A Novel Modulation and Multiplexing Technology for Reducing Out-of-Band Leakage Based on Multicarrier Schemes

XIN YU [ID], **BAO TONG** [ID], **BIAN LUANJIAN** [ID], **YU GUANGHUI** [ID], **AND HU LIUJUN** [ID]
ZTE Corporation, Shenzhen 518000, China

Corresponding author: Bao Tong (bao.tong@zte.com.cn)

ABSTRACT In this paper, a novel modulation and multiplexing technology for reducing out-of-band leakage is proposed for multicarrier schemes based on CP-OFDM. The proposed method is to spread data of N layers with N selected spreading codes, then multiplex them into a data sequence and transmit it on $2K$ subcarriers. The N spreading codes, which can suppress out-of-band leakage, are selected out from a complete set of mutual orthogonal spreading codes. The simulation results show that the data modulation and multiplexing technology effectively reduces interference with neighboring frequency bands or adjacent sub-bands for different numerologies and so significantly improves spectrum efficiency

INDEX TERMS Adjacent sub-bands, CP-OFDM, interference, out-of-band leakage, spreading codes.

I. INTRODUCTION

This Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation technology subdividing the available bandwidth into a multitude of mutual orthogonal narrowband subcarriers. The subcarriers do not interfere with each other and allow for simultaneous transmission of multiple data on multiple orthogonal subcarriers. Simple implementations with inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) can serve digital data modulation and demodulation function among different communication systems based on OFDM. In addition, combined with cyclic prefix (CP), OFDM is robust against the inter-symbol interference (ISI) and the inter-carrier interference (ICI) of multipath interference [1], [2]. OFDM has developed into a popular scheme for wideband digital communication and is reviewed as an important technology in the fourth-generation (4G) and the fifth generation (5G) wireless communication networks [3].

However, the performance of CP-OFDM system is sensitive to timing offset and frequency offset between the adjacent frequency bands [4]. This is because CP-OFDM suffers from a relative high level of out-of-band (OOB) leakage due to the large sidelobes of the OFDM subcarriers which may result a strong interference into the neighboring frequency bands[5]. The digital communication systems often call for

The associate editor coordinating the review of this manuscript and approving it for publication was Qilian Liang [ID].

a wide guard interval to reduce the impact of OOB leakage on the neighboring frequency bands but sacrificing the edge resources of transmission bands and so lowering the frequency efficiency. In addition, New Radio (NR) technology being developed as a 5G technology solution supports different subcarrier spacing values between the adjacent sub-bands within the whole transmission bandwidth [6], [7]. It means that the adjacent sub-bands have different numerologies. As a result, the existing OOB leakage of the adjacent sub-bands will lead to a stronger interference with each other [8].

Various new waveform schemes for reducing OOB leakage had been proposed just before 5G standards of R15 version were set. These new schemes include filter bank multicarrier-offset quadrature amplitude modulation (FBMC-OQAM), filter bank OFDM (FB-OFDM), universal filtered multicarrier (UFMC), filtered OFDM (F-OFDM), generalized frequency division multiplexing (GFDM) and so on [9]–[15].

Compared with CP-OFDM, these new waveform schemes have a good performance on suppressing OOB leakage, however, also have some obvious disadvantages. For example, almost all of them have complex transmitter and receiver design due to windowing or filtering process. Meanwhile, FBMC-OQAM has the real modulation feature which brings up the complex channel estimation, so it is not suitable for the multiple input multiple output (MIMO) systems [16]. FB-OFDM has slightly ICI caused by large multipath delay propagation [17], [18]. F-OFDM and UFMC require the

filter parameters change for different sub-band bandwidth, which causes complex management of the filter parameters [19], [20]. Moreover, error vector magnitude(EVM) of the sub-band edge is also worse than the mean EVM of the whole sub-band when applying filtering in F-OFDM and UFMC schemes. GFDM needs the interference cancellation processing due to the orthogonality conditions relaxation [21] which leads to a more complicated receiver. In a word, these new waveform candidates reduce OOB leakage but at a price.

Now 5G standards of R15 version still use CP-OFDM scheme for eMBB (Enhanced Mobile Broadband) scenario. According to the formula of OFDM baseband signals generation in 5G standard protocol, the time domain signals of every OFDM symbol are implicitly multiplied by a rectangular window to avoid ISI of adjacent OFDM symbols [22]. In order to reduce OOB leakage, the raised cosine pulse can be used in implementation instead of the rectangular pulse, which means windowing used to OFDM symbols [23]. However, windowing will decrease the effective length of CP which means the resistance to multipath delay is degraded, and the reduction of OOB leakage is also not enough which means some guard subcarriers are still needed between the adjacent sub-bands. For eMBB scenario where the channel bandwidth is wide, the waste of these guard subcarriers can be tolerated. But for mMTC (massive Machine Type of Communication) scenario where the channel bandwidth is narrow, the waste will not be tolerated. Moreover, many discrete narrow spectrum subbands may will be allocated for mMTC services due to scarce spectrum resource in the range of low frequency, these guard subcarriers will occupy the high proportion of these subbands, so the waste will not be tolerated more. The subsequent version of 5G standards will research on the mMTC scenario where the method of OOB leakage reduction is one of important research contents [24].

In this paper, the spreading codes are utilized to the CP-OFDM scheme to reduce OOB leakage and not to bring up the aforementioned problems. A set of spreading codes which can cancel out the sidelobe amplitude between subcarriers were selected out and utilized on the edge physical resource blocks (PRBs) of transmission bandwidth or the whole sub-bands. Multiple layers of the data can be multiplexed through the orthogonal spreading codes to improve the spectrum efficiency. Meanwhile, the additional complexities of the spreading operation in the transmitter and the despreading operation in the receiver are negligible.

The rest of the paper is organized as follows. In Section II, we formulate the Max-Min problems of the OOB power leakage sum between two subcarriers and analyse the solutions of equations. In Section III, we introduce the principle of spreading codes design and give a description of multiple layers data multiplexed through the orthogonal multiplexing method. In Section IV, the interference analysis of adjacent sub-bands for different numerologies and simulation results are provided. In Section V, we give the conclusions.

II. THE MODEL OF OOB POWER LEAKAGE SUM

As mentioned above, according to the formula of OFDM baseband signals generation in 5G standard protocol, the time domain signals of every OFDM symbol are multiplied with a rectangular window to avoid ISI of adjacent OFDM symbols. And the function $f(t)$ of the rectangular window in time domain can be expressed as follow:

$$f(t) = \begin{cases} 1 & 0 \le t \le T \\ 0 & \text{other} \end{cases} \quad (1)$$

where T is the width of rectangular window and is also the total duration of one OFDM symbol added with CP.

The spectral function $F(w)$ of the rectangular window in frequency domain can be expressed as follow:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t) e^{-j\omega t} dt = e^{-j\frac{\omega T}{2}} T \text{Sa}\left(\frac{\omega T}{2}\right) \quad (2)$$

where $\text{Sa}(x)$ is defined as $\text{Sa}(x) = \sin(x)/x$.

