spectrum as efficiently as possible [36]. A further significant aspect of computational complexity is assessed regarding several real multiplications for each multicarrier modulation (MCM) scheme. Notably, F-OFDM has affordable computational complexity [12], [35], [37].Also worthy of note is that F-OFDM can coexist with different waveforms, such as OFDM and UFMC [12], [38].One of the main advantages achieved by F-OFDM is that it is asynchronous, which is one of the goals of 5G waveforms.

The main weakness of this waveform (F-OFDM) is the filter length, and the impact of the filter length on this waveform is due to several factors. Firstly, if the filter length of F-OFDM is increase more than the normal (1/2 OFDM symbol), the effect of reduce the frequency spectrum (in frequency domain). Secondly, if the length of the filter is shorter than the normal, the increase OOB emission and increase the frequency spectrum [39]. A further systematic approach would be to identify how to produce a balance between the frequency- and time-localization of the filter that interacts with the other variables that are believed to be linked to the filter length such that the flatness of the pass-band, the sharpness of the transition band has enough attenuation in the stop-band because this is the primary challenge for future investigation [40], [41].

C. FBMC WAVEFORMS CRITERIA

The origins of the filter bank based multicarrier (FBMC) date back to the 1960*s* [23], [42]. FBMC is one of the candidates that was initially investigated by researchers and for projects in the industry in order to make it more suitable for

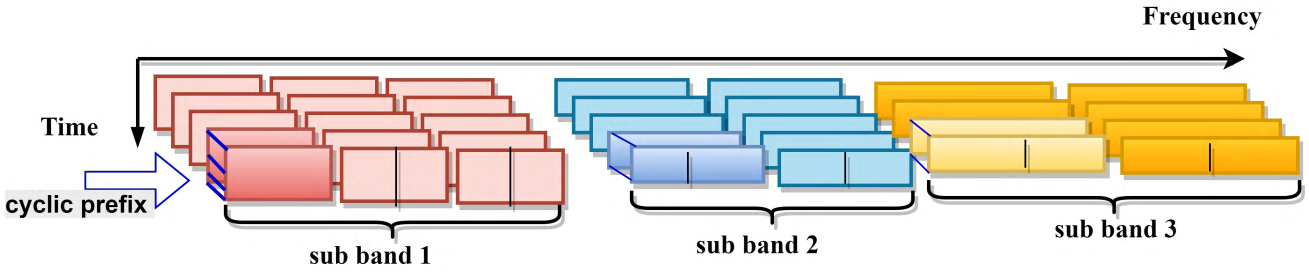

FIGURE 13. Different cyclic prefix for each specific subband.

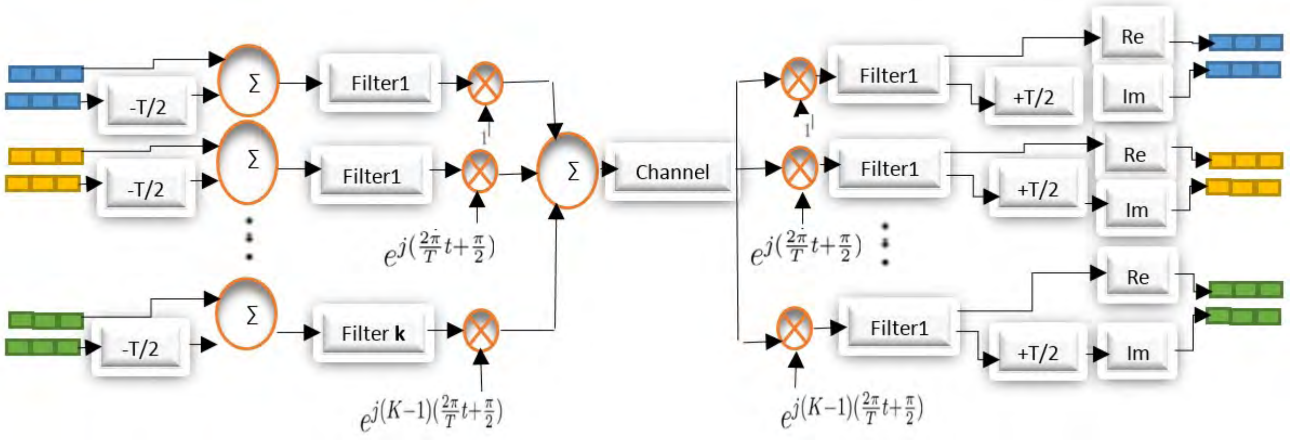

FIGURE 14. FBMC candidate.

the requirements of 5G [24], [43], [44]. The main concept of FBMC is dividing the bandwidth to the subcarrier and filtering on a per subcarrier basis to enables FBMC to be more attractive and to improve OOB thereby enhancing the spectral efficiency [20], [45], [46]. The current study has determined that FBMC has the ability and resilience to control the bandwidth by dividing the subcarrier, which enables FBMC to reduce the inter-carrier interference using some scattered spectrum resources [47].Additionally, the synchronization, channel estimation and detection can be prepared individually on each sub-carrier [48]–[50], and the filtering can lead to the avoidance of Adjacent Channel Leakage (ACL). However, the filtering cannot avoid the inter-carrier interference between successive symbols [51].

FBMC may be divided into two main areas. One depends on complex (QAM) signaling, indicated as filtered multitone (FMT) [52]. The second depends on real-valued offset quadrature amplitude modulation (QAM). OQAM symbols are indicated as FBMC/OQAM as show in the Fig. 14. FBMC/OQAM is achieved by orthogonally in the real domain to produce optimal spectral efficiency and the best spectral localization. However, FM achieves orthogonality among the subcarriers by physically decreasing their frequency domain from overlapping, thus reducing the spectral efficiency in a comparable ratio to CP-OFDM [53]. Another significant finding from the literature review was that the FBMC/OQAM reduces the inherent overheads by the long filter without CP or guard period, resulting in high spectral efficiency for long bursts and low latency [54]. In addition, the FBMC/OQAM achieves asynchronous which is one requirement of the Internet-of-Things (IoT) and 5G [55].

A serious weakness regarding 5G applications, however, is that the symbol duration of the filter bank multi-carrier (FBMC) is very long in coming from the subcarrier filtration process which requires a very long filter length to achieve reasonable filtration effects with a very small band of a single subcarrier. In FBMC, the actively increased symbol duration is appropriate for curing the multi-path fading without incurring CP overhead [56]. However, the main drawbacks associated with long symbol durations cannot be supported by small bursts of data generated by some 5G services, due to high delays and low transmission efficiencies. Further drawbacks of this candidate are that the orthogonal symbols and FBMC/OQAM are not achieved in the complex domain [20], [57], [58]. Additionally, essential interference will occur in OQAM-FBMC, which creates challenges in achieving conventional CP-OFDM pilot design and complex channel estimation algorithms and does not support the MIMO system [56].

