

The Extended Hybrid Carrier-Based Multiple Access Technology for High Mobility Scenarios

Ge Song, Xiaojie Fang, Xuejun Sha*

School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin 150001, China

* The corresponding author, email: shaxuejun@hit.edu.cn

Cite as: G. Song, X. Fang, *et al.*, “The extended hybrid carrier-based multiple access technology for high mobility scenarios,” *China Communications*, 2024, vol. 21, no. 1, pp. 53-68. DOI: 10.23919/JCC.fa.2023-0352.202401

Abstract: The hybrid carrier (HC) system rooted in the carrier fusion concept is gradually garnering attention. In this paper, we study the extended hybrid carrier (EHC) multiple access scheme to ensure reliable wireless communication. By employing the EHC modulation, a power layered multiplexing framework is realized, which exhibits enhanced interference suppression capability owing to the more uniform energy distribution design. The implementation method and advantage mechanism are explicated respectively for the uplink and downlink, and the performance analysis under varying channel conditions is provided. In addition, considering the connectivity demand, we explore the non-orthogonal multiple access (NOMA) method of the EHC system and develop the EHC sparse code multiple access scheme. The proposed scheme melds the energy spread superiority of EHC with the access capacity of NOMA, facilitating superior support for massive connectivity in high mobility environments. Simulation results have verified the feasibility and advantages of the proposed scheme. Compared with existing HC multiple access schemes, the proposed scheme exhibits robust bit error rate performance and can better guarantee multiple access performance in complex scenarios of next-generation communications.

Keywords: extended hybrid carrier system; high mo-

bility communications; multiple access

I. INTRODUCTION

With the commercial implementation of the 5G networks on a global scale, much attention is paid to the research of next-generation communication systems. The impending 6G, building upon the foundation of 5G, will continue to enhance the mobile Internet and is expected to support the vision of wider coverage, higher rates, more connections, lower latency, and others, which places higher demands on physical layer multiple access technologies [1–4].

Traditional multiple access technologies, with orthogonal frequency division multiple access (OFDMA) serving as a representative, have found wide applications within communication standards. Nevertheless, as the research progresses, the limitations of conventional multiple access technologies under high-mobility wireless channels render them inadequate for reliable communication requirements in complex scenarios, and an urgent necessity to explore new physical layer waveform technologies and multiple access technologies emerges [5–8]. On the one hand, there is an anticipation for the continued evolution and optimization of orthogonal multiple access (OMA) schemes. Researchers have extensively explored multiple access schemes that exhibit good robustness along with universality and have investigated low-complexity detection algorithms for different models. Especially, the development of new

Received: Jun. 09, 2023

Revised: Nov. 20, 2023

Editor: Yuanwei Liu

modulation technologies aimed at 6G significantly provides support for reliable transmission in high mobility scenarios [9–12]. On the other hand, considering the scarcity of spectrum resources relative to the growing number of users, non-orthogonal multiple access (NOMA) technology has been perceived as an efficient solution to the challenges of massive access. NOMA allows multiple users to use the same time-frequency resources, thereby enhancing the spectral efficiency, also known as “multi-user superposition transmission” or “layered division multiplexing”. Researchers have proposed a series of non-orthogonal multiple access schemes to serve more users through non-orthogonal designs in the power domain, code domain, and so forth. Among them, sparse code multiple access (SCMA) is a promising code domain NOMA technology and its performance is related to the design of the codebook [13–16]. Moreover, research on the joint of multiple access with other communication technologies to improve system performance has also garnered attention [17–20]. As investigations deepen, combined consideration of the novel waveform framework design and multiple access schemes has become a focal point.

In recent years, the hybrid carrier (HC) as a novel system based on the idea of carrier fusion has received increasing attention and study [21–23]. The HC scheme provides the energy spread of the signal in the time and frequency domain by weighted fractional Fourier transform (WFRFT) to form a fused signal containing the single carrier (SC) components and multi-carrier (MC) components. Compared to traditional schemes, the HC signal has a more uniform energy distribution structure and is therefore considered to have the potential for reliable data transmission over high-mobility wireless channels. Additionally, it has the advantages of low complexity along with flexibility and can be degraded into SC or MC systems, rendering it suitable for upgrading existing communication systems. Research on HC is primarily centered around the design of symbol energy distribution, joint optimization for various scenarios, physical layer security, and others. Furthermore, compatibility is leveraged to combine with other candidate waveforms to obtain performance and flexibility enhancement [24–27]. In terms of multiple access, hybrid carrier OMA schemes represented by HC-FDMA have achieved commendable application effects. The en-

ergy spread design based on carrier fusion allows them to achieve superior bit error rate (BER) performance under doubly-selective channels compared to traditional OFDMA and SC-FDMA schemes. Research on developing NOMA schemes based on hybrid carrier systems to enhance spectral efficiency and the number of user connections has also yielded certain results [28–31]. However, the energy distribution design of the existing hybrid carrier multiple access technologies is highly reliant on the four-component structure of WFRFT, which constrains further enhancement of its performance. Therefore, it is valuable to extend and optimize the hybrid carrier multiple access technology to fully exploit its robustness advantages and better support for improving the performance of the HC system.

This paper investigates the extended hybrid carrier system multiple access scheme. Leveraging the energy distribution design capability of EHC modulation, we design matched orthogonal multiple access schemes for the uplink and downlink respectively. The system architecture and principles are illustrated, and the performance of the proposed scheme is analyzed under different channel conditions. Moreover, we introduce a novel extended hybrid carrier sparse code multiple access (EHC-SCMA) scheme, elucidating its implementation flow, describing the transform domain input-output relation, and explaining the signal detection algorithm. Finally, simulations are provided to demonstrate the feasibility and advantages of the proposed scheme. The main aim of this paper is to confirm that the extended hybrid carrier multiple access scheme can better ensure reliability in complex scenarios, and is a promising alternative solution for the next generation communication systems.

The rest of this paper is organized as follows: Section II presents the basics of the HC system. Section III proposes the EHC-OMA scheme and analyzes its performance. Section IV investigates the non-orthogonal multiple access for the EHC system and describes the proposed EHC-SCMA scheme. Section V gives the simulation and discussion. Finally, conclusions are illustrated in Section VI.

II. PRELIMINARY

2.1 Hybrid Carrier System Based on WFRFT

The hybrid carrier system is proposed based on the carrier fusion concept, which can be regarded as the integration of the SC system and MC system. The classical HC system is generally implemented by WFRFT which can be expressed as

$$\mathbf{F}^\alpha \mathbf{x} = (\omega_0^\alpha \mathbf{F}^0 + \omega_1^\alpha \mathbf{F}^1 + \omega_2^\alpha \mathbf{F}^2 + \omega_3^\alpha \mathbf{F}^3) \mathbf{x}, \quad (1)$$

where $\mathbf{F}$ is the normalized Fourier transform matrix, satisfying $[\mathbf{F}]_{m,n} = \frac{1}{\sqrt{N}} \exp\left[-\frac{2\pi mn}{N}j\right]$, $m, n = 0, 1, \dots, N-1$ and $[\cdot]_{m,n}$ denotes the m th row and n th column elements. $\mathbf{F}^i \mathbf{x}$, $i = 0, 1, 2, 3$ denote the 0-3 times normalized DFT of $\mathbf{x}$ respectively. ω_l^α , $l = 0, 1, 2, 3$ are the weighting coefficients, which can be generated by

$$\omega_l^\alpha = \cos\left[\frac{(\alpha-l)\pi}{4}\right] \cos\left[\frac{(\alpha-l)\pi}{2}\right] \exp\left[\frac{3\pi(\alpha-l)}{4}j\right], \quad (2)$$

where α denotes the transform order. Due to the periodicity, $\mathbf{F}$ satisfies $\mathbf{F}^0 = \mathbf{I}$, $\mathbf{F}^1 = \mathbf{F}$, $\mathbf{F}^2 = \mathbf{\Pi}$, $\mathbf{F}^3 = \mathbf{F}\mathbf{\Pi}$, $\mathbf{F}^4 = \mathbf{I}$, where $[\mathbf{\Pi}]_{m,n} = \delta(\langle m+n \rangle_N)$, and the result of WFRFT can be considered as a weighted sum of the time domain characterizations and frequency domain characterizations of the input sequence. In particular, HC is equivalent to SC when $\alpha = 0$, and to MC when $\alpha = 1$. According to the hybrid carrier fusion mechanism, the single carrier component and the multi-carrier component of the HC signal can be expressed as

$$W_{SC}(\alpha) = |\omega_0^\alpha|^2 + |\omega_2^\alpha|^2, \quad (3)$$

$$W_{MC}(\alpha) = |\omega_1^\alpha|^2 + |\omega_3^\alpha|^2. \quad (4)$$

For any α , there is $\sum_{l=0}^3 |\omega_l^\alpha|^2 = W_{SC}(\alpha) + W_{MC}(\alpha) = 1$. By choosing the transform order, the HC system obtains more freedom in the design of the energy distribution and therefore exhibits better interference suppression performance.

2.2 Sparse Code Multiple Access

SCMA is a promising non-orthogonal multiple access scheme for mobile communication systems. Consider an SCMA system containing V independent users, and the overloading factor is denoted as $\zeta = V/K > 1$, where K is the number of the resource. The role of the

SCMA encoder is to map $\log_2 M$ bits data $\mathbf{b}_v$ of user v into M' dimension constellation and the K dimension codeword $\mathbf{c}_v$ by mapping matrix $\mathbf{\Upsilon}^v \in \mathbb{B}^{K \times M'}$. The codebook $\mathcal{C}$ is shared by the transmitter and the receiver, and M is the number of codewords. Then, for the v th user, the SCMA encoding is defined as the following mapping rule

$$f_v : \mathbb{B}^{\log_2 M \times 1} \mapsto \mathcal{C}_v, i.e., \mathbf{c}_v = f_v(\mathbf{b}_v), \quad (5)$$

where $\mathbf{b}_v \in \mathbb{B}^{\log_2 M \times 1}$ is the information vector from the v th user, $\mathcal{C}_v = \mathcal{C}_{\mathfrak{M}}^v \in \mathbb{C}^{K \times 1}$ denotes the SCMA codeword selected from the codebook, and $\mathfrak{M} = 0, 1, \dots, M-1$. Define the indicator matrix $\bar{\mathbf{F}} = [\bar{\mathbf{f}}_0, \bar{\mathbf{f}}_1, \dots, \bar{\mathbf{f}}_{V-1}]$ satisfying

$$\bar{\mathbf{f}}_v = \text{diag}(\mathbf{\Upsilon}^v (\mathbf{\Upsilon}^v)^T). \quad (6)$$

SCMA can be determined directly by the indicator matrix. The user node k' is connected to the resource node k when and only when $\bar{\mathbf{F}}$ meets $\bar{\mathbf{F}}_{k,k'} \neq 0$. For the downlink, it can be obtained that

$$\mathbf{c} = \sum_{v=0}^{V-1} |\mathbf{c}_v|^2, \quad (7)$$

where $\mathbf{c} \in \mathbb{C}^{K \times 1}$ is called the superimposed codeword. At the receiver, based on the indicator matrix, the SCMA codeword can be decoded using the message passing algorithm decoder with the computational complexity $\mathcal{O}(t' K d_c^2 M^{d_c})$, where d_c is the number of non-zero entries in each row of indicator matrix, and t' is the number of MPA iterations.

