Performance Analysis of Multicarrier Modulation Techniques for Next Generation Networks

Amare Kassaw[1,2](✉), Fikreaddis Tazeb[1], Fikreselam Gared[2],
and Dereje Hailemariam[1]

[1] Addis Ababa Institute of Technology, Addis Ababa University,
Addis Ababa, Ethiopia
derejeh.hailemariam@aait.edu.et
[2] Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia
http://www.aau.edu.et/
http://www.bdu.edu.et

Abstract. Next-generation networks are expected to provide a wide range of services and functionalities. These services impose different requirements on the physical layer. Due to ease of implementation, immunity to interference and high data rate support, orthogonal frequency division multiplexing has been the most promising multicarrier waveform to implement on current wireless networks. Whereas, to provide the expected requirements in next-generation networks, more advanced multicarrier modulation techniques are required. Hence, other alternative multicarrier modulation techniques are proposed to address the challenges of orthogonal frequency division multiplexing.

In this work, we analyze performances of candidate multicarrier modulation techniques for next-generation networks such as filter-bank multicarrier and universal filtered multicarrier. To obtain insightful analysis, we first analyze the basic principles and characteristics of each multicarrier modulation technique. Then, we compare the performances in terms of power spectral density (PSD), bit error rate (BER) and spectral efficiency (SE). Besides, the computational complexity of the proposed multicarrier modulation techniques is evaluated. Finally, numerical simulation is done to validate the theoretical analysis. The results show that FBMC has minimum out-of-band emission and this helps to be almost insensitive to multiuser interference to support different use cases in the same bands. Whereas, UFMC reveals to be the most promising waveform which gives close to OFDM performance with better out-of-band emission.

Keywords: Multicarrier modulation · Next-generation network · Spectral efficiency · Power spectral density · Computational complexity · OFDM · FBMC · UFMC

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1 Introduction

Orthogonal frequency division multiplexing (OFDM) is robust against multipath fading, simple to implement due to FFT/IFFT structures, reduce multicarrier interference, easy to integrate with adaptive modulation and multiple antenna systems. Hence, OFDM is widely employed in many wireless systems such as long term evolution (LTE) and IEEE 802.11 families [1,4]. Although OFDM is most employed modulation technique in current wireless networks, it also exhibits intrinsic drawbacks. These include high out-of-band (OOB) interference caused due to rectangular pulse shape, spectral efficiency loss due to cyclic prefix insertion, strict time and frequency synchronization requirement to achieve subcarrier orthogonality and reduce high peak-to-average power ratio (PAPR) which affect the system energy efficiency [1,5]. To mitigate these limitations, several alternative multicarrier modulation techniques have been proposed recently such as filter bank multicarrier modulation (FBMC), universal filter multicarrier modulation (UFMC), filtered OFDM, generalized frequency division multiplexing (GFDM), biorthogonal frequency division multiplexing (BFDM) and time-frequency packing (TFP) [1–3,5,7,10–12,15,22–24].

Many studies are done to evaluate performances of these candidate multicarrier modulation techniques. A comprehensive overview of modulation and multiple access schemes for fifth generation (5G) networks is presented in [8]. The authors provide an overview of orthogonal multiple access (OMA) and non-orthogonal multiple access (NOMA) schemes. Performance comparison is done in terms of OOB leakage and bit error rate. They also propose modulation schemes that are suitable for OMA and NOMA. They show that NOMA provides enhanced throughput and massive connectivity with better spectral efficiency. A comparative study between OFDM and FBMC is provided in [5]. The work analyzes the spectral efficiency and computational complexity of both waveforms. The paper shows drawbacks of OFDM and indicates that FBMC could be an alternative solution. In [7], the authors compare UFMC with OFDM in terms of time-frequency efficiency to transmit small bursts under tight response time requirements. They show that UFMC has better time-frequency efficiency than OFDM.

In [15], performance comparison of UFMC and cyclic prefix based orthogonal frequency division multiplexing (CP-OFDM) is done based on PSD and peak to average power ratio (PAPR). They show that UFMC has better PSD than OFDM and has nearly the same PAPR variation. A performance comparison of FBMC, UFMC and GFDM interms of power spectral density (PSD), spectral efficiency, PAPR and computational complexity is done in [9]. The authors claimed that UFMC gives comparable spectral efficiency to OFDM. They also prove that UFMC preserves backward compatibility with known OFDM algorithms. However, spectral efficiency comparison is done by considering only AWGN channel model. Similar to OFDM, guard interval has to be inserted in UFMC to combat inter symbol interference (ISI) caused by multipath channel. This reduces the spectral efficiency of UFMC compared to the results in [9].