One of the limitations of this explanation is that it does not design the same filter in the transmitter. FBMC/OQAM designs two filters for the odd-numbered symbols and the

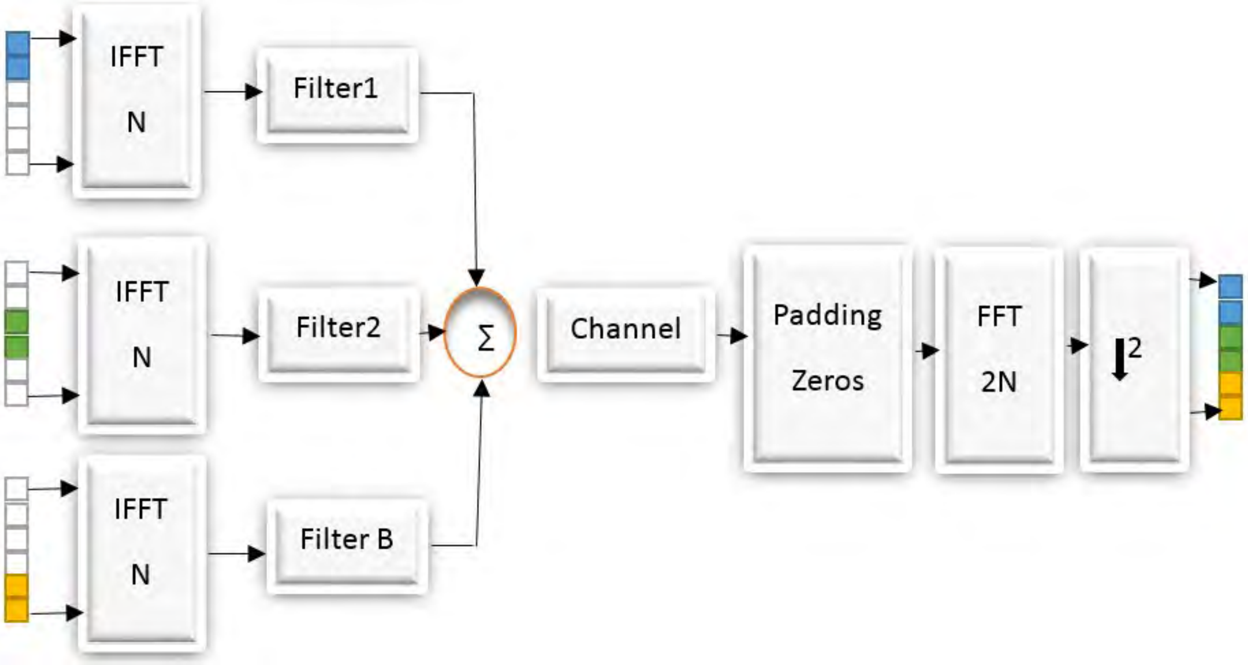

FIGURE 15. UFMC candidate.

even-numbered symbols, thereby increasing the complexity in the transmitter and receiver and increasing the latency of the system. Indeed, perhaps the most serious disadvantage of this method is that of the inherent overhead. The transition times at the transmitter and receiver burst the overhead coming from the $T/2$ time offset between the symbols and should be the length of the prototype filter equal to the total tail duration [59].

D. UFMC WAVEFORMS CRITERIA

Universal Filtered Multicarrier (UFMC) uses suitably designed filters to avoid the drawbacks of F-OFDM and FBMC and combines the advantages of the two candidates. The central concept behind UFMC is that it applies a filter to parts of contiguous subcarriers rather than single subcarriers. Fig. 15 illustrates the block diagram of a UFMC transmitter. The FIR filter of length L should be utilized for each subband and the summation of all subbands. FBMC filters one subcarrier, and F-OFDM filters an entire band. Moreover, UFMC improves spectral localization and achieves increased robustness regarding time-synchronization errors [60].

Furthermore, the filter length of the filtering groups of the subcarrier is less than one subcarrier, and the bandwidth of the filtering is more comprehensive, with shorter tails, compared with that of the subcarrier filter [61]. UFMC has three advantages. First, it is more suitable for short burst communication [6], [62]. Second, the latency is reduced, and lastly, it can use parallel multi-carrier numerologies [62]. A subband-filter supplies steeper side-lobe level dissolution for overall sharing than the effect of windowing because UFMC can use a different filter with different bands depending on the service.

Additionally, UFMC has a highly adaptive modulation scheme due to being designed identically. For example, the number of NFFT in user (1)$N1$ and filter length $L1$ equals user (2)$N2$ and $L2(N1 + L1$âĂ"1 $= N2 + L2 - 1)$,and the same filter, can be used for each subband [63]. Another notable findings for this candidate, is that it is more suitable for specific MIMO systems with coordinated multipoint (CoMP), (joint reception) and with more detail [6]. The performance of the universal filtered multicarrier (UFMC) is more achievable than OFDM by approximately 10% [64]. The most exciting finding in the literature was that UFMC is non-synchronization and non-orthogonal, which were explicitly achieved with machine-type communications and via the IoT and in car-to-car communications [11], [61].

However, one of the limitations is that the length of the filter is limited to avoid inter-symbol interference (ISI) [65]. One of the limitations of this explanation is that UFMC requires more synchronization with user mobility [11].Further, the computational complexity increases with the number of assigned subbands, increasing to approximately ten times that of OFDM complexity for a complete designation in a framework such as LTE [65]. Additionally, the orthogonality will be missed due to UFMC not being deemed suitable for high data rates. UFMC with a high delay spread should be applied to multi-tap equalizers [66].

E. GFDM WAVEFORMS CRITERIA

Generalized Frequency Division Multiplexing (GFDM) as show in the Fig. 16, is based on a classical filter bank multi-division multicarrier concept, which is currently digitally executed [27]. The main structure of GFDM is to apply

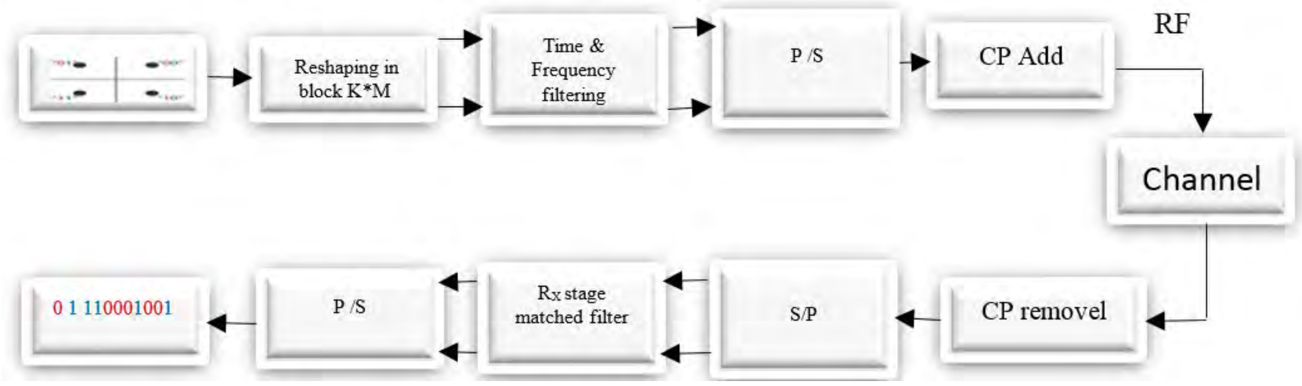

FIGURE 16. GFDM waveform candidate [67].

