Enhanced Uplink Transmission Performance Based on WFRFT for Future Communication Systems

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***Abstract*—The long term evolution-advanced (LTE-A) and worldwide interoperability for microwave access (WiMAX) standards are the two main contenders in the 4th generation (4G) wireless systems, which adopt the single carrier-frequency division multiplexing access (SC-FDMA) and orthogonal frequency division multiplexing access (OFDMA) schemes in the uplink, respectively. However, these two schemes have certain advantages and disadvantages. As the weighted fractional Fourier transform (WFRFT)-based system can merge the SC-FDMA scheme with the OFDMA scheme, it inherits these two schemes' characteristics and has the potential to obtain better performance. For enhancing the bit error rate (BER) performance of the future uplink communication, in this paper, we propose a new order selection method for the WFRFT-based system to obtain better BER performance than the existing conventional uplink SC-FDMA or OFDMA scheme concerning the peak-to-average power ratio (PAPR) and the uplink power control (UPC) under frequency selective fading channels.**

I. Introduction

Both academic and industrial research has paid a great deal of attention to the future communication system. Critical requirements for the 5th generation (5G) wireless communication have been proposed, including high data rate, large device density and ultra-low latency, etc. In different communication scenarios, different requirements on the performance are needed. For instance, in the driverless car scenario, latency and reliability are dominant while the low data rate can be accepted [1]. Greater reliability is also emphasized in a diverse variety of 5G usage scenarios [2]. This paper will focus on enhancing the bit error rate (BER) performance of existing standard communication schemes.

Worldwide interoperability for microwave access (WiMAX) standard adopts the orthogonal frequency division multiplexing access (OFDMA) scheme in the uplink and the downlink [3]. The OFDMA scheme has some advantages, like the relatively simple compensation technique for the frequency selective fading channel. However, it also has certain disadvantages, like high peak-to-average power ratio (PAPR) [4]. High PAPR can cause the power amplifier (PA) to run within the non-linear operating region, which will introduce significant signal distortion and inter-modulation between different subcarriers. For avoiding the non-linear distortion, the power back-off according to the PAPR is needed. Nevertheless, the back-off will reduce the transmit power of the PA. The single carrier-frequency division multiplexing access (SC-FDMA) scheme, which is a modification of the OFDMA scheme [3], has some advantages, including low PAPR, insensitive to the carrier frequency offset (CFO) and so on. For this reason, the long term evolution-advanced (LTE-A) standard uses the SC-FDMA scheme in the uplink [5].

Weighted fractional Fourier transform (WFRFT) has been proposed to be used in the communication system, which is called WFRFT system [6]. It is demonstrated that the WFRFT system can combat narrow-band interference than the SC-FDMA and OFDMA schemes [7]. In [8], an optimal order selecting algorithm for the WFRFT system over doubly selective fading channels is proposed. This order selecting algorithm is established through maximizing the carrier-to-interference ratio (CIR). Considering the channel equalization procedure, another optimal order selection scheme for the WFRFT system under doubly selective fading channels is also proposed by minimizing the interference power variance [9]. Nevertheless, the above-mentioned order selection algorithms only considered the communication scenario over doubly selective fading channels. It should be noted that frequency selective fading channels are more common in practical wireless communications. Besides, few works about the WFRFT system order selection have considered the influence of PAPR and the uplink power control (UPC) parameter at the transmitter. Therefore, the above-mentioned optimal order selection algorithms are not applicable in the system considering the influence of PAPR and the UPC parameter over frequency selective fading channels. In this paper, we propose a new order selection method for the WFRFT system to obtain better BER performance than the conventional SC-FDMA and OFDMA schemes in more practical system models, in which the PAPR, the UPC parameter and frequency selective fading channels are considered.

The contributions of this paper include: 1) Concerning the PAPR and the UPC parameter, a new order selection method for the WFRFT system is proposed, which can render the WFRFT system to obtain better BER performance than the conventional SC-FDMA and OFDMA schemes. 2) Through analyzing, the theoretical signal-to-noise ratio (SNR) expression with the linear frequency domain (FD) zero forcing (ZF) equalization in the WFRFT system is obtained, which can be used to choose the WFRFT system order.