In this work, we analyze the performances of FBMC and UFMC modulation techniques. To obtain insightful analysis, we first analyze the basic principles and characteristics of each waveform. Then, we compare the power spectral density, bit error rate and spectral efficiency of the proposed waveforms. Besides, the computational complexity of the waveforms is analyzed. In line with this, the main contributions of this paper are summarized as follows:

- Review candidate multicarrier waveforms for 5G and beyond networks.
- Formulate mathematical models for the spectral efficiency, BER and computational complexity for OFDM, FBMC and UFMC waveforms.
- Analyze performances of these waveforms theoretically.
- Validate the theoretical analysis via numerical simulation.

The rest of the paper is organized as follows. In Sect. 2, basics of multicarrier modulation techniques for next generation networks are presented. Performance analysis of the proposed multicarrier modulation techniques are provided in Sect. 3. Simulation results are discussed in Sect. 4 and conclusions are drawn in Sect. 5.

2 Multicarrier Modulation Techniques for Next Generation Networks

OFDM, FBMC and UFMC are the most promising multicarrier modulation techniques for next generation networks. The main differences between these modulation techniques are on the multicarrier modulation block, cyclic prefix insertion and filtering operation [1,5,6,18]. In OFDM, implementation of windowing and modulation is achieved by performing N-point FFT operation [5]. Whereas in FBMC the symbols are pulse shaped by a prototype filter that is longer than the number of subcarriers [2,5]. Efficient implementation of this structure is obtained by deploying offset-QAM staggering, FFT operation and polyphase filtering [1,2]. In UFMC, incoming quadrature amplitude modulation (QAM) symbols are grouped into blocks. And each block is modulated and filtered separately and sum up at the end. This is implemented by using N-point IFFT and Dolph-Chebyshev filtering [1,2]. At the receiver side, the inverse operations are executed in reverse order. In all the waveforms, an equalizer has to be deployed to compensate for the channel's frequency selectivity. For OFDM and UFMC, the equalizer is single-tap and for FBMC it is multi-tap [1,5,6]. In subsequent sections, we describe the fundamentals of UFMC and FBMC waveforms.

2.1 FBMC Modulation Techniques

FBMC systems have a group of filters that process common input to give common output. These filters termed as analysis filter banks (AFB) and synthesis filter banks (SFB) [3,5]. The SFB is implemented with IFFT followed by polyphase network structure whereas AFB is implemented with a polyphase network followed by an FFT [3]. The filter bank allows to control the frequency response of the transmitted signal. Due to this, different techniques are proposed to design the filter such as filtered multi-tone (FMT) [13], cosine-modulated multitone (CMT) and staggered multitone (SMT) [3]. In FMT, the subcarriers are separated by guard bands and adjacent subcarriers have not overlapping bands. It is less bandwidth efficient than OFDM, but it does not require the guard interval. Hence, it has better energy efficiency than OFDM [3]. The CMT has high bandwidth efficiency and blind detection capability. However, a 90° phase shift is introduced to adjacent subcarriers [3]. The SMT transmits a set of complex-valued QAM symbols whose real and imaginary parts are separated and time staggered by one half of the symbol duration that results offset QAM (OQAM) symbols. In OQAM-FBMC the data symbols are spaced at $T/2$ in the time domain and the subcarriers are spaced at $1/T$ in frequency domain where T is the symbol time. Therefore, in SMT the symbol rate is doubled and the symbol spacing is halved. Compared to CMT and FMT, OQAM-FBMC has highest stop–band attenuation at fixed filter length and number of subcarriers [3]. Besides, OQAM-FBMC overlaps subcarriers in frequency domain and provides high bandwidth efficiency [3].

FBMC systems can be implemented based on the frequency spreading filter bank multicarrier (FS-FBMC) and the polyphase network filter bank multicarrier (PPN-FBMC) [3]. In FS-FBMC, OQAM symbols are filtered in frequency domain and then feed to the KN-point IFFT where K is the overlapping factor of the prototype filter. At receiver side, a sliding window selects the KN-points at every samples. Then, KN-point FFT is applied and followed by equalization and filtering by prototype filter. Whereas in PPN-FBMC, the OQAM symbols are first fed to N-point IFFT and then pass through the polyphase network for filtering [13].

Thus, the main processing blocks in PPN-FBMC are the OQAM preprocessing, the filter banks and OQAM post-processing. We use the filter proposed by the physical layer for dynamic spectrum access (PHYDYAS) project [2]. Mainly, the N-subchannel filters are designed by complex modulation and the rest subchannel filters are found by frequency shifted versions of the prototype [2]. The transmit filters are modeled based on a specially designed prototype filter and are modulated by the carrier frequency. The OQAM combined with constraints on the prototype filter is used to achieve orthogonality between adjacent symbols and adjacent carriers while giving maximum spectral efficiency [2]. The complex QAM symbol is staggered and changed to real symbols by OQAM preprocessing. The reverse operation is performed at the receiver side. The real to complex conversion decreases the sample rate by a factor of two [13]. Note that the system model and detail mathematical analysis for FBMC transmission are removed due to space limitations.