circular filtering on subcarriers to improve the confining in both the time and frequency domain, which allows multi-user scheduling [67]. Additionally, each subcarrier has various bandwidths that enhance the spectrum, giving greater flexibility for use in cognitive radio. The GFDM block is made up of K subcarrier, and subcarrier M are temporally equally spaced data symbols (multisymbols per several subcarriers) [37]. The fixable size of the blocks permits the implementation of long filters based on the tail-biting digital filters as well which will reduce the total number of subcarriers [68]. The cyclic prefix with different subsymbols allows the definition of a flexible TTI period [66]. Fig. 17 illustrates the GFDM block in the time and frequency domains.

The CP should be added at the end of the block to avoid ISI from occurring [70]. An interesting finding is that the spectral location can be improved by adding windowing in the transmitter. The filter should be filtered at the same time and frequency and should be used to match the filter in the receiver [27]. The interference cancellation (IC) scheme can be implemented to improve the modulation as non-orthogonal but will increase the complexity of the receiver [71]. The GFDM system has flexible filters using both non-orthogonal filters and orthogonal filters [25], [26]. Another interesting finding was that the transmitter filtering is more flexible, resulting in low OOB and lower PAPR.

One major drawback of this candidate is that the receiver is more complex. Further limitations include the matched filter to avoid the ISI and ICI or the use of OQAM, which will make the MIMO technique more challenging [71], as well as high-order filtering and tail biting to avoid inter-subcarrier interference. Nevertheless, the cancellation of such interference coming from the inter-subcarrier still exists after filtering [27]. The system of GFDM needed both Carrier frequency offset (CFO) and Symbol time offset (STO) estimation to improve the performance. Additionally, GFDM should have used windowing in both the transmitter and receiver to reduce the sensitivity of the CFO and tone-offset (TO) [5].

VI. COMPARISON OF KPI PERFORMANCE WITH THE FOUR CANDIDATES

The previous section investigated the four 5G candidate waveforms, and the main parameters were introduced and described. In this section, the four candidates are compared against several KPI criteria, which include: computational complexity; spectral efficiency, PAPR and time and frequency offset, filter length, and short and long burst transmission of the different waveforms.

A. COMPUTATIONAL COMPLEXITY

One of the requirements of the 5G system is that it should be achieved for all waveform candidates, and it should be computationally simple so that the lifetimes of low-power devices can be extended [72]. In this section, computational complexity is investigated with different 5G waveform candidates, such as F-OFDM, FBMC, UFMC and GFDM, and compared with OFDM. A critical aspect of computational complexity depends on some real multiplications per burst for each waveform candidate [35], [73]–[75]. Table 2 shows the computational complexity equation for each of the 5G candidate waveforms [75], [76]. It also depicts the parameter standard depending on the previous study and industry developers related to the computational complexity that will be compared, as all candidates depend on that [77]–[79].

The most apparent finding from the analysis is that, when the complexity is reduced, two aspects will be affected; low-latency transmissions and low energy consumption of both the transmitter and receiver, which is an essential requirement of 5G [80]. OFDM compares the computational complexity depending on the FFT in the transmitter and receiver and the CP. OFDM has the lowest complexity of all the candidates due to the value of M being equal to one and the additional burden of CP. UFMC has the highest complexity because of the increased size of the subband, which will increase the number of subbands and increase the complexity of the system. Secondly, the complexity also depends on the number of filter taps [81]. Moreover, the receiver of UFMC that is used in the 2N FFT operation will incur an increased burden as a result [63], [82].

