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Low Complexity Implementation of Universal Filtered Multi-Carrier Transmitter

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ABSTRACT Universal Filtered Multi-Carrier (UFMC) is a promising multi-carrier modulation scheme. It can be considered as the combine of filtered OFDM and Filter Bank Multi-Carrier (FBMC) modulations. The difference among them is that filtered OFDM filters the entire band and FBMC filters the single subcarrier, while UFMC filters groups of subcarriers. It is evaluated their performance for the new conditions. While UFMC offers superior advantages, such as higher spectral efficiency, lower overhead, more robustness and less out-of-band (OOB) emission, the introduction of filters and the application of FFTs for the subband increase the implementation complexity of the transmitter. In terms of complexity, based on the analysis of UFMC transceiver structure, few low complexity implementation methods for UFMC systems are recently put forward. The low complexity solutions need to be found. In this paper, the computational complexity of different UFMC implementation methods based on lightweight structure which combines with the FIR filter and the poly-phase filter is evaluated. It is shown that the computational complexity of the UFMC transmitter can be reduced to be similar to OFDM, which is a promising solution for the advanced waveform. In addition, we analyze the effect of the filter on the power spectral density (PSD) of the proposed structure. Analysis shows that the system can be implemented with better performance by adjusting the filter parameters.

INDEX TERMS Computational complexity, FIR filter structure, IFFT, lightweight structure, poly-phase structure, power spectral density, UFMC.

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) technology can well overcome the frequency-selective fading of wireless channels, and has been successfully used in various communication systems such as Wireless Local Area Network (WLAN), 4G, and digital video broadcasting [1]. OFDM divides high rate data into a set of low rate data streams, and then each data stream is sent in parallel on a different subcarrier frequency [2]. With this structure, the frequency-selective channel can be transformed into a frequency-fading fading channel, and the problem of Inter-Symbol Interference (ISI) caused by the frequency-selective fading channel can be effectively solved. However, as OFDM uses rectangular pulses as the prototype filter, the side lobes in the frequency domain are large, while the attenuation is slow. Therefore, in fast fading channels under high-speed moving conditions, it is difficult to guarantee the orthogonality between subcarriers. The OFDM system faces huge challenges. From the perspective of wireless transmission, it is mainly reflected in the following aspects: first of all, due to the irregular timing of massive machine communication, the strict synchronization and orthogonal mechanisms required by OFDM will bring intolerable signaling overhead. Secondly, OFDM with large Out-Of-Band (OOB) emission is difficult to fully exploit the fragmentation resources between the used frequency bands. Thirdly, the system performance based on OFDM will significantly deteriorate in the case of frequency-time quasi-synchronization.

In response to these shortcomings, non-orthogonal waveforms are mainly optimized for multicarrier modulation waveforms and filtering methods to better suppress peak-to-average power ratio (PAPR) and reduce OOB emission, and improve system performance in the case of quasi-frequency synchronization [3]. Universal Filtering Multi-Carrier (UFMC) technology is a novel multicarrier modulation technique proposed by Vakilian et al. in 2013 [4], which combines the advantages of filtered OFDM and Filter Bank Multi-Carrier (FBMC). The computational complexity of traditional UFMC transmitters is tens or even hundreds of times that of traditional OFDM transmitters, which is also one of the key factors limiting the widespread

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application of UFMC technology. In [5], a reduced complexity architecture based on frequency domain processing has been proposed which significantly reduced complexity by performing filtering in the frequency domain. A low-complexity UFMC transmission based on time-domain signal processing machine was discussed in [6], the complexity reduction is achieved through the approximation of the time domain filter. In [7], it proposed a method for reducing the complexity of the UFMC transmitter with FFT pruning at the input and output. Considering the complexity reduction of hardware implementation, in [8] the system complexity was reduced in three aspects: IFFT complexity reduction, FIR filtering complexity reduction, and simplified spectrum shift coefficients generation.

Therefore, to fully utilize the advantages of UFMC technology, the computational complexity of the UFMC system must be significantly reduced. At the same time, we have noticed that the UFMC transmitter structure has a larger effect on the computational complexity. In order to reduce the computational complexity of the UFMC transmitter as well as reduce the impact on the signal accuracy, we introduce the FIR filter structure and the poly-phase filter structure based on the lightweight method into the UFMC transmitter structure. With this method, the computational complexity of the UFMC transmitter is significantly reduced.

This paper is organized as follows. In Section II, the UFMC system model is formulated. And the lightweight structure is introduced into the UFMC transmitter. The computational complexity is reduced through the FIR filter structure and the poly-phase structure. In Section III, we analyze the computational complexity of the UFMC transmitter proposed above. In section IV, we verify the theoretical analysis through simulation, and the performance of the UFMC system is optimized through the analysis of the filter. In section V, we conclude this paper.

II. SYSTEM MODEL

In this section, the typical UFMC transmitter is depicted. Then the proposed method of reducing complexity is derived.