2.2 UFMC Modulation Techniques

UFMC is a type of subband filtering based waveform where the filtering operation is applied to group of subcarriers [14,15]. In UFMC transmission, the bit streams are grouped into B-subbands, modulated by QAM modulation and converted to parallel streams. Then, IFFT is performed on each subband and the output is filtered by a filter of length L. Filtering leads to substantial reduction on out-of-band leakage and that helps to minimize harmful interference from adjacent subchannels on neighboring resource blocks [14,15].

UFMC uses Dolph-Chebyshev type filters [16]. The length of the filter depends on the size of subbands. It is characterized by an equi-ripple behavior in which all side lobes have the same height. In some works [7], the guard intervals are discarded. But, this reduces the performance in severe multipath scenarios since the time dispersion of the channel cannot be mitigated [16]. In other works, extra zero padded guard interval blocks of length $L-1$ are introduced in each UFMC block to mitigate the time dispersion. This adds extra time overhead and results to a UFMC symbol length of $N+L-1$ samples [1]. But, it helps to mitigate the channel time dispersion using single-tap frequency domain equalizer. The filtered time-domain data is added to form the UFMC waveform. Hence, in contrast to OFDM, separate IFFT operations are done on each frequency block. Besides, windowing is done to suppress the interference. At the receiver side, $2N$-point FFT is taken to demodulate each UFMC symbol. FFT followed by an equalizer and time synchronization is able to estimate the transmitted signal correctly [1].

3 Performance Analysis of Multicarrier Modulation Techniques

Various metrics are used to evaluate the performances of multicarrier modulation techniques. At the transmitter side, power spectral density and spectral efficiency are considered whereas at the receiver side bit error rate (BER) and computational complexity are used to evaluate the performance [1].

3.1 Power Spectral Density (PSD)

The PSD shows the strength of the variations of energy with frequency. It shows at which frequencies the energy variations are strong and at which frequencies the variations are weak. The PSD of multicarrier modulation systems can be calculated by summing the power spectral density of individual subcarriers. Besides, sidelobe radiation can be calculated by the PSD model of the multicarrier signal [1].

3.2 Bit Error Rate (BER)

The main cause of degradation of transmission quality and corresponding BER is the noise and multipath propagation that are random in nature. To analyze the BER characteristics of the proposed multicarrier modulation techniques, we assume the noise follows Gaussian distribution while the propagation model follows Rayleigh distribution [19].

3.3 Spectral Efficiency (SE)

To compare the spectral efficiency of the proposed multicarrier modulation techniques, we use the approach proposed in [14]. It is more applicable for multicarrier modulations and defined the spectral efficiency as the product of time efficiency and modulation efficiency as

$$\mathrm{SE}_{\mathrm{MC}} = \eta_t \eta_m \tag{1}$$

where η_t and η_m are the time and modulation efficiency of multicarrier modulation schemes, respectively. The modulation efficiency depends on the modulation order, the number of active resource blocks and the code rate [9,14]. The time efficiency measures the time overhead introduced in transmission and is defined as [7]

$$\eta_t = \frac{D_L}{D_L + T_{\mathrm{OH}}} \tag{2}$$

where D_L is the number of samples on transmitted signal dedicated to data transmission and T_{OH} is the overhead sample due to cyclic prefix, filter tails and zero padding. For all multicarrier modulations, $D_L = \beta N$ where β denotes the number of transmitted multicarrier symbols in a burst and N is the FFT size.

In OFDM, there is an overhead due to cyclic prefix. Whereas in UFMC there is an overhead caused by filtering and zero padding. The overhead in FBMC is introduced by long tail filters in each subcarrier which is independent from the length of the burst [1,5,7]. Thus, the overhead sample for each modulation technique is expressed as

$$T_{\mathrm{OH}} = \begin{cases} \beta L_{\mathrm{CP}} & \text{OFDM} \\ \beta(L_{\mathrm{ZP}} + L_f - 1) & \text{UFMC} \\ N(K - \frac{1}{2}) & \text{FBMC} \end{cases} \tag{3}$$

where K is the overlapping factor of the filters, L_{CP} is the length of cyclic prefix, L_{ZP} is the length of zero padding and L_f is the filter length. By using (2) and (3), the time efficiency of each candidate waveform is given by

$$\eta_t = \begin{cases} \frac{N}{N+L_{\mathrm{CP}}} & \text{OFDM} \\ \frac{N}{N+L_{\mathrm{ZP}}+L_f-1} & \text{UFMC} \\ \frac{\beta}{\beta+(K-\frac{1}{2})} & \text{FBMC.} \end{cases} \tag{4}$$