The rest of this paper is organized as follows: in Section II, some basic concepts about the WFRFT system, PAPR and UPC are addressed. Section III introduces the proposed

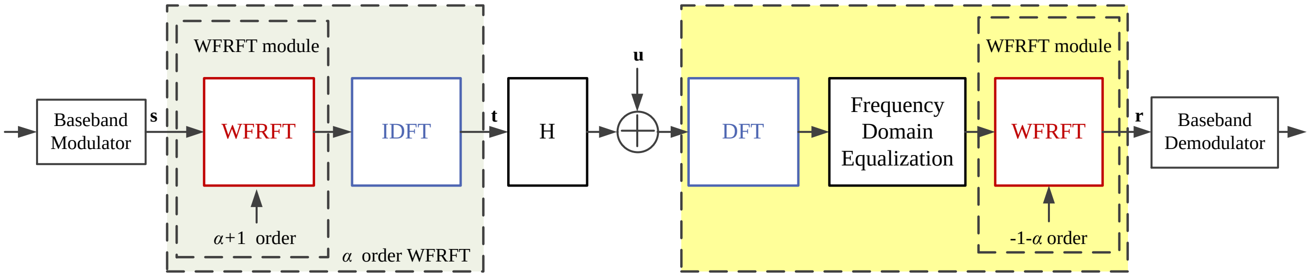

Fig. 1. Block diagram of the WFRFT system in the frequency selective fading channel.

new order selection method. The theoretical expression of the SNR after the ZF equalization is derived in Section IV. The simulation results, which verify the proposed method based on the theoretical SNR, are given in Section V. Finally, concluding remarks are drawn in Section VI.

II. Preliminaries

A. WFRFT system

The block diagram of the WFRFT system is illustrated in Fig. 1. At the transmitter of the WFRFT system, a complex vector $\mathbf{s} := [s_0, s_1, ..., s_{N-1}]^{\mathbf{t}}$ goes through the α order WFRFT, which can be expressed as [6]

$$\begin{aligned}\mathbf{t} = \mathbf{F}^{\alpha}\mathbf{s} &= (\omega_0^{\alpha}\mathbf{I} + \omega_1^{\alpha}\mathbf{F} + \omega_2^{\alpha}\mathbf{P} + \omega_3^{\alpha}\mathbf{F}^{-1})\mathbf{s} \\ &= (\omega_0^{\alpha}\mathbf{I} + \omega_1^{\alpha}\mathbf{F} + \omega_2^{\alpha}\mathbf{P} + \omega_3^{\alpha}\mathbf{PF})\mathbf{s}\end{aligned} \quad (1)$$

where $\mathbf{F}$ is the $N \times N$ unitary Fourier matrix, which can be described as $[\mathbf{F}]_{k,m} := \psi^{k\cdot m} = (1/\sqrt{N})\exp(-j2\pi km/N)$, where $\psi = (1/\sqrt{N})\exp(-j2\pi/N)$ and $[\cdot]_{k,m}$ $(k, m = 0, 1, \ldots N-1)$ denotes the specific element located at k-th row and m-th column in a matrix. $\mathbf{I}$ means the $N \times N$ identity matrix. The shift matrix $\mathbf{P}$ satisfies $[\mathbf{P}]_{k,m} = \delta(\langle k+m \rangle_N)$, where $\langle\cdot\rangle_N$ stands for the modulo-N calculation [7]. $\mathbf{F}^{\alpha}$ represents the α order $N \times N$ WFRFT matrix, which can be expressed as (2), where elements of the matrix $\mathbf{F}^{\alpha}$ are denoted by $[\mathbf{F}^{\alpha}]_{k,m} := \eta_{k,m}^{\alpha}$. The weighting coefficients $\omega_l^{\alpha}(l = 0, 1, 2, 3)$ are given by [6]

$$\omega_l^{\alpha} = \frac{1}{4}\sum_{m=0}^{3}\exp\left[\frac{j2\pi(\alpha - l)m}{4}\right] \quad (l = 0, 1, 2, 3) \quad (3)$$

where the order α is a real number, and ω_l^{α} is periodic with 4, i.e. $\omega_l^{\alpha} = \omega_l^{\alpha+4}$. Meanwhile, ω_l^{α} also has the symmetrical characteristic. Hence, the main interval of the order α is always chosen in [-1,0]. $\mathbf{F}^{\alpha}$ is also a unitary matrix, so it satisfies

$$\mathbf{F}^{-\alpha} = [\mathbf{F}^{\alpha}]^{-1} = [\mathbf{F}^{\alpha}]^{\mathrm{H}} \quad (4)$$

where $[\mathbf{F}^{\alpha}]^{\mathrm{H}}$ represents the conjugate transposed matrix of $\mathbf{F}^{\alpha}$, and $[\mathbf{F}^{\alpha}]^{-1}$ denotes the inverse matrix of $\mathbf{F}^{\alpha}$. Furthermore, it can be easily inferred that $\mathbf{F}^0 = \mathbf{I}$ and $\mathbf{F}^1 = \mathbf{F}$. The *Additive Axiom*, which has been applied in Fig. 1, is given by

$$\mathbf{F}^{\alpha+\beta} = \mathbf{F}^{\alpha}\mathbf{F}^{\beta} = \mathbf{F}^{\beta}\mathbf{F}^{\alpha} \quad (5)$$