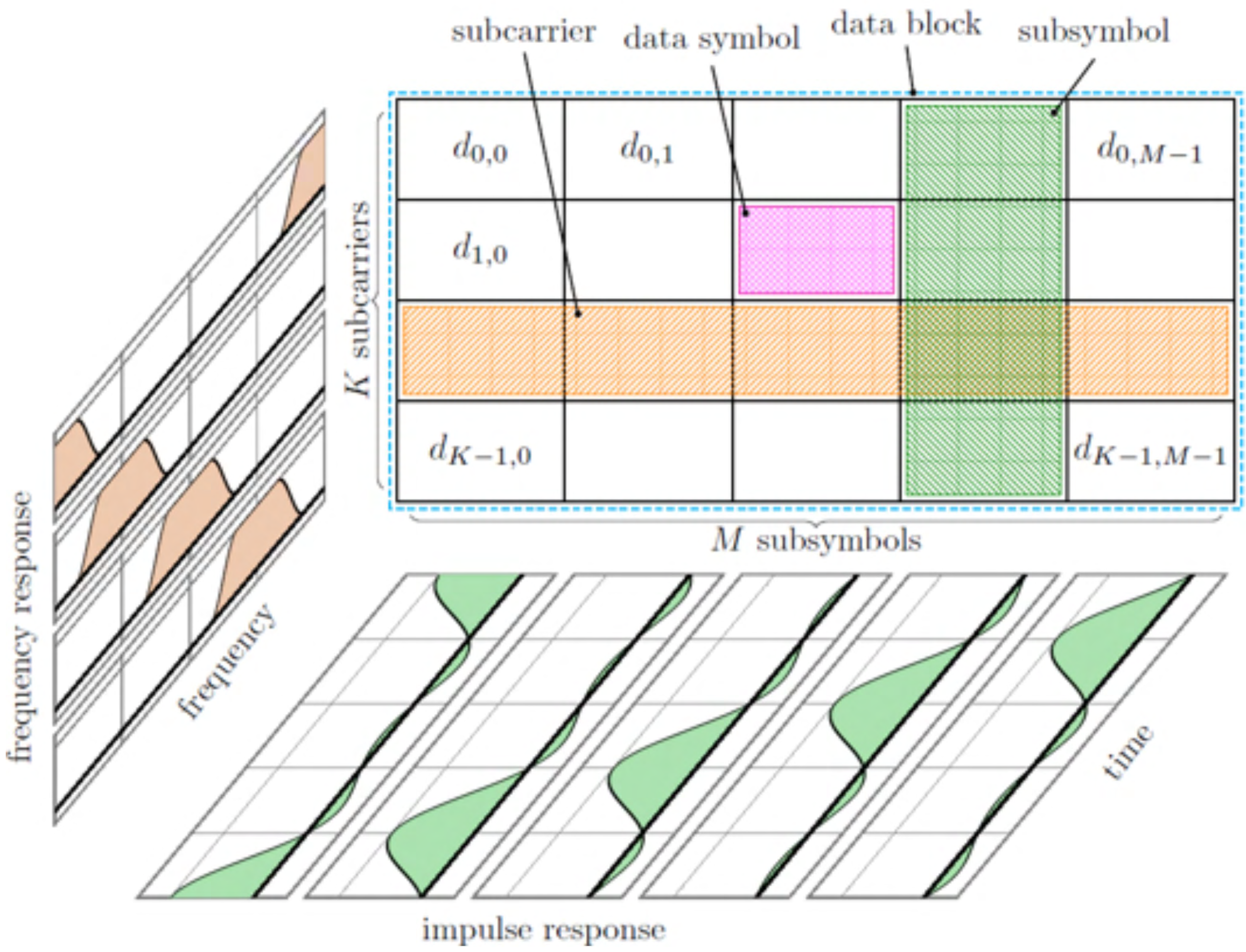

FIGURE 17. The GFDM block in the time and frequency domains [69].

Another significant finding was that the burden of F-OFDM is the computation of OFDM, and by adding the effects of transmission filtering and receiving, the filtering will increase the burden of F-OFDM [35]. Additionally, the burden of F-OFDM is less complicated than that of FBMC, GSDM and UFMC. The burden of FBMC is six times more complicated than that of OFDM and with less complexity than GFDM. Notably, the complexity of GFDM is far less than that of UFMC due to the circular filtering in GFDM having less standard filter complexity. when assume that the normalized complexity to the OFDM complexity for M = 14, N = 1024, D = 12, p = 6, NCP = 72, N = 664, L = 72 (UFMC), and L = 513 (FOFDM) as show in Table 2.

TABLE 2. The Computational Complexity Equations for Each of the 5G Candidate Waveforms.

Waveform	Number of Real Multiplications Per Burst	Normalized complexity
$N-$point FFT and IFFT	$(2 \times (N \log_2 N - 3N + 4)$	
OFDM	$M \times (2 \times (N \log_2 N - 3N + 4)$	1
F-OFDM	$M \times (2 \times (N \log_2 N - 3N + 4) + 2NL + 2 * (N + NCP) \times L)$	4.8427
FBMC	$M \times (2 \times (N \log_2 N - 3N + 4) + 4N + 8NP)$	5.7122
UFMC	$M \times (2 \times (N \log_2 N - 6N + 4) + N/D \times (N \log_2 N - 3 + 4 + 2LN))$	601.89
GFDM	$6MN \times (M + \log_2 N) + 2 \times (MN \log_2 MN - 3MN + 4)$	11.8231

B. PAPR WITH 5G WAVEFORMS

For the peak-to-average power ratio (PAPR), the main idea is to measure the PAPR as the peak amplitude of the waveform is divided by the root mean square [79]. One of the main drawbacks of OFDM is PAPR, and it should be a trade-off between the cost and the linearity of the amplifiers. The signal distortion and higher BER caused by the nonlinearity of the amplifiers is due to the high PAPR. Many methods have been used to reduce the PAPR in OFDM [15], [83], [84]. As mentioned in the literature review [85], [86] this study demonstrates that all 5G candidate waveforms suffer from of high PAPR.

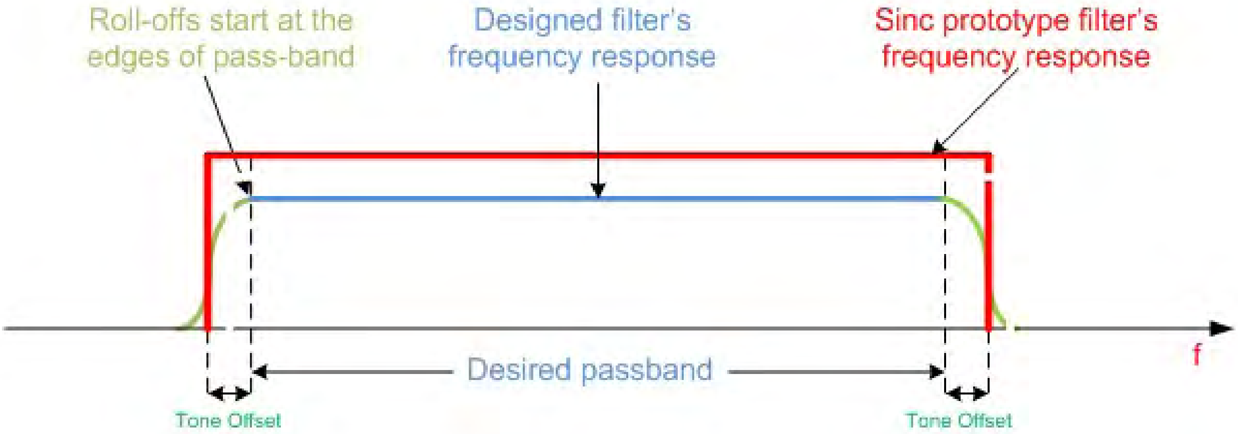

FIGURE 18. Tone Offset (TO) in the Filter Design.

The PAPR of FBMC/OQAM the lowest compared with the other candidates due to the methods applied to enhance the PAPR with OFDM applied to FBMC/OQAM, such as the pre-treated partial transmit sequence (P-PTS), tone reservation (TR), hybrid PTS-TR scheme and Active Constellation Extension [87], [88]. However, all the methods that have been applied are more complicated; this contradicts the requirements of 5G [89]. The PAPR of GFDM is reduced using the wavelet, as well as the OQAM. One unanticipated finding was the use of the OQAM to reduce the PAPR with a wavelet. Despite the inherent multicarrier [90], one of the methods to enhance the PAPR of UFMC is by applying the clipping method (classic clipping, deep clipping and smooth clipping). However, the performance of the system still worsens with PAPR compared with previous candidates [91]. Another method is investigated to reduce the PAPR-UFMC with low computational complexity, which is the conventional pretreatment solutions (PTS) method [92]. This study [21] investigated PAPR and the BER of the UFMC candidate for different modulation schemes, finding that the PAPR of UFMC is better than that of OFDM in great modulation schemes. One major drawback of this investigation is that the PAPR of UFMC in 4-265 QAM is higher than that of OFDM.

C. FILTER LENGTH

The purpose of filtering is to enhance the spectrum and avoid interference leakage to the contiguous sub-bands or subcarrier [15], [39], [93].Additionally, it enhances the frequency localization and reduces the ISI and ICI [63]. A more suitable spectral is in F-OFDM rather than OFDM due to the filtering part. The spectrum fragments are contiguous when the spectrum fragments are not neighboring, as the filtering becomes more challenging because a separate filter should be dynamically designed for every ready chunk. The filtering in F-OFDM is dependent on three points. The first point regards the flatness of the pass-band [93]. The second point is having adequate attenuation of the stop-band, and finally, the sharpness of the transition band is the third point.