A. UFMC TRANSCEIVER STRUCTURE

UFMC is a novel type of multicarrier modulation method which maintains the basic structure of OFDM system [9]. The difference between them is that UFMC system performs filtering on groups of subcarriers instead of filtering the entire band like OFDM system. In addition, the UFMC structure superimposes the subband signals to obtain the final transmitted signal instead of adding the cyclic prefix (CP), which improves the spectrum utilization. UFMC uses the zero prefix (ZP) and it is not compatible with 4G and 5G. Therefore the ZP is essential for the reconstruction in the receiver and the transmitter filter response has to be known. And the subband signals that are filtered independently increases the flexibility of the communication system, which can perform different operations processing according to the service requirements.

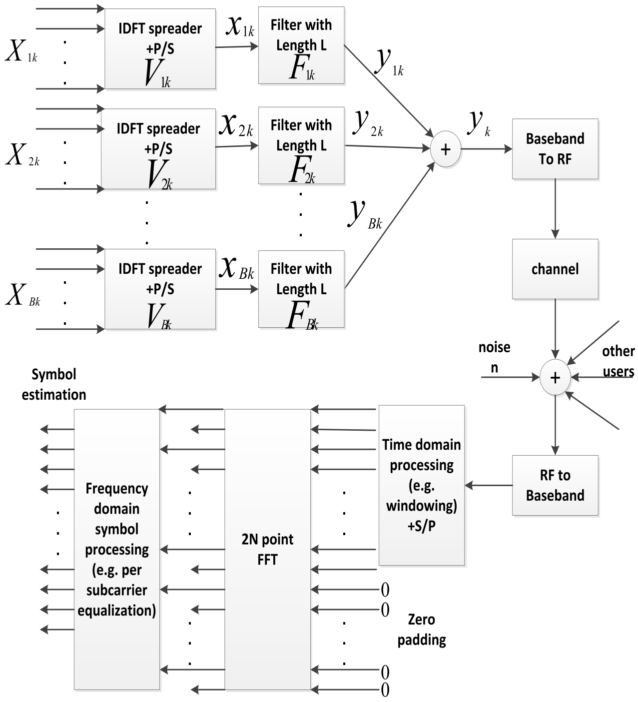

FIGURE 1. Generic UFMC transceiver.

Fig. 1 depicts the generic UFMC transceiver. The time-domain transmission signal of user k is the superposition of the subband filtered signals. While the filter length is L and the FFT length is N, the transmitted signal of the UFMC symbol can be represented in matrix-vector form as

$$\underset{[(\mathrm{N}+\mathrm{L}-1)\times 1]}{y_k} = \sum_{i=1}^{B} \underset{[(\mathrm{N}+\mathrm{L}-1)\times N]}{F_{ik}} \cdot \underset{N\times Q}{V_{ik}} \cdot \underset{[Q\times 1]}{X_{ik}} \tag{1}$$

where X_{ik} is the baseband data symbols, which is to be sent on the i-th subband ($1 \leq i \leq B$). V_{ik} denotes the matrix of N-point Inverse Discrete Fourier Transform (IDFT) containing the relevant columns of the inverse Fourier matrix. F_{ik} is the Toeplitz matrix, which is consist of the FIR filter impulse response of length L, accomplishing the linear convolution operation [5].

The signals from the subband filters are summed up together, and then the total signal is transformed to the radio frequency (RF) and then transmitted to the channel. At the receiver, the received RF signal is transformed to the baseband. Then the baseband signal is further processed in the time domain, which contains the windowing and zero-padding. After performing FFT operation, the frequency domain symbol processing includes the symbol estimation and subcarrier equalization, which is similar to OFDM system.

B. PROPOSED UFMC SIMPLIFICATION BASED ON LIGHTWEIGHT STRUCTURE

UFMC combines the simplicity of OFDM with the flexibility of FBMC. However, UFMC comes together with an increase

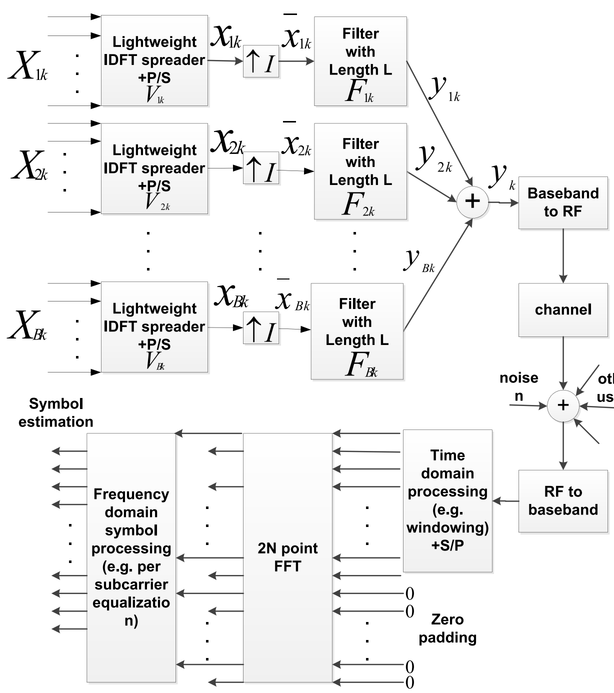

FIGURE 2. UFMC transceiver based on lightweight structure.

in the implementation complexity compared with OFDM. The implementation of filters and the application of N-point FFTs for subbands leads to high computational complexity, whereas it is performed the $2N$-point FFTs at the receiver [7].

