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Evaluation of UFMC as a Potential Waveform Contender of OFDM for Next-Generation Wireless

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***Abstract*—A number of waveforms have recently been proposed to replace the orthogonal frequency division multiplexing (OFDM) for the next-generation wireless systems. Among them, the universal filtered multi-carrier (UFMC) stands out to be a promising modulation method for the fifth-generation (5G) and beyond. The performance of the UFMC scheme is investigated in this paper and it is compared to that of OFDM. Specifically, the power spectral density (PSD) of the UFMC signal and the bit-error-ratio (BER) of the UFMC-based communication system are investigated for different numbers of subcarriers used and for different filter length values. Furthermore, the performance of UFMC and that of OFDM are compared under similar values of system parameters. Our simulations demonstrate that UFMC is capable of flexibly performing for the next-generation wireless and may thus be a promising next-generation waveform.**

***Keywords*—Orthogonal frequency division multiplexing (OFDM), universal filtered multicarrier (UFMC), 5G and beyond, power spectral density (PSD), bit-error-ratio (BER).**

I. Introduction

The demands for high-rate, low-latency and ultra-reliable voice and video communications have necessitated the rapid proliferation of new wireless access technologies. New communication standards are being rolled out to meet the user demands. Fifth generation (5G) and beyond systems have drawn considerable interest due to its potential of providing huge system capacity, high transmission rate, and of facilitating video transmissions, Internet of things (IoT), and so on [1]. Orthogonal frequency division multiplexing (OFDM) was considered as a popular modulation technique for the 4G long term evolution (LTE), [2]. This is mainly because of the high bandwidth efficiency it provides, its capability to overcome the channel-induced dispersion and the employment of the frequency-domain single-tap equalization it supports.

However, in the context of the massive machine-type communications supporting a huge number of users in the 5G and beyond networks, OFDM imposes a range of disadvantages, namely, the carrier and timing synchronization problem and the poor filter response resulting in spectral leakage [1], [3], [4]. A number of waveforms have been investigated for overcoming the above-mentioned disadvantages of OFDM. Universal filtered multicarrier (UFMC) is one of such modulation formats which can be viewed as a specific type of filtered OFDM with zero-padding [1], [5], Although the orthogonality of the user subcarriers may be maintained, the delay spread of the channel sometimes destroys the orthogonality and as a result, UFMC may be termed as a quasi-orthogonal system [6], [7], In this scheme, zero-padding replaces the cyclic prefixes of cyclic-prefixed OFDM. Additionally, UFMC was found to be useful for multiple access, and especially suitable for short bursts compared to filter-bank multicarrier (FBMC) systems [3], [4], [8]. Furthermore, rather than using filter banks on all subcarriers, UFMC employs a subband-based filtering method. Thus the data transmission rate and the power spectral density may be adaptively chosen [9], [10].

Against this background, in this paper, we evaluate the different characteristics of UFMC waveform and compare these to the corresponding characteristics of OFDM. Specifically,

1) We comprehensively study the power spectral density (PSD) of the UFMC transmit signal for different filter lengths and different offsets, and compared it to OFDM.
2) The error performance of UFMC-based communication is investigated for different filter-lengths and for different numbers of subcarriers. The error performance is also compared to that of the OFDM-based system.

We organize the rest of this paper as follows. An overview of the proposed scheme is provided in Section II. The simulation setup is mentioned in Section III and Section IV presents the performance results and the associated discussions. Finally, the paper is concluded in Section V.

II. System Overview

Here, the overall UFMC system is outlined by the schematic diagram of Fig. 1, whereas Fig. 2 and Fig. 3 detail the subband transmitter and the receiver, respectively.

