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Implementation of a 5G Filtered-OFDM Waveform Candidate

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Abstract

To meet the higher data rates that are expected with a new class of services offered by 5G systems, the lower layer of the 5G systems has to be flexible. For this, 5G waveforms must enable multiple accesses needed to support the features of the anticipated wireless communication services, which will involve different traffic types. Therefore, the waveforms must support a wide range of traffic types within the same band. This paper presents the filtered orthogonal frequency-division multiplexing waveform (F-OFDM) and compares it with the original cyclic prefix OFDM waveform used in 4G systems. Besides, the filter bank multicarrier modulation waveform as a 5G waveform candidate is evaluated. Future 5G systems, in addition to handling different traffic types, must be capable of addressing spectrum fragmentation-related problems by utilizing spectrum localization. The orthogonality and synchronicity of the 5G waveforms will help address these requirements. In addition, the use of 5G waveforms will facilitate reducing the amount of signaling information considerably, especially when supporting a large number of users. The new waveforms will also support multiple input and multiple output cases and applications. This paper presents simulation results that demonstrate the capability of the F-OFDM candidate waveform for use in 5G systems.

Keywords: 5G waveform, 4G waveform, filter bank multicarrier modulation, filtered orthogonal frequency-division multiplexing, orthogonal frequency-division multiplexing.

I. INTRODUCTION

Orthogonal frequency-division multiplexing (OFDM) is the key technique used in 4G LTE systems. This technique addresses the frequency selection problems and improves the spectrum efficiency [1]. Multicarrier systems employ OFDM, in which the modulation is dependent on the inverse fast Fourier transform (IFFT) and the cyclic prefix (CP) guards the symbols. Since the impactful introduction of the 4G LTE systems in 2010, excellent communication network services have been offered across the globe. Given that a new network generation is introduced every 10 years to address the spectrum-related requirements as well as the growing data rate needs, the industry needs to focus on the future networks and overcome the drawbacks of LTE systems. Following the inception of 5G systems, several new multicarrier schemes have been identified as potential candidates. The filtered OFDM have stood out as a major contender because of its additional advantage: the capability to filter the entire band. Besides, the subcarriers are defined by the sinc-filter in the frequency of the domain but not the sinc-shapes that make them have a suitable form in accordance with the design of the filter whose sidelobe levels are reduced [2].

A 5G network is expected to 1) show tolerance to misalignment in time-frequency, 2) reduce out-of-band emission, and 3) offer dedicated services for different needs and characteristic channels [3,4]. With the introduction of 5G networks, the European Union METIS objectives are to provide world-class services by 2020. The 5G networks are expected to improve the mobile data per area 1,000 times and support approximately 10–100 × connected devices. In addition, user data rates 10–100 times higher and battery life approximately 10 times longer are expected to be realized for facilitating low-power massive machine-type communication. Lastly, the EU METIS aims to reduce the end-to-end latency in the network by five times [5] within the same period. All these changes will only be possible if the relevant factors are considered together. First, there should be a better utilization of the available spectrum; a new spectrum above 6 GHz should be used, and there should be small cells generation as well as the introduction of MIMO. The new requirements and specifications of the 5G network necessitate a new air interface to be defined and implemented. The 4G networks are based on OFDM modulation; to meet the 5G specifications, an alternative multicarrier that can improve the 4G systems by reducing the bands of guards in frequency as well as removing the cyclic prefix, is necessary. The major shortcomings associated with CP-OFDM are poor spectral confinement and inflexible waveform, which could seriously affect the future networks that 5G systems seek to offer. To ensure optimal usage of the present bandwidths, which are less than GHz [6], dynamic spectrum aggregation is a must. As indicated earlier, OFDM technologies suffer from a high out-of-band (OOB) emission as well as resource base granularity that influences the allocation of subcarriers to low-data communication services. In the case of high mobility, there could be cases of frequency shifts caused by Doppler effects. Wunder et al. [7] also stated that it is difficult to obtain latency reduction in OFDM. In addition, there is a reduction in the efficiency of the spectrum upon application of the CP.

Therefore, designing a network system taking into consideration the waveform flexibility, which can solve the 5G problems in the physical layer, is important. This paper presents a comparison of the filtered OFDM and the filter bank multicarrier (FBMC) waveforms in terms of the probability of error occurrence.