Then the low complexity solutions must be found. The lightweight structure is described and applied to the existing implementation method for UFMC transmitter to reduce the computational complexity. It replaces the traditional N-point IFFT with a lightweight IFFT, which reduces the computational complexity of the UFMC transmitter by reducing the number of IFFT points [6]. UFMC transceiver based on the lightweight structure is illustrated by Fig. 2.

First, a lightweight IFFT operation is used to replace the N-point IFFT operation [10]. The computational complexity is reduced by reducing the number of IFFT calculation points. The number of the lightweight IFFT calculation points can be written as follows:

$$q = 2^{\log_2 Q} \tag{2}$$

where Q is the number of subcarriers of the subband, which is the width of the subband. For simplicity, in this paper we constrain Q to an integer power of two. When Q is not an integer power of two, Q is zero-padded to satisfy the condition of an integer power of two.

After lightweight processing, the output signal is interpolated by factor I which is given by

$$I = \frac{N}{q} \tag{3}$$

Besides the lightweight processing, the rest of the structure is basically the same as the above UFMC structure.

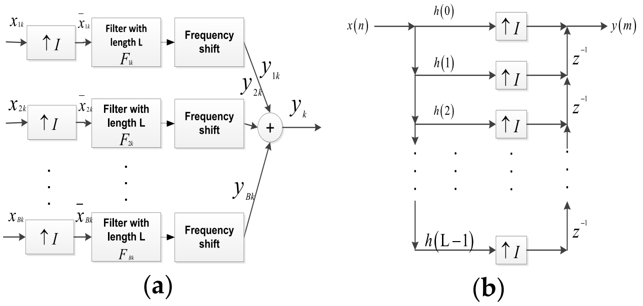

FIGURE 3. Optimization of interpolation filtering structure: (a) Inter-polation filtering structure; (b) Efficient FIR filter structure based on integer factor I interpolation system.

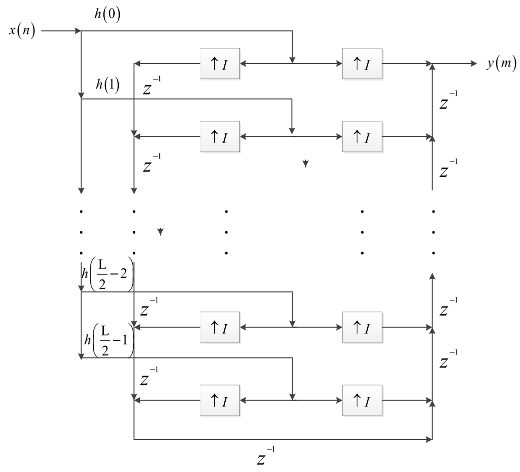

FIGURE 4. Efficient interpolation structure using linear phase FIR filter.

C. OPTIMIZATION BASED ON THE FIR FILTER SRUCTURE

After the interpolation process by factor I, the interpolation structure and the FIR filter exactly constitute the FIR filter structure of factor I interpolation system, as shown in Fig. 3a.

Interpolation by factor I will cause a mirror image of the original input signal spectrum, but it will not cause loss of signal information [11]. Therefore, the FIR filter structure based on factor I interpolation will reduce the computational complexity of the transmitter while ensuring signal information which is an efficient structure. It is illustrated by Fig. 3b.

Considering the linear phase FIR filter, the computational complexity can be further reduced according to the symmetry of $h(n)$. The efficient structure is shown in Fig. 4.

Finally, the signals obtained after the above processing are added together to form final UFMC transmitted signal.

D. OPTIMIZATION BASED ON THE POLY-PHASE FILTER STRUCTURE

The efficient FIR filter structure of the interpolation system according to the factor I can be implemented with a set of shorter poly-phase filter banks [12]. Assuming that the length of the FIR filter is L $(L = QI)$, the poly-phase filter bank is composed of I shorter filters of length Q $(Q = L/I)$.

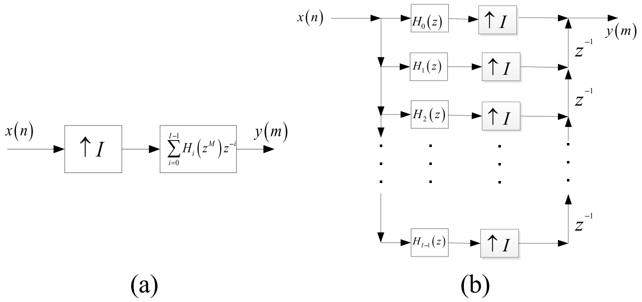

FIGURE 5. **Optimization of the structure: (a) Interpolation filtering structure; (b) Poly-phase filter structure.**

We perform poly-phase decomposition on filter $H(z)$ corresponding to the interpolator and is given by

$$\begin{aligned} H(z) &= \sum_{n=-\infty}^{\infty} h(n)z^{-n} = \sum_{i=0}^{I-1}\sum_{k=-\infty}^{\infty} h(kI+i)z^{-kI}z^{-i} \\ &= \sum_{i=0}^{I-1} H_i(z^I)z^{-i} \end{aligned} \tag{4}$$

$$H_i(z) = \sum_{k=-\infty}^{\infty} h(kI+i)z^{-k} \tag{5}$$

Therefore, we cascade the interpolator and the filter to get the following poly-phase decomposition in Fig. 5.