To accomplish proper filtering performance and with no guard subcarrier between the adjacent subbands, a filter length Tw up to $T/2$. should be used. The current study found that, to achieve acceptable passband flatness of the filter, it should use the sinc bandwidth B more significantly than the subband because the time-windowing of the sinc filter causes ripples in the transition bands, known as the Gibbs effect [94]. Additionally, the tone offset that is added on each side is to ensure that the resulting filter has a flat passband, as well as frequency roll-offs that begin at the edges of the pass-band. Fig. 18 illustrates the tone offset (TO) in the filter design [95].

Moreover, filtering complexity is dependent on the number of filter taps. The complexity of the time-domain implementation is greater than that of the frequency-domain because the frequency-domain is not effective regarding the number of filter taps. The length of the filter in F-OFDM depends on the size of the subband. If the subband is of a small size, the length of the filter will be reduced [80]. The filter length is lower of compared to that of FBMC, specifically RB-F-OFDM as well as OFDM [35]. Additionally, the ISI of F-OFDM is negligible which is caused by the end-to-end filtering and long tails in the time domain.

While this study [64] investigates entire band filtering, the filter length of the FBMC is smaller than that of F-OFDM. However, the filter that is used with FBMC has a narrower frequency. The need for long filter lengths is to avoid ISI and ICI because the symbols will overlap in the time domain [37]. The ICI caused in FBMC is because the carriers are not orthogonal. To achieve suitable performance of a prototype, the filter length should be increased [11], [96].

Furthermore, the UFMC filter length is shorter than the FBMC filter due to the size of the subband being wider than the FBMC subcarrier signal. Therefore, UFMC is of lower complexity than FBMC for this aspect [11], [97]. Reference [98] shows how to reduce the filter length of UFMC compared with CP-OFDM and with a better BER. However,

TABLE 3. Filter Length Recommendations With Different Waveforms.

Waveform	Shaping Filter	Recommended for Filter Length
OFDM	Whole Band	Less Than the CP Length
F−OFDM	Sub-band	Equal to Half of the Symbol Duration
FBMC	Subcarrier	Four Times More Than the Symbol Duration
UFMC	Sub-band	Equal to the Cyclic Prefix Length
GFDM	Subcarrier	Greater Than the Symbol Duration

TABLE 4. How to calculate the spectral efficiency with different waveform candidates.

Spectral Efficiency With Different Candidates	**Parameters**
$\eta_{OFDM} = m \times \frac{N_{FFT}}{N_{FFT} + N_{CP}}$	m: modulation order N_{FFT} = FFT size N_{CP} :Cyclic prefix
$\eta_{UFMC} = m \times \frac{N_{FFT}}{N_{FFT} + L - 1}$	L: Filter length $= N_{CP} + 1$
FBMC= $\frac{m \times S}{S + K + 0.5}$	S: number of symbols K: Spreading factor
$\eta_{GFDM} = \frac{m \times k \times M}{M + K}$	

the filter length is equal to the CP length and is sensitive to the time difference. Moreover, UFMC is not suitable for an application that requires the synchronization of time.

On the other side, GFDM filtering is circular pulse shaping, which effectively produces a circular convolution thereby removing all the filter transients by the operation of tail biting filtering [70], [99].The filter length, however, should be longer than the symbol duration to avoid ICI. Notably, prototype filtering is more complex compared with precise candidates and therefore requires further investigation to enhance the performance of GFDM. Table 4 depicts the recommended filter lengths with different waveforms.

D. LATENCY

One of the key requirements to be undertaken in 5G is to reduce the latency to 1 *ms* with an exponential rise of the data traffic [100], [101]. If the number of subcarriers is the same in all candidates, the CP−OFDM will be useful due to the short transceiver latency. The main reason is due to the use of IFFT/ FFT as well as CP. The filtering used in the waveform candidates will naturally increase the latency in the system. The lowest latency in FBMC when using the shortest filter and the best time-frequency localization feature is when the length of the filter should equal the FFT, and the latency is equal to $1.5T$ because of the OQAM (delay equals to $T/2$) [74]. Another factor that may affect the latency is the oversampling factor [102]. Additionally, the circular convolution when using the CP increases the latency it will increase the block processing which is specific to the GFDM candidate [5]. With the subband filtering aspect of MCM, the UFMC trades with ZP and with the filter transition period and the latency of UFMC with the same CP−OFDM. The F−OFDM needs buffering to absorb the filter transition period, which will increase the latency. A reasonable approach to overcome (abrupt transitions) could be to increase the latency evaluated as the filter length minus one. Latency can be achieved through good time− localization as several reports have shown that latency is dependent on several factors:

1) Reduce or remove the cyclic prefix tol enhance the latency of the system.
2) Power consumption is one factor that can enhance the latency.
3) Reducing the filter length reduces the complexity of the system because of low latency.
4) Supporting short burst transmutation as show in UFMC.

Alternately, there is a definite need for low latency given it has a significant impact on the requirements of services, while other services may not be affected [103].

E. SPECTRAL EFFICIENCY

Spectral efficiency refers to how to optimize the data rate that should be transmitted across a given bandwidth to produce better data utilization without losing any area in the spectrum or expression bits per second per Hertz. The maximum spectral efficiency is achieved when the spacing between subcarrier (F), is multiplied by symbol duration (T), and the result should be equal to one which is the condition for maximum spectral efficiency (SE) [104] as shown in (6).

$$T \cdot F = 1 \tag{6}$$

In general terms, this means that the measure of SE is inversely proportional to (6). If the SE is more than one, it will be faced with two problems. Firstly, in the time domain it will require a longer time to transmit one symbol. The second problem, this one in the frequency domain is that it should use an additional frequency band for the transmission or through amalgamating both causes [33].

The spectral efficiency index (SEI)is assumed to play a critical role in evaluating the spectral efficiency of the waveform candidates. The value range is the optimum SEI between $0 \leq$ SEI ≤ 1 with SEI $= 1$. One drawback of the OFDM is that it uses the cyclic prefix and guard band, OFDM, and has a side lobe which results in OFDM having limited spectral efficiency [105]. Furthermore, LTE−OFDM loses 17% of the total specific spectrum due to the side lobe, 10%, and CP 7% [106]. A reasonable approach to overcome this issue that leads to an overall efficiency reduction could depend on the SEI−CP−OFDM (7).

$$SEI_{CP-OFDM} = \frac{T}{T_{CP}} < 1 \tag{7}$$

5G will avoid these drawbacks to enhance the spectra of different waveform candidates. Besides, the 5G system requires a new type of multiple access technology to enhance large spectral efficiency and high access capability to increase the capacity of the system as show in (6) [10].