The remainder of this paper is organized as outlined. In section 2, the waveforms to be compared are introduced, while section 3 presents the block diagram of the waveforms compared in section 2. Section 4 illustrates the metrics including TFE-time-frequency efficiency. The performance of the technique is discussed in section 5, based on an extensive simulation. Conclusions and suggestions for future work are stated in section 6.

II. THEORETICAL BACKGROUND

OFDM is a widely used multicarrier modulation (MCM) technology. Two OFDM candidates with a low level of maturity used in the early days are filtered multitone and filter bank multicarrier (FBMC). In the recent past, FOFDM has entered the competition for consideration in the fifth generation of mobile cellular networks. Unlike the previous generation in which the subcarriers are filtered by subcarrier, 5G networks are subband filtered. As mentioned earlier, this section discusses the 5G waveform candidates. Some important parameters are:

M: number of subcarriers

K: amount of subsymbols

Ts: sampling time

T: time frame of OFDM symbol

c: carrier symbol in a complex constellation

a: real-valued transmitted symbol

II.I Orthogonal frequency-division multiplexing (OFDM)

The advantage of the OFDM is its ability to use an overlapping subcarrier for modulating the parallel data streams, thereby making the technique more effective than the traditional technique as far as bandwidth efficiency is concerned. To avoid the related intercarrier interference, the subcarriers used must be orthogonal. Fast Fourier transform is used to drive the needed set of orthogonal subcarriers. In OFDM, the low-rate data streams are modulated into the subcarriers to ensure flat fading in each of the subcarrier used. OFDM is a simple method that is used in various applications, especially in unit modulation in which the data transmitted occupies the entire bandwidth available. An important point to note is that the OFDM data are modulated via narrowed subcarriers that have a bandwidth smaller than the bandwidth of the channel, thereby leading to the development of a flat fading condition in each of the subcarriers used. Besides, the cyclic prefix (CP) is used after every symbol of the subcarrier. The CP represents the tail samples, with the LCP as its length. The presence of these symbols improves the channel flatness in each of the subcarriers, thereby enhancing the probability of selecting the channel frequency. The transmission in OFDM is performed symbol-by-symbol, meaning that K = 1.

The base band symbol is defined as $k \in [-L_{cp}, M-1]$, as follows:

$$S_{OFDM}(K) = \sum_{m=0}^{M-1} c_m e^{\frac{j2\pi mk}{M}} , (1)$$

where c_m is the symbol transmitted in every m subcarrier. The entire operation is realized by using IFFT and FFT. The major strength of OFDM is its ability to maintain the transmission orthogonality through a time-depressive channel. A similar technique for channel equalization and estimation is applied to retrieve the orthogonality at the receiver.

II.II Filter bank multicarrier (FBMC)

A major contribution of the FBMC technique to network systems is the introduction of structured transmission that allows the system to meet the requirements of Balian–low theorem [8]. The strength of the FMBC is that it uses or employs a better pulse shape than OFDM that enables FMBC to retain the orthogonality and transmission at the Nyquist rate. As mentioned earlier, OFDM transports complex symbols at the subcarrier but in FBMC, the complex symbols are moved separately in the duration of half a symbol (T/2). Le Floch et al. discuss the features of FMBC in detail [9]. The following formula is a baseband representation of FBMC for any integer k [10].

$$S_{FBMC}(K) = \sum_{n \in Z} \sum_{m=0}^{M-1} a_{m,n} \underbrace{g(k-nN1) e^{\frac{j2\pi mk}{M}} e^{j\emptyset m,n}}_{g_{m,n}(k)} , (2)$$

where g is the filter and NI = M/2, which offsets ΦM that serves as an extra stage to the subcarrier m as well as index n, represented as $\pi/2(n + m)$. M and N are real values of the symbols transported and received from the imaginary parts of the QAM constellation. To achieve a good reconstruction, the g filter must satisfy the following orthogonality conditions:

$$R\left\{\sum_{k \in Z} g_{m,n}(k) . g^*_{p,q}(k)\right\} = \delta_{m,p} \delta_{n,q} \quad , (3)$$

where $*$ indicates complex conjugate. $\delta m,p = 1$ if $m = p$ and $\delta m,p = 0$ if $m \neq p$.

Both OFDM and FBMC benefit from fast FFT/IFFT algorithms. However, OFDM is not as complex as the FMBC. This complexity is a result of working with half duration of symbols, performing the IFFT/FFT at twice the rate. Moreover, the additional blocks of filters add to the complexity of the filters. The effect of this additional complexity depends on the scheme selected during the implementation phase [1].

