A Filtered OFDM Using FIR Filter Based on Window Function Method

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***Abstract*—Orthogonal Frequency Division Multiplexing (OFDM) is designed to combat the effect of multipath reception, by dividing the wide band frequency selective fading channel into many narrow flat sub-channels, which improves the spectral efficiency and significantly mitigates the intersymbol interference (ISI). However, OFDM can not meet the demand for 5G heterogeneous service scenarios since it has a high out-of-band emission and a large peak-to-average power ratio (PAPR), and it only supports one kind of waveform parameter in the whole bandwidth. The Filtered-OFDM (F-OFDM) is proposed as a candidate technique for 5G high-data rate wireless communication system. This paper proposes a finite impulse response (FIR) digital filter based on window function method to achieve the F-OFDM, and discusses the performance of different window functions implemented in the F-OFDM. Simulation results show that the proposed F-OFDM is easy to be implemented and has a very low out-of-band emission with the same bit error rate (BER) performance compared to the conventional OFDM.**

***Index Terms*—Orthogonal Frequency Division Multiplexing (OFDM), Filtered-OFDM (F-OFDM), finite impulse response (FIR), window function, 5G.**

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) which comes from multicarrier modulation (MCM) technology is now considered a key technology for the broadband wireless communication systems such as 4G/TD-LTE/LTE-Advanced communication systems [1] [2]. OFDM is designed to combat the effect of multipath reception, by dividing the wide band frequency selective fading channel into many narrow flat sub-channels [3], and it improves the spectral efficiency and significantly mitigates the intersymbol interference (ISI) [4]. With the rapid growth of wireless communication service, the LTE system can not meet the wireless communication demand and a higher data rate wireless communication system is required. Nowadays, the 5G has become a research hotspots in this case. OFDM can not meet the 5G heterogeneous service scenarios demand because it has a high out-of-band emission and a large peak-to-average power ratio (PAPR) [5], and it only supports one kind of waveform parameter in the whole bandwidth. And the Filtered-OFDM (F-OFDM) which actually is a modified form of OFDM is proposed for 5G [6] [7] [8]. F-OFDM divides the whole bandwidth of the system into a number of subbands, and every subband is filtered by different filters to set different waveform parameters according to the different service scenarios.

Basically, there are three types of OFDM-based block transmission schemes: cyclic prefix OFDM (CP-OFDM), zero padding OFDM (ZP-OFDM), and time domain synchronous OFDM (TDS-OFDM) [1]. CP-OFDM has its limitations in spectral properties and in conjunction with relaxed time-frequency alignment, while a new discussed contender is Filter-Bank based Multi-Carrier (FBMC) with better spectral properties but new drawbacks introduced by offset quadrature amplitude modulation and long filter lengths [7] [9]. OFDM with index modulation (OFDM-IM) was discussed in [2], and it proposed multiple-input multiple-output OFDM-IM (MIMO-OFDM-IM) scheme by combining OFDM-IM and MIMO transmission techniques. Ying-Che Hung and Shang-Ho Tsai [10] used the beamforming (or precoding) technique in MIMO to reduce the high PAPR in MIMO-OFDM system while the precoding process increases the computational complexity at the transmitter [11]. And a new OFDM using the C-transform (C-OFDM) is introduced in [12], which not only achieves reduction in the PAPR but also has better BER performance. Hao Lin [8] proposed a flexible OFDM which enables a flexible subband configuration and targets a multi-service scenario, and it also provides a good compromise between the FBMC with offset quadrature amplitude modulation and the classical CP-OFDM system.

In this paper, we propose a finite impulse response (FIR) digital filter based on window function method to achieve the F-OFDM. The proposed F-OFDM is easy to implement and has a very low out-of-band emission with the same bit error rate (BER) performance compared to the conventional OFDM. Also, we compared the performance of different window functions implemented in the F-OFDM including Kaiser, Hamming, Chebyshev and Blackman-Harris windows. And the different window functions may result in different attenuation shapes and coefficients, which may help us to choose the proper window function to design the filter.