Finally, the spectral efficiency of the proposed multicarrier modulation techniques is given by

$$\mathrm{SE}_{\mathrm{MC}} = \begin{cases} \frac{mN}{N+L_{\mathrm{CP}}} & \text{OFDM} \\ \frac{Nm}{N+L_{\mathrm{ZP}}+L_f-1} & \text{UFMC} \\ \frac{\beta m}{\beta+(K-\frac{1}{2})} & \text{FBMC} \end{cases} \tag{5}$$

where m is number of loaded bits in each subcarrier.

3.4 Computational Complexity

The computational complexity is evaluated in terms of the number of real valued multiplications and additions. To formulate the computational complexity of the proposed multicarrier modulation techniques, we assume the transmitter and the receiver are perfectly synchronized and there are N subcarriers from which N_0 is occupied with symbols. We only consider the signal generation, reception and equalization operation for the multicarrier signal. Whereas we do not consider the operation involved to channel encoder, decoder and channel estimation. Complex multiplication can be done with three real valued multiplication and complex addition requires two real valued multiplication. Thus, for N-point FFT the number of real valued additions and multiplications are given by [21]

$$\begin{aligned} A_{\text{FFT}} &= 3N\log_2 N - 3N + 4 \qquad \text{Addition} \\ M_{\text{FFT}} &= N\log_2 N - 3N + 4 \qquad \text{Mulitiplication.} \end{aligned} \tag{6}$$

Based on the above assumptions, we calculate the complexity of the proposed multicarrier modulation techniques as follows.

Computational Complexity of CP-OFDM: The basic blocks in OFDM is the IFFT at the transmitter, the FFT and equalizers at the receiver. OFDM divides the total bandwidth into N-point IFFT/FFT, so the channel equalizer has single-tap coefficient per subcarrier. After some mathematical analysis, the total number of real valued multiplications and additions for OFDM with N-point FFT/IFFT using split-radix algorithm is summarized in Table 1 [21].

Table 1. Computational complexity of OFDM.

	Number of addition operation	Number of multiplication operation
Transmitter side	$3N\log_2 N - N + 2L_{\text{CP}} + 4$	$N(\log_2 N + 1) + 4L_{\text{CP}} + 4$
Receiver side	$3N\log_2 N - N + 2L_{\text{CP}} + 2N_0 + 4$	$N\log_2 N - 3N + 4N_0 + 4$

Computational Complexity of FBMC: The transmitter and receiver in FBMC systems are composed of filtering operation with N-parallel polyphase components working twice the symbol rate. The basic blocks which perform multiplication and addition are polyphase filter networks, OQAM pre/post-processing, and IFFT/FFT operation. The OQAM processing is considered to have only simple multiplication by ± 1 and $\pm j$ [5]. As shown in [2], the transmitter consists of N-point IFFT, N-branch polyphase filters with length of $L_p = KN$ and frequency shifting or phase rotation to get polyphase filters from the prototype. At the receiver side, the same operation is performed in reverse order. Thus, the total number of real valued multiplications and additions for FMBC systems with N-point FFT/IFFT using split-radix algorithm is summarized in Table 2.

Table 2. Computational complexity of FBMC with OQAM.

	Number of addition operation	Number of multiplication operation
Transmitter side	$2(3N(\log_2 N-1)+4)+4N\,(K-1)+2N_0$	$2(N\log_2 N-3N+4)+4NK+4N_0$
Receiver side	$4N(K-1)+2(3N(\log_2 N-1)+4)+(4L_{\text{eq}}-2)N_0$	$4NK+4L_{\text{eq}}N_0+2\,(N\log_2 N-3N+4)$

Computational Complexity of UFMC: If we have B data blocks obtained by dividing N subcarriers, each block will have N/B subcarriers. The transmitter modulates each of the B-subbands as follows; first frequency domain symbols are brought to time domain using an N_{SB}-point IFFT where N_{SB} is the IFFT size on each subband. Then, filtering is performed in the frequency domain and all subbands are summed and transmitted. At the receiver side, windowing, $2N$-point FFT, equalization and signal recovery operation are performed. B number of IFFT with N_{SB} subbands results $M_{\text{FFT}}(N_{\text{SB}})$ complexity and to convert into frequency domain it results $M_{\text{FFT}}(2N_{\text{SB}})$ complexity at the receiver. Filtering each blocks with L-length filters result to $2N_{\text{SB}}$ complexity. Thus, the total number of real valued multiplications and additions for UFMC systems with N-point FFT/IFFT using split-radix algorithm is summarized in Table 3.