II.III Filtered OFDM (F-OFDM)

F-OFDM is another of the many proposed multicarrier modulation schemes. This technique introduces the process in the time domain. Its bandwidth is designed for a certain subband although it is not equivalent to one PRB. Each of the

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subband used is modulated separately using the classical OFDM modulation scheme. F-OFDM does not fix the filter length of the CP, providing more freedom during filter design. The FOFDM signal is defined by K OFDM subsymbols of length M + Lcp. Once the L-length time domain is applied, the filter fi on each subband i, the FOFDM I is given by k ∈ [−Lcp, KM + (K - 1)L_{CP} + L – 2] as [11]:

$$S_{F-OFDM}(k) = \sum_{i=1}^{B} \sum_{n=0}^{K-1} \sum_{l=0}^{L-1} \sum_{m=0}^{M-1} c_m^i e^{\frac{j2\pi(k-1-Lcp)m}{M}} f_i(l) \quad , (4)$$

where $C^j_{m,n}$ represents the complex symbols for the subcarrier m, subsymbol n and subband i. Depending on the schemes of the different modulation, only a fraction of the M subcarriers may need to be activated. The target for the FOFDM is the uplinks that have narrow subbands corresponding to few tens of subcarriers that must be considered during implementation.

III. SYSTEM MODELS

III.I OFDM

Coding schemes such as conventional codes are very important in the digital domain; they are used to collect and code the binary input data bits. The coded bit stream is then interleaved to enhance diversity gain after which the bits are put together and mapped using the matching points in the constellation [11]. The complex data is serialized. Therefore, the known mapping schemes are mapped together with known pilot symbols to obtain the modulated data mentioned in **Fig. 1**. The IFFT operator is then performed on the parallel complex data after serialization has been applied to the parallel converter. Again, the transformed data is put together according to the number of required subcarriers for transmission. In every block of data, the CP is inserted in accordance to the system specification after which the data is multiplexed in a serial order. At this level, the data is modulated with OFDM and is ready for transmission. To convert the digital data to analog, a digital-to-analog converter is used. Next, RF modulation is performed, and the signal is converted to a transportable frequency. In the event it is transmitted using the antenna, the OFDM signals overcome the challenges of the wireless network channel [1].

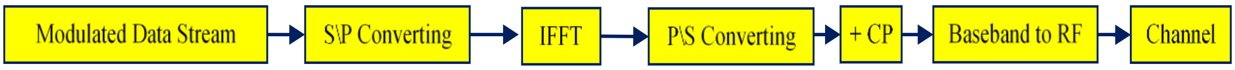

Fig. 1. OFDM transmitter scheme

An analog-to-digital converter is used at the receiver end to downconvert and reconvert the data into digital form. At this point, we find it important to prioritize the frequency offset because of the mobility of the channel. Therefore, frequency retrieval must be carried out when the bottom-conversion performance is satisfactory. The timing synchronization symbol is achieved or realized after the digitization process. The FFT is applied to achieve demodulation. Afterwards, the demodulated pilots are used to perform channel estimation. The resulting data stream is complex, and it has to be demapped in accordance to the transmission constellation. At this point, the originally moved bit stream is retrieved using the FEC technique and de-interleaving methods. In 3GPP LTE and IEEE 802.11, the OFDM is the widely used multicarrier format [1].

III.II FBMC

The filter bank can be implemented by adapting the simple block captured in the diagram shown in **Fig. 1**. It is important to have the IFFT and FFT extended. In OFDM, the data stream is used to modulate one carrier and is also applied as one input of the IFFT. In the case of a filter block having an overlapping factor identified as K, as indicated in **Fig. 3**, the data stream only modulates 2K-1 carriers. Therefore, to generate all the necessary carriers, the transmitter needs to be appended with a filter bank with an IFFT extension of size K M. Besides, each data element is moved to the 2K-1 inputs of the IFFT, that is, from (i-I) K +1 to (i+1) K -1. This is carried out after multiplication by the filter frequency coefficients. As indicated in **Fig. 2**, the data element is distributed over a number of IFFT inputs. For each inputted data, the IFFT output is a block of K M samples. Because the rate of symbols is 1/M, the K consecutive IFFT outputs overlap in the time domain. In this sense, an overlap and a sum operation are used to define the filter bank output as shown in **Fig. 3** [1].