The remainder of this paper is organized as follows. In Section II, we describe the basic F-OFDM link and the design of FIR filter based on window function, and give some design criteria for the digital FIR filter. Section III gives the simulation and analysis of F-OFDM compared to the conventional OFDM. From which we can see that the higher order modulation may need a higher passband and the better out-of-band emission performance may occupy more bandwidth. This paper is closed with concluding remarks in

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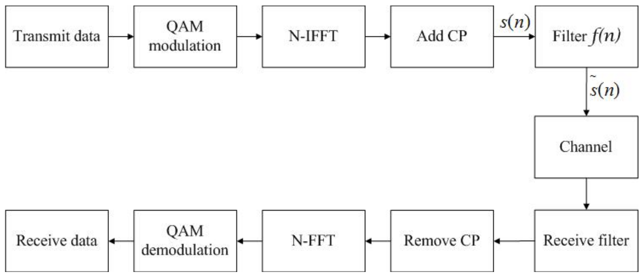


Fig. 1. Diagram of F-OFDM transmission.

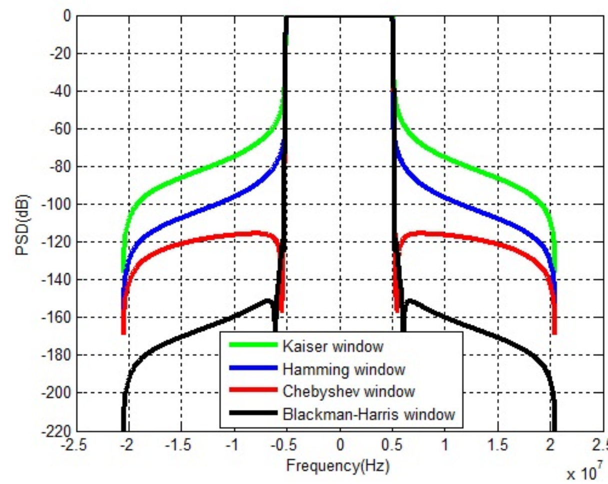


Fig. 2. PSDs of different window functions.

Section IV.

II. F-OFDM COMMUNICATION SYSTEM

In this section, we describe the basic F-OFDM link, the design of FIR digital filter based on window function method and how to filter the conventional OFDM to achieve the proposed F-OFDM.

A. Communication link

A complete F-OFDM communication link is shown in Fig. 1. The transmit data is discrete binary stream, and modulation is the technique by which the signal wave is transformed in order to send it over the communication channel and to minimize the effect of noise [3]. In LTE system, quadrature amplitude modulation (QAM) is used and here we also use QAM with different modulation orders. IFFT is performed on the modulated signal to make it into OFDM symbol and N is the IFFT/FFT size. CP is added to avoid intersymbol interference caused by the delay spread of wireless channels [13], while the CP size varies with the different communication scenarios. The filter $f(n)$ is the FIR digital filter which can use different kinds of window functions to achieve F-OFDM. The channel is the additive white gaussian noise (AWGN) wireless channel or the multipath wireless channel or the combination of the two channels. And the receiver is the inverse process of the transmitter.

A typical OFDM symbol $s(n)$ is expressed as:

$$s(t) = \sum_{i=0}^{N-1} d_i rect(t - t_s - \frac{T}{2}) e^{j2\pi f_i (t-t_s)}, t_s \leq t \leq t_s + T, \tag{2}$$

where N is the number of subcarriers, d_i denotes the complex data symbol. T is the symbol duration and f_i is the subcarrier frequency. $rect(t)$ is the rectangle function.