Table 3. Computational complexity of UFMC.

	Number of addition operation	Number of multiplication operation
Transmitter side	$B[A_{\text{FFT}}(N_{\text{SB}})+A_{\text{FFT}}(2N_{\text{SB}})]\ +4N_{\text{SB}}(B-1)+A_{\text{FFT}}(2N)$	$B[M_{\text{FFT}}(N_{\text{SB}})+M_{\text{FFT}}(2N_{\text{SB}})\ +8N_{\text{SB}}]+M_{\text{FFT}}(2N)$
Receiver side	$A_{\text{FFT}}(2N)+2N_0$	$M_{\text{FFT}}(2N)+4N_0$

Finally, the total computational complexity of each multicarrier modulation technique is calculated by adding the number of additions and multiplications on both the transmitter and receiver side.

4 Simulation Results and Analysis

4.1 Simulation Setup and Parameters

To compare the performances of the proposed multicarrier modulation techniques, we consider a single cell system with single antenna base station and a user with single receiving antenna. We also assume perfect channel state information both at the transmitter and receiver. Furthermore, we assume OFDM and UFMC waveforms employ guard intervals to mitigate inter symbol interference. Part of the simulation parameters considered in this work is shown in Table 4. The simulation parameters may vary in accordance with each comparison metrics.

Table 4. Parts of simulation parameters.

Parameters	Value	Remark
FFT size	64/1024	Vary as required
Subcarrier spacing	15 kHz	Same as LTE
Symbol mapping	16 QAM	Efficient scheme
OFDM parameters		
Length of CP	72	As in LTE
UFMC parameters		
Filter length	73	Assumed as $L_{\mathrm{cp}} + 1$
Subband size	12	Proposed in [7]
Guard interval	72	Equal with CP
Size of FFT (N_{SB})	64	Consider to minimize computational complexity
FBMC parameters		
Overlapping	$K = 4$	Gives better sidelobe [2]
Prototype Filter	PHYDYAS filter	Proposed in [2]

4.2 Power Spectral Density (PSD) Comparison

Here, we analyze the normalized power spectral density of OFDM, FBMC and UFMC systems with respect to the normalized frequency. We consider 64-subcarriers with 15 kHz spacing and overlapping factor of 4. For UFMC, we use subband size of 12, Dolph-Chebyshev filter with stop-band attenuation of 40 dB [2]. The length of the filter is assumed to be the length of cyclic prefix plus one. The prototype filter for FBMC is PHYDYAS filter with length $L = NK$ at $K = 4$ [2]. Figure 1 shows the power spectral density of CP-OFDM, FBMC and UFMC.

The result shows that the proposed multicarrier modulation techniques have different side-lobe radiations. Having low out-of-band (OOB) emission is advantageous to support asynchronous transmission. It is shown that FBMC and UFMC achieve lower out-of-band emission compared to CP-OFDM. Due to the block filtering, UFMC achieves lower OOB leakage compared to OFDM but it is outperformed by FBMC. As shown in the figure, UFMC attains −60dB OOB emission around 33 normalized frequency. Whereas, OOB emission for FBMC decays completely before a normalized frequency of 20. FBMC can attain −60dB interference level easily which is sufficient to meet the regulatory constraints for many applications. Besides, low side-lobe level in FBMC allows advanced utilization of the allotted spectrum and this helps to improve the spectral efficiency.

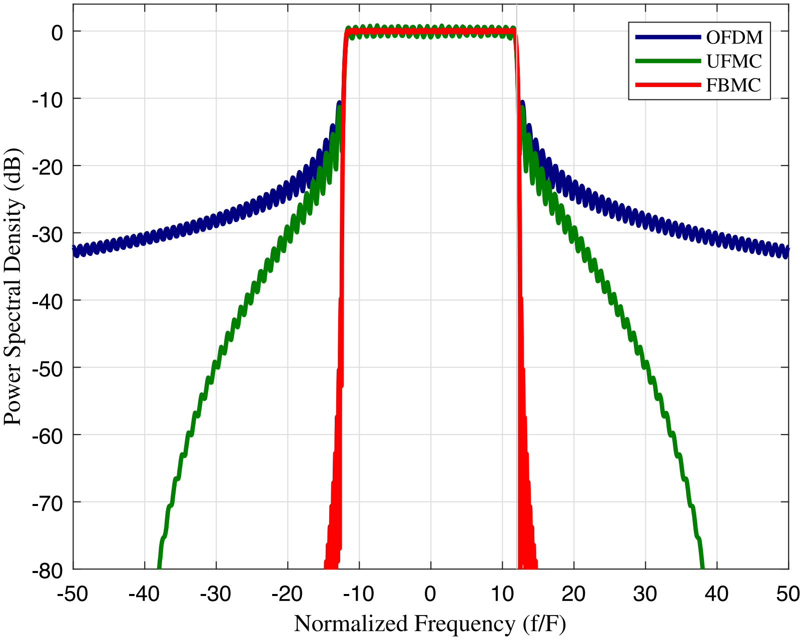


Fig. 1. Power spectral density of OFDM, UFMC, FBMC.