Fig. 2. FBMC transmitter scheme

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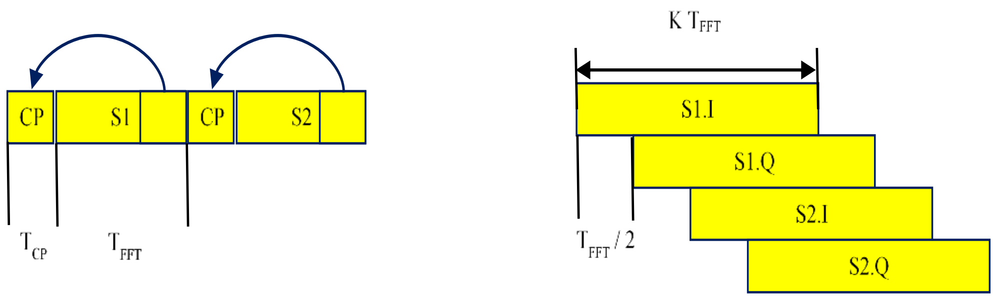

Fig. 3. FBCM vs. OFDM frames

An FFT extension of size K M is also important in the implementation of the receiver. In this scenario, the FFT input blocks overlap and the situation is described as the classical sliding window. With the application of a de-spreading operation, the data elements are recovered during the FFT output [11]. Importantly, the data retrieving process relies on the frequency coefficient of the Nyquist filter. The K M samples or K multicarrier symbols is the delay of the system and occurs when the receiver–transmitter connection occurs. Simplicity is the greatest advantage of the scheme shown in **Fig. 2**. It is similar to the scheme shown in **Fig. 1** that is completed function before and after FFT/IFFT. The major difference between the two is the complexity following the increment in the size of the FFT from the original M to KM. Considerable redundancy is observed in the computations because of the overlapping behavior of the domain of the FFT inputs and IFFT outputs [12]. This problem can be reduced using a certain idea or scheme [1].

III.III F-OFDM

Fig. 4 shows the transmitter scheme. M is the number of carriers while Ni denotes the number of subcarriers. In every carrier, there are Ni subcarriers. In each F-OFDM symbol, Ni data are mapped in the frequency domain where an IFFT of size Ni is applied to every carrier and appended with CP. This is performed to ensure the clarity of the received signal. The outputs or results of each stage are then fed to a filter parametrized by a filter prototype. After M stages are summed, the symbols are then transmitted [13]. In terms of complexity, there is a slight increase in F-OFDM compared to OFDM. The next section describes the complexity of these two techniques. The receiver scheme entails the selection of a window of size MN that is followed by the FFT stage. This ensures that the receiver has a low complexity similar to that of OFDM. The following are the major differences with respect to the conventional systems [11]:

1. When a subband filter is added to OFDM, there is no change in the existing OFDM.

2. The filtering for each subband (subband BW ≥ 1 RB).

3. Independent subcarrier spacing/ CP distant/ TTI for every subband.

4. A low guard tone between the neighboring subbands.

5. Asynchronous transmission due to perfect OOB performance.

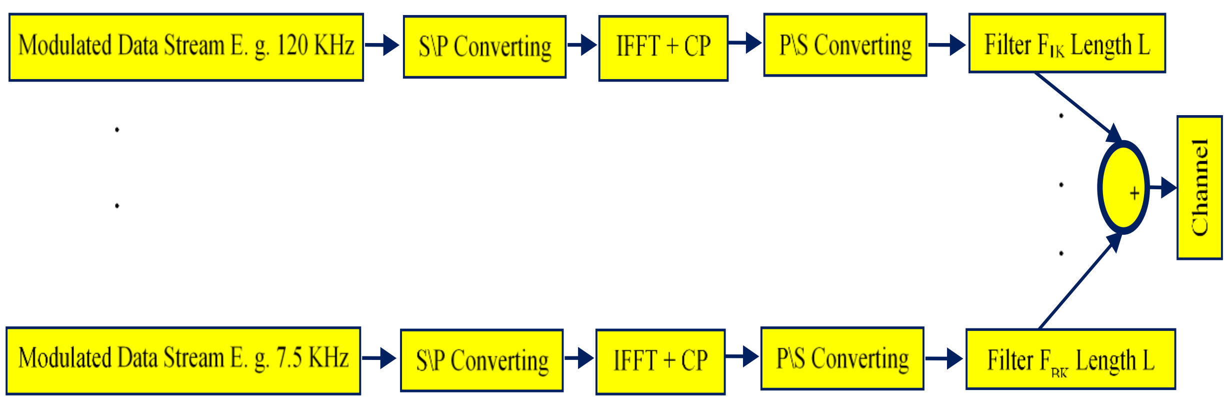

Fig. 4. F-OFDM transmitter scheme

IV. COMPARISON METRICS

This section provides a detailed comparison of the different waveforms under discussion. The comparison is performed in terms of the following metrics: tail issue, mobility, complexity, latency, spectrum confinement, spectral efficiency, and 4G compatibility.

IV.I Spectral efficiency

Because of the addition of a CP of length Tcp, OFDM is not able to achieve the maximum value. Therefore, the efficiency reduction is defined as follows:

$$\eta_{OFDM} = \frac{T}{T+T_{CP}} < 1 \text{ , (5)}$$

In contrast, the FBMC does not involve any spectral issues as far as the Nyquist rate is concerned and does not have CP. For this reason, it is able to achieve efficiency as defined by the following equation [1]:

$$\eta_{FBMC} = \frac{T}{T.F} = 1 \text{ , (6)}$$

F represents the spacing between the subcarriers. The maximum system efficiency is achieved when T = 1. In the end, F-OFDM retains the OFDM process and makes use of the FIR as a filter. However, this filtering does not reduce the spectral efficiency. This means that the F-OFDM spectral efficiency is equal to that of OFDM [11].

IV.II Tail issue

The tail issue is an important factor in a burst transmission. It connotes the potential overlaps between two bursts. It therefore means that the symbols are not separated in the time domain. Instead, some parts of the symbol are overlapped. This issue is depicted in the FBMC scheme. In OFDM, the tail issue exists because each symbol is isolated in the domain. The difference between F-OFDM and OFDM is that F-OFDM uses a filter length that is longer than the standard CP length. In this sense, the additional filtering results in the tail issue [11].

IV.III Spectrum confinement

The two major issues with the OFDM are the spectral leakage, which is caused by waveform fragmentation, and the rectangular pulse shape. The first problem can be solved comfortably by ensuring that the edges of the symbol decrease to zero. To solve the second problem in FMBC, the rectangular filter has to be replaced with a prototype filter that is characterized by high-frequency localization and a length longer than that of FFT. FIR filtering addresses the discontinuity problem in F-OFDM. In FBMC, the improvement in spectrum confinement is less [11].

IV.IV Mobility

The efficiency of 5G systems is highly dependent on mobility robustness. The FBMC scheme possesses better robustness against the Doppler effect because of the subcarrier filtering process. The F-OFDM scheme on the other hand addresses the Doppler effect similar to the OFDM. The advantage of this scheme is that the subcarrier spacing can be widened for a specific subband to serve the needs of high-mobility users [11].

IV.V Latency

The latency metric is another defining feature for the 5G System. OFDM has a short transceiver because of CP effects and FFT transform (T+TCP). With any extra filtering technique, the latency is increased. FMBC has the highest latency [11].

IV.VI Complexity

OFDM is characterized by low modem complexity. Simplicity is normally achieved when working on advanced modulation. In the FBMC scheme, the complexity is double that in OFDM. For F-OFDM modulation, FIR filtering is used on top of the OFDM modulation. The complexity level of F-OFDM is between the levels for OFDM and FMBC [11].

IV.VII Compatibility with 4G

4G compatibility is an important consideration. However, this does not mean that the new receiver is capable of decoding the LTE waveforms. Instead, it connotes that the new system must have the capacity to reuse existing LTE techniques such RS and MIMO coding. For FBMC systems, because of QAM signaling, only real-valued symbols are transmitted. In addition, research shows that, in the F-OFDM scheme, the signal contained inside the subband has the same characteristics as the OFDM signal [11].

V. SIMULATION RESULTS AND ANALYSIS

The BER performance index is used to evaluate the capacity-approaching. It is given as the SNR over an AWGN channel. The objective of this section is to examine the FBMC performance and the F-OFDM waveforms and then subject the results to a detailed comparison with those of OFDM. An analysis using MATLAB software was performed to evaluate the following performance metrics: power spectral density (PSD), probability of bit error rate (BER), and peak-to-average power ratio (PAPR). Before doing simulations, our predictions are that the first two metrics yield positive results, while in terms of the PAPR, the OFDM will perform well because of the filtering effect in both F-OFDM and FBMC that improves PAPR as far as FBMC is concerned.