Accordingly, the spectrum of one OFDM symbol can be obtained by convoluting the signals of all subcarriers in the OFDM symbol with the Eq.(2). Let T_{sym} denotes the effective OFDM symbol duration and T_{cp} denotes the length of the CP. The total duration of one OFDM symbol is $T = T_{\text{sym}} + T_{\text{cp}}$ and the subcarrier spacing is $2\pi/T_{\text{sym}}$. The Fig.1 (a) and (b) respectively show the amplitudes and phases of the spectrum of six continuous subcarriers assuming they carry the same data of 1. Set the horizontal coordinates as angular frequency w of the first subcarrier and use it as the baseline to plot the six subcarriers numbered by subcarrier 1, subcarrier 2, ..., subcarrier 6. We can see that these curves of spectrum have the offset by $2(s\text{-}1)\pi/T_{\text{sym}}$ which is more than $2(s\text{-}1)\pi/T$, where s represents the serial number of the above six subcarriers. When s is bigger, the deviation between $2(s\text{-}1)\pi/T_{\text{sym}}$ and $2(s\text{-}1)\pi/T$ is bigger. According to Fig.1 (b), we think the deviation respectively for $s = 1$ and $s = 2$ is relatively smaller, so we think that the spectral phase variations of subcarrier 2 and subcarrier 3 in out of the range of the continuous six subcarriers are almost the same as that of subcarrier 1. It means, if subcarrier 1 and subcarrier 2 carry the inverse data, the OOB leakage of the two subcarriers will almost be canceled out. In a similar way, if subcarrier 1 and subcarrier 3 carry the inverse data, the OOB leakage of the two subcarriers will also be canceled mostly. However, if subcarrier 1 and the other subcarrier ($s > 2$) carry the inverse data, the OOB leakage of the two subcarrier will be canceled less because the deviation for $s > 2$ is relatively bigger. Moreover, the two subcarriers ($s > 2$) will undergo different channel coefficients in fading channel which will also impact on the cancellation of the OOB leakage at the receiver of different numerology sub-bands. So we will only analyse the two cases of subcarrier 1 vs. subcarrier 2 and subcarrier 1 vs. subcarrier 3 in the following part of this paper. In the following part of this section we will formulate and analyse the sidelobe characteristics of the two subcarriers including subcarrier 1 and 2 or subcarrier 1 and 3 which
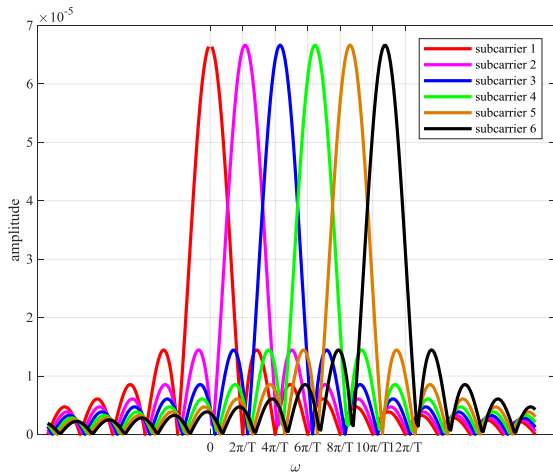
(a) the amplitudes of spectrum
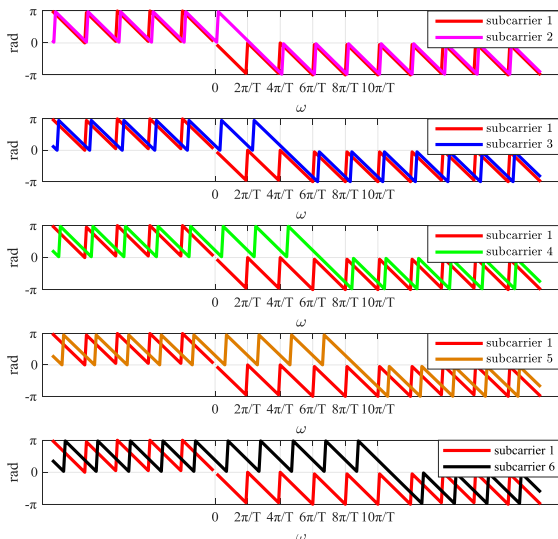
(b) the phases of spectrum

FIGURE 1. Spectrum schematic diagram of six continuous subcarriers.

means the adjacent subcarriers or the spaced subcarriers by one.

For simplicity, assuming that the datum carried on the subcarrier 1 is 1 and the datum carried on another subcarrier has the same power but different phase θ. So a spectrum model of the two subcarriers is constructed as follow:

$$G(\omega, \theta) = F(\omega) + e^{j\theta} F\left(\omega - p\frac{2\pi}{T_{\text{sym}}}\right) \quad (3)$$

where $p = 1$ is for subcarrier 2 and $p = 2$ for subcarrier 3 respectively.

The range of OOB leakage can be assumed reasonably to be $[2(n + p)\pi/T_{\text{sym}}, +\infty)$, where n is the positive integer. So the sum of OOB power leakage in this range can be

described as follow

$$W(\theta) = \int_{\frac{2(n+p)\pi}{T_{\text{sym}}}}^{+\infty} G^*(\omega, \theta) G(\omega, \theta) d\omega \quad (4)$$

where the $G^*(w + \theta)$ is the conjugate of $G(w + \theta)$. The equation (4) shows that the sum of OOB power leakage is the function of independent variable θ. We will search the appropriate different phase values θ to make $W(\theta)$ of the Eq.(4) minimum or maximum. Take the derivative formula of phase of equation (4) as follow:

$$\frac{dW(\theta)}{d\theta} = \frac{d\int_{\frac{2(n+p)\pi}{T_{\text{sym}}}}^{+\infty} G^*(\omega, \theta) G(\omega, \theta) d\omega}{d\theta}$$
$$= j\left(e^{j\theta} - e^{-j\theta} e^{jp\frac{2\pi T}{T_{\text{sym}}}}\right) A \quad (5)$$

where d()/dθ denotes taking the derivative formula of independent variable θ and A is a constant without independent variable θ.

Supposing that the equation (5) is equal to 0, we can get the phase value below.

$$\theta = p\pi T/T_{\text{sym}} \approx p\pi \text{ or } \theta = p\pi T/T_{\text{sym}} - \pi \approx p\pi - \pi \quad (6)$$

Because of $p = 1$ or 2 and equivalent to 0 in terms of phase value, it can be obtained that the equation (5) is equal to 0 when $\theta \approx 0$ or π. It means, the $W(\theta)$ has the maximum when the phase θ is approximately equal to 0 and has the minimum when the phase θ is approximately equal to π. For simplicity, it can mean that the OOB power leakage sum is the maximum when the two subcarriers have the same phase and the OOB power leakage sum is the minimum when the two subcarriers have the inverse phase.