III. EXTENDED HYBRID CARRIER ORTHOGONAL MULTIPLE ACCESS

3.1 Extended Hybrid Carrier Frequency Division Multiple Access

In this section, we propose a novel extended hybrid carrier multiple access scheme for the uplink. The proposed scheme combines the energy spread concept of hybrid carrier with the model of frequency division multiple access and is referred to as the extended hybrid carrier frequency division multiple access (EHC-FDMA). Since the enhanced capability of energy dis-

tribution design, the proposed scheme provides superior interference suppression performance compared to the HC-FDMA scheme. Simultaneously, the compatible framework renders it suitable for the smooth evolution of the hybrid carrier multiple access system. The block diagram of the proposed scheme is depicted in Figure 1.

Consider a multiple access system with V users. At the transmitter, as shown in Figure 1(a), assuming that N_v subcarriers can be assigned to the v th user. Then, for each data block, the sequence $\mathbf{s}^v$ of length N_v obtained by baseband mapping can be regarded as a signal in the transform domain. Transform it to the frequency domain by EWFRFT as

$$\tilde{\mathbf{s}}^v = \mathcal{F}[\mathbf{s}^v] = \sum_{l=0}^{N_v-1} \omega_l \mathcal{T}_l[\mathbf{s}^v], \quad (8)$$

where $\mathcal{T}_l[\cdot] = (\mathcal{T}^l)[\cdot]$ is the base operator of the transform, which can be chosen as a cyclic shift operator, and $\boldsymbol{\Omega} = [\omega_0, \omega_1, \dots, \omega_{N_v-1}]^T$ denotes the weighting coefficient vector, which can be generated by the following method.

$$\omega_l = \frac{1}{N_v} \sum_{k=0}^{N_v-1} \exp \left[\left(\beta_k - \frac{2\pi}{N_v} lk \right) j \right]. \quad (9)$$

The frequency domain sequence of length N_v is mapped to the subcarrier assigned to the user v , and the subcarriers occupied by other users are filled with zeros. The signal is transformed to the time domain expressed as

$$\mathbf{x}^v = \mathbf{F}^{-1} \boldsymbol{\Theta}^v \tilde{\mathbf{s}}^v = \mathbf{F}^{-1} \boldsymbol{\Theta}^v \mathbf{E}_v \mathbf{s}^v, \quad (10)$$

where $\mathbf{E}_v$ is the extended weighted fractional Fourier transform matrix. Let $\psi_{k'}^v, 0 \leq k' \leq N_v - 1$ denote the subcarrier index allocated to user v , then the subcarrier mapping matrix $\boldsymbol{\Theta}^v$ meets

$$\Theta_{k,k'}^v = \begin{cases} 1, k = \psi_{k'}^v \\ 0, k \neq \psi_{k'}^v \end{cases}, 0 \leq k \leq L-1. \quad (11)$$

The sequence is processed by cyclic prefix insertion and sent through a single antenna. Assume that the

signals from V user terminals are transmitted through separate channels to reach the base station. After removing the cyclic prefix and other operations, the baseband signal can be expressed as

$$\mathbf{y} = \sum_{v=0}^{V-1} \mathbf{H}^v \mathbf{x}^v + \mathbf{z}, \quad (12)$$

where $\mathbf{H}^v$ denotes the time domain channel matrix of the user v and $\mathbf{z}$ is additive white Gaussian noise. By transforming the received signal into the frequency domain and performing subcarrier demapping along with the corresponding inverse EWFRFT, the transform domain signal of the v th user can be expressed as

$$\mathbf{r}_v = \mathbf{E}_v \boldsymbol{\Theta}_v^H \mathbf{F} \sum_{v=0}^{V-1} \mathbf{H}^v \mathbf{F}^{-1} \boldsymbol{\Theta}^v \mathbf{E}_v \mathbf{s}^v + \mathbf{E}_v \boldsymbol{\Theta}_v^H \mathbf{F} \mathbf{z}. \quad (13)$$

Due to the channel time-frequency dispersion, the orthogonality between signals of different users is destroyed at the base station, causing multi-user interference. Jointly considering the received signals of multi-user, let $\mathbf{s} = h(\mathbf{s}^0, \mathbf{s}^1, \dots, \mathbf{s}^{V-1})$ denote the equivalent transmitted signal, where $h(\mathbf{a}_0, \mathbf{a}_1, \dots, \mathbf{a}_k) = [\mathbf{a}_0^T, \mathbf{a}_1^T, \dots, \mathbf{a}_k^T]^T$, then we have

$$\mathbf{r} = \tilde{\mathbf{E}}^H \tilde{\mathbf{H}} \tilde{\mathbf{E}} \mathbf{s} + \tilde{\mathbf{E}}^H \mathbf{P}^H \mathbf{F} \mathbf{z}, \quad (14)$$

where $\mathbf{P} = [\boldsymbol{\Theta}^0, \boldsymbol{\Theta}^1, \dots, \boldsymbol{\Theta}^{V-1}]$ denotes the permutation matrix. $\tilde{\mathbf{H}} = \mathbf{P}^H \mathbf{F} \sum_{v=0}^{V-1} \mathbf{H}^v \mathbf{F}^{-1} \mathbf{P} \tilde{\mathbf{T}}^v$ is the time domain equivalent channel matrix and $\tilde{\mathbf{T}}^v$ is the diagonal matrix satisfying $\tilde{\mathbf{T}}_{k,k}^v = \delta \left(\left\lfloor \frac{k - \bar{n}_v}{N_v} \right\rfloor \right)$, $\bar{n}_v = \sum_{v'=0}^{v-1} N_{v'}$. $\tilde{\mathbf{E}} = \text{diag}[\mathbf{E}_0, \mathbf{E}_1, \dots, \mathbf{E}_{V-1}]$. Let $\mathbf{H}_E = \sum_{v'=0}^{V-1} \mathbf{H}_{v'}$. $\tilde{\mathbf{E}}^H \tilde{\mathbf{H}} \tilde{\mathbf{E}}$ denote the transform domain equivalent channel matrix, then $\mathbf{r}$ can be obtained as

$$\mathbf{r} = \mathbf{H}_E \mathbf{s} + \mathbf{z}'. \quad (15)$$

The estimated signal $\hat{\mathbf{s}} = \mathbf{G} \mathbf{r}$ is obtained by performing transform domain signal detection on $\mathbf{r}$. Next, the performance of the proposed scheme is analyzed. Assuming that minimum mean square error (MMSE) detection is employed, the estimated signal can be ex-

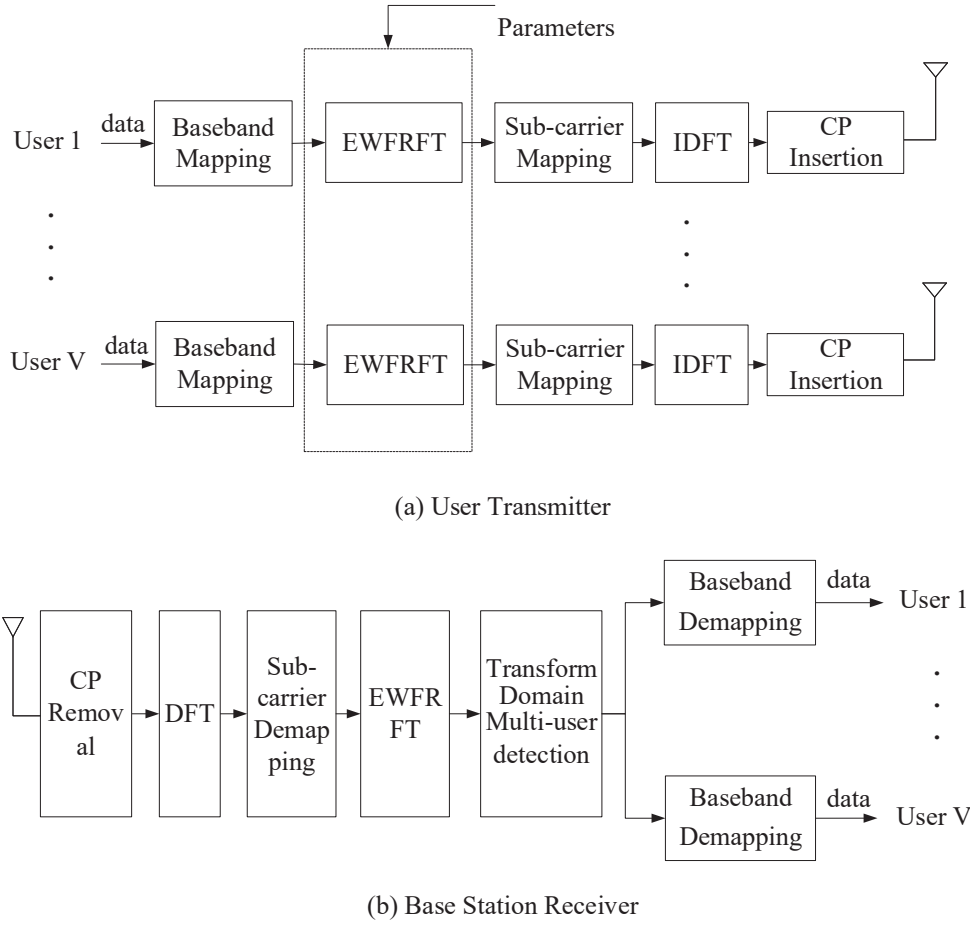


Figure 1. The block diagram of the EHC-FDMA system.