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V.I Power spectral efficiency

A comparison of OFDM, F-OFDM, and FBMC in terms of PSD is shown in **Fig. 5**, where the PSD is denoted in dB as well as the function of the normalized frequency. The figure shows that the OOB power is very low in FBMC in comparison to the power in the corresponding band. In this sense, we can clearly see that FBMC has a better PSD than F-OFDM and OFDM.

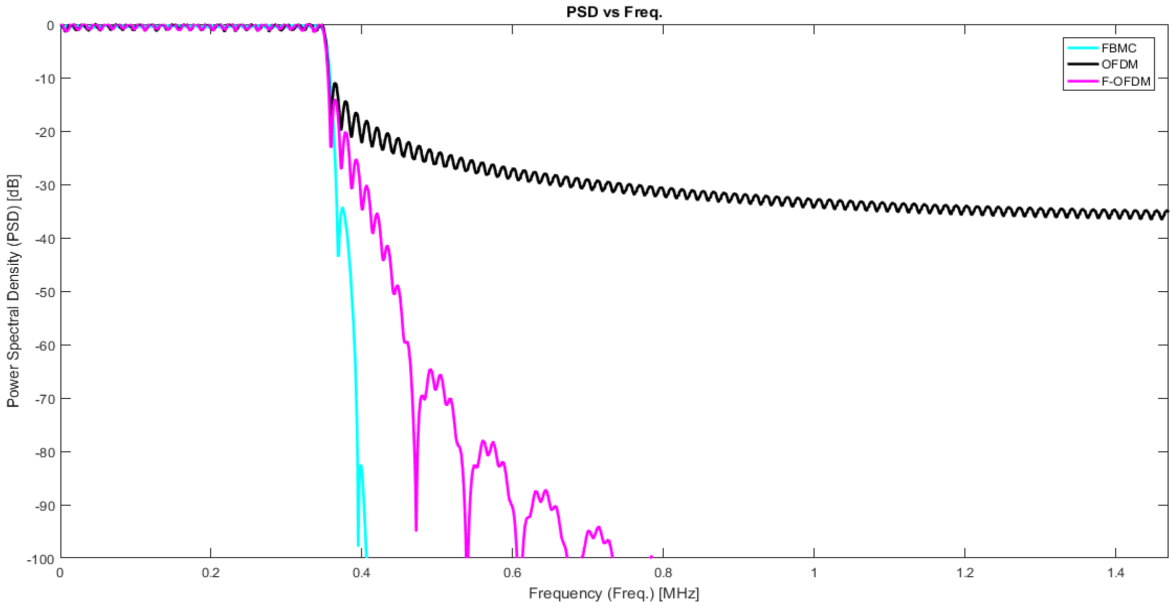


Fig. 5. PSD comparison between FBMC, OFDM, and F-OFDM

V.II Bit error rate

The BER for the F-OFDM, FBMC, and OFDM schemes is shown in **Fig. 6**. The figure demonstrates that the modulation level and BER have a direct relationship. The simulation outcomes indicate that FBMC and OFDM waveforms' performance is the same as far as BER is concerned. In this sense, we can argue that F-OFDM has the best BER compared with FBMC and OFDM.