If let $\{s_{n,k}\}_{k=0}^{N-1}$ with $E|s_{n,k}|^2 = \sigma_s^2$ be the complex symbols to be transmitted at the nth OFDM block, then the OFDM signal has another expression in [4]:

$$s_n(t) = \sum_{k=0}^{N-1} s_{n,k} e^{j2\pi k \Delta f t}, 0 \leq t \leq T_s, \tag{3}$$

where N is also the number of subchannels, T_s and Δf are the symbol duration and the subchannel space respectively.

From the formula we can see that the OFDM is actually the inverse discrete Fourier transform (IDFT) of the data symbol d_i and OFDM modulation can be easily achieved by inverse fast Fourier transform (IFFT). So the demodulation of OFDM can be performed by using FFT.

B. Filter design

The F-OFDM signal $\widetilde{s}(n)$ is obtained by passing the signal $s(n)$ through a filter $f(n)$, which can be described as a convolution process:

$$\widetilde{s}(n) = s(n) * f(n). \tag{4}$$

According to the property of Fourier transform (Convolution theorem in time domain): Convolution in time domain corresponds to the multiplication in frequency domain. So the filtering process in frequency domain is:

$$\widetilde{S}(e^{jw}) = S(e^{jw}) F(e^{jw}). \tag{5}$$

$$\begin{aligned} W(w) =& 0.54 W_R(w) + 0.23[W_R(w - \frac{2\pi n}{N-1}) + W_R(w + \frac{2\pi n}{N-1})] \\ &\approx 0.54 W_R(w) + 0.23[W_R(w - \frac{2\pi}{N}) + W_R(w + \frac{2\pi}{N})], (N \gg 1), \end{aligned} \tag{1}$$

where $W_R(w) = \dfrac{sin(\frac{Nw}{2})}{sin\frac{w}{2}}$.

TABLE I
PARAMETERS OF F-OFDM.

Parameter	F-OFDM setting
Number of carriers	1000
IFFT/FFT size	4096
Modulation	4|8|16|64|256 QAM
Bandwidth	10 MHz
Carrier spacing	10 KHz
Symbol duration	1/10 KHz=100us
CP size	(1/4|1/8|1/16|1/32)*4096
Filter order	256|512|1024|2048
Channel	AWGN channel or multipath channel+AWGN channel

In the following, we use the window function method to design the FIR filter and we use a Hamming window for example. A Hamming window function is:

$$w(n) = [0.54 - 0.46cos(\frac{2\pi n}{N-1})]R_N(n), \tag{6}$$

where $R_N(n)$ is rectangular sequence.

The amplitude-frequency response function of the Hamming window function is given by (1).

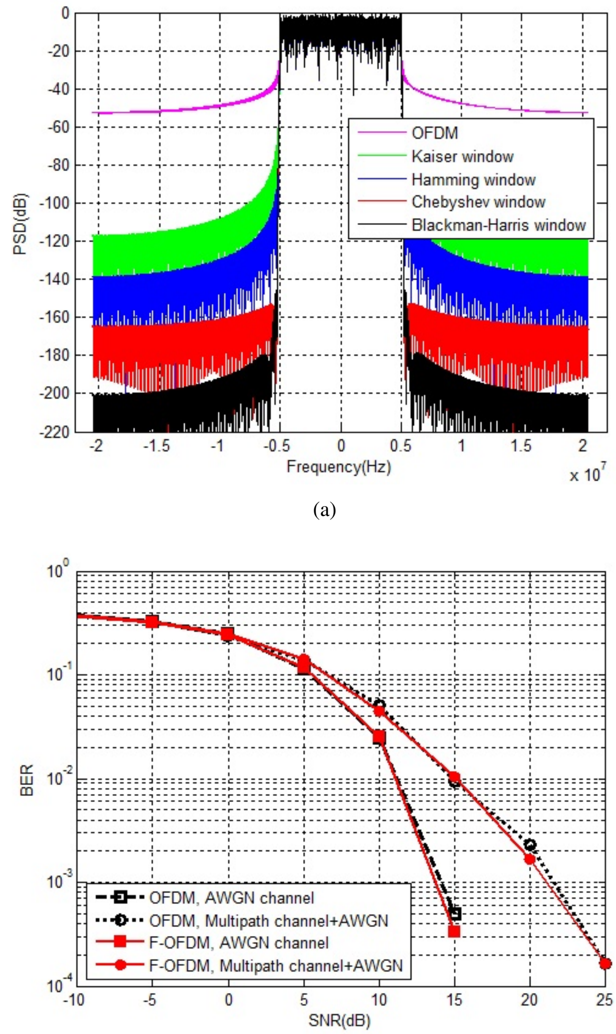
Therefore, the FIR filter is:

$$\begin{aligned} f(n) =& f_d(n) \cdot w(n) \\ &= f_d(n) \cdot [0.54 - 0.46cos(\frac{2\pi n}{N-1})]R_N(n), \end{aligned} \tag{7}$$

where $f_d(n)$ is the ideal linear phase filter.

Fig. 2 shows the power spectral density (PSD) of 4 kinds of window function filters including Kaiser, Hamming, Chebyshev and Blackman-Harris windows. From Fig. 2 we can see that the different window functions result in different attenuation shapes and coefficients. The Kaiser window has a high stop band attenuation while the Blackman-Harris window has a lowest stop band attenuation which can reach -160 dB. And the Chebyshev window has a very narrow transition band. Here we give some design criteria of the digital FIR filter:

1) The filter has no attenuation in main band so that all the useful signals can pass the filter without loss.
2) The filter attenuates to the stop band quickly and has a very narrow transition band to prevent the out-of-band signals.
3) The higher order of filter can result in the better performance, and the higher order can result in the larger computation cost. Thus we have to find the balance between the performance and the computation cost of the filter.



(a)

(b)

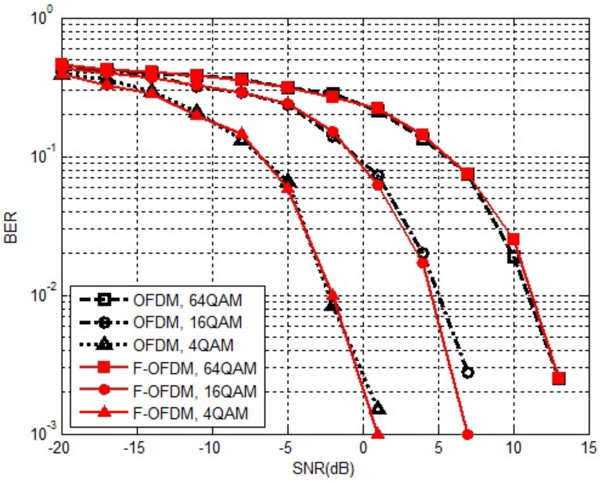
Fig. 3. (a)PSDs of F-OFDM using different window functions (b)BER of F-OFDM using Chebyshev window function compared to the conventional OFDM.

4) Finally, the filter with lower stop band attenuation should be used. However, the lower stop band attenuation results in the bad performance in BER, which we will discuss later in this paper.