This method using the poly-phase filter structure can significantly reduce the complexity of the interpolation filter structure, thereby reducing the computational complexity of UFMC transmitters, which is an efficient implementation structure of the UFMC transmitter.

III. COMPLEXITY ANALYSIS

In this section we compare the computational complexity of the traditional OFDM transmitter, traditional UFMC transmitter, UFMC transmitter based on the poly-phase filter structure, UFMC transmitter based on the FIR filter structure and UFMC transmitter based on the linear phase FIR filter structure.

For the UFMC transmitter structure, the computational complexity of multiplication is much higher than that of addition. Therefore, we more focus on the number of required multiplication operations compared with addition operations. The well-known theoretical method is [13], which forms the basis of the complexity analysis. And the calculation complexity of N-point IFFT can be expressed as:

$$\begin{aligned} C_M(N) &= \frac{34}{9}N\log_2 N - \frac{124}{27}N - 2\log_2 N \\ &\quad -\frac{2}{9}(-1)^{\log_2 N}\log_2 N + \frac{16}{27}(-1)^{\log_2 N} + 8 \end{aligned} \tag{6}$$

$$M = \log_2 N \tag{7}$$

Then we make quantitative analysis for the present proposal structures.

A. COMPUTATIONAL COMPLEXITY OF THE TRADITIONAL OFDM TRANSMITTER

For the traditional OFDM transmitter, based on an N-point FFT operation, the computational complexity is simply given by

$$\begin{aligned} C_{\text{CP-OFDM}} &= C_M(\text{N}) \\ &= \frac{34}{9}N\log_2 N - \frac{124}{27}N - 2\log_2 N \\ &\quad -\frac{2}{9}(-1)^{\log_2 N}\log_2 N + \frac{16}{27}(-1)^{\log_2 N} + 8 \end{aligned} \tag{8}$$

B. COMPUTATIONAL COMPLEXITY OF THE TRADITIONAL UFMC TRADITIONAL

Assuming that N is the total number of subcarriers in the system, the entire band consisting of N subcarriers is divided into B subbands, where each subband can be allocated with Q consecutive subcarriers. From the above analysis, it can be seen that the computational complexity of the traditional UFMC transmitter can be divided into two parts: one is the B IFFTs of size N, and the other is the B linear convolution operations that the length of the two input sequences is N and L, respectively.

The computational complexity of the B IFFTs of size N is:

$$\begin{aligned} C_1 &= B\cdot C_M(N) \\ &= B\cdot\left(\frac{34}{9}N\log_2 N - \frac{124}{27}N - 2\log_2 N\right. \\ &\quad \left.-\frac{2}{9}(-1)^{\log_2 N}\log_2 N + \frac{16}{27}(-1)^{\log_2 N} + 8\right) \end{aligned} \tag{9}$$

While four complex multiplications and two real additions are needed to complete a complex multiplication, the computational complexity of the B linear convolution operations with the input sequence lengths of N and L without considering the effect of real addition on the computational complexity is:

$$C_2 = 4\cdot B\cdot N\cdot L \tag{10}$$

The overall computational complexity of the traditional UFMC transmitter is given by

$$\begin{aligned} C_{\text{UFMC}} &= C_1 + C_2 \\ &= B\cdot\left(\frac{34}{9}N\log_2 N - \frac{124}{27}N\right. \\ &\quad -2\log_2 N - \frac{2}{9}(-1)^{\log_2 N}\log_2 N \\ &\quad \left.+\frac{16}{27}(-1)^{\log_2 N} + 8 + 4NL\right) \end{aligned} \tag{11}$$

As previously showed, the computational complexity of the traditional UFMC transmitter is related to the total number of subcarriers N and the filter length L which has nothing to do with the subband width Q. Therefore, the UFMC transmitter has a high computational complexity as the value of N is much larger than Q.

C. COMPUTATIONAL COMPLEXITY OF THE UFMC TRANSMITTER BASED ON THE FIR FILTER STRUCTURE

Assuming each subband can be allocated with Q consecutive subcarriers which also denote the number of lightweight IFFT points. For the interpolator does not increase addition or multiplication, we do not consider the real number addition when calculating computational complexity. From the above analysis, it can be seen that the computational complexity of the UFMC transmitter based on the lightweight IFFT can be divided into three parts: one is the B lightweight IFFT operations of length Q, and the other is the B interpolation sequences with low pass FIR filters of length L, and the third is the frequency shift operations on the time domain signals of B subbands.