In the next section, based on the above analysis and theoretical derivation, we will consider designing a kind of spreading codes for OFDM systems to suppress OOB leakage. The kind of spreading codes includes 2 or 4 elements and has at least two elements with inverse phase.

III. DESIGNED SPREADING CODES AND PROPOSED ORTHOGONAL MULTIPLEXING METHOD

In this section, we introduce the design of spreading codes and the method of multiple layers of data multiplexing. The spreading code is used on one layer of data transmission. A group of mutual orthogonal spreading codes are used on multiple layers of data transmission. We give some simulations to evaluate the effectiveness of reducing OOB leakage.

A. SPREADING CODES

According to the above formulation and analysis of OOB leakage sum, we design a kind of spreading codes, which allows canceling of the sidelobe amplitude between subcarriers in the frequency domain to help reducing OOB leakage. The kind of spreading codes complies with the following characteristics.

1) Each spreading code comprises one or two pairs of elements and each pair have two elements.

2) According to the analysis in previous section, the adjacent subcarriers or the spaced subcarriers by one can cancel mostly the OOB leakage of the each other. We design the two elements in each pair have a π phase difference or corresponding elements between neighboring pairs have a π phase difference.

The Fig.2 gives a detailed description about phase difference between two elements in each pair or between neighboring pairs. For example, the spreading code $[1, -1]$ has a pair with two elements and the two elements in the pair have a π phase difference. The spreading code $[1, -1, -1, 1]$ has two pairs and each pair has two elements. Both of the two elements $[1, -1]$ in the first pair and the two elements $[-1, 1]$ in the second pair have a π phase difference respectively. At the same time, the neighboring pair $[1, -1]$ and $[-1, 1]$ have a π phase difference. In the following part of this section we will introduce how to use the designed spreading codes.
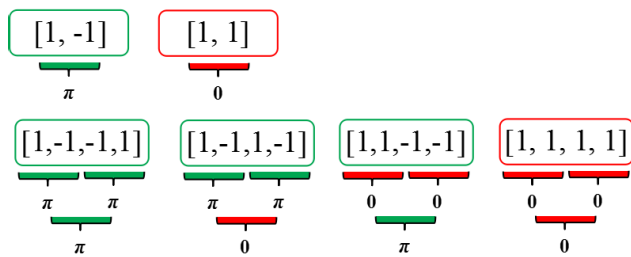

FIGURE 2. The phase difference between two elements in each pair and corresponding elements in neighboring pairs when $K = 1$ and 2.

At the transmitter, M data are spread by a designed spreading code with the length of 2K to obtain M groups of spread data, K = 1 or 2. Each group of spread data has 2K elements and M groups of spread data have M×2K elements. The spread sequence with M groups of spread data is modulated on the edge of the transmission frequency bands in OFDM systems and occupies continuous M×2K subcarriers.

Here is an example to describe that how the M×2K elements occupy the continuous M×2K subcarriers. If M = 2 and the 2 data are D_1 and D_2 respectively, and the selected spreading code is $[1, -1, -1, 1]$, then the 2 groups of spread data are below:

$$D_1 \times [1, -1, -1, 1] \rightarrow [D_1, -D_1, -D_1, D_1]$$
$$D_2 \times [1, -1, -1, 1] \rightarrow [D_2, -D_2, -D_2, D_2] \quad (7)$$

In the Eq.(7), the datum D_1 is spread by the spreading code $[1, -1, -1, 1]$ to obtain the first group of spread data $[D_1, -D_1, -D_1, D_1]$. And the datum D_2 is spread by the spreading code $[1, -1, -1, 1]$ to obtain the second group of spread data $[D_2, -D_2, -D_2, D_2]$. The two groups of spread data have 8 elements $[D_1, -D_1, -D_1, D_1, D_2, -D_2, -D_2, D_2]$ together and occupy the continuous subcarriers from 1 to 8 on the edge of the transmission bandwidth.

To illustrate the effectiveness of the spreading codes suppressing OOB leakage, we compare the power spectrum density (PSD) simulation results of normal OFDM and

TABLE 1. Simulation parameters.

| Parameter	Quantity
Modulation Order	QPSK
Subcarrier Spacing	15 kHz
Symbol Interval	1/14 ms
System Bandwidth	10 MHz
Transmission Bandwidth	9 MHz

spread OFDM. In this paper, the normal OFDM refers to the conventional CP-OFDM without any spread operation and the spread OFDM refers to CP-OFDM utilizing the modulation technology with the spreading codes. In the Fig.3, we select the spreading codes $[1, -1]$ and $[1, -1, -1, 1]$, $[1, -1, 1, -1]$, $[1,1, -1, -1]$ for comparison. The main parameters utilized in the simulation are summarized in the Table 1. The 9MHz transmission bandwidth is divided into 50 resource blocks (RBs) with 12 subcarriers in each RB. Only the data on the two edge RBs (including 24 continuous subcarriers) at the two ends of transmission bandwidth are spread by the spreading codes and the data on the other middle RBs are directly modulated without any spread operation.

The Fig.3 shows that the spreading codes suppress OOB leakage effectively and each spreading code of the three spreading codes with K = 2 has a little of different effectiveness level. The first spreading code $S_1 = [1, -1, -1, 1]$ is the most effective for suppressing the OOB leakage because it satisfies two conditions simultaneously. The two conditions are that two elements in each pair have a π phase difference and corresponding elements between neighboring pairs have also a phase π difference. The second spreading code $S_2 = [1, -1, 1, -1]$ is less effective than S_1 because it only complies with two elements in each pair having a π phase difference but the phase between the neighboring pairs is the same. The third spreading code $S_3 = [1,1, -1, -1]$ is the least effective due to just meeting corresponding elements between neighboring pairs having a π phase difference but the phase within each pair is the same. For the spreading code $[1, -1]$ of K = 1, it is less effective than S_1 and better than S_2 and S_3 because it complies with two elements in each pair having a π phase difference.