pressed as

$$\begin{aligned} \hat{s}_t^v = & \sum_{n=0}^{L-1} \left| \tau_{\rho_{v,t},n} \right|^2 \frac{\gamma |\Lambda_n|^2}{1 + \gamma |\Lambda_n|^2} s_t^v + \sum_{n=0}^{L-1} \tau_{\rho_{v,t},n}^{-1} \frac{\gamma \Lambda_n^* z_n}{1 + \gamma |\Lambda_n|^2} \\ & + \sum_{g=0, g \neq t}^{N_v-1} \sum_{n=0}^{L-1} \tau_{\rho_{v,t},n}^{-1} \tau_{n,\rho_{v,g}} \frac{\gamma |\Lambda_n|^2}{1 + \gamma |\Lambda_n|^2} s_g^v \\ & + \sum_{v'=0, v' \neq v}^{V-1} \sum_{q=0}^{N_{v'}-1} \sum_{n=0}^{L-1} \tau_{\rho_{v,t},n}^{-1} \tau_{n,\rho_{v',q}} \frac{\gamma |\Lambda_n|^2}{1 + \gamma |\Lambda_n|^2} s_q^{v'}, \end{aligned} \quad (16)$$

where the second and third rows of the equation denote subcarrier interference and multi-user interference for the t symbol of the v th user, respectively. $\tau_{n,m}$ denotes the n th row and m th column element of matrix $\mathbf{Q} = \mathbf{R}^H \tilde{\mathbf{E}}$ where $\tilde{\mathbf{H}} = \mathbf{D} \mathbf{\Lambda} \mathbf{R}^H$, and $\rho_{\varepsilon,t} = \sum_{v'=0}^{\varepsilon-1} N_{v'} + \iota$. Then the theoretical BER under J -QAM modulation

can be expressed as

$$P_b = \frac{1}{L} \sum_{v=0}^{V-1} \sum_{t=0}^{N_v-1} \frac{4c_1}{\log_2 J} Q \left(\sqrt{c_2 \gamma_t^v} \right), \quad (17)$$

where $c_1 = 1 - \frac{1}{\sqrt{J}}$, $c_2 = \frac{3}{J-1}$, Q function is defined as $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt$, $x \geq 0$. Let $\bar{\Gamma}_n = \frac{\gamma |\Lambda_n|^2}{1 + \gamma |\Lambda_n|^2}$, and γ_t^v denote the equivalent signal-to-noise ratio, satisfying

$$\gamma_t^v = \mathbb{E} \left[\left| \tau_{\rho_{v,t},n} \right|^2 \bar{\Gamma}_n \right] / \left(\frac{1}{L} - \mathbb{E} \left[\left| \tau_{\rho_{v,t},n} \right|^2 \bar{\Gamma}_n \right] \right). \quad (18)$$

In particular, for the frequency-selective channels, the equivalent channel matrix satisfies

$$\mathbf{H}_E = \tilde{\mathbf{E}}^H \mathbf{P}^H \sum_{v=0}^{V-1} \tilde{\mathbf{H}}^v \mathbf{P} \tilde{\mathbf{Y}}^v \tilde{\mathbf{E}}, \quad (19)$$

where $\bar{\mathbf{H}}^v = \mathbf{F}\mathbf{H}^v\mathbf{F}^H$ is a diagonal matrix satisfying $\bar{H}_{k,k}^v = \sum_{i=0}^{\eta-1} h_i e^{-\frac{2\pi i k}{L}}$. Let $\bar{\mathbf{\Lambda}} = \mathbf{P}^H \sum_{v=0}^{V-1} \bar{\mathbf{H}}^v \mathbf{P} \bar{\mathbf{\Gamma}}^v$, and the estimated signal under MMSE equalization can be expressed as

$$\hat{\mathbf{s}} = \mathbf{G}\mathbf{r} = \tilde{\mathbf{E}}^H (\bar{\mathbf{\Lambda}}^H \bar{\mathbf{\Lambda}} + \sigma^2 \mathbf{I})^{-1} \bar{\mathbf{\Lambda}}^H \bar{\mathbf{\Lambda}} \tilde{\mathbf{E}} \mathbf{s} + \mathbf{z}', \quad (20)$$

where $\bar{\mathbf{\Lambda}} = \text{diag} [\bar{\Lambda}_0, \bar{\Lambda}_1, \dots, \bar{\Lambda}_{L-1}]$ is a diagonal matrix and $\mathbf{G}\mathbf{H}_E$ is a blocked diagonal matrix, indicating that different users remain orthogonal and is not affected by the multiple access interference. Therefore, the detection can be performed separately. For the v th user, we have

$$\begin{aligned} \hat{\mathbf{s}}^v &= \mathbf{G}^v \mathbf{H}_E^v \mathbf{s}^v + \mathbf{G}^v \mathbf{z}^v \\ &= \mathbf{E}_v^H (\bar{\mathbf{\Lambda}}_v^H \bar{\mathbf{\Lambda}}_v + \sigma^2 \mathbf{I})^{-1} \bar{\mathbf{\Lambda}}_v^H \bar{\mathbf{\Lambda}}_v \mathbf{E}_v \mathbf{s}^v + \mathbf{z}'_v, \end{aligned} \quad (21)$$

where $\mathbf{H}_E^v = \mathbf{E}_v^H \bar{\mathbf{\Lambda}}_v \mathbf{E}_v$ denotes the equivalent channel matrix of the v th user $\bar{\mathbf{\Lambda}}_v = \text{diag} [\bar{\Lambda}_{\rho_{v,0}}, \bar{\Lambda}_{\rho_{v,1}}, \dots, \bar{\Lambda}_{\rho_{v,N_v-1}}]$, and $\mathbf{G}^v = \mathbf{E}_v^H (\bar{\mathbf{\Lambda}}_v^H \bar{\mathbf{\Lambda}}_v + \sigma^2 \mathbf{I})^{-1} \bar{\mathbf{\Lambda}}_v \mathbf{E}_v$ is the transform domain equalization matrix. Then the estimated signal can be expressed as

$$\begin{aligned} \hat{s}_t^v &= \sum_{n=0}^{N_v-1} |\varepsilon_{t,n}^v|^2 \frac{\gamma |\bar{\Lambda}_{\rho_{v,n}}|^2}{1 + \gamma |\bar{\Lambda}_{\rho_{v,n}}|^2} s_t^v + \sum_{n=0}^{N_v-1} \frac{\varepsilon_{t,n}^{-1} \gamma \bar{\Lambda}_{\rho_{v,n}}^* z_n}{1 + \gamma |\bar{\Lambda}_{\rho_{v,n}}|^2} \\ &+ \sum_{g=0, g \neq t}^{N_v-1} \sum_{n=0}^{N_v-1} \varepsilon_{t,n}^{-1} \varepsilon_{n,g}^v \frac{\gamma |\bar{\Lambda}_{\rho_{v,n}}|^2}{1 + \gamma |\bar{\Lambda}_{\rho_{v,n}}|^2} s_g^v, \end{aligned} \quad (22)$$

where $\varepsilon_{n,m}^v$ denotes the n th row and m th column element of the matrix $\mathbf{E}_v$. We know that when the transform parameters satisfy $\beta_k = \beta_{k-2^\phi} - \frac{k-2^\phi}{2^{\log_2 N_v - 1 - \phi}} \pi - \langle \log_2 N_v \rangle_2 \frac{\pi}{2} \left\lfloor \frac{1}{\phi - \varsigma + 1} \right\rfloor$, $2^\varsigma \leq k \leq N_v - 1$, where $\phi = \lfloor \log_2 k \rfloor$, $\varsigma = \lfloor \log_2 N_v / 2 \rfloor$, the extended weighted fractional Fourier transform matrix satisfies the following relation

$$|\varepsilon_{n,m}^v|^2 = \frac{1}{N_v}, n, m = 0, 1, \dots, N_v - 1. \quad (23)$$

Therefore, the equivalent signal-to-noise ratio can be

expressed as

$$\gamma_t^v = \sum_{n=0}^{N_v-1} \frac{\gamma |\bar{\Lambda}_{\rho_{v,n}}|^2}{1 + \gamma |\bar{\Lambda}_{\rho_{v,n}}|^2} \bigg/ \sum_{n=0}^{N_v-1} \frac{1}{1 + \gamma |\bar{\Lambda}_{\rho_{v,n}}|^2}. \quad (24)$$

It can be found that

$$\gamma_0^v = \gamma_1^v = \dots = \gamma_{N_v-1}^v, v = 0, 1, \dots, V - 1. \quad (25)$$

At this point, according to the property of Q function, the following Jensen inequality holds and satisfies the condition of taking the minimum value.

$$\begin{aligned} P_b &= \frac{1}{L} \sum_{p=0}^{L-1} \frac{4c_1}{\log_2 J} Q(\sqrt{c_2 \gamma_p}) \\ &\geq \frac{1}{V} \frac{4c_1}{\log_2 J} \sum_{v=0}^{V-1} Q\left(\frac{1}{N_v} \sum_{t=0}^{N_v-1} \sqrt{c_2 \gamma_t^v}\right). \end{aligned} \quad (26)$$

That is, the BER of the proposed scheme can be expressed as

$$P_b = \frac{1}{V} \frac{4c_1}{\log_2 J} \sum_{v=0}^{V-1} Q\left(\sqrt{c_2 \frac{\sum_{n=0}^{N_v-1} \frac{\gamma |\bar{\Lambda}_{\rho_{v,n}}|^2}{1 + \gamma |\bar{\Lambda}_{\rho_{v,n}}|^2}}{\sum_{n=0}^{N_v-1} \frac{1}{1 + \gamma |\bar{\Lambda}_{\rho_{v,n}}|^2}}}\right). \quad (27)$$

According to the hybrid carrier fusion mechanism, the equivalent signal-to-noise ratio of the conventional HC-FDMA scheme is the weighted superposition of SC components and MC components, with the power allocation scheme controlled by the transform order. However, due to the constraints of the four-component structure, it is challenging to satisfy the condition shown in Eq.(25), thereby revealing defects in its BER performance. In contrast, the proposed scheme exhibits superior time-frequency energy distribution design capability, enabling improved compensation for channel interference and multiple access interference, and thus displaying superior performance.