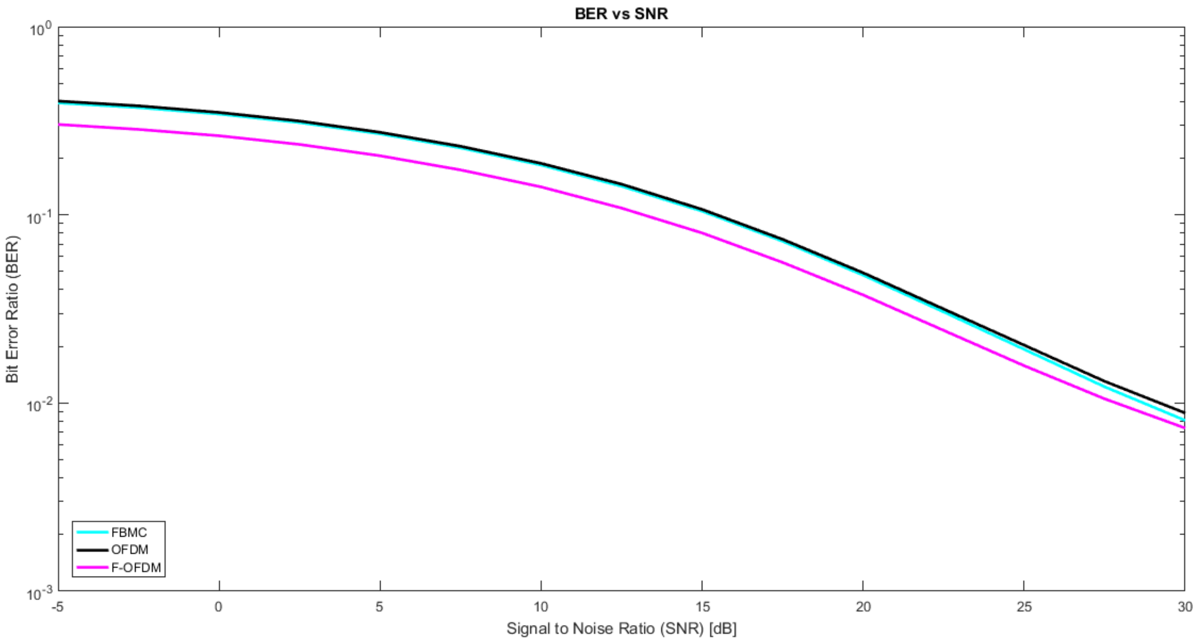
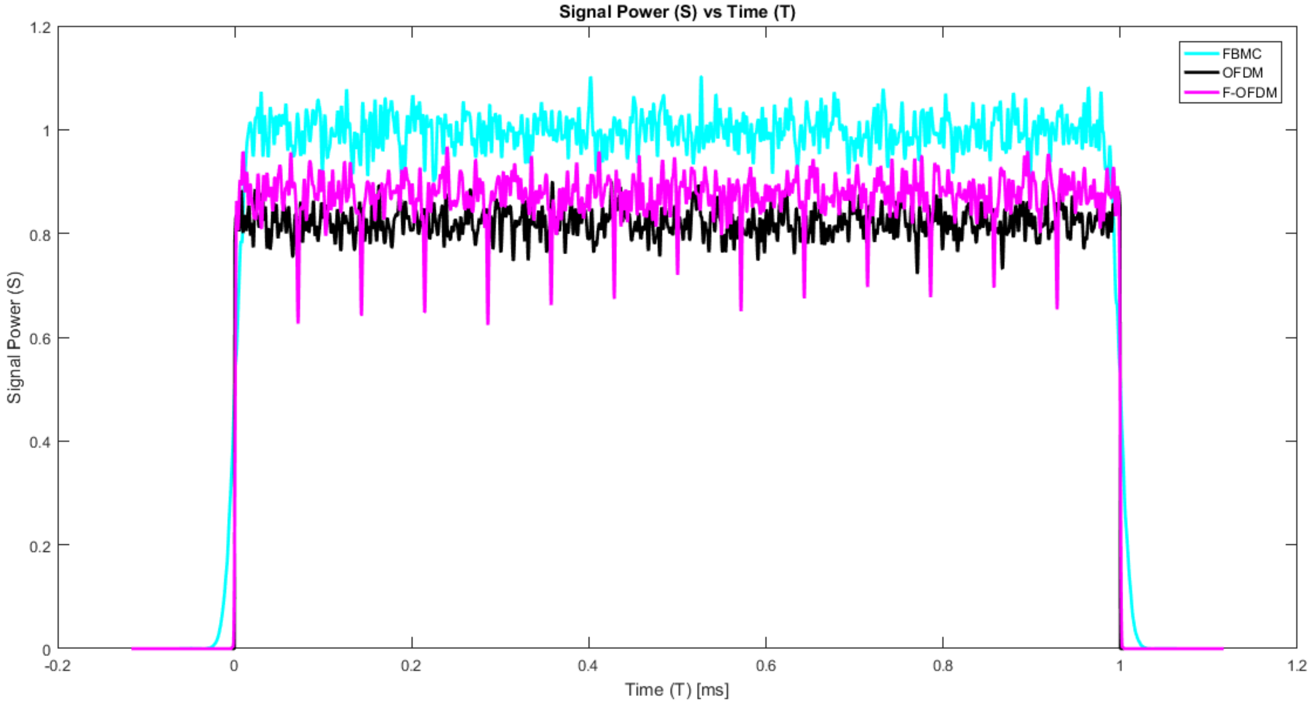