For normal OFDM, the system bandwidth and transmission bandwidth are 10 MHz and 9 MHz respectively, so the guard band is 0.5 MHz wide each at the two ends of system bandwidth. The Fig.3 (b) is the enlargement of the left end of system bandwidth. From the Fig.3 (b), we can see that the OOB leakage of spread OFDM using the first spreading code at the frequency point of about -4.7 MHz has dropped to the level of normal OFDM at the frequency point of -5 MHz. So the guard band can be reduced by about 0.3 MHz bandwidth, which means that there are more resources to transmit data and the spectrum efficiency is increased. The added resources of the two ends are 0.6 MHz bandwidth together and are more than 3 RB. However, transmission bandwidth for 10 MHz channel bandwidth is 52 RB in 5G
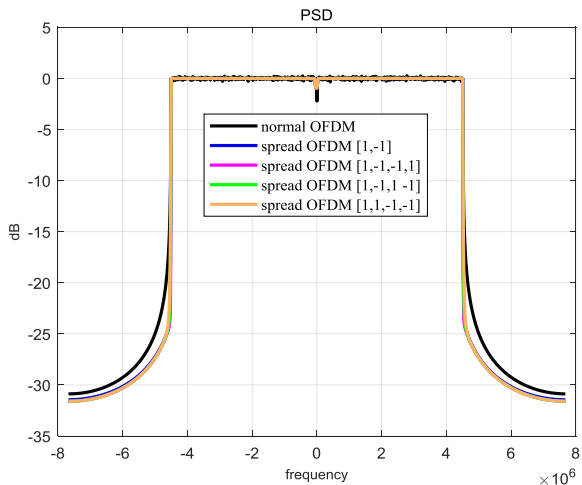
(a) the PSD of the whole system bandwidth
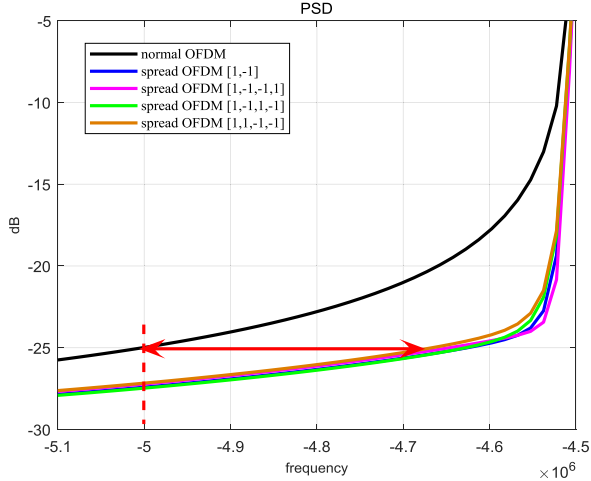
(b) the PSD of the left end of the system bandwidth

FIGURE 3. OOB leakage comparison between normal OFDM and spread OFDM using spreading codes [1, −1], [1, −1, −1, 1], [1, −1, 1, −1], [1,1, −1, −1] phase difference between two elements in each pair and corresponding elements in neighboring pairs when K =1 and 2.

standard protocol[25] and only 2 RB are added compared with 4G system by some implementation methods including using raised cosine pulse instead of rectangular pulse.

For comparison, we also select the rest spreading codes of a complete set of orthogonal spreading codes except those in the Fig.3 for simulation. The PSD simulation results of spread data respectively with the rest spreading codes [1,1] and [1,1,1,1] are showed in the Fig.4. These rest spreading codes do not satisfy either of the above two conditions, so they don't suppress OOB leakage but enhance it.

The size of $M \times 2K$ spread data is $2K$ times of the size of M original data, so the data transmission efficiency is also reduced by $2K$ times if not considering the gained more resources at the edge to transmit data. For example, the spread data using the spreading code [1, −1] will reduce the data transmission efficiency to 50% in the edge RB resource, and the spread data using the spreading code S_1, S_2 or S_3 individually will reduce the data transmission efficiency to 25%
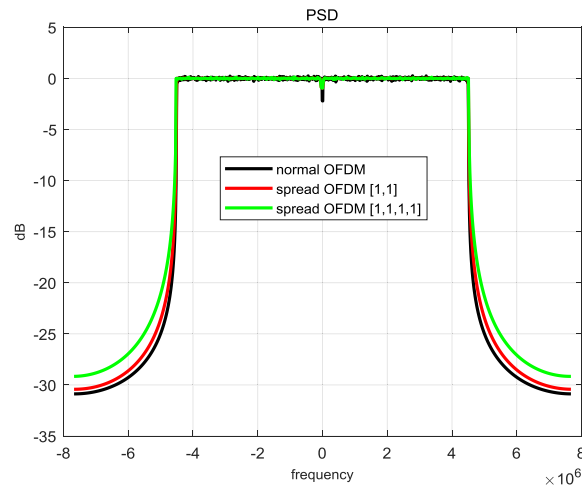

FIGURE 4. OOB leakage comparison between normal OFDM and spread OFDM using spreading codes [1,1], [1,1,1,1].

in the edge RB resource. To improve the data transmission efficiency, we propose the method of multiple layers of data multiplexed by the orthogonal spreading codes. The orthogonal spread data occupy the same time frequency resources to improve spectral efficiency. In the next subsection, we will also discuss the effectiveness of the orthogonal multiplexing method to suppress OOB leakage.

B. A GROUP OF MUTUAL ORTHOGONAL SPREADING CODES

In this subsection, we mainly discuss the method of N layers of data multiplexed by N mutual orthogonal spreading codes and its effectiveness of suppressing OOB leakage. At the transmitter, the data of each layer are spread by one of the mutual orthogonal spreading codes to obtain the spread data of each layer. Then the N layers of spread data are combined into a data sequence together and modulated on continuous $2K$ subcarriers. At the receiver, the data sequence modulated on continuous $2K$ subcarriers multiplies respectively with each spreading code of the mutual orthogonal spreading codes to demodulate each layer of original data. Here is an example to describe that how the N layers of data are multiplexed by the N mutual orthogonal spreading codes and occupy the continuous $2K$ subcarriers at the transmitter.

If $N = 3$ and the data of 3 layers are D_1, D_2 and D_3 respectively, and the 3 mutual orthogonal spreading codes are [1, −1, −1, 1], [1, −1, 1, −1] and [1,1, −1, −1] respectively, then the 3 layers of multiplexed data are below:

$$
\left.
\begin{array}{l}
D_1 \times [1, -1, -1, 1] \rightarrow [D_1, -D_1, -D_1, D_1] \\
D_2 \times [1, -1, 1, -1] \rightarrow [D_2, -D_2, D_2, -D_2] \\
D_3 \times [1, 1, -1, -1] \rightarrow [D_3, D_3, -D_3, -D_3]
\end{array}
\right\} + \Rightarrow \quad (8)
$$

$[D_1 + D_2 + D_3, -D_1 - D_2 + D_3, -D_1 + D_2 - D_3, D_1 - D_2 - D_3]/\sqrt{3}$ In the Eq.(8), the datum D_1 is spread by the first spreading code [1, −1, −1, 1] to obtain the first layer of spread data [D_1, −D_1, −D_1, D_1]. The datum D_2 is spread by

the second spreading code [1, −1, 1, −1] to obtain the second layer of spread data

[D_2, −D_2, D_2, −D_2]. The datum D_3 is spread by the third spreading code [1,1, −1, −1] to obtain the third layer of spread data [D_3, D_3, −D_3, −D_3]. Then these three layers of spread data are multiplexed into a data sequence and their power are normalized to obtain [$D_1 + D_2 + D_3$, −D_1-D_2 + D_3, −D_1+D_2-D_3, D_1-D_2-D_3]/$\sqrt{3}$ and occupy the continuous subcarriers from 1 to 4.