3.2 Extended Hybrid Carrier Orthogonal Power Layered Multiple Access

In this subsection, we design a novel orthogonal multiple access scheme for the downlink, aimed at the enhancement of HC-OMA system performance. Unlike

existing multiple access schemes, each user can occupy the entire time-frequency resources in the proposed scheme. The symbols of different users superimpose on the time-frequency plane in the form of power layered multiplexing and maintain transform domain orthogonality. Hence, we call it the extended hybrid carrier orthogonal power layered multiplex access (EHC-OPLMA) scheme. Due to the uniform signal distribution, the proposed scheme exhibits superior anti-fading performance, further improving the reliability of the multiple access scheme. Figure 2. illustrates the basic structure of the proposed scheme. At the base station, the extended hybrid carrier modulation is performed on the transform domain signal after symbol mapping, which can be expressed as

$$\mathbf{x} = \mathbf{E} \sum_{v=0}^{V-1} \Theta^v \mathbf{s}^v, \quad (28)$$

where $\mathbf{E}$ denotes the extended hybrid carrier modulation matrix of size $L \times L$. In this system, each user can utilize all the available time-frequency resources, thus gaining better channel diversity. At the receiver, since multiplexed power layers are orthogonal in the transform domain, the signal of different users can be separated and extracted. For the v th user, we can obtain

$$\mathbf{y}_v = \mathbf{H}^v \mathbf{E} \mathbf{s} + \mathbf{z}_v, \quad (29)$$

where $\mathbf{H}^v$ is the channel matrix of user v and $\mathbf{s} = \sum_{v=0}^{V-1} \Theta^v \mathbf{s}^v$. Due to the even energy spread, different symbol mapping methods have little effect on the EHC-OPLMA downlink, so we assume that a continuous symbol mapping scheme is adopted. The extended hybrid carrier demodulation is conducted as

$$\mathbf{r}_v = \mathbf{E}^{-1} \mathbf{y}_v = \mathbf{H}'_v \mathbf{s} + \mathbf{z}'_v, \quad (30)$$

where $\mathbf{z}'_v = \mathbf{E}^{-1} \mathbf{z}_v$ and $\mathbf{H}'_v = \mathbf{E}^{-1} \mathbf{U}'_v \mathbf{\Lambda}'_v \mathbf{V}'_v \mathbf{E}$ denotes the equivalent channel matrix of the v th user, and $\mathbf{\Lambda}'_v$ denotes the diagonal matrix composed of the eigenvalues $\Lambda'_n, n = 0, 1, \dots, L-1$. Then the detector using the MMSE criterion can be expressed as $\mathbf{G}'_v = \bar{\mathbf{E}}^{-1} [(\mathbf{\Lambda}'_v)^H \mathbf{\Lambda}'_v + \sigma^2 \mathbf{I}]^{-1} (\mathbf{\Lambda}'_v)^H \bar{\mathbf{E}}$ and $\tau_{n,m}^v$ denote the n th row and m th column element of $\bar{\mathbf{E}}^v = (\mathbf{V}'_v)^H \mathbf{E}$. Then the estimated signal can be expressed

as

$$\begin{aligned} \hat{s}_t^v &= \sum_{n=0}^{L-1} |\tau_{t,n}^v|^2 \frac{\gamma |\Lambda_n^v|^2}{1 + \gamma |\Lambda_n^v|^2} s_t + \sum_{n=0}^{L-1} \tau_{t,n}^{-1} \frac{\gamma \Lambda_n^{v*}}{1 + \gamma |\Lambda_n^v|^2} z_n^v \\ &+ \sum_{g=\rho_{v,0}, g \neq t}^{\rho_{v,N_v}-1} \sum_{n=0}^{L-1} \tau_{t,n}^{-1} \tau_{n,g}^v \frac{\gamma |\Lambda_n^v|^2}{1 + \gamma |\Lambda_n^v|^2} s_g \\ &+ \sum_{v'=0, v' \neq v}^{V-1} \sum_{q=\rho_{v',0}}^{\rho_{v',N_{v'}}-1} \sum_{n=0}^{L-1} \tau_{t,n}^{-1} \tau_{n,q}^{v'} \frac{\gamma |\Lambda_n^v|^2}{1 + \gamma |\Lambda_n^v|^2} s_q. \end{aligned} \quad (31)$$

The third and fourth terms of the equation represent the multipath interference and multi-user interference after compensation, respectively. We define $e_t^v = \hat{s}_t^v - s_t^v$ as the residual interference of the t th symbol of user v . Then, for the proposed scheme, the total residual interference can be expressed as

$$\mathbf{I} = \sum_{v=0}^{V-1} \sum_{n=0}^{N_v-1} \frac{\sigma_z^2}{|\Lambda_n^v|^2 + \sigma_z^2}. \quad (32)$$

The overall residual interference in the system is related to the channel conditions each user experiences, independent of the signal processing method. Consequently, the EHC-OPLMA scheme alters only the distribution of residual interference, without introducing additional multipath or multiple access interference. The proposed scheme implements uniform energy spread through extended hybrid carrier modulation. And the residual interference of each symbol can be shared by the entire time-frequency resource, thereby exhibiting stronger residual interference suppression capability, a prominent advantage of the proposed scheme. For the v th user, the equivalent signal-to-noise ratio can be expressed as

$$\gamma_t^v = \sum_{n=0}^{L-1} |\tau_{t,n}^v|^2 \frac{\gamma |\Lambda_n^v|^2}{1 + \gamma |\Lambda_n^v|^2} \bigg/ \sum_{n=0}^{L-1} |\tau_{t,n}^v|^2 \frac{1}{1 + \gamma |\Lambda_n^v|^2}. \quad (33)$$

Owing to the energy distribution design, the proposed scheme achieves more uniform residual interference. Consequently, for each user, the equivalent signal-to-noise ratio of different symbols is identical over the single-selective channels, meeting the optimal BER condition under Jensen inequality, and the results are close in the case of the doubly-selective channels. Specifically, in the frequency-selective channels, we

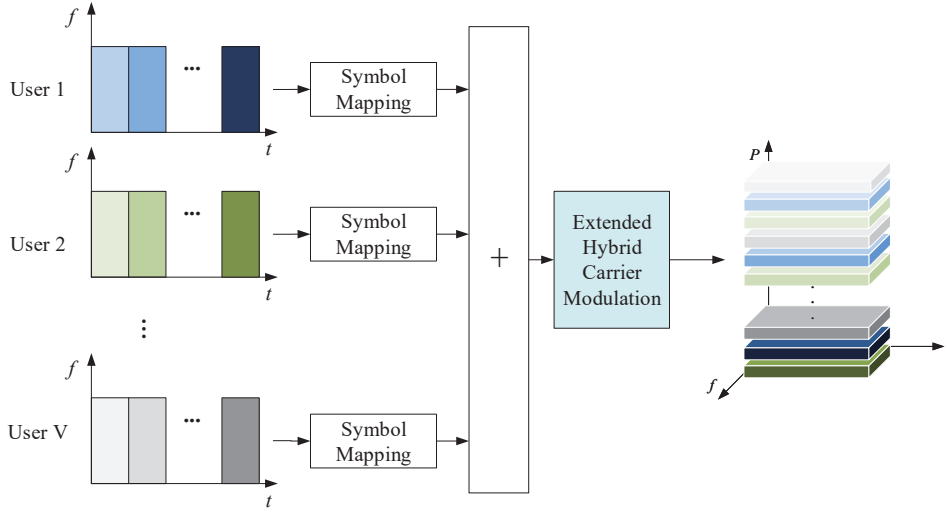


Figure 2. The model of the EHC-OPLMA scheme.

have

$$|\tau_{t,n}^v|^2 = |[\mathbf{F}\mathbf{E}]_{t,n}|^2 = \frac{1}{L}, t, n = 0, 1, \dots, L-1. \quad (34)$$

Therefore, the BER satisfies

$$\begin{aligned} P_b^v &= \frac{1}{N_v} \sum_{t=0}^{N_v-1} \frac{4c_1}{\log_2 J} Q \left(\sqrt{c_2 \sum_{n=0}^{L-1} \gamma |\Lambda_n^v|^2 \bar{K}_n^v} / \sum_{n=0}^{L-1} \bar{K}_n^v \right) \\ &\leq \frac{1}{N_v} \sum_{t=0}^{N_v-1} \frac{4c_1}{\log_2 J} Q \left(\sqrt{c_2 / (\Omega_{MC}^t + E[\Omega_{SC}^n]) - c_2} \right) \\ &= P_{HC}^v, \end{aligned} \quad (35)$$

where $\bar{K}_n^v = \frac{1}{1 + \gamma |\Lambda_n^v|^2}$, $\Omega_{MC}^t = W_{MC} / (1 + \gamma |\Lambda_t^v|^2)$ and $\Omega_{SC}^n = W_{SC} / (1 + \gamma |\Lambda_n^v|^2)$ are related to the transform parameter α . Similarly, under the time-selective channels, since $|\mathbf{E}_{t,n}|^2 = 1/L, t, n = 0, 1, \dots, L-1$, we can obtain

$$P_b^v = \frac{1}{N_v} \sum_{t=0}^{N_v-1} \frac{4c_1}{\log_2 J} Q \left(\sqrt{c_2 \tilde{\gamma}_t^v} \right) \leq P_{HC}^v. \quad (36)$$

The proposed scheme constructs a power layered multiplexing model through extended hybrid carrier modulation and achieves higher gain as each user fully utilizes the available time-frequency resources. Compared to the HC-OMA system, the proposed scheme

exhibits a notable performance improvement over both single-selective channels and doubly-selective channels.

IV. EXTENDED HYBRID CARRIER NON-ORTHOGONAL MULTIPLE ACCESS

In this section, we investigate the non-orthogonal multiple access technology of the extended hybrid carrier system, proposing an EHC-SCMA scheme based on transform domain signal processing. The proposed scheme combines the carrier fusion advantage of the extended hybrid carrier signal with the massive connectivity capability of non-orthogonal multiple access, which can better meet the requirements of the next-generation communication systems.