4.3 Spectral Efficiency Comparison

To evaluate the spectral efficiency, we consider the parameter based on LTE network with 10 MHz, QAM symbol mapping and an FFT size of 1024. For OFDM, size of CP is 72 samples. For UFMC, we use Dolph-Chebyshev filter of length 73 and length of padding is $L_{\mathrm{ZP}} = 72$ with block size of 12. As discussed before, for CP-OFDM and UFMC the spectral efficiency is a function of the FFT size and modulation order but it is independent on the burst duration. Whereas in FBMC, it depends on the frame duration. To compare the proposed multicarrier modulation techniques, we calculate the number of bits that can be transmitted under given modulation efficiency and transmission time of 0.1-300 ms. The result in Fig. 2 shows that UFMC without guard interval gives nearly the same spectral efficiency to that of OFDM. But, in frequency selective fading channel the removal of guard interval results in degradation of the BER. So, we also include UFMC with zero padding (ZP) that help to mitigate ISI. This results lower spectral efficiency in UFMC. The spectral efficiency of FBMC is independent on type of propagation channel, because unlike UFMC and OFDM there is no extra guard interval insertion to mitigate the frequency selectivity of the channel.

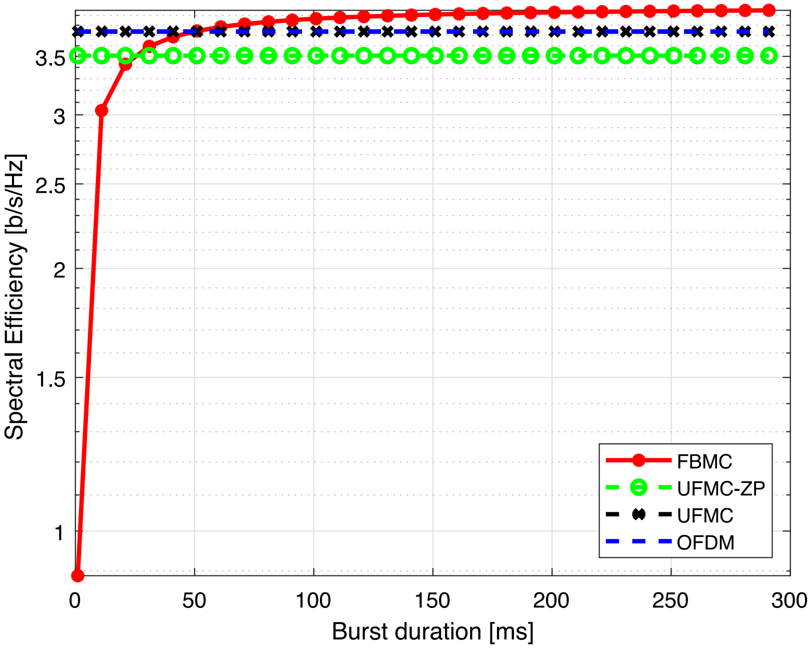


Fig. 2. Spectral efficiency of candidate multicarrier waveforms. We assume FFT size of $N = 1024$.

In Fig. 3, we plot the spectral efficiency by increasing the number of loaded bits in each subcarrier. The results shows that FBMC is not convenient at short transmission time. Whereas, the spectral efficiency of CP-OFDM and UFMC is independent on the burst duration. But, it is a function of FFT size and modulation parameters.

4.4 Bit Error Rate (BER) Comparison

To evaluate the BER performances of the candidate waveforms, we consider a carrier frequency of 2.5 GHz and an ITU-R Vehicular-A channel model with main parameters proposed in [19]. We use a Rayleigh fading propagation channel model with channel length and delay profile given in Table 5. The channel fading is assumed to be static for the duration of the symbol and perfect channel state information and synchronization are assumed. Besides, we use $N = 64$ subcarriers with 15 kHz subcarrier spacing for all waveforms. The measurements for the BER performance is taken with 300 channel realizations and 3 symbols for each channel realizations.