Each spreading code of N mutual orthogonal spreading codes has different effect for suppressing OOB emission, for example, $S_1 > S_2 > S_3$ in the Fig.3. Therefore when transmitting one layer of data, the most effective spreading code, i.e., S_1 is selected to modulate the data suppressing OOB leakage. When transmitting two layers of data, the most and the secondary effective spreading codes, i.e., S_1 and S_2 are selected to modulate the data suppressing OOB leakage. When transmitting three layers of data, all effective spreading codes, i.e., S_1, S_2 and S_3 are selected to modulate data suppressing OOB leakage.

The Fig.5 compares the OOB leakage between the normal OFDM and the spread OFDM using N mutual orthogonal spreading codes, where $N = 1$ 2, 3, 4. The $N = 4$ in the simulation includes the bad spreading code $S_4 = [1,1,1,1]$ and its curve is overlapped with the PSD of the normal OFDM. The simulation assumptions are the same as Table 1.

The Fig.5(b) is the enlargement of the left end of system bandwidth. According to the simulation results, it is obvious that the orthogonal multiplexing method is an effective way to suppress OOB leakage. And the effectiveness of suppressing OOB leakage is adverse to the transmission efficiency of the edge RB resource. When transmitting $N = 1$ layer of data, the system has the best effectiveness of suppressing OOB leakage but with only 25% transmission efficiency. When transmitting $N = 2$ layers of data, the system has the second better effectiveness of suppressing OOB leakage with 50% transmission efficiency. When transmitting $N = 3$ layers of data, the system has the third better effectiveness of suppressing OOB leakage with 75% transmission efficiency.

In practice, we can make a balance between the effectiveness of suppressing OOB leakage and transmission efficiency. For instance, when the scenario has the poor quality of channel and strong mutual interference with neighboring frequency bands, transmitting $N = 1$ layer of data is most desirable. It not only reduces interference at most to the neighboring frequency bands, but also gets the receipt SNR gains about 6 dB by occupying 4 subcarriers per datum which will also resist the interference from the neighboring frequency bands better. When the scenario has the better quality of channel and less mutual interference with neighboring frequency bands, transmitting $N = 3$ layers of data is more appropriate. It not just suppresses the interference to the neighboring frequency bands, but also improves the transmission efficiency.

Furthermore, a set of weighting coefficients can also be used to obtain a weighted sum of the multiple layers of data.
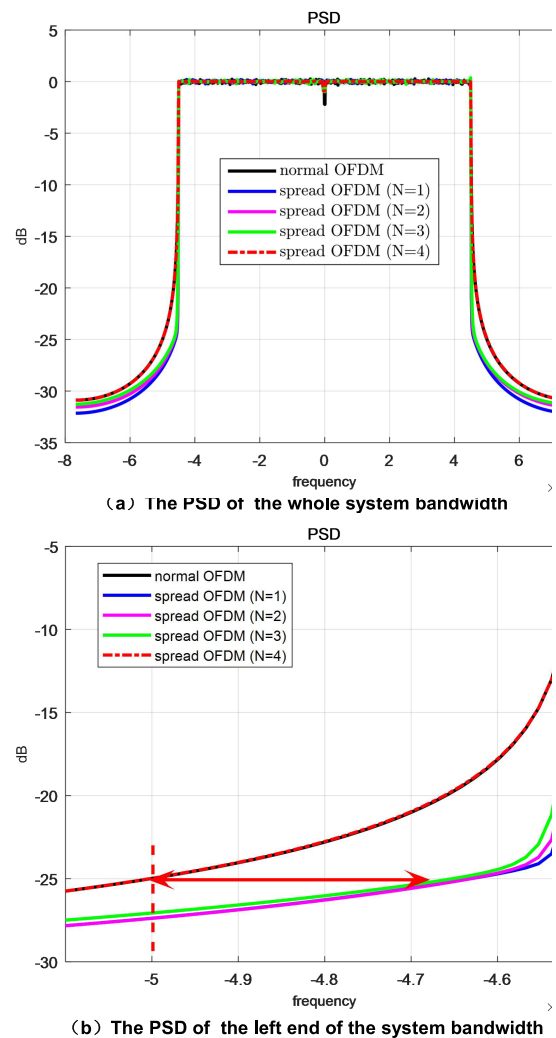

(a) The PSD of the whole system bandwidth

(b) The PSD of the left end of the system bandwidth

FIGURE 5. OOB leakage comparison between normal OFDM and spread OFDM using a group of mutual orthogonal spreading codes.

A weighted sum is beneficial for a balance between the effectiveness of suppressing OOB leakage and transmission efficiency. Because different spreading codes have different effectiveness for suppressing OOB leakage. For example, more power is allocated to the layer of spread data with spreading code S_1, and less power is allocated to the layer of spread data with spreading code S_3. That means the bigger weighted coefficient to S_1 and the smaller weighted coefficient to S_3.

At another point of view, as shown in the Fig.5, the PSD of transmitting $N = 4$ layers of data is the same as that of normal OFDM, because the spreading code $S_4 = [1,1,1,1]$ increases the OOB leakage and cancels out the effectiveness of the other spreading codes suppressing OOB leakage. So it is unsuitable for using a complete set of mutual orthogonal spreading codes to suppress OOB leakage. As a consequence, transmitting $N = 3$ layers of data is equivalent to remove the bad spreading code S_4 from a complete set of mutual orthogonal spreading codes S_1, S_2, S_3 and S_4 in order to obtain good out-of-leakage performance at the cost of reducing a

little the spectral efficiency. Transmitting $N = 2$ layers of data is equivalent to remove the bad spreading code S_4 and the least effective spreading code S_3 from a complete set of mutual orthogonal spreading codes in order to obtain better out-of-leakage performance at the cost of reducing more the spectral efficiency. In the actual demand, the spreading codes with less effectiveness of suppressing OOB leakage can be removed in turn, which achieves the balance between the effectiveness of suppressing OOB leakage and the data transmission efficiency.

IV. INTERFERENCE ANALYSIS AND SIMULATION RESULTS

A. ANALYSIS AND SOLUTION OF INTERFERENCE FROM ADJACENT SUB-BANDS

The OFDM system transmits multiple simultaneous data on multiple mutual orthogonal subcarriers. When the adjacent transmission sub-bands have different numerologies, the orthogonality between them will lose and the OOB leakage problem will leads to the interference between the adjacent sub-bands and so degrades transmission performance. In this section, the above spreading and multiplexing method is proposed for the multicarrier modulation technology to reduce the interference with adjacent sub-bands existing different numerologies.