Fig. 6. BER comparison for FBMC and F-OFDM with respect to OFDM

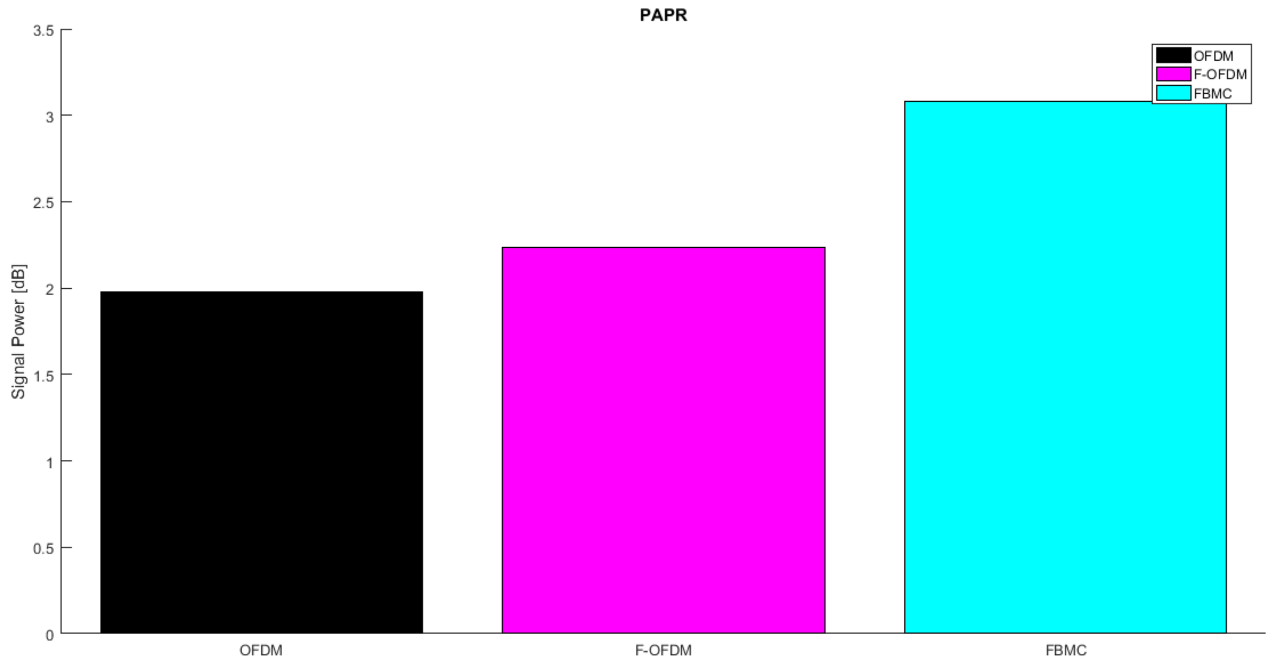
V.III Peak-to-average power ratio

A CP has been found to provide better amplitude that minimizes the PAPR and improves power amplifier performance. In addition, the CP enables a better coexistence with OFDM and reception of small FFT sizes.

At the same time, the PAPR problem increases. Therefore, we deduce that OFDM will have the best PAPR value when compared to F-OFDM and FBMC. FBMC will not have a good PAPR because it uses the filtering process and lacks the CP in the symbols. These theoretical findings are confirmed in **Fig. 7** that presents the PAPR and signal power of the three schemes.



(a)



(b)

Fig. 7. Comparison between OFDM, F-OFDM, and FBMC in terms of: (**a**) Signal power and (**b**) PAPR.

VI. CONCLUSION

This study investigated two major candidates for 5G systems, namely, F-OFDM and FBMC. A detailed comparison of these candidate waveforms with the conventional CP-OFDM waveform was performed. Through simulation, it has been confirmed that each of the waveforms has positive and negative impacts on various parameters. In this regard, we have noted that other criteria need to be considered to select the perfect waveform generation. We considered the tail issues, latency, complexity, and many other factors. Both F-OFDM and FBMC waveforms improve the power spectral density but affect the PAPR ratio negatively. At the same time, the F-OFDM has been found to improve the BER rate. We conclude our study by asserting that F-OFDM is a better candidate for 5G networks when compared to other schemes investigated in this work.

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