The computational complexity of the B lightweight IFFTs of size Q is:

$$\begin{aligned} C_1 &= B \cdot C_M(Q) \\ &= B \cdot \left(\frac{34}{9} Q \log_2 Q - \frac{124}{27} Q - 2 \log_2 Q \right. \\ &\quad \left. - \frac{2}{9} (-1)^{\log_2 Q} \log_2 Q + \frac{16}{27} (-1)^{\log_2 Q} + 8 \right) \quad (12) \\ M' &= \log_2 Q \quad (13) \end{aligned}$$

The computational complexity of the B FIR filters of length L is:

$$C_2 = 4 \cdot B \cdot Q \cdot L \quad (14)$$

Similarly, the computational complexity of the B linear phase FIR filters of length L is:

$$C_2' = 2 \cdot B \cdot Q \cdot L \quad (15)$$

The frequency shifting computational complexity of the B subbands time domain signals is:

$$C_3 = 4 \cdot B \cdot (N + L - 1) \quad (16)$$

where $(N + L - 1)$ is the length of the time domain signals. All operations for UFMC sum up into

$$\begin{aligned} C_{\text{FIR\_UFMC}} &= C_1 + C_2 + C_3 \\ &= B \cdot \left(\frac{34}{9} Q \log_2 Q - \frac{124}{27} Q - 2 \log_2 Q \right. \\ &\quad - \frac{2}{9} (-1)^{\log_2 Q} \log_2 Q + 8 + 4QL \\ &\quad \left. + \frac{16}{27} (-1)^{\log_2 Q} + 4\,(N + L - 1) \right) \quad (17) \\ C_{\text{LPFIR\_UFMC}} &= C_1 + C_2' + C_3 \\ &= B \cdot \left(\frac{34}{9} Q \log_2 Q - \frac{124}{27} Q - 2 \log_2 Q \right. \\ &\quad - \frac{2}{9} (-1)^{\log_2 Q} \log_2 Q + 8 + 2QL \\ &\quad \left. + \frac{16}{27} (-1)^{\log_2 Q} + 4\,(N + L - 1) \right) \quad (18) \end{aligned}$$

where $C_{\text{FIR\_UFMC}}$ represents the computational complexity of UFMC transmitter based on the FIR filter structure, and $C_{\text{LPFIR\_UFMC}}$ represents the computational complexity of UFMC transmitter based on the linear phase FIR filter structure.

As can be seen from the above formula, the computational complexity of the UFMC transmitter based on the lightweight IFFT is significantly lower than that of the traditional UFMC transmitter. And it can be further reduced based on the FIR filter structure.

D. COMPUTATIONAL COMPLEXITY OF THE UFMC TRANSMITTER BASED ON THE POLY-PHASE FILTER STRUCTURE

The computational complexity of the B lightweight IFFT operations of length Q is:

$$\begin{aligned} C_1 &= B \cdot C_M(Q) \\ &= B \cdot \left(\frac{34}{9} Q \log_2 Q - \frac{124}{27} Q - 2 \log_2 Q \right. \\ &\quad \left. - \frac{2}{9} (-1)^{\log_2 Q} \log_2 Q + \frac{16}{27} (-1)^{\log_2 Q} + 8 \right) \quad (19) \end{aligned}$$

The computational complexity of the B poly-phase filter structures is:

$$\begin{aligned} C_2 &= 4BQ \sum_{i=0}^{M-1} \left\lceil \frac{L - i}{M} \right\rceil \quad (20) \\ M &= \frac{N}{Q} \quad (21) \end{aligned}$$

The frequency shift computational complexity of the B subbands time-domain signals is:

$$C_3 = 4 \cdot B \cdot (N + L - 1) \quad (22)$$

The analysis shows that the computational complexity of the UFMC transmitter based on the poly-phase filter structure is:

$$\begin{aligned} C_{\text{Polyphase\_UFMC}} &= C_1 + C_2 + C_3 \\ &= B \cdot \left(\frac{34}{9} Q \log_2 Q - \frac{124}{27} Q - 2 \log_2 Q \right. \\ &\quad - \frac{2}{9} (-1)^{\log_2 Q} \log_2 Q + \frac{16}{27} (-1)^{\log_2 Q} + 8 \\ &\quad \left. + 4Q \sum_{i=0}^{M-1} \left\lceil \frac{L - i}{M} \right\rceil + 4\,(N + L - 1) \right) \quad (23) \end{aligned}$$

The above section is a quantitative analysis of the computational complexity of different transmitter structures. In the next section, we will make a simulation analysis of the above theoretical derivation.

IV. NUMERICAL ANALYSIS

In this section, the computational complexity of the proposed schemes is numerically analyzed. Furthermore, in order to improve system performance, we quantitatively analyze the power spectral density.