Assuming that the subcarriers spacing of the adjacent transmission sub-bands A and B are f_A and f_B respectively and described by a simple mathematical relationship $f_A = mf_B$ where m is positive integer. When m is equal to 1, the subcarriers spacing of two adjacent sub-bands is the same, which means that the subcarriers between two adjacent sub-bands are orthogonal with each other. When m is equal to 2, the subcarriers spacing of the sub-band A is twice of that of the sub-band B. Therefore, the subcarriers of sub-band A are orthogonal with the even subcarriers but non-orthogonal with the odd subcarriers of the sub-band B when we assume that the even subcarriers of the sub-band B are just spaced integer multiple of f_A with the subcarriers of the sub-band A. Generally, when m is greater than 1, there will be some subcarriers of the sub-band B which are non-orthogonal with the subcarriers of sub-band A. The non-orthogonal problem brings on the interference between two adjacent sub-bands. In this section the above proposed spreading and multiplexing method will be used to reduce the interference.

In order to reduce the mutual interference with non-orthogonal subcarriers, the two adjacent sub-bands can use data modulation method as follows

1) For the sub-band A, modulate the spread data utilizing the spreading and multiplexing method on all the continuous subcarriers in the edge RB resource closed to the sub-band B in the frequency domain.

2) For the sub-band B, modulate the spread data utilizing the spreading and multiplexing method only on part of subcarriers in the edge RB resource closed to the sub-band A in the frequency domain. The part of subcarriers have $(n/m) \cdot f_A$ frequency spacing with the

subcarriers of the sub-band A where the positive integer n isn't an integer multiple of m. It means that the part of subcarriers are non-orthogonal with the subcarriers of the sub-band A. The rest subcarriers in the edge RB resource of the sub-band B have an integer multiple of f_A frequency spacing with the subcarriers of the sub-band A, that is, being orthogonal. Consequently, these rest subcarriers can directly transmit data without using the spreading and multiplexing method.

In the next subsection, we will simulate the performance of the sub-band B interfered with the sub-band A when the sub-band A uses the proposed spreading and multiplexing method.

B. B.SIMULATION RESULTS

We assume that there are two users. They are the interference user A whose data are transmitted in the sub-band A and the target user B whose data are transmitted in the sub-band B. The subcarrier spacing of the sub-band A is 30 kHz and that of the adjacent sub-band B is 15 kHz. Both of sub-band A and the sub-band B comprise 2 RB with 12 subcarriers per RB and respectively occupy the 0.72 MHz and 0.36 MHz transmission bandwidth. So the subcarrier spacing of the interference user A and the target user B have the relationship of $f_A = m \cdot f_B$ and $m = 2$. In the simulations, we set the gap as 30 kHz between the sub-band A and the sub-band B which implies all of the subcarriers of the sub-band A are non-orthogonal with the odd subcarriers of the sub-band B. Due to only 2 RB bandwidth occupied, we set the interference user A utilizing the spreading and multiplexing method to transmit the spread data on the all subcarriers of the sub-band A and the target user B utilizing the spreading and multiplexing method to transmit the spread data on the odd subcarriers of the sub-band B in the simulations.
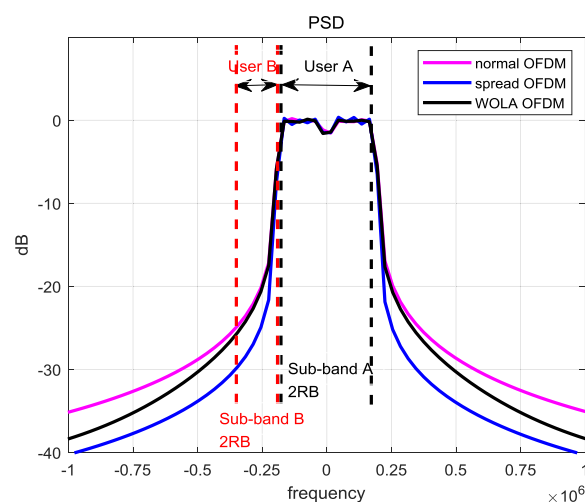

FIGURE 6. The PSD of interference user A with different modulation methods and the interference shown to target user B within the spectral range of sub-band B.

The Fig.6 shows the PSD of interference user A using different modulation methods respectively, including the normal

OFDM, the spread OFDM ($N = 3$) and WOLA (Weighted Overlap and Add) OFDM[26,27] (WOLA OFDM means windowing used to OFDM symbols). The interference user A uses the MCS (Modulation Code Scheme) of 64QAM with 3/4 code rate. According to the simulation results, we can observe that, within the spectral range of sub-band B, the suppressing effectiveness of OOB leakage of interference user A using spread OFDM with $N = 3$ layers of spread data outperforms that of using WOLA OFDM with raised-cosine windowing where weighted overlap occupies the 1/4 length of CP. It means that the interference to target user B is less when interference user A using spread OFDM than using WOLA OFDM.

For better analyzing the effectiveness of spread OFDM in suppressing OOB leakage from the interference user A to the target user B, we simulate the BLER (block error rate) vs SNR (signal noise ratio) and BLER vs A_b/N_0 (the energy per bit to noise power spectral density ratio) curves. The main parameters utilized in this simulation are summarized in the Table 2. We set the interference user A and the target user B are synchronous in time and frequency domain in AWGN simulation. Subsequently, we also set the two users have deviation in synchronization with a little of carrier frequency offset (CFO) and symbol time offset (STO) in fading channel simulation.

TABLE 2. Simulation parameters.

Parameter	Interference User A	Target User B
MCS	64QAM,Code Rate=3/4	
Subcarrier Spacing	30 kHz	15 kHz
Symbol Interval	1/28 ms	1/14 ms
Receiving Power Ratio	1:1	
RB Numbers	2 RB (24 subcarriers)	
Sub-band Width	0.72 MHz	0.36 MHz
Channel Model	AWGN(Additive White Gaussian Noise)	
Detection Algorithm on Receiver	MMSE (Minimum Mean Square Error)	
Spread Processing	Spread data on the all subcarriers	Spread data on the odd subcarriers
WOLA Processing	Root-raised cosine windowing(1/4 CP)	

The Fig.7 plots the BLER vs SNR curves of the target user B in three cases including without the interference of user A, interfered with the interference user A using spread OFDM ($N = 3$) and interfered with the interference user A using WOLA OFDM. It could be observed that, compared with the third case, the target user B in the second case has the better performance with 2.6 dB gains when BLER = 0.1. Moreover, the target user B in the second case almost reaches the effectiveness of the first case without any interference.