As shown in Fig. 1, the WFRFT module is placed before IDFT or after DFT at the transceivers. Between IDFT and WFRFT at the transmitter, there may exist some other signal processing, e.g., frequency mapping, which is not displayed here. The transmitted WFRFT symbol $\mathbf{t}$ experiences the frequency selective fading channel $\mathbf{H}$ and additive white Gaussian noise (AWGN) $\mathbf{u}$. At the receiver, received signals are processed by DFT, the frequency domain equalization and the $(-1-\alpha)$ order WFRFT module.

B. PAPR and uplink power control

As mentioned above, the OFDMA scheme has higher PAPR than the SC-FDMA scheme. The WFRFT scheme can change the PAPR characteristic from the SC-FDMA PAPR ($\mathrm{PAPR_{SC}}$) to the OFDMA PAPR ($\mathrm{PAPR_{OFDM}}$) by adjusting the WFRFT order α from 0 to -1. To illustrate the PAPR characteristic, simulation results are given for OFDMA, SC-FDMA and WFRFT signals with 512 subcarriers and oversampling factor 8 ($L = 8$). Fig. 2 shows the complementary cumulative distribution function (CCDF) of PAPR of WFRFT signals for 16-QAM in different orders. The horizontal axis represents the threshold $\mathrm{PAPR_0}$ for the PAPR, and the vertical axis stands for the probability that the PAPR of a WFRFT signal block exceeds the threshold. It is shown that the SC-FDMA scheme ($\alpha = 0$) has the lowest PAPR, and the OFDMA scheme ($\alpha = -1$) has the highest PAPR. The PAPR of the WFRFT scheme becomes higher as α varies from 0 to -1. For details of $\mathrm{PAPR_0}$ in 16-QAM and 64-QAM at the probability [PAPR>$\mathrm{PAPR_0}$] = 10^{-3}, see Table I. Even though α is chosen from discrete values in this table, it can be inferred that the WFRFT system PAPR ($\mathrm{PAPR_{WFRFT}}$) can continuously change from the $\mathrm{PAPR_{SC}}$ to the $\mathrm{PAPR_{OFDM}}$, as the α is a continuous variable from 0 to -1.

$$\mathbf{F}^{\alpha} = \frac{1}{\sqrt{N}}\begin{bmatrix} \omega_0^{\alpha} + \omega_1^{\alpha} + \omega_2^{\alpha} + \omega_3^{\alpha} & \omega_0^{\alpha} + \omega_1^{\alpha} + \omega_3^{\alpha} & \cdots & \omega_0^{\alpha} + \omega_1^{\alpha} + \omega_3^{\alpha} \\ \omega_0^{\alpha} + \omega_1^{\alpha} + \omega_3^{\alpha} & \omega_0^{\alpha} + \omega_1^{\alpha}\psi^{1\cdot 1} + \omega_3^{\alpha}\psi^{-1\cdot 1} & \cdots & \omega_0^{\alpha} + \omega_1^{\alpha}\psi^{(N-1)\cdot 1} + \omega_2^{\alpha} + \omega_3^{\alpha}\psi^{-1\cdot(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ \omega_0^{\alpha} + \omega_1^{\alpha} + \omega_3^{\alpha} & \omega_0^{\alpha} + \omega_1^{\alpha}\psi^{1\cdot(N-1)} + \omega_2^{\alpha} + \omega_3^{\alpha}\psi^{-(N-1)\cdot 1} & \cdots & \omega_0^{\alpha} + \omega_1^{\alpha}\psi^{(N-1)\cdot(N-1)} + \omega_3^{\alpha}\psi^{-(N-1)\cdot(N-1)} \end{bmatrix} \quad (2)$$

TABLE I
COMPARISONS OF $PAPR_0$[dB] FOR WFRFT SIGNALS FOR DIFFERENT MODULATIONS AND ORDERS (PROBABILITY[PAPR>$PAPR_0$]=10^{-3}).