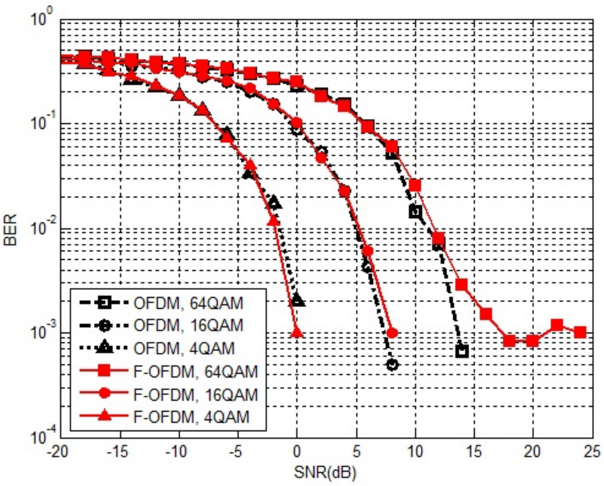
III. SIMULATION AND ANALYSIS

In this paper, the F-OFDM simulation parameters are shown in table I. For the FIR filter, the sampling frequency is 40.96 Mbps and to balance the performance and the computation cost of the filter, the filter order is set to be 1024. The cutoff frequency is 5.06 MHz (i.e. the passband of the filter is 10.12 MHz) which is a little larger than the bandwidth and we will discuss how it can influence the performance of the F-OFDM later.

From Fig. 3 (a) we can see the PSDs of F-OFDM using different window functions compared to the conventional OFDM. The F-OFDM has a very low out-of-band emission



(a)



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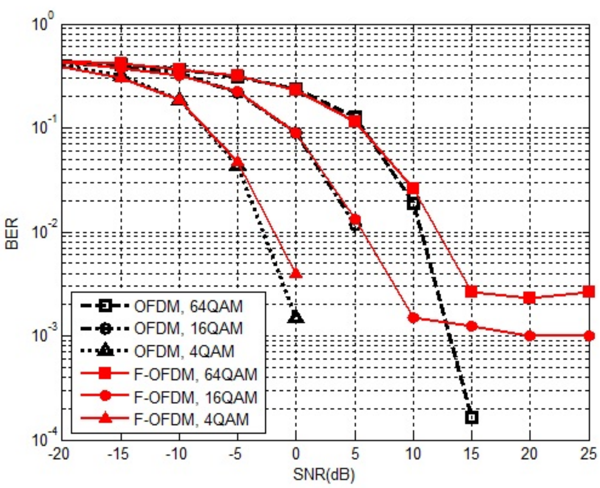
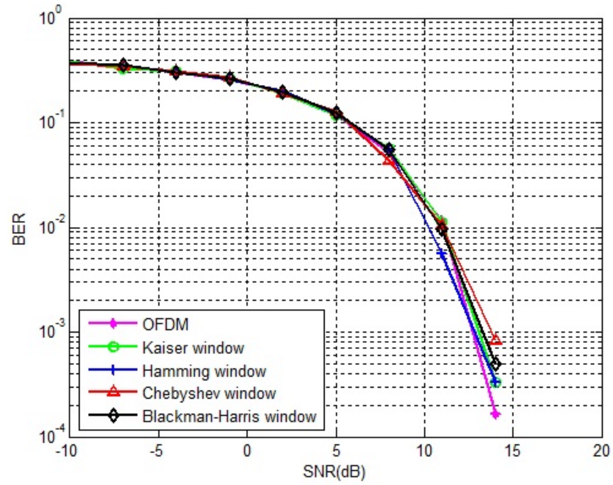
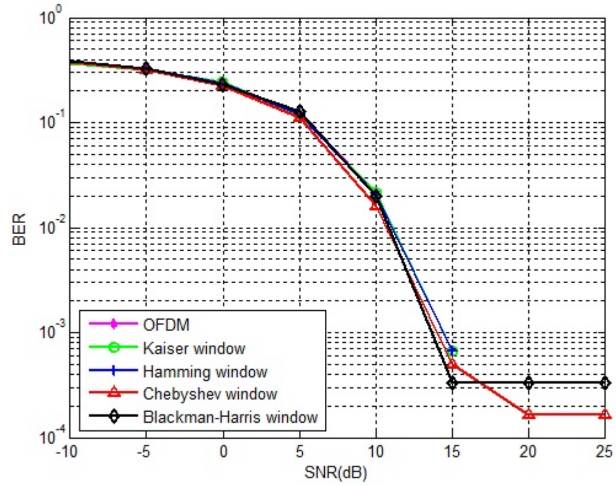


(c)

Fig. 4. (a)BER of F-OFDM and OFDM in the bandwidth of 10.12 MHz (b)BER of F-OFDM and OFDM in the bandwidth of 10.06 MHz (c)BER of F-OFDM and OFDM in the bandwidth of 10 MHz.