4.1 In Downlink

Consider a downlink scenario with V users. At the base station, the signal of different users is processed in the transform domain with coding and superposition, which can be expressed as

$$\mathbf{S}_q = \sum_{v=0}^{V-1} \mathbf{s}_q^v, \quad (37)$$

where $\mathbf{s}_q^v \in \mathbb{C}^{K \times 1}$ denotes the q th SCMA codeword of the v th user. In this system, V users share K orthogonal resources. Symbol mapping is performed on the superposition result, and each codeword is assigned

to the $M \times N$ transform domain grid to obtain the transform domain transmit signal $\mathbf{S}$. The time domain signal $\mathbf{x}$ is obtained by EHC modulation and series-parallel conversion, which can be expressed as

$$\mathbf{x} = \text{vec}(\mathbf{X}^T) = (\mathbf{E} \otimes \mathbf{I}_M) \text{vec}(\mathbf{S}^T), \quad (38)$$

where $\text{vec}(\cdot)$ denotes the vectorization operator, and $\otimes$ denotes the Kronecker product. Let $\mathbf{s} = \text{vec}(\mathbf{S}) = h(\mathbf{S}_0, \mathbf{S}_1, \dots, \mathbf{S}_{L/K-1})$, then we have $\mathbf{x} = \mathbf{P}_{M,N}(\mathbf{I}_M \otimes \mathbf{E})\mathbf{s}$ and the permutation matrix can be expressed as

$$\mathbf{P}_{M,N} = \begin{bmatrix} \mathbf{I}_M \otimes \mathbf{e}_N^T(0) \\ \mathbf{I}_M \otimes \mathbf{e}_N^T(1) \\ \vdots \\ \mathbf{I}_M \otimes \mathbf{e}_N^T(N-1) \end{bmatrix}. \quad (39)$$

After EHC modulation, the CP is inserted and RF processing is conducted. Figure 3. depicts the model of the proposed scheme, where M and N are generally chosen as an integer multiple of K . In the EHC-SCMA scheme, the energy spread is feasible both between codewords and within codewords. When $M = 1$, the energy of each codeword is extended equally over the entire data block containing MN/K codewords, achieving a uniform distribution of symbol energy. In the following analysis, we will use this case, and the results will be easily extended to other conditions.

At the receiver, as shown in Figure 4, after removing CP and other operations, the signal is first processed by the extended hybrid carrier demodulation, followed by a two-stage detector combining transform domain signal detection and SCMA decoding to obtain the estimated signal. For the v th user, the transform domain equivalent baseband signal can be expressed as

$$\mathbf{r}_v = \mathbf{E}^{-1} \sum_{i=0}^{\eta-1} h_i^v \mathbf{\Xi}_i^{l_i^v} \mathbf{\Delta}^{k_i^v} \mathbf{x} + \mathbf{z}'_v, \quad (40)$$

where $\mathbf{z}_v$ denotes Gaussian white noise, $\mathbf{H}^v$ denotes the channel matrix of user v , and h_i^v is the complex gain of the i th path. $\mathbf{\Xi}_i^{l_i^v}$ is the

permutation matrix, which satisfies $\mathbf{\Xi}_{m,n}^{l_i^v} = \delta(\langle m - n - l_i^v \rangle_L)$, and $\max(l_i^v) < L$. $\mathbf{\Delta}^{k_i^v} = \text{diag}[1, \exp(2\pi k_i^v j/L), \dots, \exp(2\pi k_i^v (L-1)j/L)]$ is the diagonal matrix. Then the equivalent channel matrix $\mathbf{H}'_v$ of the v th user can be expressed as

$$\mathbf{H}'_v = \mathbf{E}^{-1} \sum_{i=0}^{\eta-1} h_i^v \mathbf{\Xi}_i^{l_i^v} \mathbf{\Delta}^{k_i^v} \mathbf{E}. \quad (41)$$

Since the extended hybrid carrier modulation matrix is a circulant matrix, it can be decomposed into $\mathbf{E} = \mathbf{F}^H \mathbf{\Sigma} \mathbf{F}$ by the Fourier transform matrix of size $L \times L$, where $\mathbf{\Sigma} = \text{diag}[\varpi_0, \varpi_1, \dots, \varpi_{N-1}]$ and $\omega_k = \frac{1}{L} \sum_{n=0}^{L-1} \exp(-2\pi jkn/L) \varpi_n$. Then i th path of the equivalent channel matrix can be expressed as

$$\mathbf{H}'_{v,i} = h_i^v \mathbf{F}^H \mathbf{\Sigma}^{-1} \mathbf{\Pi}_i^v \mathbf{F} \mathbf{\Delta}^{k_i^v} \mathbf{F}^H \mathbf{\Sigma} \mathbf{F}, \quad (42)$$

where $\mathbf{\Xi}_i^v = \mathbf{F} \mathbf{\Xi}_i^{l_i^v} \mathbf{F}^H$ and satisfying $\mathbf{\Xi}_i^v(k, k) = \exp\left(\frac{-2\pi k l_i^v}{L} j\right)$. Let $\mathbf{\Phi} = \mathbf{F} \mathbf{\Delta}^{k_i^v} \mathbf{F}^H$, then we have

$$\Phi_{p,q} = \frac{1}{L} \frac{\exp(2\pi(k_i^v - p + q)j) - 1}{\exp(2\pi(k_i^v - p + q)j/L) - 1}. \quad (43)$$

When k_i^v is an integer, $\Phi_{p,q} = \delta(\langle p - q - k_i^v \rangle_L)$ holds, and when k_i^v is a fraction, we have

$$|\Phi_{p,q}| \leq \frac{L-1}{L} \left| \cos\left(\frac{\pi(k_i^v - p + q)}{L}\right) \right| + \frac{1}{L}. \quad (44)$$

It can be seen that $|\Phi_{p,q}|$ decreases rapidly as $|\pi(k_i^v - p + q)/L|$ increases, so we can consider only the case of $\bar{k}_i^v - \kappa_i^v \leq k_i^v \leq \bar{k}_i^v + \kappa_i^v$, where $\bar{k}_i^v$ denotes integer Doppler and $|\Phi_{p,q}|$ is less than the sensitivity threshold in the case of $|k_i^v - p + q| > \kappa_i^v$. At this point, we obtain that $\Phi_{p,q}$ takes a nonzero value when $\langle p - \bar{k}_i^v - \kappa_i^v \rangle_L \leq q \leq \langle p - \bar{k}_i^v + \kappa_i^v \rangle_L$. Then the equivalent channel matrix can be expressed as

$$\mathbf{H}'_{v,i} = h_i^v \sum_{g=0}^{2\kappa_i^v} \mathbf{\Psi}_g^{i,v}. \quad (45)$$

Let $\bar{k}_{i,g}^v = \bar{k}_i^v - \kappa_i^v + g$, then when $q = \langle p - l_i^v + \bar{k}_{i,g}^v - c_{g'} \frac{L}{v} \rangle_L$, the elements of row p and column q in $\mathbf{\Psi}_g^{i,v}$ are nonzero, which can be expressed

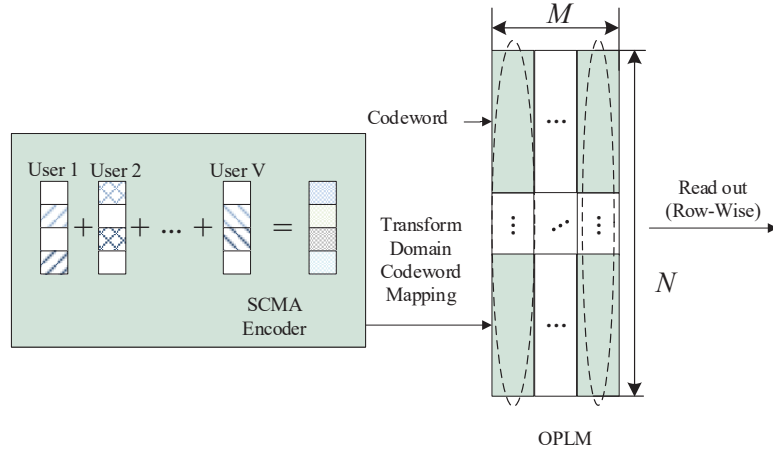


Figure 3. The model of EHC-SCMA in downlink.

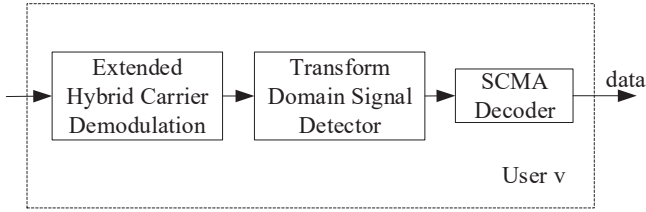


Figure 4. The block diagram of the receiver.

as

$$\Psi_g^{i,v}(p, q) = \frac{1}{L} \exp \left(\frac{2\pi q \bar{k}_{i,g}^v}{L} j \right) T_{g'}, \quad (46)$$

where $c_{g'}$ stands for $c_{i,g}^v(g')$ meeting $c_{i,g}^v(g') = c(g') - c(g') \delta \left(\langle \bar{k}_{i,g}^v \rangle_{\bar{v}} \right)$, and $\bar{v} = 2^{\lfloor \frac{\log_2 L}{2} \rfloor}$, $c = 1, \dots, \bar{v}$. Let $\varphi_{i,g}^v = \sum_{d=0}^{\bar{v}-1} \exp(j\beta'_{v,d})/\bar{v}$, and $\beta'_{\bar{v},d} = \beta_{\langle d - \bar{k}_{i,g}^v \rangle_{\bar{v}}} - \beta_d + 2\pi c_{g'} d / \bar{v}$, then $T'_{g'}$ can be expressed as $T'_{g'} = \varphi_{i,g}^v T'_{g'}$, where

$$T'_{g'} = \exp \left(-j \frac{\pi}{L} \bar{k}_{i,g}^v 2 \right) \frac{\exp(2\pi j (k_i^v - \bar{k}_{i,g}^v)) - 1}{\exp(2\pi j (k_i^v - \bar{k}_{i,g}^v)/L) - 1}. \quad (47)$$

In this way, we obtain the transform domain input-output relation of the signal. It can be found that the equivalent channel matrix has good sparsity and is suitable for low-complexity detection algorithms. Finally, the estimated signal is obtained by the SCMA detector separately. The proposed scheme achieves

the symbol extension and superposition of multi-user through extended hybrid carrier modulation. The available time-frequency resources can be occupied by the symbol of each user, thereby obtaining higher diversity. At the receiver, the user processes and detects the received signals in the transform domain to cope with the delay and Doppler spread of the doubly-selective channels. Compared to the existing SCMA scheme, due to the uniform energy distribution design of the proposed scheme, the channel interference of each codeword is shared by all codewords, which effectively reduces the impact of residual interference on detection, thereby enhancing the reliability of the multiple access scheme.