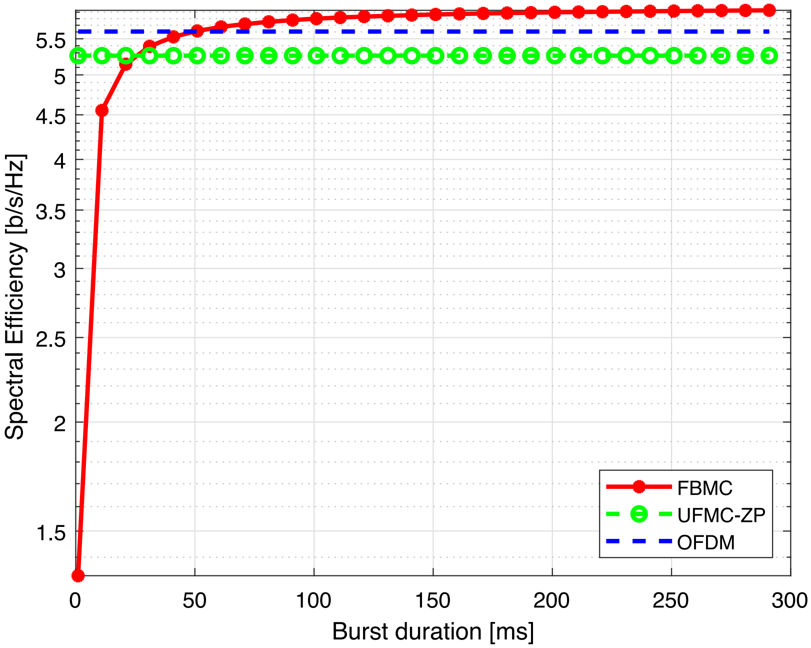
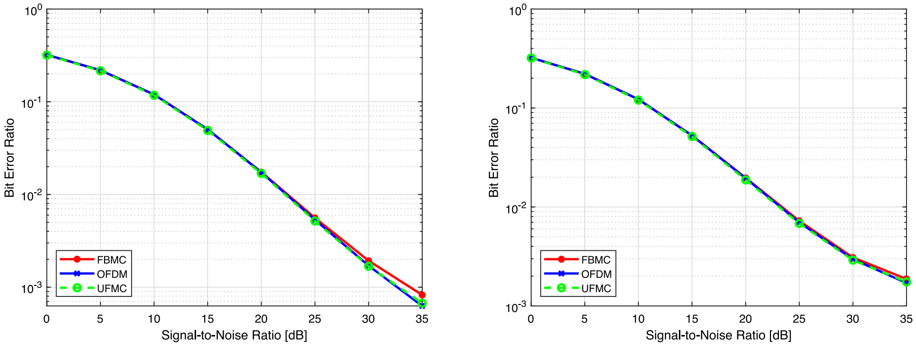


Fig. 3. Spectral efficiency of candidate multicarrier waveforms. We assume FFT size of $N = 1024$ and six bits are loaded on each subcarrier.

Table 5. Considered ITU-R vehicular A channel power delay profile [19].

Relative tap delay (ns)	Average power (dB)
0	0.0
310	-1
710	-9
1090	-10
1730	-15
2510	-20

Figure 4(a) shows the BER performances of the proposed waveforms when the Doppler frequency is zero ($f_d = 0\,\text{Hz}$). Since, ISI caused by multipath has been completely canceled by the insertion of CP, OFDM has better performance at low Doppler frequency. Also, the UFMC curve is almost aligned with CP-OFDM. Which is achieved by zero padding with length of CP. While for FBMC, since the bandwidth of each subcarrier is small enough to make the channel approximately flat, the ISI introduced by pulse shaping is nearly imaginary. Therefore, FBMC is approximately orthogonal in the real domain and this gives good BER performance. But, compared to UFMC and OFDM, additional 1.4 dB is required to achieve a BER of 10^{-3}. We also show the result by increasing the Doppler frequency ($f_d = 300\,\text{Hz}$). Since the delay spread become longer and channel become more frequency selective which is difficult to estimate and tracked accurately, the performances of all the waveforms degrade significantly as shown in Fig. 4(b).



(a) For f_d =0 Hz.

(b) For f_d =300 Hz.

Fig. 4. BER performance of candidate waveforms in ITU-R Vehicular A channel model. The number of subcarrier is 64 with 6 bits in each subcarrier.

4.5 Computational Complexity Comparison

To compare the computational complexity of the candidate multicarrier modulation techniques, we consider a downlink system with single antenna configuration both at the user and the BS. The results are obtained by considering low complex equivalent implementations of the transceivers presented in Sect. 3. Figure 5 shows the number of real valued multiplications for the proposed multicarrier modulation techniques with respect to the length of the transmitted symbols. The result shows that when the number of transmitted symbol increases, the number of real valued multiplication is also increased.