As mentioned above, the transmission efficiency using spread OFDM with $N = 3$ layers is 75%. For a fair comparison with the same spectrum efficiency, we set the data modulated on the middle 18 subcarriers in the third case WOLA OFDM and the other 6 subcarriers at the two edge of the sub-band are set as guard subcarriers without any data,
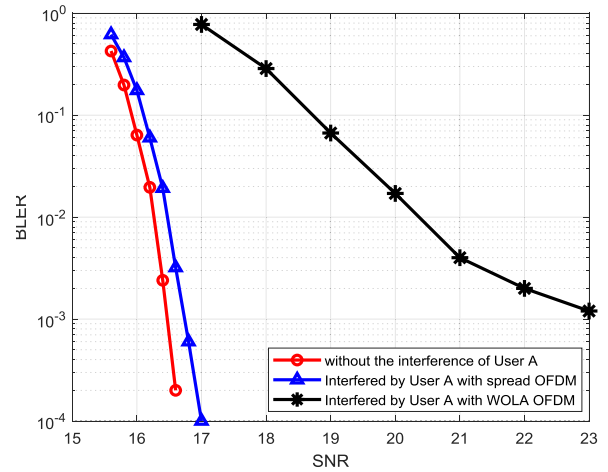

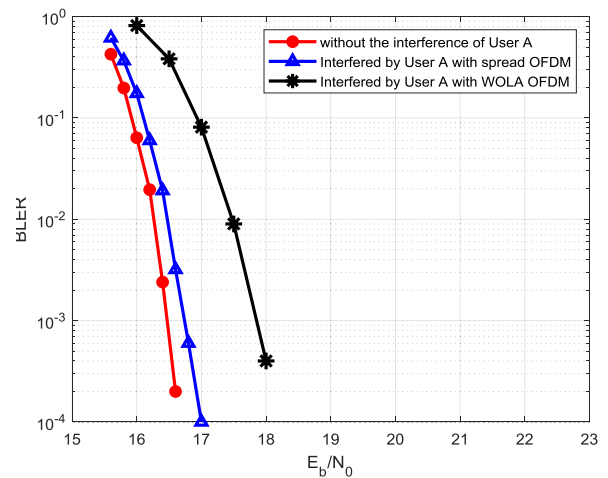**FIGURE 7.** BLER vs SNR curves of target user B in three cases.

FIGURE 8. BLER vs A_b/N_0 curves of target user B in three cases.

which means the transmission efficiency in the third case is also 75%. The power of sub-band keeps the same. So we can use A_b/N instead of SNR. The 6 extra guard subcarriers between user A and user B in the third case will further reduce the interference of user A to user B. The BLER vs A_b/N curves of the target user B in the three cases are shown in the Fig.8 Compared with the third case, the performance gain in the second case is about 0.8 dB when BLER = 0.1. On the other hand, besides the performance gain, the second case doesn't occupy the overhead of CP. However, the third case WOLA OFDM occupies the overhead of CP which means the decrease of the effective length of CP and less resistance to multiparty delay.

For a further comparison of performance between the three cases, we select a fading channel instead of the AWGN channel. The channel model used in the Fig.9 is the tapped delay line-A (LTD-A)[28] with DS (delay spread) = 100 NS. The channel estimation is assumed ideal. Moreover, we set CFO and STO of interference user A to be 1 kHz and 1/4 CP long respectively. The other simulation parameters are the same as
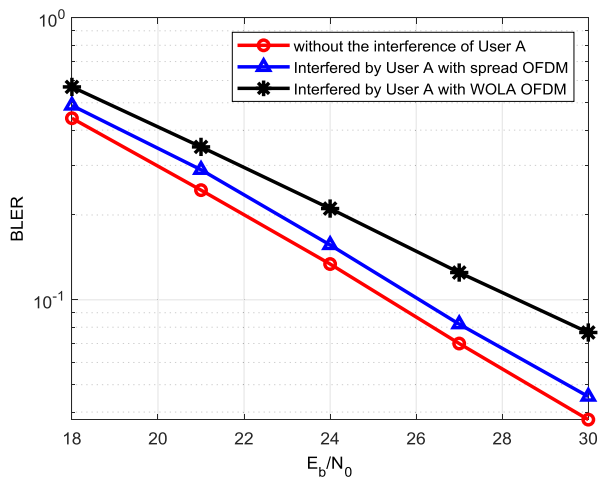
FIGURE 9. BLER vs A_b/N_0 curves of target user B in three cases in fading Channel. The CFO and STO of user A are 1 kHz and 1/4 CP long respectively.

in Fig. 8. As shown in the Fig. 9, the user B in the second case still almost reaches the same performance of the first case without the interference of user A and outperforms the third case with 2.2 dB gains when BLER = 0.1. This is because that although the channel coefficients of different subcarriers are different in fading channel, the differences between adjacent subcarriers or the spaced subcarriers by one are very small which means that the spreading codes with K = 1 or 2 can still suppress the OOB leakage very well when coherent bandwidth outdistances the subcarrier interval. The impact of CFO and STO of interference user A on the OOB leakage are also small.

So we make a conclusion that the proposed new data modulation method suppresses OOB leakage effectively and reduces the interference with adjacent sub-bands for different numerologies, and keeps high transmission efficiency by multiplexing several layers of data using orthogonal spreading codes.

V. CONCLUSION

In this paper, the orthogonal spreading codes selected out from a complete set of mutual orthogonal spreading codes are introduced to suppress OOB leakage for the multicarrier modulation schemes based CP-OFDM technology. The proposed data modulation method reduces interference with the neighboring frequency bands or adjacent sub-bands effectively and so improves the spectrum efficiency. At the same time, multiple layers of data multiplexed makes a trade-off between OOB leakage and transmission efficiency according to the channel conditions. The simulation results show that the novel modulation and multiplexing technology greatly suppresses OOB leakage and reduces the interference with adjacent sub-bands for different numerologies.

The novel modulation and multiplexing technology can be used not only in the edge of frequency bands and in adjacent sub-bands with different numerologies, but also in

some narrow bandwidth systems such as NB-IOT (Narrow Bandwidth-Internet of Things) which requires the lower OOB leakage.

REFERENCES

[1] A. Sahin, I. Guvenc, and H. Arslan, "A survey on multicarrier communications: Prototype filters, lattice structures, and implementation aspects," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1312–1338, 3rd Quart., 2014.

[2] T. Hwang, C. Yang, G. Wu, S. Li, and G. Ye Li, "OFDM and its wireless applications: A survey," *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 1673–1694, May 2009.

[3] X. N. Fernando, "Fi-Wi for 4G, 5G, and OFDM wireless networks," in *Radio Over Fiber for Wireless Communication: From Fundamentals to Advanced Topics*. Hoboken, NJ, USA: Wiley, 2014, pp. 215–227.

[4] A. Aminjavaheri, A. Farhang, A. Rezazadehreyhani, and B. Farhang-Boroujeny, "Impact of timing and frequency offsets on multicarrier waveform candidates for 5G," in *Proc. IEEE Signal Process. Signal Process. Edu. Workshop (SP/SPE)*, Salt Lake City, UT, USA, Aug. 2015, pp. 178–183.

[5] S. Tiwari, S. Chatterjee, and S. S. Das, "Comparative analysis of waveforms for fifth generation mobile networks," in *Proc. IEEE Int. Conf. Adv. Netw. Telecommun. Syst. (ANTS)*, Bangalore, India, Nov. 2016, pp. 1–6.

[6] P. Guan, D. Wu, T. Tian, J. Zhou, X. Zhang, L. Gu, A. Benjebbour, M. Iwabuchi, and Y. Kishiyama, "5G field trials: OFDM-based waveforms and mixed numerologies," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1234–1243, Jun. 2017.