4.2 In Uplink

In this subsection, we introduce the uplink of the proposed EHC-SCMA scheme, as shown in Figure 5. For the v th user, the SCMA is conducted and the signal is converted to the time domain by codeword mapping and extended hybrid carrier modulation. The add/remove CP and RF processing modules are omitted from the block diagram for simplicity. The transmit signal for the v th user can be expressed as

$$\mathbf{x}_v = \text{vec}(\mathbf{X}_v^T) = (\mathbf{E} \otimes \mathbf{I}_M) \mathbf{s}_v, \quad (48)$$

where $\mathbf{s}_v = h(S_0^v, S_1^v, \dots, S_{(L-1)/K}^v)$, S_k^v is the k th codeword of SCMA. A diagram of its codeword mapping and extended hybrid carrier modulation is given

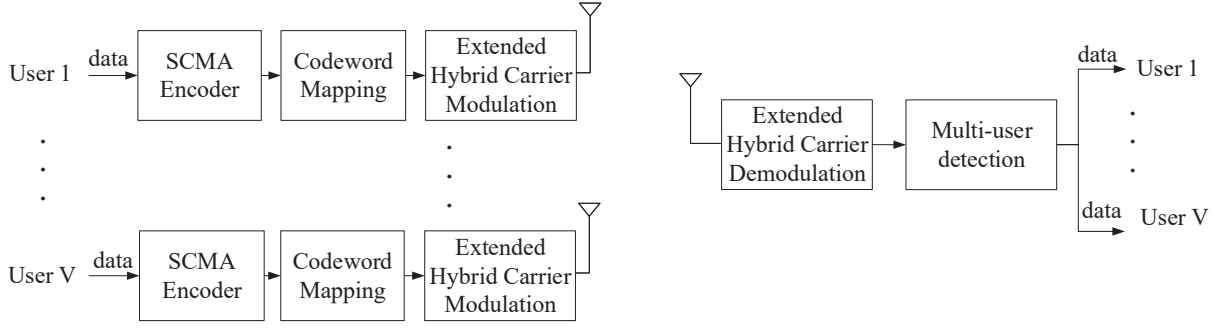


Figure 5. Block diagram of the EHC-SCMA in uplink.

in Figure 6. The SCMA codewords are allocated along the readout direction with energy spread in blocks between different codewords, and generally satisfying $M = \xi K, \xi \in \mathbb{Z}$.

At the receiver, the signal after transform domain signal processing can be expressed as

$$\begin{aligned} \mathbf{r} &= (\mathbf{E}^{-1} \otimes \mathbf{I}_M) \sum_{v=0}^{V-1} \mathbf{H}^v (\mathbf{E} \otimes \mathbf{I}_M) \mathbf{s}_v + (\mathbf{E}^{-1} \otimes \mathbf{I}_M) \mathbf{z} \\ &= \mathbf{H} \bar{\mathbf{s}} + \bar{\mathbf{z}}, \end{aligned} \quad (49)$$

where $\bar{\mathbf{s}} = h(s_0, s_1, \dots, s_{V-1})$, $\mathbf{H}$ is the equivalent channel matrix can be expressed as

$$\mathbf{H} = \sum_{v=0}^{V-1} \mathbf{H}^v \mathbf{\Gamma}_v, \quad (50)$$

where $\mathbf{\Gamma}_v = \mathbf{e}_V(v) \otimes \mathbf{I}_L$, and $\mathbf{H}^v$ can be expressed as

$$\begin{aligned} \mathbf{H}^v &= (\mathbf{E}^{-1} \otimes \mathbf{I}_M) \mathbf{H}^v (\mathbf{E} \otimes \mathbf{I}_M) \\ &= \sum_{i=0}^{\eta_v-1} h_i^v (\mathbf{E}^{-1} \otimes \mathbf{I}_M) \mathbf{F}^H \mathbf{\Xi}_v^i \mathbf{F} \mathbf{\Delta}^{k_i^v} (\mathbf{E} \otimes \mathbf{I}_M). \end{aligned} \quad (51)$$

Let $\bar{\mathbf{H}}_i^v = (\mathbf{E}^{-1} \otimes \mathbf{I}_M) \mathbf{F}^H \mathbf{\Xi}_v^i \mathbf{F} \mathbf{\Delta}^{k_i^v} (\mathbf{E} \otimes \mathbf{I}_M)$, then we have $\mathbf{H} = \sum_{v=0}^{V-1} \sum_{i=0}^{\eta_v-1} h_i^v \bar{\mathbf{H}}_i^v \mathbf{\Gamma}_v$. Assume $k_i^v \in \mathbb{Z}$, and we can obtain $\bar{\mathbf{H}}_i^v$ satisfying the following relation.

$$\bar{\mathbf{H}}_i^v(s, t) = \begin{cases} \exp\left(\frac{2\pi k_i^v t}{L} j\right) \mathbf{T}_i^v, & t = \langle s - \xi_i^v \rangle_L \\ 0, & \text{otherwise,} \end{cases} \quad (52)$$

where $\xi_i^v = l_i^v - M k_i^v + c \nu_i^v \frac{L}{v'}$, $\nu_i^v = 1 - \delta(\langle k_i^v \rangle_{v'})$, $c = 1, \dots, v'$, and $v' = 2^{\lfloor \frac{\log_2 N}{2} \rfloor}$. $\mathbf{T}_i^v$ meets $\mathbf{T}_i^v =$

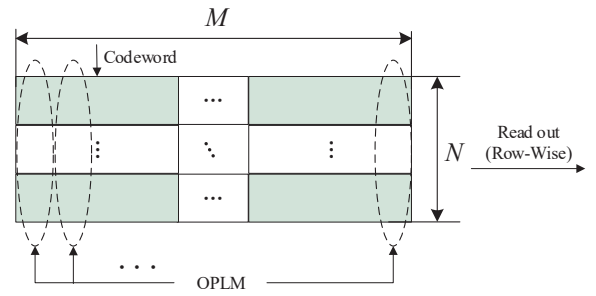


Figure 6. The model of EHC-SCMA in uplink.

$\exp(-j \frac{\pi}{N} k_i^v t) \varphi_i^v$. It can be found that the equivalent channel matrix has good sparsity and the received signal can be expressed as

$$r_b = \sum_{v=0}^{V-1} \sum_{i=0}^{\eta_v-1} \sum_{c=1}^{v'} \bar{\mathbf{H}}_{i,c}^v(b, b'_c) \bar{s}_{b'_c + Lv}, \quad (53)$$

where $b'_c = \langle b - l_i^v + M k_i^v - c \nu_i^v \frac{L}{v'} \rangle_L$. In addition, considering that the SCMA codeword $\mathbf{S}_k^v$ contains only M' non-zero elements, the above input-output relation can be further simplified as

$$r_b = \sum_{v=0}^{V-1} \sum_{i=0}^{\eta_v-1} \sum_{d=1}^{d_v} \tilde{\mathbf{H}}_i^v(b, \varphi_{b,d}) \tilde{s}_{\varphi_{b,d}}^v, \quad (54)$$

where $\tilde{\mathbf{H}}_i^v = \bar{\mathbf{H}}_i^v \mathbf{\Pi}^v$ satisfying $\tilde{\mathbf{H}}_i^v(b, \varphi_{b,d}) = \sum_{c=1}^{v'} \exp(2\pi k_i^v b'_c j / L) \mathbf{T}_i^v \left(1 - \delta(e_{b'_c} \mathbf{\Pi}_{\varphi_{b,d}}^v)\right)$ and $\mathbf{\Pi}^v = \mathbf{I}_{L/K} \otimes \mathbf{\Upsilon}^v$. $\varphi_{b,d}$ is the label of the d th non-zero element of the b th row of $\tilde{\mathbf{H}}_i^v$. $\tilde{\mathbf{H}}$ is the equivalent channel matrix generated by $\tilde{\mathbf{H}} = [\tilde{\mathbf{H}}^0 | \dots | \tilde{\mathbf{H}}^{V-1}]$ by removing invalid columns, and $\tilde{\mathbf{s}}^v = \mathbf{s}_v \mathbf{\Pi}^v$ denotes the equivalent input signal after removing zeros.

In this way, we obtain the input-output relation of the uplink. Due to the effect of transform domain non-orthogonality and channel multipath, it is an obstacle to performing transform domain detection before SCMA decoding for the signal as in the downlink. Considering the sparsity of the equivalent channel matrix, we use a message passing algorithm for multi-user detection.

The input-output relation can be expressed as $r_b = \sum_{k \in \xi_b} \mathbf{h}_{b,k} \tilde{\mathbf{s}}_k$, and $\tilde{\mathbf{s}}_k = \tilde{\mathbf{s}}_{M'(\bar{k}-1):M'\bar{k}-1}^{[k/N]}$, where $\bar{k} = k - N \lfloor \frac{k}{N} \rfloor$, $N = L/K$. In the transform domain message passing model, each frame contains VL/K user nodes $\tilde{\mathbf{s}}_k$, and L resource nodes r_b . $\tilde{\mathbf{s}}_k \in \tilde{\mathcal{C}}^{[k/N]}$, where $\tilde{\mathcal{C}}^v$ denotes the equivalent codebook for the v th user. When $\mathbf{h}_{b,k} = \tilde{\mathbf{H}}_{b,M'(\bar{k}-1):M'\bar{k}-1}$ is not a zero vector, the user node $\tilde{\mathbf{s}}_k$ is connected to the resource node r_b . The set of user nodes connected to r_b is denoted as ξ_b , and the set of resource nodes connected to $\tilde{\mathbf{s}}_k$ is denoted as ξ^k . The message passing from user node to resource node is defined as $V_{\tilde{\mathbf{s}}_k \rightarrow r_b}$ and can be initialized as $V_{\tilde{\mathbf{s}}_k \rightarrow r_b} = \log(\frac{1}{M})$. And the message passing from the resource node to the user node can be expressed as

$$U_{r_b \rightarrow \tilde{\mathbf{s}}_k}(m) = \max_{i'} \left(\sum_{k' \in \xi_b, k' \neq k} V_{\tilde{\mathbf{s}}_{k'} \rightarrow r_b}(\chi_{k'}^{i'}) - \frac{1}{N_0} \left\| r_b - \mathbf{h}_{b,k} \tilde{\mathcal{C}}_m^{[k/N]} - \sum_{k' \in \xi_b, k' \neq k} \mathbf{h}_{b,k'} \tilde{\mathcal{C}}_{\chi_{k'}^{i'}}^{[k'/N]} \right\|^2 \right). \quad (55)$$

The updating of $V_{\tilde{\mathbf{s}}_k \rightarrow r_b}$ can be expressed as

$$V_{\tilde{\mathbf{s}}_k \rightarrow r_b}(m) = \sum_{r_{b'} \in \xi^k, r_{b'} \neq r_b} U_{r_{b'} \rightarrow \tilde{\mathbf{s}}_k}(m). \quad (56)$$

After iteration, the final probability of each symbol is calculated, and the symbol for which the posterior probability value takes the maximum value is selected as the estimation result expressed as

$$\hat{\mathbf{s}}_k^v = \mathcal{C}_{\mathcal{M}}^v, \mathcal{M} = \underset{b' \in \xi^k}{\operatorname{argmax}} \left(\sum U_{r_{b'} \rightarrow \tilde{\mathbf{s}}_k}(\mathcal{M}) \right). \quad (57)$$

The proposed EHC-SCMA scheme can be viewed as a fusion of the extended hybrid carrier power layered

multiplexing and the concept of multi-user superposition transmission. Through the transform domain signal processing, the symbol energy superimposition is extended to multiple codewords, hence exhibiting a stronger ability to suppress residual interference. The proposed scheme shows the advantages of the superior energy distribution design and the high spectral efficiency, which can achieve robust BER performance under multi-user scenarios.