Modulation	$\alpha = 0$	$\alpha = -0.1$	$\alpha = -0.2$	$\alpha = -0.3$	$\alpha = -0.4$	$\alpha = -0.5$	$\alpha = -0.6$	$\alpha = -0.7$	$\alpha = -0.8$	$\alpha = -0.9$	$\alpha = -1$
16-QAM	8.96	9.13	9.60	10.06	10.53	10.93	11.23	11.43	11.51	11.55	11.56
64-QAM	9.18	9.34	9.73	10.18	10.63	10.99	11.27	11.46	11.58	11.59	11.59

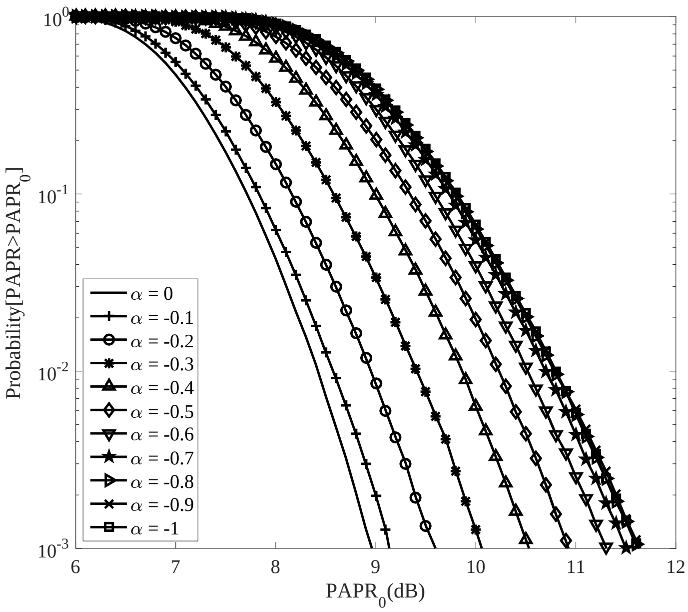

Fig. 2. CCDF of PAPR of WFRFT signals with 512 subcarriers for 16-QAM modulation in different orders.

For achieving the maximum output power (MOP) of a PA at the transmitter, the PA should operate near the saturation region. However, signals with high PAPR will run within the non-linear operating region. In order to ensure that the probability of output signal frames with nonlinear distortion is less than a threshold, input back-off (IBO) will be applied to shift the average power to a lower point. The IBO factor is the ratio of the PA saturation power to the input signal average power, which is given by

$$\begin{aligned} \text{IBO} &= 10\log_{10}\left(\frac{P_{sat}}{P_{av}}\right) \\ &= P_{sat}[\text{dB}] - P_{av}[dB] \end{aligned} \tag{6}$$

where P_{sat}[dB] and P_{av}[dB] are the PA saturation power and the input average signal power, respectively. For guaranteeing that signal peaks do not exceed the linear region at an assumed probability, IBO has to be not less than the corresponding $PAPR_0$ [10].

Concerning the PA IBO, the average transmit power P_t [dBm] is

$$P_t = P_{max} - \text{IBO} \tag{7}$$

where P_{max} is the PA maximum output power without the IBO, which is assumed to be 35 dBm in this paper. IBO is defined as (6), and IBO $\geq$ $PAPR_0$. When IBO is

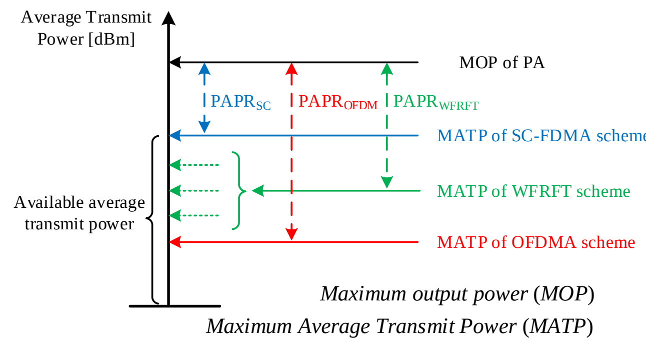

Fig. 3. Uplink average transmit power diagram considering PAPR for different schemes.

equal to $PAPR_0$, the average transmit power is called maximum average transmit power (MATP). For example, at the probability[PAPR>$PAPR_0$]=10^{-3}, $PAPR_0$ equals 10.53 dB for 16-QAM and $\alpha = -0.4$, referring to Table I. Hence, the MATP is 24.47 dBm for this case according to (7). The available uplink average transmit power diagram considering PAPR for different schemes is shown in Fig. 3. The SC-FDMA scheme has the lowest PAPR, so it has the highest MATP. Nevertheless, the OFDMA scheme obtains the lowest MATP because of its highest PAPR. Meanwhile, the WFRFT scheme acquires the moderate MATP, because it can adjust its PAPR between the $PAPR_{SC}$ and the $PAPR_{OFDM}$.

