

OFDMA-Based Unsourced Random Access in LEO Satellite Internet of Things

Jiaqi Fang^{1,2}, Gangle Sun^{1,2}, Wenjin Wang^{1,2,*}, Li You^{1,2}, Rui Ding³

¹ National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China

² Purple Mountain Laboratories, Nanjing 211100, China

³ Institute of Telecommunication Satellite, CAST, Beijing 100094, China

* The corresponding author, email: wangwj@seu.edu.cn

Cite as: J. Fang, G. Sun, *et al.*, “Ofdma-based unsourced random access in leo satellite internet of things,” *China Communications*, 2024, vol. 21, no. 1, pp. 13-23. **DOI:** 10.23919/JCC.fa.2023-0354.202401

Abstract: This paper investigates the low earth orbit (LEO) satellite-enabled coded compressed sensing (CCS) unsourced random access (URA) in orthogonal frequency division multiple access (OFDMA) framework, where a massive uniform planar array (UPA) is equipped on the satellite. In LEO satellite communications, unavoidable timing and frequency offsets cause phase shifts in the transmitted signals, substantially diminishing the decoding performance of current terrestrial CCS URA receiver. To cope with this issue, we expand the inner codebook with predefined timing and frequency offsets and formulate the inner decoding as a tractable compressed sensing (CS) problem. Additionally, we leverage the inherent sparsity of the UPA-equipped LEO satellite angular domain channels, thereby enabling the outer decoder to support more active devices. Furthermore, the outputs of the outer decoder are used to reduce the search space of the inner decoder, which cuts down the computational complexity and accelerates the convergence of the inner decoding. Simulation results verify the effectiveness of the proposed scheme.

Keywords: LEO; OFDMA; satellite; unsourced random access; UPA

I. INTRODUCTION

The Internet of Things (IoT) plays a pivotal role in 5G, aiming to provide services for massive devices to make the Internet more immersive and pervasive [1–3]. However, current terrestrial networks, restricted by geographical limitations and high costs, struggle to serve remote areas like deserts, oceans, and forests. Recognizing the wide coverage of low earth orbit (LEO) satellites, the 3rd Generation Partnership Project (3GPP) has initiated a study on supporting the LEO satellite-enabled IoT networks with the 5G New Radio (NR) to provide services in these remote areas [4]. In the wide coverage area of a single LEO satellite, there may be a vast number of devices to serve, with their data packets being sporadic and short [5]. For such scenarios grant-based random access schemes result in significant excessive overhead, network congestion, and high transmission latency [6, 7]. To address this issue, there has been a surge in researches dedicated to incorporate the LEO satellite-enabled IoT networks with the grant-free random access, in which devices transmit signals to LEO satellites directly without a scheduling process [8–11].

Preceding researches mainly focus on integrating the grant-free sourced random access (SRA) with the LEO satellite-enabled IoT networks [8–11]. Each device in the SRA should be allocated a unique pilot for the channel estimation (CE) and the active user dec-

Received: Jun. 10, 2023

Revised: Oct. 27, 2023

Editor: Wei Bai

tection (AUD). As the number of devices in the LEO satellite-enabled IoT network proliferates, however, the SRA scheme becomes increasingly inefficient and unfeasible due to the arduous task of allocating unique pilots to each device. Alternatively, the grant-free un-sourced random access (URA) is more competitive [12]. In the URA scheme, all the devices share a common codebook, and the primary responsibility of the receiver is to recover the transmitted messages without necessarily identifying the specific devices. As it is independent from the number of devices in the network, the URA scheme, in theory, supports an unlimited number of devices [13–16]. However, the original URA encounters a challenge in that its codebook size expands exponentially with the number of information bits transmitted, resulting in high decoding complexity [17]. To mitigate this computational burden, the coded compressed sensing (CCS) URA is proposed to divide device messages into shorter segments, considerably reducing the codebook size [18–20]. In current terrestrial IoT networks, CCS URA stands out for its low implementation cost [21–25]. Considering the power limitations of LEO satellites, investigating the CCS URA is crucial for the LEO satellite-enabled IoT networks [26].

In order to mitigate the implementation costs and optimize the interaction procedure, it is essential for the LEO satellite-enabled IoT networks to exploit the technology commonalities with the current 5G NR, where the orthogonal frequency division multiple access (OFDMA) is adopted [3]. In this context, we propose the LEO satellite-enabled CCS URA scheme in the OFDMA framework, where a massive uniform planar array (UPA) is equipped on the satellite for improving the system spectral and energy efficiency [27, 28]. In LEO satellite communications, long propagation delay and large Doppler frequency offset, attributable to the long transmission distance and the high relative speed between the satellite and devices, can be mitigated to an extent through the precompensation at the device side [26]. However, for IoT devices operating under stringent cost constraints, residual timing and frequency offsets after compensation are inevitable [29, 30]. These residuals induce phase shifts in signal transmissions, rendering conventional terrestrial CCS URA receivers ineffective. We delve into addressing this challenge, and our primary contributions are summarized as follows:

- We propose the OFDMA-based CCS URA scheme for the UPA-equipped LEO satellite-enabled IoT networks.
- We expand the inner codebook with predefined timing and frequency offsets, and then formulate the inner decoding as a tractable compressed sensing (CS) problem.
- By harnessing the intrinsic sparsity of the UPA-equipped LEO satellite angular domain channels, we design an outer decoder that leverages the discriminating power of the angles to support more active devices.
- Building on the proposed inner decoder and outer decoder, a joint inner and outer decoder is proposed to further enhance the system performance, where the output of the outer decoder are employed to reduce the search space of the inner decoder, thereby reducing the computational complexity and facilitating the convergence of the inner decoding.