[7] A. A. Zaidi, R. Baldemair, H. Tullberg, H. Bjorkegren, L. Sundstrom, J. Medbo, C. Kilinc, and I. Da Silva, "Waveform and numerology to support 5G services and requirements," *IEEE Commun. Mag.*, vol. 54, no. 11, pp. 90–98, Nov. 2016.

[8] X. Zhang, L. Zhang, P. Xiao, D. Ma, J. Wei, and Y. Xin, "Mixed numerologies interference analysis and inter-numerology interference cancellation for windowed OFDM systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7047–7061, Aug. 2018.

[9] L. Yang, "Study on waveforms candidates for 5G networks," *Mobile Commun.*, vol. 41, no. 4, 2017.

[10] A. Hammoodi, L. Audah, and M. A. Taher, "Green coexistence for 5G waveform candidates: A review," *IEEE Access*, vol. 7, pp. 10103–10126, Jan. 2019.

[11] F. Schaich and T. Wild, "Waveform contenders for 5G—OFDM vs. FBMC vs. UFMC," in *Proc. 6th Int. Symp. Commun., Control Signal Process. (ISCCSP)*, Athens, Greece, May 2014, pp. 457–460.

[12] Z. He, L. Zhou, Y. Chen, and X. Ling, "Filter optimization of out-of-band emission and BER analysis for FBMC-OQAM system in 5G," in *Proc. IEEE 9th Int. Conf. Commun. Softw. Netw. (ICCSN)*, Guangzhou, China, May 2017, pp. 56–60.

[13] M. Mukherjee, L. Shu, V. Kumar, P. Kumar, and R. Matam, "Reduced out-of-band radiation-based filter optimization for UFMC systems in 5G," in *Proc. Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Dubrovnik, Croatia, Aug. 2015, pp. 1150–1155.

[14] T. H. Nguyen, D. Q. Nguyen, L. H. Thai, and T. K. Nguyen, "Out of band analysis in various 5G-NR downlink waveforms with different numerologies," in *Proc. 3rd Int. Conf. Recent Adv. Signal Process., Telecommun. Comput. (SigTelCom)*, Hanoi, Vietnam, Mar. 2019, pp. 5–9.

[15] I. B. Franco de Almeida and L. Leonel Mendes, "Linear GFDM: A low out-of-band emission configuration for 5G air interface," in *Proc. IEEE 5G World Forum (5GWF)*, Silicon Valley, CA, USA, Jul. 2018, pp. 311–316.

[16] F. Schaich, "Filterbank based multi carrier transmission (FBMC)—Evolving OFDM: FBMC in the context of WiMAX," in *Proc. Eur. Wireless Conf. (EW)*, Lucca, Italy, 2010, pp. 1051–1058.

[17] W. C. Zhang, Y. Xin, and G. H. Yu, "A novel multicarrier scheme named FB-OFDM for 5G," *ZTE Technol. J.*, vol. 22, no. 3, pp. 22–25, 2016.

[18] X. Yu, Y. Guanghui, Y. Xiao, Y. Zhen, X. Jun, and G. Bo, "FB-OFDM: A novel multicarrier scheme for 5G," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Athens, Greece, Jun. 2016, pp. 271–276.

[19] H.-F. Wang and Y.-F. Huang, "Performance evaluation of the universal filtered multi-carrier communications under various multipath fading propagation conditions," in *Proc. IEEE 8th Int. Conf. Awareness Sci. Technol. (iCAST)*, Taichung, Taiwan, Nov. 2017, pp. 466–469.

[20] L. Yang and Y. Xu, "Filtered-OFDM system performance research based on Nuttall's Blackman-Harris window," in *Proc. IEEE 17th Int. Conf. Commun. Technol. (ICCT)*, Chendu, China, Oct. 2017, pp. 687–691.

[21] M. Kim and D. Y. Kwak, "Generalized OFDM," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Jeju, South Korea, Oct. 2017, pp. 650–655.

[22] *Physical Channels and Modulation*, document TS38211-f20, 3GPP, NR, 2018.

[23] Sumarsana, A. Muayyadi, and D. Arseno, "Performance analysis of generalized frequency division multiplexing in various pulse-shaping filter for next generation communication systems," in *Proc. IEEE Asia Pacific Conf. Wireless Mobile (APWiMob)*, Bandung, Indonesia, Sep. 2016, pp. 41–45.

[24] K. Chen-Hu, R. P. Leal, and A. G. Armada, "Reducing the interference by adapting the power of OFDM for mMTC," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Porto, Portugal, Jun. 2018, pp. 1–5.

[25] *User Equipment (UE) Radio Transmission and Reception*, document TS38101-f40, 3GPP, NR, 2018.

[26] *R1-162199-Waveform Candidates*, Qualcomm, San Diego, CA, USA, 2016.

[27] R. Zayani, Y. Medjahdi, H. Shaiek, and D. Roviras, "WOLA-OFDM: A potential candidate for asynchronous 5G," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Washington, DC, USA, Dec. 2016, pp. 1–5.

[28] *Study on Channel Model for Frequencies From 0.5 to 100 GHz*, document TR38901-e00, 3GPP, 2017.

BAO TONG was born in Taonan, Jilin, China, in 1992. She received the B.S. and M.S. degrees in information and communication engineering from Dalian Maritime University. From 2015 to 2018, she researched on visible light communication based on OFDM. She is the author of four articles. Her research interests include unipolar optical OFDM and low PAPR signal.
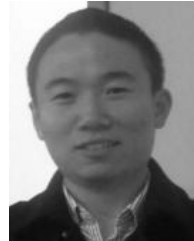
BIAN LUANJIAN received the B.S. degree in electronics and information engineering and the M.S. degree in signal and information processing from Harbin Engineering University, Harbin, China, in 2007 and 2010, respectively. He is currently working in wireless communication technology and standard pre-researching with ZTE Corporation. Since 2010, he has been a Technology and Standard Pre-researching Engineer in ZTE Corporation and researches physical layer technology of wireless communication. He provided more than 130 contributions to 3GPP group and disclosed more than ten patents.

XIN YU was born in Linchuan, Jiangxi, China, in 1976. He received the B.S. degree in physics from Nanchang University, in 1997, the M.S. degree in optics from the Anhui Institute of Optics and Fine Mechanics Acadamia Sinica, in 2000, and the Ph.D. degree in electromagnetic field and microwave technology from the Beijing University of Posts and Telecommunications, in 2003.From 2003 till 2018, he worked with wireless communication in ZTE Corporation. He had submitted more than 100 contributions to 3GPP and 3GPP2, and applied more than 100 patents. His research interests include new waveform, low PAPR signal, modulation, demodulation, receiver algorithms, and so on.

YU GUANGHUI, photograph and biography not available at the time of publication.

HU LIUJUN, photograph and biography not available at the time of publication.

・・・