Considering the path loss, the received average signal power P_r [dBm] at the base station (BS) is

$$P_r = P_t + 20\log_{10}\left(\frac{\lambda}{4\pi d_0}\right) - 10\log_{10}\left(\frac{d}{d_0}\right)^{3.8} \tag{8}$$

where P_t is the average transmit power shown in (7). d_0 is the reference distance, and d is the the distance between the BS and the user equipment (UE). The second term of (8) represents the free space electromagnetic loss, and the third term is the propagation loss. For the 2 GHz carrier frequency, d_0 and λ are 100 m and 0.15 m, respectively [11].

The uplink transmit power is also controlled by the uplink power control (UPC) parameter to guarantee that signals are received with the appropriate power. From Fig. 3, the UPC can adjust the SC-FDMA scheme average transmit power from 0 to the MATP of SC-FDMA scheme, the OFDMA scheme average transmit power from 0 to the MATP of OFDMA scheme, and the WFRFT scheme average transmit power from 0 to the MATP of WFRFT scheme. As this paper focuses on the order selection method for WFRFT systems, the power control mechanism is not considered here. The power control to the uplink UE is assumed as a given system parameter at the UE side, which means that the UE has known the UPC parameter, and how to adjust and calculate the UPC parameter is not considered here.

III. A New Order Selection Method

In this section, the proposed order selection method for the uplink WFRFT system is presented. The PAPR, the UPC parameter and channel conditions are needed in the order selection method.

Step 1: obtain the OFDMA IBO (IBO_{OFDM}) and the SC-FDMA IBO (IBO_{SC}) according to the PAPR and the UPC parameter. For example, when the UPC parameter requires 23.2 dBm transmit power for 16-QAM modulaiton, from Table I, the SC-FDMA and OFDMA schemes both can meet the UPC requirement, i.e., $IBO_{OFDM} = IBO_{SC} = 35 - 23.2 = 11.8$ dB. However, when the UPC parameter requires 23.6 dBm transmit power for 16-QAM modulation, the OFDMA scheme cannot meet the UPC requirement. Therefore, it has to transmit signals at its MATP level (23.44 dBm), i.e., $IBO_{OFDM} = 11.56$ dB. Meanwhile, the SC-FDMA scheme can still meet the UPC requirement, and IBO_{SC} equals 11.4 dB, which is more than its $PAPR_0$ (8.96 dB).

Step 2: there are two cases to be considered. Case 1: if $PAPR_{OFDM} > IBO_{SC}$, the $PAPR_{WFRFT}$ is set to be equal to IBO_{SC}, and the α_s ($0 \geq \alpha_s > -1$) order for the WFRFT system is selected according to $PAPR_{WFRFT}$. This means that the α_s order WFRFT signal $PAPR_0$ is the same as IBO_{SC}. At the same time, the IBO_{WFRFT} is set to $PAPR_{WFRFT}$. Case 2: if $IBO_{SC} \geq PAPR_{OFDM}$, go to the next step diretly.

Step 3: case 1: compare these three scheme SNRs ($\alpha = 0, -1, \alpha_s$) to find which scheme has the highest one, based on IBO_{OFDM}, IBO_{SC}, IBO_{WFRFT}, α_s order and channel conditions. $\alpha = -1$ is the selected order if the OFDMA scheme has the highest SNR, $\alpha = 0$ for the SC-FDMA scheme, and α_s for the WFRFT scheme. Case 2: compare the SC-FDMA and OFDMA scheme SNRs based on IBO_{OFDM}, IBO_{SC} and channel conditions. The scheme which has better SNR will be selected.

IV. Analysis of SNR with ZF Equalization

The SNR influences the signal demodulation performance at the receiver. WFRFT can change the SNR, so analytic SNR expressions for these three schemes are needed to compare their performance. As the cyclic prefix (CP) is employed to eliminate the inter-symbol interference (ISI) and inter-carrier interference (ICI) in communication systems, the channel matrix $\mathbf{H}$ is a circulant one, and can be diagonalized by the Fourier matrix:

$$\mathbf{H} = \mathbf{F}^{-1}\mathbf{Q}\mathbf{F} \tag{9}$$

where $[\mathbf{Q}]_{k,k} := \lambda_k$ $(k = 0, 1...N-1)$ are eigenvalues of $\mathbf{H}$, and other elements of $\mathbf{H}$ are 0. The received signals after the ZF equalization $\mathbf{W}_{ZF}$ and the WFRFT can be formulated as