V. SIMULATION RESULTS

In this section, simulation results are presented to illustrate the advantages of the proposed scheme. In the simulation, a carrier frequency of 5.9 GHz, sub-carrier spacing of 15 kHz, and the assumption of perfect channel state information at the receiver are used. Performance for both uplink and downlink will be verified.

We first evaluated the EHC-OMA system. In the simulation, it is assumed that there are 4 users with equally allocated resources in the system. The signal of each user experiences independent channels and the MMSE detector is employed at the receiver. Figure 7. presents the theoretical and simulation results of the bit error rate of the EHC-OMA uplink over the frequency-selective channels. The QPSK signal is adopted without considering the coding gain. ITU Pedestrian-B channel mode is used to generate the frequency-selective channels, and the relative delay and the average power are [0, 200, 800, 1200, 2300,

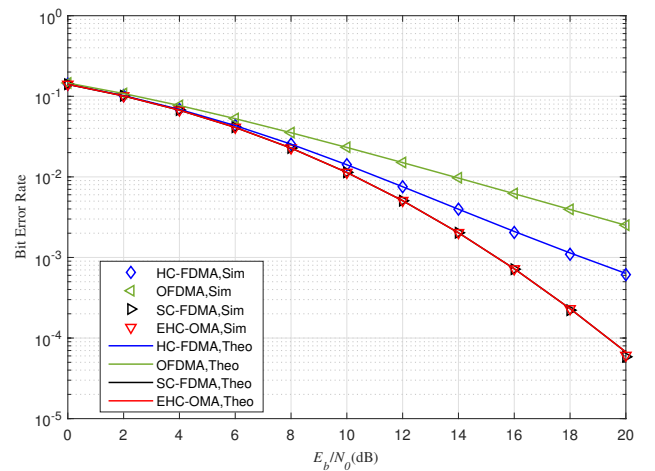


Figure 7. BER performance of EHC-OMA system in uplink over the frequency-selective channels.

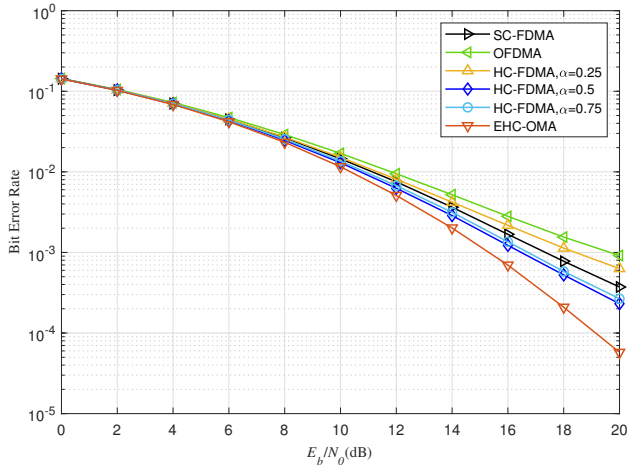


Figure 8. BER performance of EHC-OMA system in uplink over the doubly-selective channels.

3700]ns and [0, -0.9, -4.9, -8.0, -7.8, -23.9]dB respectively. It can be seen that the theoretical curves overlap with the simulation results, and the proposed scheme can achieve optimal bit error rate performance under the same subcarrier mapping scheme, which is consistent with the results of the theoretical analysis.

For the doubly-selective channels, we consider the EVA model with the multipath delay [0, 30, 150, 310, 370, 710, 1090, 1730, 2510]ns and the average power [0, -1.5, -1.4, -3.6, -0.6, -9.1, -7.0, -12.0, -16.9]dB. The normalized Doppler shift FDT is used to describe the time-varying properties. Figure 8. presents the BER performance of the uplink when FDT is 0.001. The HC-OMA schemes with different parameters are provided for comparison. Simulation results show that

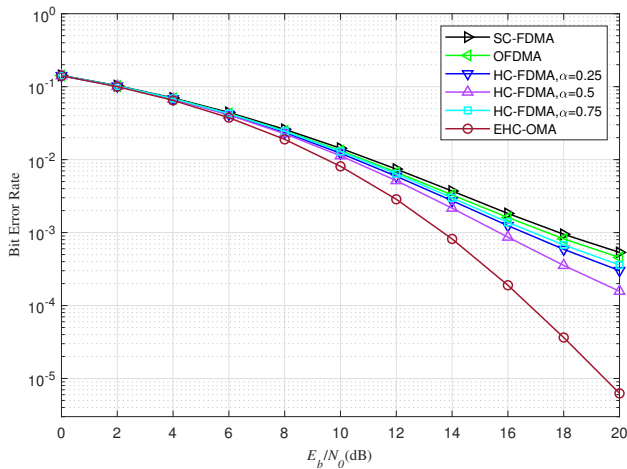


Figure 9. BER performance of EHC-OMA system in downlink over the doubly-selective channels.

the proposed scheme achieves significant performance advantages. Compared to the optimal parameter HC scheme, SC-FDMA, or OFDMA scheme, it has a performance gain of no less than 1.5dB, 2dB, and 4dB at the BER of 10^{-3} respectively. Figure 9. gives the BER comparison of the EHC-OMA downlink, where FDT=0.002. Compared to the HC scheme, due to the implementation of a completely uniform symbol energy distribution design, the performance advantage of the proposed scheme is more pronounced.

Figure 10. to Figure 12. evaluate the EHC-NOMA scheme. We consider an EHC-SCMA system containing 6 users with the overloading factor $\lambda = 150\%$. The SCMA codebook proposed in [32] is chosen for the simulation. The factor matrix is shown in Eq. (58), and the mapping matrix can be obtained from $\bar{\mathbf{F}}$.

$$\bar{\mathbf{F}} = \begin{bmatrix} 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}. \quad (58)$$

Figure 10 examines the performance of the uplink EHC-SCMA system under different FDT, using a transform domain message passing algorithm for detection, demonstrating that the proposed scheme outperforms the SCMA scheme in terms of bit error rate under various Doppler conditions. Figure 11 presents the simulation results for the downlink and offers a

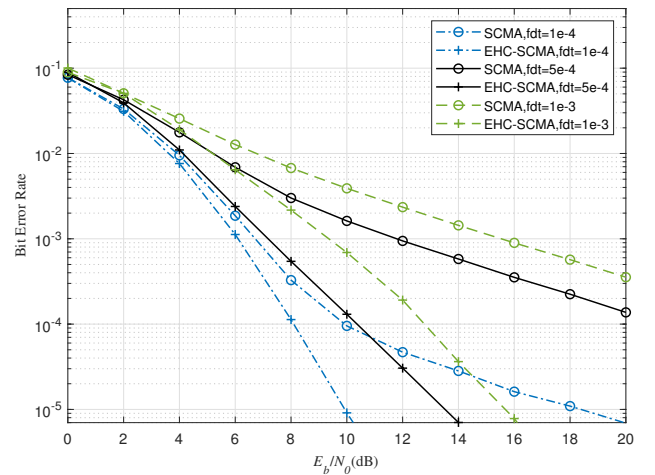


Figure 10. BER performance of EHC-SCMA system in uplink over different FDT.

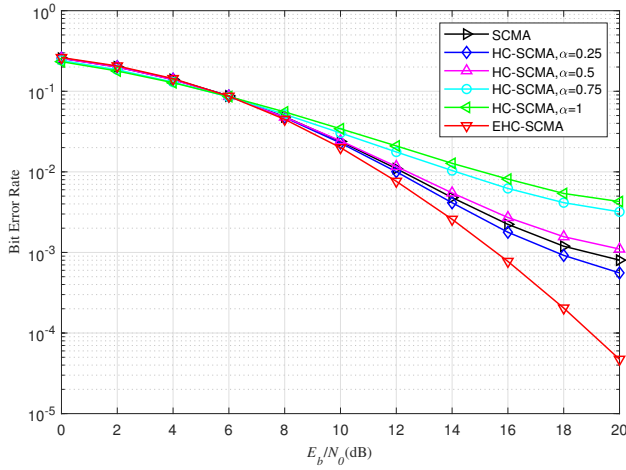


Figure 11. BER performance of EHC-SCMA system in downlink over the doubly-selective channels.

comparison with the HC-SCMA scheme. A two-stage detector with MMSE and MPA in the transform domain is adopted. Notably, HC-SCMA degrades to the SCMA scheme when $\alpha = 0$ and to the MC-SCMA scheme when $\alpha = 1$. Compared to the existing scheme, our proposed scheme, due to exhibit stronger channel distortion compensation capability, showcases superior BER performance and reliability benefits, making it well-suited for supporting massive connectivity in high-mobility scenarios. Lastly, we present the relationship between the bit error rate and the number of iterations. As illustrated in Figure 12, the BER decreases with each iteration, stabilizing gradually. We observed that typically, five iterations are sufficient to achieve stable BER performance. The proposed scheme achieves significant performance gains at the cost of a minor increase in complexity.