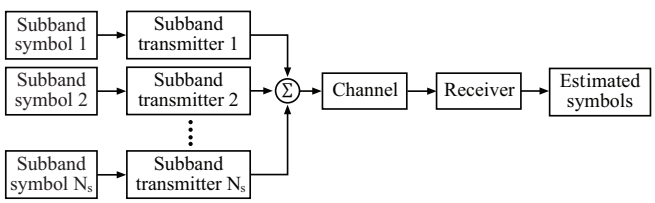


Fig. 1: The overall block diagram of UFMC

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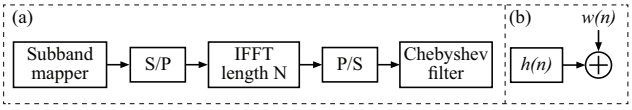


Fig. 2: (a) UFMC Transmitter's block diagram, (b) Channel

As shown in Fig. 1, the UFMC transmitter first partitions the incoming bits into a number of N_S subbands and the bits corresponding to each subbands are mapped to quadrature amplitude modulation (QAM) symbols. As a result, we have N_S subband symbol streams, namely subband symbol stream 1, subband symbol stream $2, \cdots$, subband symbol stream N_S. Each of these subband symbol streams are transmitted over the corresponding subband transmitters. The UFMC symbol stream is formed by superimposing all the subband streams transmitted, and is transmitted over the channel. The signal received from the channel is demodulated by the receiver using the UFMC-specific demodulation procedure.

A. The Subband-based Transmitter

As shown in Fig. 2, the symbols corresponding to the subband transmitters are passed through an N-point inverse fast Fourier transform (IFFT) processor. The IFFT processor converts the frequency-domain (FD) subband symbols to the time-domain (TD). The output of IFFT processor from each of the subband transmitters is filtered with a view to reducing the undesired out-of-band signal emissions, A Dolph Chebyshev window-type of prototype filter with specified side-lobe attenuation may be employed for filtering the time-domain subband signal [4], The output of the N_S subband transmitters are superimposed keeping a pre-specified offset length. The superimposed UFMC signal is transmitted over the channel. We have assumed a multipath Rayleigh fading channel for our simulations.

The superimposed time domain UFMC modulated signal of user k may be expressed as [4], [5], [7]:

$$\boldsymbol{x}_k = \sum_{i=1}^{N_S} \boldsymbol{F}_{i,k}\, \boldsymbol{V}_N \boldsymbol{s}_{i,k}, \tag{1}$$

where $\boldsymbol{s}_{i,k}$ denotes the i-th subband QAM symbol vector of a particular user k, N_S indicates the number of subbands, $\boldsymbol{V}_N$ stands for the $N \times N$ IFFT matrix, and $\boldsymbol{F}_{i,k}$ is the $(N+L-1) \times N$ Toeplitz matrix composed of the impulse responses of the prototype filters, and indicating a linear convolution with L representing the filter length.

In this context we define a joint time-frequency efficiency η_{T-F} as [4], [7]:

$$\eta_{T-F} = \eta_T \times \eta_F, \tag{2}$$

where η_T represents the time-domain efficiency and is given by $\eta_T = \frac{L_D}{(L_D+L_T)}$ with L_D denoting the length of the information carrying symbols in a symbol stream and L_T referring to the length of the tail of the stream, and the frequency-domain efficiency η_F is expressed by $\eta_F = \frac{N_U}{N}$ with N_U indicating the number of usable subcarriers out of a number of N subcarriers.

B. The Receiver

As shown in Fig. 3, the UFMC receiver is also FFT-based like the OFDM receiver. The time-domain received symbols are zero padded for reducing intersymbol interference and for compensating the channel distortion and as a result, every alternate subcarrier represents the subcarrier's main lobe. Due to the necessity of taking the effect of the subband-based filtering into consideration, we have to take $2N$-point FFT processing as applied on the time domain received symbols. The even subcarrier symbols are neglected for acquiring N-length data symbols. The original symbols are then demapped after equalizing the channel and the subband filtering.