$$\begin{aligned} \mathbf{r} &= \mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}\mathbf{F}\mathbf{H}\mathbf{F}^{\alpha}\mathbf{s} + \mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}\mathbf{F}\mathbf{u} \\ &= \mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}\mathbf{F}\mathbf{F}^{-1}\mathbf{Q}\mathbf{F}\mathbf{F}^{\alpha}\mathbf{s} + \mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}\mathbf{F}\mathbf{u} \\ &= \mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}\mathbf{Q}\mathbf{F}^{1+\alpha}\mathbf{s} + \mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}\mathbf{F}\mathbf{u} \end{aligned} \tag{10}$$

where $\mathbf{u}$ is the AWGN with variance N_0, and $\mathbf{W}_{ZF}$ is euqal to $\mathbf{Q}^{-1}$. So $\mathbf{W}_{ZF}\mathbf{Q} = \mathbf{I}$. (10) can be rewritten as

$$\mathbf{r} = \mathbf{s} + \mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}\mathbf{F}\mathbf{u} \tag{11}$$

Due to the central limitation theorem, $\mathbf{d} = \mathbf{F}\mathbf{u} := [d_0, d_1, ..., d_{N-1}]^{\mathbf{t}}$ is still uncorrelated AWGN with variance N_0. $\mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}$ can be written as

$$\mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF} = \begin{bmatrix} \frac{1}{Q_0}\eta_{0,0}^{-\alpha-1} & \frac{1}{Q_1}\eta_{0,1}^{-\alpha-1} & \cdots & \frac{1}{Q_{N-1}}\eta_{0,N-1}^{-\alpha-1} \\ \frac{1}{Q_0}\eta_{1,0}^{-\alpha-1} & \frac{1}{Q_1}\eta_{1,1}^{-\alpha-1} & \cdots & \frac{1}{Q_{N-1}}\eta_{1,N-1}^{-\alpha-1} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{Q_0}\eta_{N-1,0}^{-\alpha-1} & \frac{1}{Q_1}\eta_{N-1,1}^{-\alpha-1} & \cdots & \frac{1}{Q_{N-1}}\eta_{N-1,N-1}^{-\alpha-1} \end{bmatrix} \tag{12}$$

Therefore, the output noise of $\mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}$ is

$$\begin{aligned} \mathbf{v} &= \mathbf{F}^{-\alpha-1}\mathbf{W}_{ZF}\mathbf{F}\mathbf{u} \\ &= \left[\sum_{n=0}^{N-1}\frac{1}{Q_n}\eta_{0,n}^{-\alpha-1}d_n, \sum_{n=0}^{N-1}\frac{1}{Q_n}\eta_{1,n}^{-\alpha-1}d_n, \ldots \sum_{n=0}^{N-1}\frac{1}{Q_n}\eta_{N-1,n}^{-\alpha-1}d_n\right]^{\mathbf{t}} \end{aligned} \tag{13}$$

As d_n are uncorrelated, the k_{th} subcarrier noise is AWGN with variance $\sigma_{v,k}^2$, i.e.,

$$\sigma_{v,k}^2 = \sum_{n=0}^{N-1} |\eta_{k,n}^{-\alpha-1}|^2 \frac{1}{|Q_n|^2} N_0 \tag{14}$$

The uplink power control parameter and PAPR are considered in this paper and different α order WFRFT symbols have different PAPR, so the average power $E_{s,\alpha}$of the transmitted symbols is determied by (8) and α. Therefore, the k_{th} subcarrier SNR can be obtained that

$$SNR_{\alpha,k} = \frac{E_{s,\alpha}}{\sigma_{v,k}^2} \tag{15}$$

The WFRFT system is consistent with the OFDMA system when $\alpha = -1$, which means that the SNR expression (15) can be used in the OFDMA system. In the same way, the SNR expression (15) for $\alpha = 0$ is also adapted to obtain the SNR of the SC-FDMA system. According to the proposed order selection method in Section III and the theoretical SNR expression, the appropriate order of the WFRFT system can be obtained.

V. Simulation Results

In this section, we provide some representative simulation results for evaluating BER performance of the uplink WFRFT system with the proposed order selection method, compared with conventional SC-FDMA and OFDMA schemes. The single-cell model and long enough CP are assumed, so that ISI and ICI are perfectly eliminated. The WFRFT system considered here is an uplink system with 10 MHz bandwidth, and the noise power spectrum density is -170 dBm/Hz. So the sample time interval is $T = 100$ ns. The carrier frequency is 2 GHz, and the PA maximum output power is 35 dBm. Simulations are conducted over the frequency selective fading channel. The channel multipath delays are [0 200 800 1200