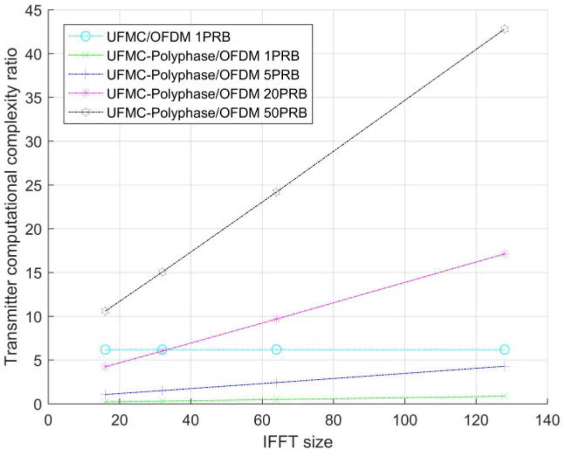

FIGURE 6. **Computational complexity of UFMC transmitter based on the poly-phase filter structure.**

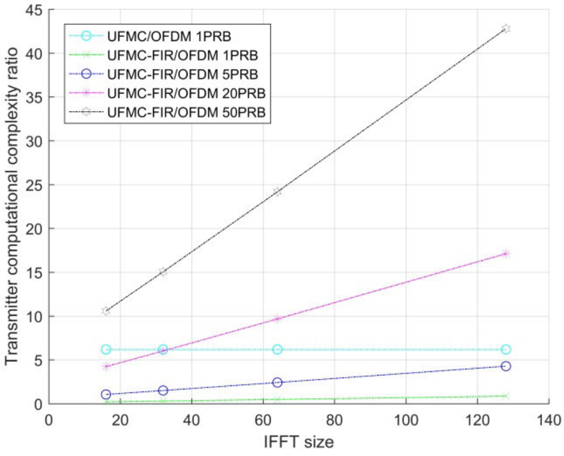

FIGURE 7. **Computational complexity of UFMC transmitter based on the FIR filter structure.**

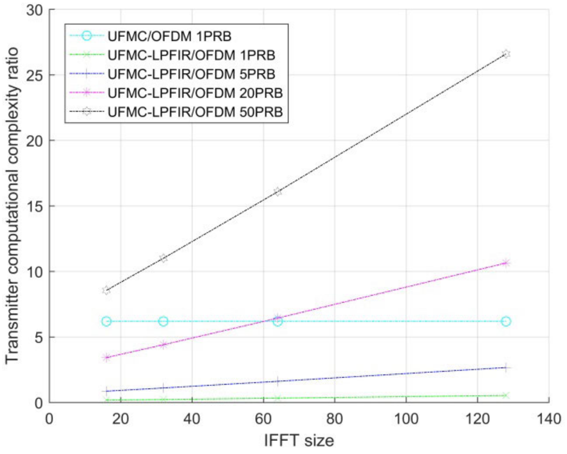

FIGURE 8. **Computational complexity of UFMC transmitter based on the linear phase FIR filter structure.**

A. COMPUTATIONAL COMPLEXITY ANALYSIS

For all the results in this part, the system simulation parameters in this comparison are: $N = 1024$, $Q = 16$, $L = 43$, $B = 1, 5, 20, 50$ respectively. Note that the overhead of the multiplication operation in the actual transmitter structure is much higher than the addition operation. Therefore, we focus on the impact of the multiplication operation on the complexity of the transmitter structure.

Fig. 6 shows the complexity of the traditional OFDM transmitter, the traditional UFMC transmitter and the UFMC transmitter based on the poly-phase filter structure. The traditional OFDM transmitter complexity is independent of the allocation size, while the computational complexity of the traditional UFMC transmitter is closely related to the number of subbands. The traditional UFMC transmitter for an allocation of one subband has about factor 6 higher complexity compared with the traditional OFDM transmitter, while the actual number of subbands of the UFMC transmitter is much greater than 1, which results in the UFMC transmitter with a complexity of several hundred times that of the OFDM transmitter. The UFMC transmitter based on the poly-phase filter structure can greatly reduce the complexity of the system. It scales linear with the number of subbands B. When $B = 50$, the computational complexity of the UFMC transmitter based on the poly-phase filter structure is 10.57 times that of the traditional OFDM transmitter. While this value is growing with the number of subbands, the computational complexity of the proposed method is much lower than the exact method, as the signal is constructed by the lightweight IFFT rather than the initial size.

Fig. 7 shows the complexity of the traditional OFDM transmitter, the traditional UFMC transmitter and the UFMC transmitter based on the FIR filter structure. Similarly, the UFMC transmitter based on the FIR filter structure greatly reduces the computational complexity of the transmitter. When the number of allocated subbands $B = 20$, the computational complexity of the filter-structured UFMC transmitter is approximately 4.23 times that of the traditional OFDM transmitter, which computational complexity is on the same order of magnitude.

Fig. 8 shows the complexity of the traditional OFDM transmitter, the traditional UFMC transmitter and the UFMC transmitter based on linear phase FIR filter structure. Compared with the previous UFMC transmitter based on the poly-phase structure and the UFMC transmitter based on the FIR filter structure, the computational complexity of the UFMC transmitter based on the high-efficiency FIR filter structure is further reduced. When $B = 50$, the present proposal would result in UFMC multi-carrier modulator complexity of about 8.55 times the traditional OFDM transmitter complexity, which allows further potential complexity reductions, making UFMC transmitters almost as simple as OFDM transmitters.