Let the time-domain signal after linear convolution of the channel transfer co-efficients of different users and addition of white Gaussian noise be denoted by $\boldsymbol{y}$. After appropriately appending the $(N+L-1)$ zeroes, taking the $2N$-point FFT after discarding the even subcarriers, the frequency-domain UFMC signal may be expressed as [7], [11]:

$$\hat{\boldsymbol{x}} = \begin{bmatrix} e_1 \\ e_3 \\ e_5 \\ \vdots \\ e_{2N-1} \end{bmatrix} \boldsymbol{V}_{2N}^H \begin{bmatrix} \boldsymbol{y} \\ \boldsymbol{0}_{(N+L-1)\times 1} \end{bmatrix}, \tag{3}$$

where $\boldsymbol{V}_{2N}^H$ denotes the $(2N \times 2N)$ FFT matrix, and $\boldsymbol{e} = [e_1, e_3 \cdots e_{2N-1}]^T$ indicates the consideration of the odd subcarriers only. After appropriate channel equalization and equalization of the filter coefficients, the symbols may be demodulated.

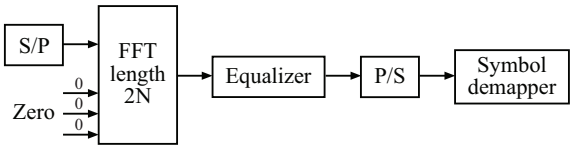
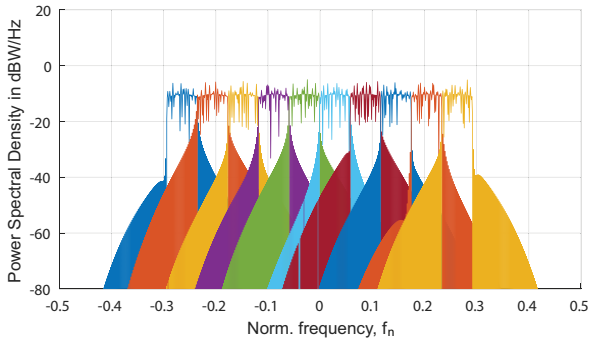


Fig. 3: UFMC receiver's block diagram

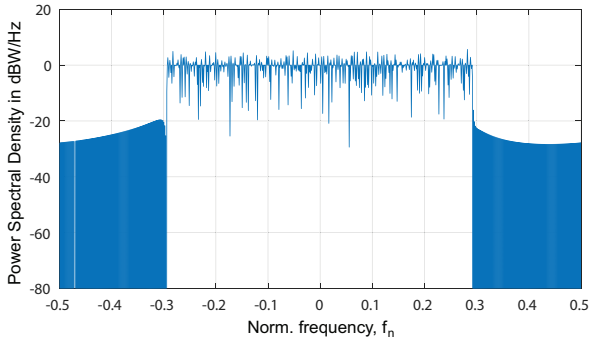
C. OFDM versus FBMC versus UFMC

OFDM is a widely-used modulation method for 4G LTE systems. It is a popular technique for point-to-point as well as for the downlink of LTE system for overcoming the impairments due to the channel-induced dispersion, for employment of simple frequency-domain equalizers, and for efficient parallel implementation with the aid of IFFT. OFDM, however, fails to cope with the requirement of low out-of-band emissions, and the strict synchronization requirement imposed by 5G and beyond wireless systems. New modulation formats are being considered to meet these requirements. FBMC maybe employed for meeting the above-mentioned requirements [8]. However, FBMC employs filtering over the entire frequency band. UFMC may be viewed as a generalization of FBMC, where filtering is employed over a subband. UFMC is helpful

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(a)



(b)

Fig. 4: (a) PSD of UFMC signal for subband size=30, number of subband=10, filter length=20, and side-lobe attenuation=140 dB.(b) PSD of OFDM signal using number of subcarriers=300.

due to its high power spectral density and its capability for the mitigation of multiuser interferences.