(a)



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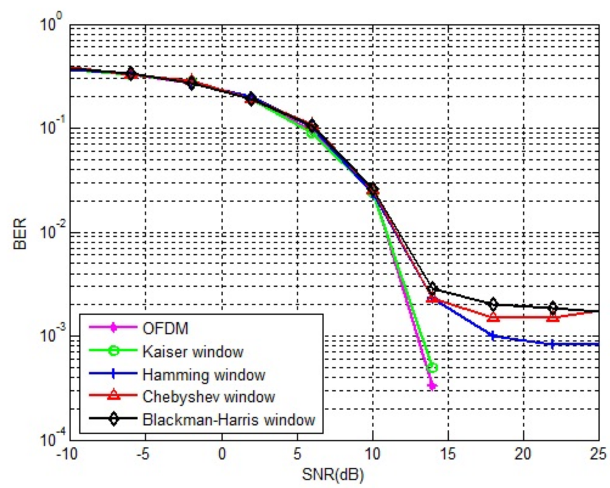

(c)

Fig. 5. (a)BER of F-OFDM for all window functions in the bandwidth of 10.12 MHz (b)BER of F-OFDM for all window functions in the bandwidth of 10.08 MHz (c)BER of F-OFDM for all window functions in the bandwidth of 10.04 MHz.

which can achieve 80∼150 dB lower than the conventional OFDM, and the Blackman-Harris window can reach -200 dB. Not only the F-OFDM has a good low out-of-band emission performance, but also it has the same performance of BER as the conventional OFDM. Fig. 3 (b) shows the F-OFDM has the same BER curves compared to the conventional OFDM under different channel conditions. So the F-OFDM can achieve a very low out-of-band emission with maintaining the BER performance which could be a strong candidate in the 5G air interface.

In the following, we analyse how the cutoff frequency of window function influences the performance of the F-OFDM. A Chebyshev window function is used in F-OFDM and its BER performance is shown in Fig. 4 (a). Fig. 4 (a) shows both F-OFDM and OFDM BER curves in different constellation number QAM by setting cutoff frequency 5.06 MHz (i.e. the passband of the filter is 10.12 MHz compared to the 10 MHz of the signal bandwidth, and the excess 0.12 MHz is used for protecting). The F-OFDM has the same curves as OFDM in different QAM. And we reduce the cutoff frequency to 5.03 MHz (i.e. the passband is 10.06 MHz) and 5 MHz (i.e. the passband is 10 MHz) to obtain the Fig. 4 (b) and Fig. 4 (c). We can see that the 64 QAM BER of F-OFDM performance is bad in Fig. 4 (b) and the 16 QAM BER performance of F-OFDM starts to go bad in Fig. 4 (c). We can draw a conclusion that the higher order modulation of F-OFDM needs a higher passband of window function filter to keep the performance.

The performance of different window functions has been shown in Fig. 5. Also, Fig. 5 (a) has a sufficient filter passband (10.12 MHz) for filtering and all the window functions have the same performance compared to the OFDM. The passband is changed to 10.08 MHz in Fig. 5 (b) and the BER performance of Blackman-Harris window and Chebyshev window get bad. And the passband is set to be 10.04 MHz in Fig. 5 (c) and we can see that only Kaiser window keeps the same performance as OFDM. By comparing the Fig. 5 with the Fig. 3 (a), we can find that the lower out-of-band emission performance of window function needs much larger passband. That is to say, the window function filter achieves the lower out-of-band emission performance by occupying a larger bandwidth of filter. Thus the filter with a larger bandwidth can achieve a better out-of-band emission performance and we can change the window function of F-OFDM according to the communication scenarios.