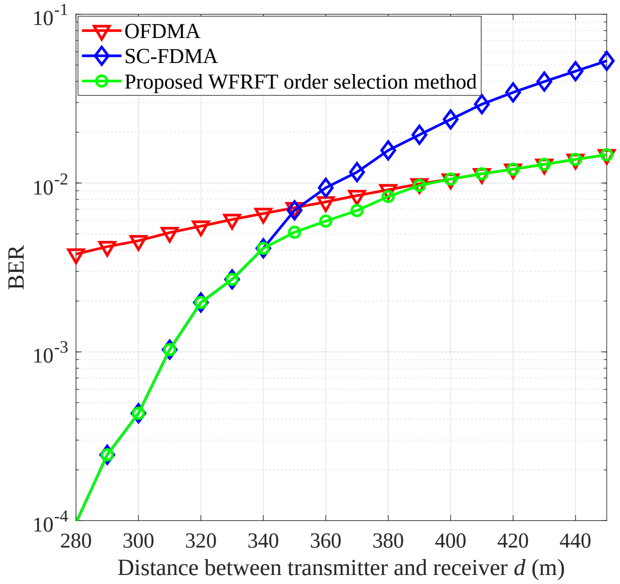

Fig. 4. BER performance of the WFRFT system with 16-QAM and the frequency domain ZF equalization over the selective fading channel (UPC = 24.07 dBm).

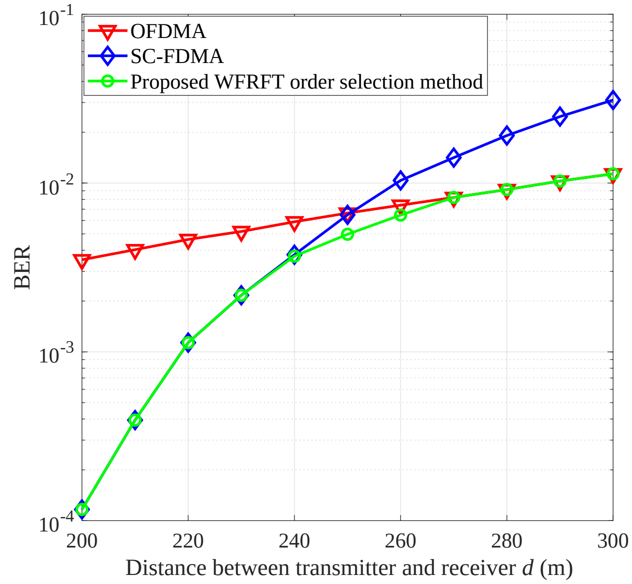

Fig. 5. BER performance of the WFRFT system with 64-QAM and the frequency domain ZF equalization over the selective fading channel (UPC = 24.37 dBm).

2300 3700] ns, and the channel mutipath average path gains are [1 0.8118 0.3223 0.1590 0.1690 0.0040]. It is assumed that the power control parameter to the uplink UE is set to a given parameter in one simulation condition. The BS has the perfect channel knowledge, and adopts a linear frequency domain ZF equalization.

Suppose that the uplink UE adopts the 16-QAM modulation and the UPC parameter requires 24.07 dBm transmit power, i.e., UPC = 24.07 dBm. From Section III and Table I, IBO_{OFDM} =$\text{PAPR}_{\text{OFDM}}$ =11.56 dB and IBO_{SC} =10.93 dB. As $\text{PAPR}_{\text{OFDM}}$ >IBO_{SC}, $\text{PAPR}_{\text{WFRFT}}$ = IBO_{SC} = 10.93 dB according to the proposed order selection method in Section III. So we choose the WFRFT order α_s which satisfies $\text{PAPR}_{\text{WFRFT}}$ = 10.93 dB, i.e., $\alpha_s = -0.5$. Even though the OFDMA scheme cannot meet the UPC parameter requirement, it transmits signals with its MATP level 23.44 dBm. Actually, the OFDMA scheme transmits signals below the UPC requirement, and this can benefit other users because of its lower inter-user interference to other users.

Fig. 4 shows the 16-QAM BER performance of the WFRFT system with the FD ZF equalization over the selective fading channel. It can be seen that when $d < 340$, the $(\alpha = 0)$ WFRFT scheme can obtain the best BER performance. When $340 \leq d \leq 400$, the $(\alpha = -0.5)$ WFRFT scheme has the best BER performance. When $400 < d$, the $(\alpha = -1)$ WFRFT scheme acquires the best BER performance. Therefore, according to the proposed order selection method, $\alpha = 0$ is selected for $d < 340$, $\alpha = -0.5$ for $340 \leq d \leq 400$, and $\alpha = -1$ for $400 < d$.