Previous studies evaluating FBMC observed UFMC reducing the OBB emission thereby reducing the spectral leakage by transmission subcarriers to the unused neighboring band. Moreover, FBMC−OQAM is more suitable to enhance the spectral efficiency because of well− localized time and frequency traits caused by pulse shaping filtering per subcarrier [56]. Furthermore, FBMC OQAM respects the Nyquist−rate and does not use the cyclic prefix which means that it can achieve good spectral efficiency as shown in (8). These waveform candidates will be more suitable compared with OFDM [37]. Nevertheless, this study [63] shows UFMC to be more suitable to enhance the spectral efficiency, than FBMC and OFDM due to it being more robust to multi−user interference and having low complexity.

$$SEI_{OQAM} = \frac{1}{T \cdot F} = 1 \tag{8}$$

However, UFMC needs the guard band to reduce adjacent channel interference (ACI), as well as the length of zero padding, which should be equal to a length of the FIR filter minus one. Also, the length of the filter used with UFMC and the stopband attenuation leads to a reduction of spectral efficiency [82], [107]. Accordingly, if the ZP equals CP, used with UFMC, this will result in spectral efficiency equal to that of CP−OFDM as shown in the (9) below.

$$\begin{aligned} SEI_{UFMC} &= \frac{T}{T+T_{ZP}} < 1 = SEI_{CP-OFDM} \\ &= \frac{T}{T+T_{CP}} < 1 \quad if\ T_{ZP} = T_{CP} \end{aligned} \tag{9}$$

The GFDM can be enhanced by the spectral efficiency as it does not require using the guard band to avoid ACI. In other words, in this study, it suggests to insert the guard symbols with the GFDM system specific to the multi−path channel environment, and as a result, the spectral efficiency is reduced [80]. Besides, prior studies have indicated the importance of the size block of GFDM; increasing the size block will increase the spectral efficiency due to using one CP per size block compared with OFDM [51]. Also, in the SEI−GFDM equation, when K modulated symbol equals one, the SEI is equal to CP−OFDM, whereas, by increasing the value of K, a result greater than one will enhance the GFDM spectral, as show in the (10).

$$SEI_{GFDM} = \frac{T}{T+T_{CP}} < 1 \tag{10}$$

F−OFDM is used to filter the entire band and does not decrease the spectral efficiency because the F−OFDM symbol overlaps in the time domain. Otherwise, F−OFDM cannot achieve non-contiguous chunks of spectrum compared with the previous candidates [37], [105]. The above analysis of spectral efficiency of waveform candidates is based on the Gabor concept and presumes continuous transmission. Table 3 depicts how to calculate the spectral efficiency with different waveform candidates [51].

F. SPECTRAL COEXISTENCE

Despite the fact that studies on coexistence in communications date to twenty years, it has gained increased importance in the last 10 years. There is a growing body of literature that recognizes the importance of spectral coexistence in wireless networks. The spectral coexistence in wireless networks discussed two systems coexisting in the same spectral band, what was called spectral pooling [108].In addition, the spectral coexistence enables 5G to achieve the demean of 5G requirement. Furthermore, 5G should cover all the incumbent systems as well as the ability for coexistence. In addition, the physical layer (PHY−5G) should be flexible and robust asynchronous interference coming from neighboring communication [105], [109].

New communication models and previous system increased the load to radio spectrum, which has previously been appeased. Some parts of this challenge has been solved. The rest can be revealed in two directions. The first direction, relies on new parts of spectrum (above 6 *GHz*). The second is using the licensed spectrum by a free chunk of incumbent users [110]. Fig. 19 shows useful approaches that have been used in the spectral coexistence for wireless networks categorization as follows:

1) NON-SYNCHRONIZATION AND SYNCHRONIZATION COEXISTENCE

There is a rapid demand for the development of phone devices and software with better technological performance. This growth is accompanied by complicated traffic in various signals supplied by various telecommunication companies. Although, this enhancement is related to the field of wireless communication, but the amount of spectrum resources is limited [111]. There are many suggestions presented by previous scholars to enhance spectrum resources. A suitable formulation for the coexistence between two different systems that based mainly on physical layer, has been presented. Therefore, synchronization coexistence between various networks is required for transforming data from one network to another. This process of synchronization called a coordinating methods can be applied between licensed and unlicensed networks, for example, the current request to investigate coexistence between Wi−Fi and LTE−M [112].

The mechanism of coexistence called Listen before talk had been applied in medium access control [110], [113]. The application of this techniques requires an interchanges channel between two systems [114]. This requires exchanging information between the systems, but better exchanging performance was indicated by excluding information, i.e., zero send information between systems that had been called non-synchronization coexistence. This is the performance under investigation in the current study [114]. The best method with no information exchange are preferred, as done with non-Synchronization Coexistence. This shows that both unsynchronized systems will differ on the basis of time and frequency.

2) HOMOGENEOUS WAVEFORM

The coexistence in homogeneous waveforms had a regulatory priority in similar frequency band. For example, the use of