III. Simulation Set-up

We have simulated the UFMC-based as well as the OFDM-based communication systems using MATLAB 2021a simulation environment. We have investigated the PSD of the transmitted signals for both schemes. The error performance of both the schemes is also verified and compared by simulation experiments. We use the number of subbands, the size of each subband, the length of the Chebyshev filter, and the side-lobe attenuation as the UFMC parameters. The subband offset may be computed to be the half of the difference between the FFT-size used and the size of the total number of subbands considered. Random data bits are generated as input. Then the data bits are modulated, passed through the channel, and demodulated by UFMC and OFDM scheme. The signal's PSD and BER are compared for both UFMC and OFDM.

Fig. 4 portrays the PSD of UFMC and OFDM signals using similar parameter values. Specifically, the PSD of the UFMC system is shown in Fig. 4a as a function of the normalized frequency, f_n in radian/sample (which is related to the frequency and the sampling rate, f_s). The PSD of Fig. 4a is obtained by using a subband size of 30, total number of subbands=10, filter length=20, and side-lobe attenuation=140 dB. Fig. 4b

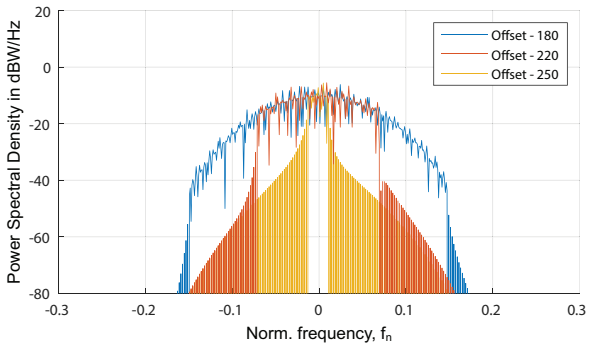


Fig. 5: PSD of UFMC signal for different offset values.

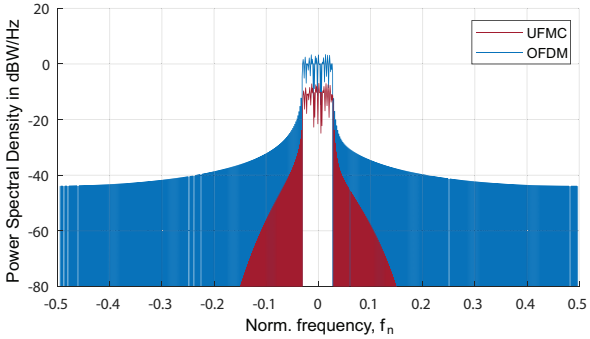


Fig. 6: PSD comparison between OFDM and UFMC using single subband of 30 subcarriers.

shows the PSD of OFDM signal with the same total number of subcarriers=30, and the length of cyclic prefix (CP)=20. For both the schemes, the FFT-size is 512.

For a better comparison, we have shown the PSD of the UFMC scheme for three values of the subband offset in Fig. 5. Specifically, we have considered the size of the subband offsets to be 180, 200, and 250 of a single-subband scheme and the PSD of the UFMC signal corresponding to these offset values are shown in Fig 5. As seen from Fig 5, the higher the offset value, the more selective the system is.

IV. Results and Discussion

This section investigates the performance of both the UFMC and the OFDM scheme and compares them. UFMC is based on partitioning full-band symbols into subband symbols. For each subband, the modulation technique is applied individually. Each subband is made of a group of subcarriers.

Fig. 6 shows the PSD of UFMC as compared to OFDM using 30 subcarriers for both. As a fair comparison, we see from Fig. 6 that UFMC has less emission of side-lobe power than the OFDM system. As a result, UFMC has more potential to prevent interference among subcarriers than OFDM. As there is no CP in UFMC, the same bits are not repeated, and thus the entire spectrum is utilized efficiently. Hence, the spectral efficiency of UFMC is higher than that of OFDM.