B. POWER SPECTRAL DENSITY ANALYSIS

In this part, the power spectral density (PSD) of the UFMC transmitter proposed above is numerically analyzed. The system simulation parameters in this comparison are: $N = 1024$,

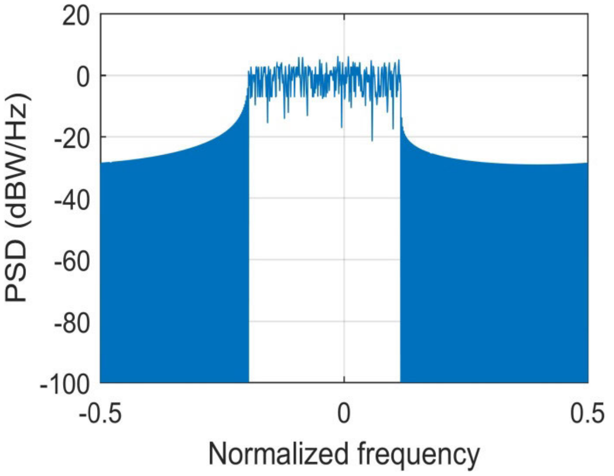

FIGURE 9. Power spectral density of OFDM.

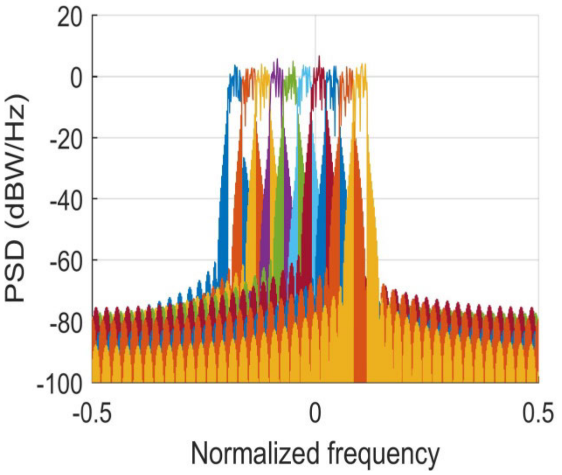

FIGURE 10. Power spectral density of UFMC.

$B = 10$, $Q = 16$, $L = 43$. Then, we consider the effect of side lobes attenuation on the power spectral density of the proposed UFMC transmitters.

Fig. 9 shows power spectral density of the traditional OFDM transmitter.

Fig. 10 shows power spectral density of the traditional UFMC transmitter using subband filters with side lobe attenuation of 40dB. The UFMC side lode is much lower than that of OFDM. Therefore, UFMC is more resistant to interferences between subcarriers arising from the frequency shift in the channel. The UFMC side lobe is an essential criterion for the system. The traditional UFMC transmitter can effectively suppress OOB emission compared to the traditional OFDM transmitter, while its computational complexity is far higher. The UFMC transmitter based on the FIR filter structure not only reduce the computational complexity, but also reduce the impact of OOB.

Fig. 11, Fig. 12, and Fig. 13 shows the power spectral density of the proposed structure that the side lobe attenuation of the Chebyshev filter is 40dB, 60dB, and 80dB respectively. As shown in the figure, we find that changing the side lobe attenuation of the filter can effectively improve the proposed UFMC transmitter structure.

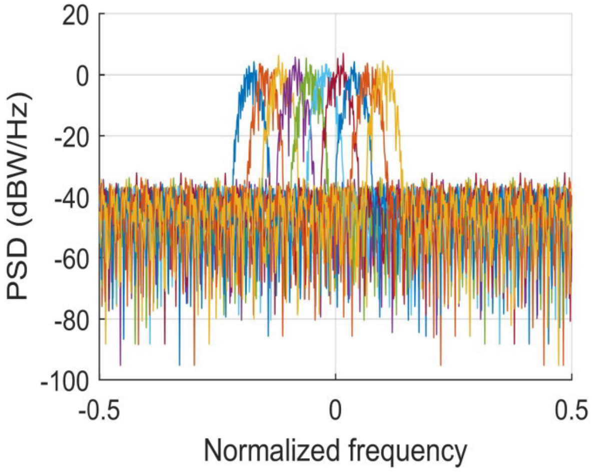

FIGURE 11. Power spectral density of the proposed structure with 40dB side lobe attenuation.

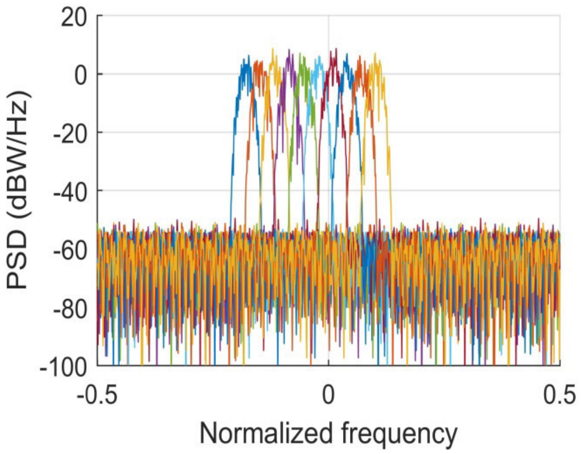

FIGURE 12. Power spectral density of the proposed structure with 60dB side lobe attenuation.