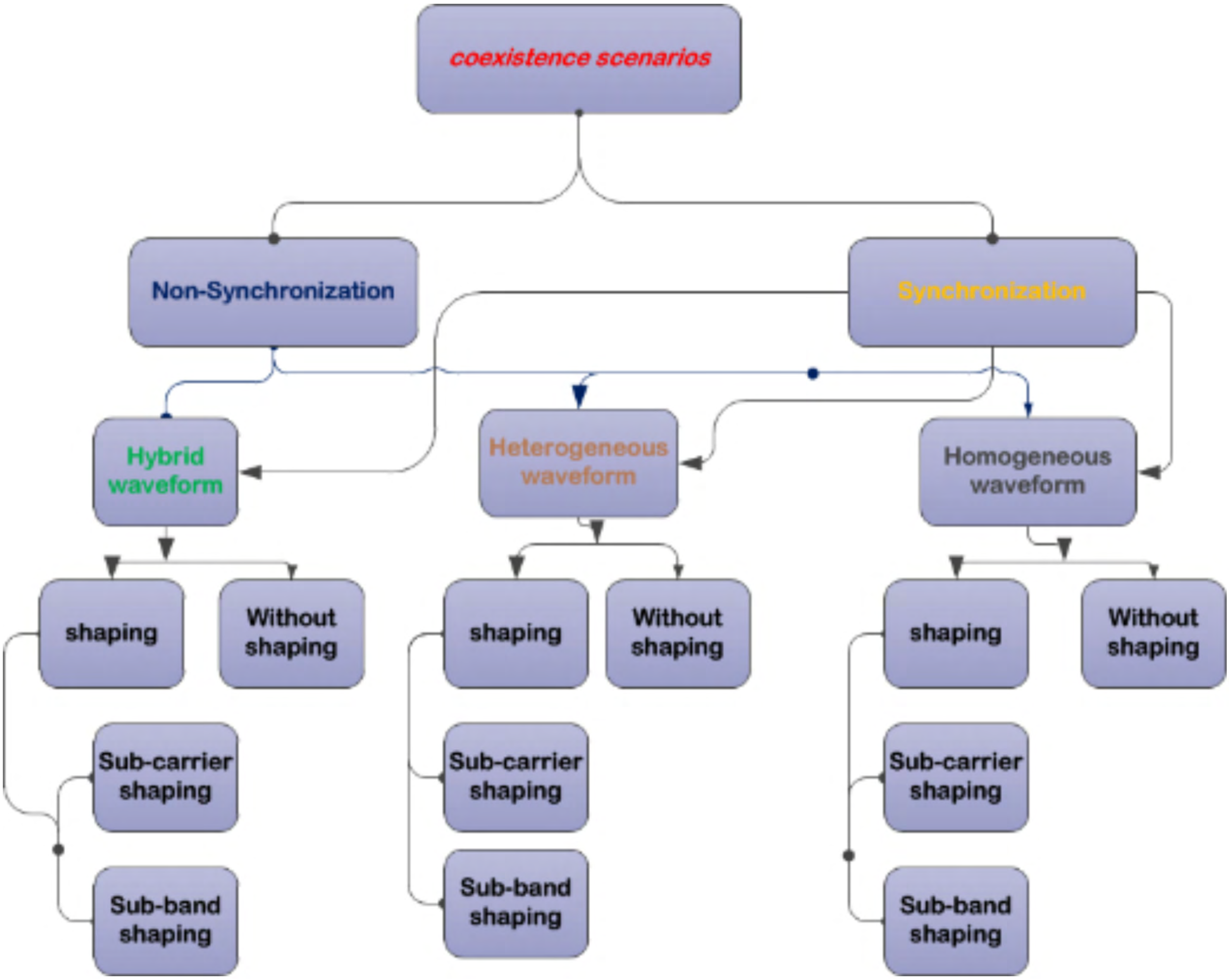

FIGURE 19. The spectral coexistence for wireless networks categorization.

two Wi−Fi networks with similar physical layers, as presented in Table 5, shows the coexistence in homogeneous waveforms in previous studies. Currently, homogeneous systems are classified into two parts; shaping and without shaping. The study will address the importance of the shaping part for the process of coexistence. Without shaping, however, has had a limited level of application in the field of wireless communication. The investigations showed the ability to classifying shaping parts into sub-carrier and sub-band shaping such as the coexistence between FBMC (subcarrier) and UFMC (subband) with similar priorities.

3) HETEROGENEOUS WAVEFORM

Heterogeneous waveforms are defined as the process of coexistence between two different types of waveforms such as, the coexistence between an IEEE 802.22 network and IEEE 802.11*a* network or cellar network. It is characterized with two main parts called shaping and without shaping. In comparison to a homogeneous system, a heterogeneous system can be described as challenging coexistence between systems due to the missing alignment in time and frequency as well as the physical layer. But, there is an ability to create coexistence between its shaping and without shaping parts, unlike in the homogenous system. Table 6 explains some previous studied examples for the coexistence in heterogeneous systems.

Finally, a hybrid coexist waveform differs from the above mentioned types in the ability to create coexistence between multiple waveforms. In addition, previous studies indicates that it is able to achieve a better spectrum sharing method [127].

VII. PREVIOUSSE COEXISTENCE STUDIESY

Quite recently, a considerable attention has been paid to investigation the coexistence between secondary and CP−OFDM users. Later on, some researchers have identified the necessity for a certain interference in order to create cognitive radio deployment [106]. In terms of suitable waveform, researchers were not able to identify the proper type of

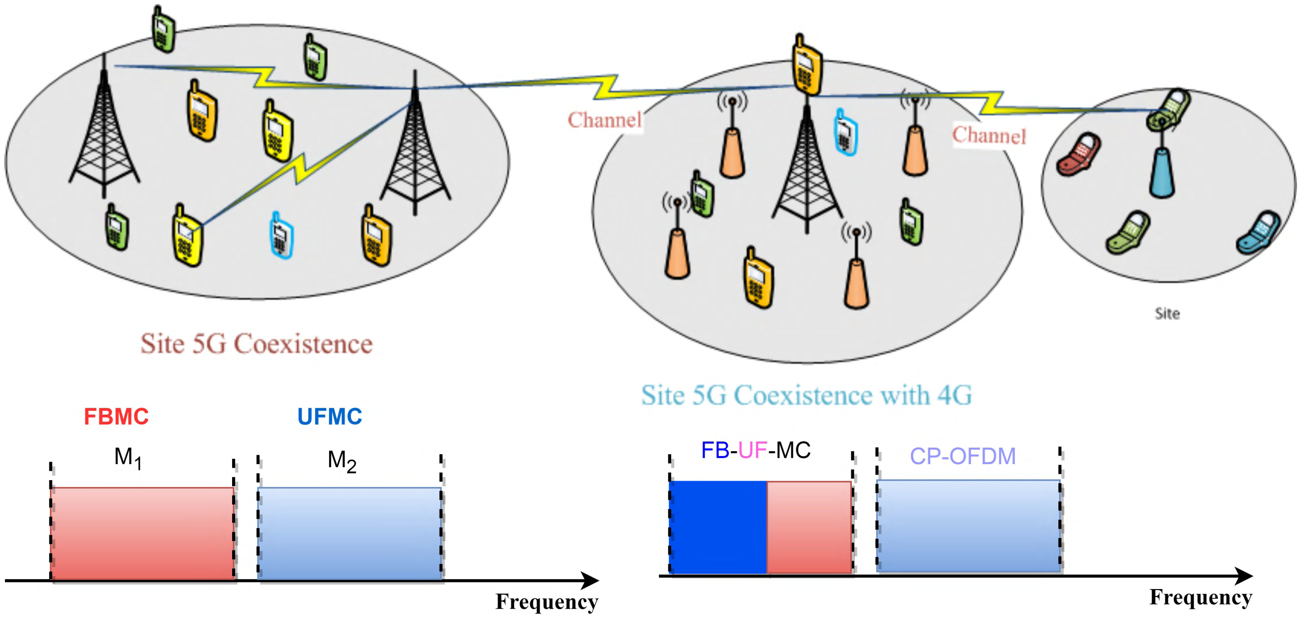

FIGURE 20. Green coexistence 5G waveform.

TABLE 5. Coexistence Homogeneous Waveform.