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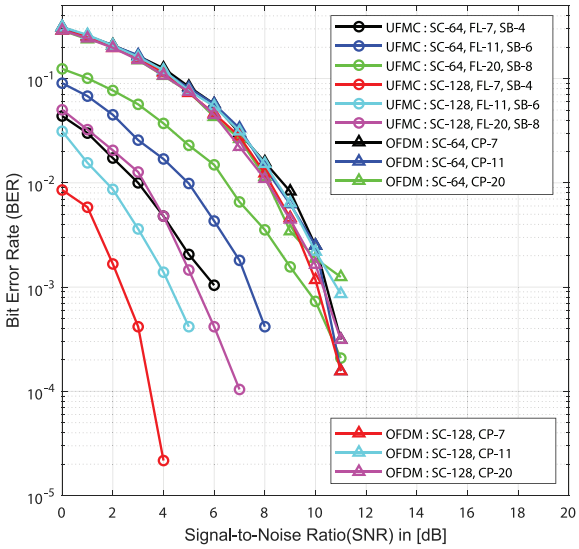


Fig. 7: BER performance for UFMC and OFDM using different system parameters.

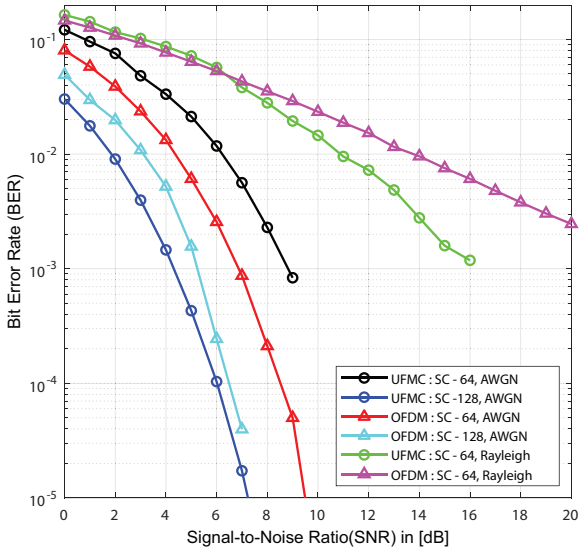


Fig. 8: BER performance for UFMC and OFDM for 64 and 128 subcarriers under both the AWGN and the Rayleigh multipath channel.

Fig. 7 illustrates the BER for different filter lengths and for different numbers of subbands. We have used three modes of UFMC setup for comparing BER with OFDM. For UFMC, we consider the filter length of 7 and 20, and number of subbands=4 and 8, filter length=11 and number of subbands=6, For OFDM setup the CP length is varied from 16. The number of subcarriers is used for UFMC and OFDM is 64 and 128. Although the performance of UFMC deteriorates with increasing filter length, the reason for the worse performance is that bandwidth decreases as filter length increases. It is also obvious that UFMC performs better than OFDM.

Fig. 8 depicts the BER performance for different numbers of subcarriers. We consider both the AWGN channel and a 6-tap Rayleigh multipath channel for this investigation. It shows that both UFMC and OFDM have small BER. But UFMC has better synchronization than OFDM. The error performance of UFMC is seen to be better than that of OFDM under both the AWGN channel and the Rayleigh multipath channel scenarios.

V. Conclusion

In this paper, UFMC has been investigated as a potential next-generation modulation format. The PSD of the UFMC transmit signal and the error performance of the scheme have been studied in detail and compared to those of OFDM. We have illustrated the basic transmitter and receiver functionality and evaluated the scheme employing different parameters namely the number of subcarriers used, the filter length, the number of subbands, the offset length, the filter side-lobe attenuation, and above all, the channel SNR. We have shown that UFMC has less out-of-band emissions than OFDM, and does not require complex synchronization, making it suitable for IoT devices. Additionally, subband filtering in UFMC can reduce the subband gap, and makes it suitable for short burst applications compared to FBMC. Thus our evaluation has suggested that UFMC may be a game-changing modulation format for the 5G and beyond wireless systems.

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