Simulation results show that compared with the hybrid carrier multiple access scheme, the proposed scheme effectively improves the bit error rate performance of the system, which is an advantage brought about by its unique energy distribution design and power layered multiplexing structure. In addition, unlike the hybrid carrier multiple access scheme, which relies on parameter selection to obtain performance advantages, the proposed scheme has better channel adaptability. It can achieve robust bit error rate performance without acquiring channel state information at the transmitter, demonstrating its feasibility and advantage in achieving multiple access and reliable com-

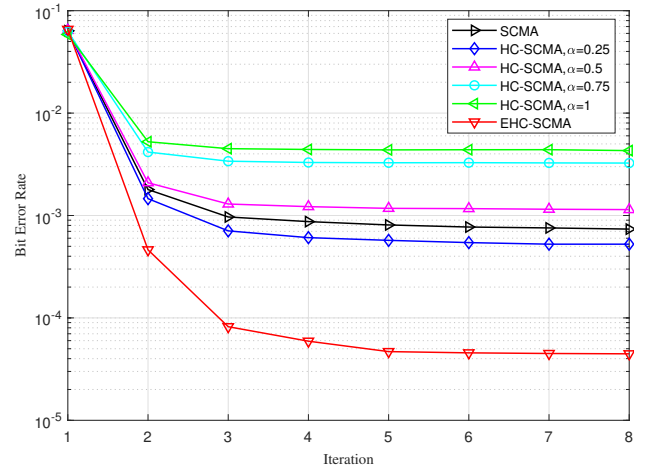


Figure 12. BER performance of EHC-SCMA system in downlink versus the iterations.

munication under complex channel conditions.

VI. CONCLUSION

This paper concerns the multiple access issue and studies a novel multiple access scheme for the extended hybrid carrier system, proposing corresponding OMA schemes for uplink and downlink respectively. The proposed scheme fully utilizes the time-frequency energy distribution design capability of the EHC system to average out residual interference and improves the BER performance compared to the HC scheme at the cost of a slight increase in computational complexity. On this basis, regarding the demand for massive connectivity, the EHC-SCMA scheme is proposed. The distribution of the codewords in the transform domain is studied, and a message passing algorithm detector is designed for the uplink. The proposed scheme combines EHC modulation and SCMA, possessing both excellent bit error rate performance and superior capability of multiple access, which can better meet the complex scenarios and requirements of the next-generation communication system. Future research will focus on low-complexity channel estimation algorithms, and extending the proposed scheme to the multi-antenna scenario is considered.

ACKNOWLEDGEMENT

This work was supported in part by the National Natural Science Foundation of China under Grant U23A20278, in part by the National Natural Science

Foundation of China under Grant 62171151, in part by the Fundamental Research Funds for the Central Universities under Grant HIT.OCEF.2021012.

References

- [1] C. Wang, X. You, *et al.*, "On the road to 6g: Visions, requirements, key technologies, and testbeds," *IEEE Communications Surveys and Tutorials*, 2023, vol. 25, no. 2, pp. 905–974.
- [2] M. Noor-A-Rahim, Z. Liu, *et al.*, "6g for vehicle-to-everything (v2x) communications: Enabling technologies, challenges, and opportunities," *Proceedings of the IEEE*, 2022, vol. 110, no. 6, pp. 712–734.
- [3] D. C. Nguyen, M. Ding, *et al.*, "6g internet of things: A comprehensive survey," *IEEE Internet of Things Journal*, 2022, vol. 9, no. 1, pp. 359–383.
- [4] H. Tataria, M. Shafi, *et al.*, "6g wireless systems: Vision, requirements, challenges, insights, and opportunities," *Proceedings of the IEEE*, 2021, vol. 109, no. 7, pp. 1166–1199.
- [5] Y. Cai, Z. Qin, *et al.*, "Modulation and multiple access for 5g networks," *IEEE Communications Surveys and Tutorials*, 2018, vol. 20, no. 1, pp. 629–646.
- [6] L. Dai, B. Wang, *et al.*, "Non-orthogonal multiple access for 5g: Solutions, challenges, opportunities, and future research trends," *IEEE Communications Magazine*, 2015, vol. 53, no. 9, pp. 74–81.
- [7] Y. Mao, O. Dizdar, *et al.*, "Rate-splitting multiple access: Fundamentals, survey, and future research trends," *IEEE Communications Surveys and Tutorials*, 2022, vol. 24, no. 4, pp. 2073–2126.
- [8] L. Dai, B. Wang, *et al.*, "A survey of non-orthogonal multiple access for 5g," *IEEE Communications Surveys and Tutorials*, 2018, vol. 20, no. 3, pp. 2294–2323.
- [9] R. M. Augustine and A. Chockalingam, "Interleaved time-frequency multiple access using ofts modulation," *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, 2019, pp. 1–5.
- [10] R. Chong, S. Li, *et al.*, "Achievable rate upper-bounds of uplink multiuser ofts transmissions," *IEEE Wireless Communications Letters*, 2022, vol. 11, no. 4, pp. 791–795.
- [11] W. Yuan, S. Li, *et al.*, "New delay doppler communication paradigm in 6g era: A survey of orthogonal time frequency space (otfs)," *China Communications*, 2023, vol. 20, no. 6, pp. 1–25.
- [12] V. Khammammetti and S. K. Mohammed, "Spectral efficiency of ofts based orthogonal multiple access with rectangular pulses," *IEEE Transactions on Vehicular Technology*, 2022, vol. 71, no. 12, pp. 12 989–13 006.
- [13] Q. Luo, P. Gao, *et al.*, "An error rate comparison of power domain non-orthogonal multiple access and sparse code multiple access," *IEEE Open Journal of the Communications Society*, 2021, vol. 2, pp. 500–511.
- [14] V. Vikas, A. Rajesh, *et al.*, "A comprehensive technique to design scma codebooks," *IEEE Communications Letters*, 2022, vol. 26, no. 8, pp. 1735–1739.
- [15] Y. Zheng, J. Xin, *et al.*, "A low-complexity codebook design scheme for scma systems over an awgn channel," *IEEE Transactions on Vehicular Technology*, 2022, vol. 71, no. 8, pp. 8675–8688.
- [16] C. Huang, B. Su, *et al.*, "Downlink scma codebook design with low error rate by maximizing minimum euclidean distance of superimposed codewords," *IEEE Transactions on Vehicular Technology*, 2022, vol. 71, no. 5, pp. 5231–5245.
- [17] Z. Ding and H. V. Poor, "Design of thz-noma in the presence of beam misalignment," *IEEE Communications Letters*, 2022, vol. 26, no. 7, pp. 1678–1682.
- [18] S. Zhao, Z. Zou, *et al.*, "Joint design scheme of resource allocation for intelligent reflecting surface assisted millimeter wave noma system," *Journal on Communications*, 2022, vol. 43, no. 12, pp. 113–122.
- [19] H. Wen, W. Yuan, *et al.*, "Otfscma: A downlink noma scheme for massive connectivity in high mobility channels," *IEEE Transactions on Wireless Communications*, 2023.
- [20] Y. Dursun, F. Fang, *et al.*, "Hybrid noma based mimo offloading for mobile edge computing in 6g networks," *China Communications*, 2022, vol. 19, no. 10, pp. 12–20.
- [21] L. Mei, X. Sha, *et al.*, "The approach to carrier scheme convergence based on 4-weighted fractional fourier transform," *IEEE Communications Letters*, 2010, vol. 14, no. 6, pp. 503–505.
- [22] C. Ma, X. Sha, *et al.*, "An equal component power-based generalized hybrid carrier system," *IEEE Communications Letters*, 2019, vol. 23, no. 2, pp. 378–381.
- [23] H. Dong, X. Fang, *et al.*, "Secure transmission for miso wiretap channels using general multi-fractional fourier transform: An approach in signal domain," *IEEE Transactions on Vehicular Technology*, 2022, vol. 71, no. 8, pp. 8702–8716.
- [24] Z. Wang, X. Chen, *et al.*, "Ber analysis of integrated wfrft-ofts waveform framework over static multipath channels," *IEEE Communications Letters*, 2021, vol. 25, no. 3, pp. 754–758.
- [25] X. Lin, L. Mei, *et al.*, "Efficient fast-convolution based hybrid carrier system," *IEEE Transactions on Wireless Communications*, 2022, vol. 21, no. 5, pp. 3508–3522.
- [26] Z. Wang, L. Mei, *et al.*, "Ber analysis of wfrft precoded ofdm and gfdm waveforms with an integer time offset," *IEEE Transactions on Vehicular Technology*, 2018, vol. 67, no. 10, pp. 9097–9111.
- [27] Q. Cheng, V. Fusco, *et al.*, "Wfrft-aided power-efficient multi-beam directional modulation schemes based on frequency diverse array," *IEEE Transactions on Wireless Communications*, 2019, vol. 18, no. 11, pp. 5211–5226.
- [28] X. Sha, X. Qiu, *et al.*, "Hybrid carrier cdma communication system based on weighted-type fractional fourier transform," *IEEE Communications Letters*, 2012, vol. 16, no. 4, pp. 432–435.
- [29] X. Wang, L. Mei, *et al.*, "Enhanced uplink transmission performance based on wfrft for future communication systems," *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, 2018, pp. 1–6.
- [30] X. Wang, F. Labeau, *et al.*, "Performance of uplink wfrft-based hybrid carrier systems with non-orthogonal multiple access," *IET Communications*, 2018, vol. 12, no. 15, pp. 1891–1899.
- [31] S. Wang, K. Lai, *et al.*, "Low papr scma systems based on carrier techniques," *2021 IEEE/CIC International Confer-*

ence on Communications in China (ICCC), 2021, pp. 370–375.

- [32] Y. Chen and J. Chen, “On the design of near-optimal sparse code multiple access codebooks,” *IEEE Transactions on Communications*, 2020, vol. 68, no. 5, pp. 2950–2962.

Biographies



Ge Song is currently pursuing the Ph.D. degree with the School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin, China. She received B.S. degree and the M.S. degree from Harbin Institute of Technology, Harbin, China, in 2018 and 2020 respectively. Her research interests include physical waveform design and transform domain signal processing in communication system. Email: songge0621@163.com.



Xiaojie Fang received his B.Sc., M.Sc. and Ph.D. degrees from Department of Electronics and Information Engineering, Harbin Institute of Technology in 2010, 2012, and 2018 respectively. During 2015 to 2016, he was a visiting scholar in the Broadband Communications Research Group (BBCR), Department of Electrical and Computer Engineering, University of Waterloo, Canada. He is currently a post-doctoral research fellow and an assistant professor at the Department of Electronics and Information Technology, Harbin Institute of Technology. His current research interests include physical layer security, coding and modulation theory. Email: fangxiaojie@hit.edu.cn.



Xuejun Sha received the Ph.D. degree in communications and electronics systems from the Harbin Institute of Technology, in 1995. He was a Post-Doctoral Fellow with Korea University, Seoul, South Korea. He became a Lecturer and a Professor in 1994 and 2000, respectively. He is currently a Professor with CRC, School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin, China. His research interests include communication network, wireless ad-hoc network, and broadband wireless access. Email: shaxuejun@hit.edu.cn.