Author(s)	Network	Technique(s)	Strengths and Weaknesses
Garcia Villegas [111] & E Garcia [112]	WLAN-WLAN	• An Infrastructure-based Methods • Distributed spectrum sharing method	• Easy to implement and maximizes the total throughput • Coordination overhead
Han Ko [113]	WRAN-WRAN	Infrastructure–based methods	• Few changes on existing standards • Maintenance of control entities
H ElSawy [114] & M Deylami	WPAN-WPAN	• Control Channel-based • Coexistence detection and coexistence mitigation	• Low cost, efficient resource management • More synchronization
D Lee [116] & A Morimoto [117]	Cellular-Cellular	• Cooperative Multi-Point • Cooperative Multi-Point	• Easy to implement specific to the MIMO system • Coordination overhead

waveform that fits the process of coexistence. The Power Spectrum Density model has been widely adopted for computing the coexistence between users in incumbent and new systems for the implementation CP-OFDM [108], [128].

One of the criteria of CP–OFDM is high OOB emission. This make it improper for the implementation of spectrum sharing between users [129]. This result was one of the motivations that encouraged researchers to find a new waveform that is able to achieve the coexistence between the mentioned users. In order to improve the spectral localization, it has been suggested to replace CP–OFDM with FB–MC waveforms. Moreover, another applicable suggestion is to replace CP–OFDM with UFMC and F–OFDM [15], [82].

This work will adopt FBMC for the purpose of acquiring high spectral localization. One of the requirements for this work is insuring that no overlapping will occur between subcarriers. Thus, a guard band has been used in FMT modulation [130], [131] However, while this maintains the advantages that a guard band has, FMT will suffer bandwidth efficiency losses. Although, OFDM/OQAM allow subcarriers to overlap, but it had been adopted to increase efficiency. The real sample modulation in PAM differs from FMT.

This enables PAM [20], [74] to transmute on every subcarriers. A double sample rate will be required for OFDM–OQAM. In order to avoid the previous drawbacks, FBMC–PAM modulation will be adopted [132]. Additionally, a cyclic plus shape has been applied to avoid the double number of subcarriers. This solution has been offered by GFDM [27]. But, it comes together with higher OOB emissions. This is due to the traction in time and rectangular window that process will cause [25]. Whatever the drawbacks that previous 5G waveforms encountered, the lower OOB emissions has been achieved than those of CB–OFDM. This is due to the filtering of the transmitted samples. The benefit for using FBMC and UFMC waveforms in coexistence with CP–OFDM is the improvement of PSD [128], [133], [134].

TABLE 6. Previous study of heterogeneous coexistence waveform.

Author(s)	Network	Technique(s)	Strengths and Weaknesses
C. Zhai, 2014 [118], B. Kaufman 2009 [111] & Subramanian 2005 [119]	Cellular & Ad Hoc	• Dynamic Channel Selection • Distributed Power Control • Spatial Spectrum Reuse	• simultaneous spectrum access • no synchronization requirement, coordination-free, • spectrum sensing overhead, low efficiency due to lack of global information,
R. Vatti 2016 [120], Zhang 2013 [121]	WLAN & WPAN	Infrastructure-based Methods	• Few changes on existing standards • Maintenance of control entities
Sur 2015 [122]	WLAN & Bluetooth	• Control Channel-based • Coexistence detection and coexistence mitigation	• Low cost, efficient resource management • More synchronization
Sum 2011 [123]	WRAN & 802.11af	• Cooperative Multi-Point • Cooperative Multi-Point	• Easy to implement specific with MIMO system • Coordination overhead

The previous studies had been built on the proposition that PSD will be very useful with FB−OFDM for creating coexistence with CP−OFDM users. References [26] and [28] show that numerous studies have been carried out both in academia and industry on the coexistence between FB−MC waveforms and CP−OFDM because of its encouraging outcomes. However, the outcomes of this experimental work [26], did not include comparisons of the achieved values for error vector magnitude with multiply secondary waveforms. Thus, it did not describe clearly the outcomes for using FB−MC for coexistence.

Other researchers such as Fettweis *et al.* [27] and Nee and Prasad [28] approved in their experimental work that 3 goodput of theta uplink receiver was distracted by the interference of the secondary transmitter. They found that the use of GFDM will enable highest transmission of power at $3dB$ rather than OFDM. Although, this is important, it was not what was expected from the PSD based model. Li and Stuber [29] Show the ability to transmit more power by using $9dB$ rather than CP−OFDM without destroying the TV signal in a study on the secondary coexistence in OFDM/OQAM with TV receiver. Again, regardless of the importance of this study, but it did not comply with the expected results for using PSD. Reference [10] indicates that using FB−MC with one guard subcarrier will results high power without interfering with the primary.

All studies mentioned previously were based on some qualitative measurements and high level of analysis, but there do not seem to be good reliability or representation for PSD−based approach. Thus, it seems that merely referencing PSD as secondary signal for computing interference in heterogeneous scenarios is not enough. This urges the necessity of finding an innovative approach as a replacement because of the limitations that PSD had [30]. It is good to mention that limited number of studies have been conducted for study on the coexistence between systems with different waveforms. Resent study conducted by Han and Lee [31] to investigate coexistence between UF−OFDM and CP−OFDM systems. This study did not compare the results of using UF−OFDM and CP−OFDM in secondary systems.

VIII. TOWARDS GREEN COEXISTENCE 5G WAVEFORMS

The aim of this paper is to prepare green coexistence 5G waveform for next-generation through new method of coexistence between FB−UF-MC with the incumbent CP−OFDM. Fig. 20 shows the coexistence between the FBMC with UFMC and the second part with the incumbent CP−OFDM. The first coexist will be give us the diversity in different application and control for the filter length as well as reduce the complexity by reduce the length of filter with low latency. The second coexistence with CP−OFDM will be control the interference between the two system. The main goal of coexistence is enhance the PSD with low interference and an acceptable range of EVM. Green coexistence proposed in this chapter but also can be for different types of wireless cellular networks such as LTE, Wi-Fi, WiMAX and WSN.

IX. CONCLUSION

This review had carried out an extensive investigation on 5G. waveforms. It started with explaining waveforms structure and description in detail. Then, a comparison between 5G. candidates (F−OFDM, FBMC, UFMC and GFDM) under KPI related factors had been implemented. The outcomes of this process had been compared with the findings of previous works in the literature. This review analyzed the roles of all 5G. candidates that were more complicated than OFDM. However, F-OFDM and UFMC are more flexible in reducing the complexity, compared to FBMC and GFDM. The study found that PAPR rates for all candidates are lower than OFDM. This may be a result for using filter and windowing techniques. The review found that a better performance to reduce the PAPR was FBMC/OQAM and GFDM more than F-OFDM and UFMC.

This review investigated the effects of the filter length on 5G. waveform candidates. This part affected the performance of the waveforms and its usefulness in the overall complexity, latency and spectral efficiency. It approved that all candidates acquired spectral efficiency more than OFDM waveforms. However, a better spectral efficiency attained by FBMC waveform obtained in high spectral localization. This criterion will result in a suitable coexistence with CP-OFDM to enhance the PSD of CP-OFDM. Finally, the review found that a finest models to evaluate the coexistence scenario were PSD and EVM models. These findings have several significant implications for the future practice of developers and researchers in this area.

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