IV. Conclusion

In this paper, we proposed a Filtered OFDM using window function FIR filter. The FIR filter is obtained by cutting off the ideal linear phase filter with a finite length window function. The F-OFDM signal is achieved by convoluting the original OFDM signal with the FIR filter. The proposed F-OFDM is easy to be implemented and has a very low out-of-band emission with the same BER performance compared to the conventional OFDM. It can be filtered by different filters to set different waveform parameters according to the different service scenarios, and the F-OFDM is sensitive to the passband of filter. The numerical results show higher order modulation needs a higher passband and the better (lower) out-of-band emission performance occupies more bandwidth. The proposed F-OFDM is helpful for us to design the filter to achieve the F-OFDM.

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References

[1] Linglong Dai, Zhaocheng Wang, and Zhixing Yang, "Time-Frequency Training OFDM with High Spectral Efficiency and Reliable Performance in High Speed Environments," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 4, pp. 695-707, May 2012.

[2] Ertugrul Basar, "Multiple-Input Multiple-Output OFDM with Index Modulation," *IEEE Signal Processing Letters*, vol. 22, no. 12, pp. 2259-2263, September 2015.

[3] Mrs. S. S. Ghorpade, and Mrs. S. V. Sankpal, "Behavior of OFDM system using MATLAB simulation," *International Journal of Innovative Technology and Reach*, vol. 1, no. 3, pp. 249-252, May 2013.

[4] Taewon Hwang, Chenyang Yang, Gang Wu, Shaoqian Li, and Geoffrey Ye Li, "OFDM and Its Wireless Applications: A Survey," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 4, pp. 1673-1694, May 2009.

[5] Jialing Li, Kenneth Kearney, Erdem Bala, and Rui Yang "A resource block based filtered OFDM scheme and performance comparison," *2013 20th International Conference on Telecommunications (ICT)*, pp. 1-5, May 2013.

[6] Arman Farhang, Mohammad Molavi Kakhki, and Behrouz Farhang-Boroujeny "Wavelet-OFDM versus filtered-OFDM in power line communication systems," *2010 5th International Symposium on Telecommunications (IST)*, pp. 691-694, December 2010.

[7] Thorsten Wild, Frank Schaich, and Yejian Chen, "5G air interface design based on Universal Filtered (UF-)OFDM," *2014 19th International Conference on Digital Signal Processing (DSP)*, pp. 699-704, Augeust 2014.

[8] Hao Lin, "Flexible Configured OFDM for 5G Air Interface," *IEEE Access*, vol. 3, pp. 1861-1870, October 2015.

[9] Shixian Lu, Daiming Qu, and Yejun He, "Sliding Window Tone Reservation Technique for the Peak-to-Average Power Ratio Reduction of FBMC-OQAM Signals, "*IEEE Wireless Communications Letters*, vol. 1, no. 4, pp. 268-271, Aug. 2012.

[10] Ying-Che Hung and Shang-Ho Tsai, "PAPR Analysis and Mitigation Algorithms for Beamforming MIMO OFDM Systems," *IEEE Transactions on Wireless Communications*, vol. 13, no. 5, pp. 2588-2600, May 2014.

[11] Sen-Hung Wang, Chih-Peng Li, Kuan-Chou Lee and Hsuan-Jung Su, "A Novel Low-Complexity Precoded OFDM System With Reduced PAPR," *IEEE Transactions on Signal Processing*, vol. 63, no. 6, pp. 1366-1376, March 2015.

[12] Hussein A. Leftah and Said Boussakta, "Novel OFDM Based on C-Transform for Improving Multipath Transmission," *IEEE Transactions on Signal Processing*, vol. 62, no. 23, pp. 6158-6170, December 2014.

[13] Da Chen, Xiang-Gen Xia, Tao Jiang, and Xiqi Gao, "Properties and Power Spectral Densities of CP Based OQAM-OFDM Systems," *IEEE Transactions on Signal Processing*, vol. 63, no. 14, pp. 3561-3575, July 2015.