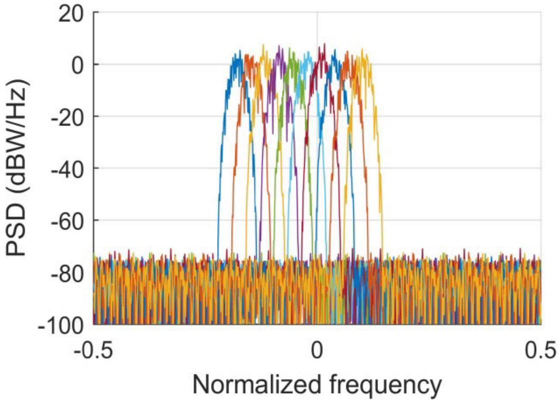

FIGURE 13. Power spectral density of the proposed structure with 80dB side lobe attenuation.

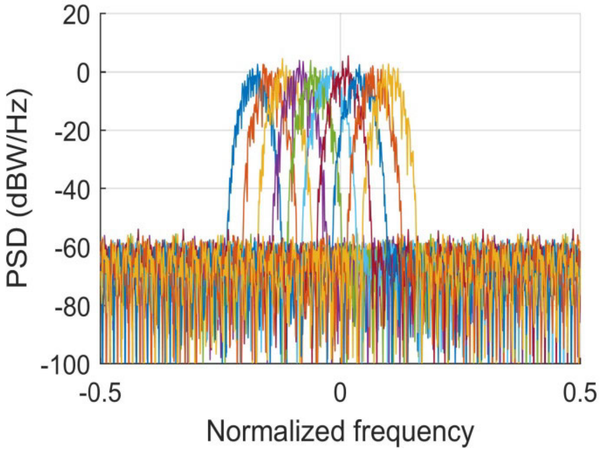

FIGURE 14. Power spectral density of the proposed structure with the filter length L = 43.

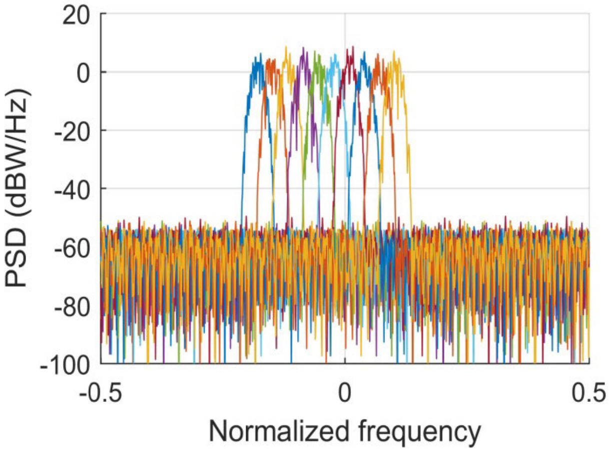

FIGURE 15. Power spectral density of the proposed structure with the filter length L = 73.

It can be seen that as the side lobe attenuation of the filter increases, the out-of-band emission of the transmitter is effectively suppressed, so we can improve the performance of the transmitter by appropriately increasing the filter side lobe attenuation.

In addition, the length of the filter can also affect the performance of the proposed UFMC transmitter, as shown in the Fig. 14 and Fig. 15. When the side lobe attenuation of the Chebyshev filter is 60dB and the filter length is $L = 43$, 73 respectively, the power spectral density of the transmitter is obtained by simulation. By comparing the power spectral density at different lengths, the power spectrum density of each subband is better when the filter length $L = 73$, which is very important for accurate transmission of the useful communication signals.

In summary, the proposed UFMC transmitter structure can greatly reduce the computational complexity of the system. And we can improve the system performance by adjusting the filter parameters of the transmitter, which also shows the importance of the filter design in the UFMC transmitter. Excellent performance filters can effectively optimize the transmitter structure.

V. CONCLUSION

UFMC is a generalization of F-OFDM and FBMC modulations technique. At the cost of increasing complexity of the transmitter and equalizer, it obtains good performance of the system under quasi-synchronization. Reducing the complexity of the UFMC transmitter is critical to the implement of the UFMC structure. We introduce lightweight IFFT into the UFMC transmitter, combining the FIR filter structure and the poly-phase filter structure to further reduce the computational complexity of the UFMC transmitter. With the proposed methods, the UFMC transmitter computational complexity is similar to OFDM. The proposed approach is more than one order of magnitude less complex than the traditional UFMC transmitters. At the same time, the system performance can be improved by adjusting the system filter, while the setting of the filter parameters has a certain effect on the system performance. Power spectral density is an important measure of UFMC system performance. By adjusting the FIR filter structure, we can get a better power spectral density compared with the unused. Finally, future work should consider optimizing the filter design and the multi-level of the FIR filter structure. Besides, the complexity reduction of UFMC transceiver have a great impact on the system speed, future work should also consider the hardware implementation complexity of the proposed approach.

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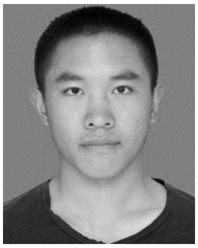

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