The 64-QAM BER performance of the WFRFT system with the FD ZF equalization is shown in Fig. 5. The similar results to Fig. 4 can also be concluded. The $(\alpha = 0)$ WFRFT scheme and the $(\alpha = -1)$ WFRFT scheme have the best performance, respectively, for $d < 230$ and $270 < d$. When $230 \leq d \leq 270$, the $(\alpha = -0.4)$ WFRFT scheme can obtain the best BER performance. From the simulation results, it can be easily verified that the WFRFT scheme with the proposed order selection method can obtain better BER performance than the single conventional SC-FDMA or OFDMA scheme under the same condition. It can also be concluded that when the uplink UE is near the BS, the $(\alpha = 0)$ WFRFT scheme should be used. When the UE is far from the BS, the $(\alpha = -1)$ WFRFT scheme should be applied. When the UE is in the intermediate region, the $(-1 \leq \alpha \leq 0)$ WFRFT scheme should be selected. It should be noted that we do not compare the order selection methods in [8] and [9] with our proposed one. Because these two methods are mainly for doubly selective fading channels and do not consider the influence of PAPR and the UPC parameter. So these two methods cannot be used in our more practical system model.

These results can be explained by the theoretical analysis of SNR in Section IV. At the same time, the mechanism of these results can also be explained as follows. When the uplink UE is near the BS, the received signals have high SNR and the AWGN is small relative to desired user signals. Therefore, the frequency selective fading residual interference after the frequency domain equalization has more dominant effects than the AWGN. For the $(\alpha = 0)$ WFRFT scheme, the IDFT at the receiver can spread all the frequency selective fading residual interference over a part of symbols, which can mitigate the impacts of the frequency selective fading residual interference in this situation. Meanwhile, the $(\alpha = 0)$ WFRFT scheme can have higher SNR because of its lower PAPR. The ($-1 < \alpha < 0$) WFRFT scheme can only spread a part of the frequency selective fading residual interference, because the process of WFRFT ($-1 < \alpha < 0$) has the muticarrier (OFDMA) and SC-FDMA components. Hence, the ($\alpha = 0$) WFRFT scheme can obtain the best BER performance of these schemes, when the UE is near the BS.

When the uplink UE is far from the BS, received signals have very low SNR, and the AWGN becomes much greater relative to desired user signals. At this time, after the IDFT at the ($\alpha = 0$) WFRFT scheme receiver all the frequency selective fading residual interference is spread over a part of symbols, more sample points have a higher probability to make wrong bit decisions because of the frequency selective fading residual interference and the strong AWGN. That is to say, some sample points may not exceed decision boundaries only with the strong AWGN. Nevertheless, on this basis the spread frequency selective fading residual interference may make these points cross decision boundaries. As mentioned before, WFRFT ($-1 < \alpha < 0$) can spread a part of the frequency selective fading residual interference, because of its multicarrier and SC-FDMA components. In the ($\alpha = -1$) WFRFT scheme, the frequency selective fading residual interference is not spread at the receiver because of the absence of WFRFT, and the frequency selective fading residual interference only affects the original sample points in the frequency domain. Therefore, the frequency selective fading residual interference in the ($\alpha = -1$) WFRFT scheme affects fewer sample points, and the ($\alpha = -1$) WFRFT scheme can obtain the best BER performance, when the UE is far from the BS.

When the UE is in the intermediate region, the received SNR is also in the intermediate region. The WFRFT scheme can have the same transmit power as the SC-FDMA scheme through adjusting the WFRFT order. At the same time, WFRFT signals are composed of the SC-FDMA and muticarrier components, which can make a part of frequency selective fading residual interference spread. Therefore, the WFRFT scheme ($-1 \leq \alpha \leq 0$) can obtain the best BER performance of these schemes, when the UE is in the intermediate region.

VI. Conclusion

A new order selection method for the future uplink communication system based on WFRFT has been proposed in this paper, in which the PAPR and the UPC parameter are considered. According to the proposed order selection method, when the UPC parameter to the uplink UE is given, the selected order α is concerned with the distance between the BS and the uplink UE. When the uplink UE is near the BS or far from the BS, the ($\alpha = 0$) WFRFT scheme or the ($\alpha = -1$) WFRFT scheme should be utilized. When the UE is in the intermediate region, the ($-1 \leq \alpha \leq 0$) WFRFT scheme can obtain the best BER performance. Through simulations, the uplink WFRFT system with the proposed order selection method has been verified to obtain better BER performance than the single conventional uplink SC-FDMA or OFDMA system under the frequency selective fading channel.

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