We also evaluate the computational complexity by assessing the numerical overhead of the candidate waveforms under two different scenarios. For this evaluation, we assume an FFT size of $N = 1024$ with subcarrier spacing of 15kHz, transmission bandwidth of 10 MHz and maximum number of subcarrier fitting to given bandwidth is 665. To minimize the interface in asynchronous transmission, we use the number of guard subcarriers proposed in [17]. Accordingly, the number of subcarriers that actually carry data symbols is assumed to be $N_0 = 664$ for FBMC, $N_0 = 586$ for CP-OFDM and $N_0 = 658$ for UFMC. We consider the complexity due to data symbol processing only. Hence, the complexity due to channel estimation, channel encoding/decoding, synchronization and pilot symbol generation are neglected here.

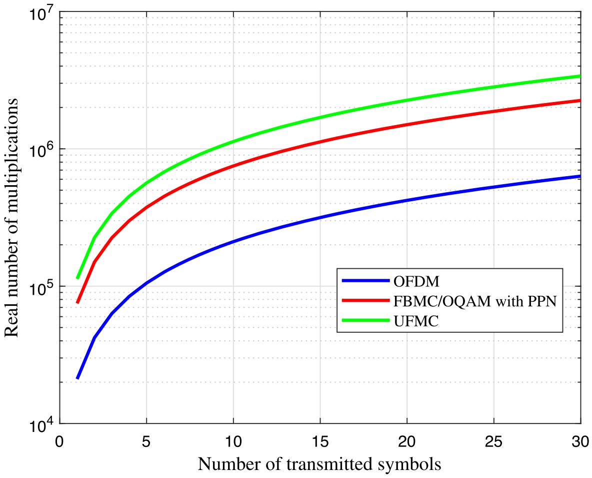


Fig. 5. Computational complexity of considered multicarrier modulation techniques.

We assume two deferent propagation scenarios. In the first case, ITU-R Vehicular-A channel model with medium delay spread is considered. As discussed in [20], with Vehicular-A channel model, assuming that the receiver is well synchronized both in time and frequency, it is sufficient to use one tap equalizer for FBMC. Longer equalizers may require to compensate synchronization imperfections but it adds the complexity. In OFDM, the CP length is assumed to be $L_{\mathrm{cp}} = 1/14$ of useful symbol duration. In the second case, we assume high frequency-selective Vehicular-B channel model that is considered in 3GPP-LTE system development [20]. Here, we use longer sub-channel equalizer in FBMC with $L_{\mathrm{eq}} = 5$ and the guard intervals in OFDM is increased to $L_{\mathrm{cp}} = 1/8$ of the useful symbol. The zero prefix of UFMC is assumed to have the same length to the cyclic prefix of OFDM.

Table 6 summarizes the computational complexity of each waveforms under the proposed system setups. The results show that both UFMC and FBMC have higher computational complexity than OFDM. With optimized implementation, FBMC requires 3.6× more real number of multiplications than OFDM to transmit the same amount of symbols. This is due to addition of filtering operation and increase on length of equalizer to mitigate the frequency selectivity of the channel. Efficient implementation of UFMC results around 5.5× more complexity than OFDM.

Table 6. Number of multiplications and additions at two different scenarios.

Multicarrier techniques	Real number of	Case I	Case II
OFDM	Multiplications	21,800	22,024
	Additions	59,032	59,144
UFMC	Multiplications	122,376	122,376
	Additions	354,052	354,052
FBMC	Multiplications	67,600	79,888
	Additions	138,256	150,544

5 Conclusion

In this work, we evaluate the performances of FBMC and UFMC in terms of power spectral density, BER, spectral efficiency and computational complexity. The result shows that FBMC has lower OOB emission due to pulse-shaping filters instead of rectangular windows employed in OFDM systems. Besides, FBMC is almost insensitive to multiuser interference. Due to block filtering, UFMC achieves lower OOB leakage compared to OFDM but it is outperformed by FBMC. It is also shown that, when the transmission time gets longer, the spectral efficiency of FBMC is outperforming that of OFDM and UFMC. But, during short burst transmission, FBMC suffers from long filter tails and the spectral efficiency is lower than UFMC and OFDM. The spectral efficiency of UFMC is lower than OFDM due to its filter tails in addition to the guard interval.

We also show that under high fading environment, waveforms with sufficient guard interval has the best performance. However, addition of guard interval costs the spectral efficiency. Besides, the computational complexity of the proposed waveforms at the propagation channel with medium to high delay spread is provided. The result shows that the complexity of FBMC and UFMC is higher than OFDM. This is mainly due to filtering operation and multi-tap equalizers to mitigate channel interference.

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