The rest of this paper is organized as follows: Section II illustrates the system overview and the channel model. The details of the proposed OFDMA-based CCS URA is given in Section III. Section IV elaborates the design of the receiver. Numerical simulation results are presented in Section V. Finally, Section VI concludes this paper.

II. SYSTEM MODEL

2.1 System Overview

In the considered scenario, a LEO satellite equipped with a half-wavelength spaced $M = M_x M_y$ UPA provides services to K_{tot} single-antenna devices. Within a given time interval, $K_a \ll K_{\text{tot}}$ devices are active and send messages to the LEO satellite. Taking into account the implementation cost, we propose the OFDMA-based CCS URA scheme for this LEO satellite-enabled network, where all active devices transmit on the shared OFDMA resource elements. Within the OFDMA resource elements grid, an OFDM symbol encompasses N_T subcarriers, in which N_c adjacent subcarriers are available for active devices. The transmission of each active device occupies the same N_{sym} OFDM symbols, i.e., the total number of available resource elements is $N_c N_{\text{sym}}$.

Denote $\mathcal{L}$ as the set of messages transmitted by active devices. The system performance is expressed in terms of the PUPE

$$\text{PUPE} = \frac{|\mathcal{L} \setminus (\mathcal{L} \cap \hat{\mathcal{L}})|}{|\mathcal{L}|} + \frac{|\hat{\mathcal{L}} \setminus (\mathcal{L} \cap \hat{\mathcal{L}})|}{|\hat{\mathcal{L}}|}, \quad (1)$$

where $\hat{\mathcal{L}}$ denotes the estimation of $\mathcal{L}$ output by the receiver on LEO satellite.

2.2 Channel Model

In light of the considerable altitude of the LEO satellite, it is reasonable to posit that the angles of arrival (AoA) of all propagation paths emanating from the same device are congruent. Following this, the channel $\mathbf{h}_k \in \mathbb{C}^{M \times 1}$ of device- k can be written as [27]

$$\mathbf{h}_k = \beta_k \mathbf{u}_k^x \otimes \mathbf{u}_k^y, \quad (2)$$

where $\otimes$ represents the Kronecker product, β_k represents the channel gain exhibiting the Rician fading distribution with the Rician factor κ , i.e.,

$$\begin{aligned} \Re[\beta_k] &\sim \mathcal{N}(\beta_k, \sqrt{\frac{\kappa}{2(\kappa+1)}}, \frac{1}{2(\kappa+1)}), \\ \Im[\beta_k] &\sim \mathcal{N}(\beta_k, \sqrt{\frac{\kappa}{2(\kappa+1)}}, \frac{1}{2(\kappa+1)}), \end{aligned} \quad (3)$$

the steering vector $\mathbf{u}_k^d \in \mathbb{C}^{M_d \times 1}$, $d = x, y$, is given by $\mathbf{u}_k^d = [1, e^{-j\pi\phi_k^d}, \dots, e^{-j(M_d-1)\pi\phi_k^d}]^T$, $\phi_k^x = \sin \theta_k^y \cos \theta_k^x$, $\phi_k^y = \cos \theta_k^y$, θ_k^x and θ_k^y are the physical angles shown in Figure 1. We adopt the block fading channel model, i.e., the channel $\mathbf{h}_k, \forall k$ remain static over all of the $N_c N_{\text{sym}}$ available resource elements.

III. OFDMA-BASED CCS URA

Following the works in [13], we propose the OFDMA-based CCS URA scheme shown in Figure 2, which includes the outer encoding, the inner encoding, the OFDMA mapping, the inner decoding, and the outer decoding processes. The outer encoder partitions original messages into numerous segments, each of which is appended with parity check bits. Subsequently, in the inner encoding process, the outer codewords are mapped to codewords in a common inner codebook, which will be further mapped to different OFDMA

resource elements to be transmitted. Upon successful transmission, the inner decoder identifies the transmitted segmented messages, and then the outer decoder stitches these segmented messages to recover the original messages.

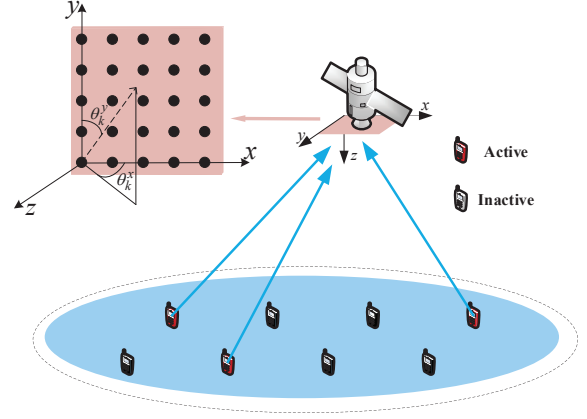


Figure 1. The LEO satellite-enabled CCS URA system.

3.1 Outer Encoding

Let $\mathbf{w}_k \in \{0, 1\}^{B \times 1}$ denote the original message of device- k . In the outer encoding process, $\mathbf{w}_k$ is divided into L segments, i.e., $\mathbf{w}_{k,1}, \mathbf{w}_{k,2}, \dots, \mathbf{w}_{k,L}$, where $\mathbf{w}_{k,l} \in \{0, 1\}^{B_l \times 1}$ and $\sum_{l=1}^L B_l = B$. The parity check bits $\mathbf{p}_{k,l} \in \{0, 1\}^{P_l \times 1}$ is generated by

$$\mathbf{p}_{k,l} = \sum_{i=1}^{l-1} \mathbf{G}_{l,i} \mathbf{w}_{k,i}, \quad (4)$$

where $\mathbf{G}_{l,i} \in \{0, 1\}^{P_l \times B_j}$ is the generation matrix whose elements follow the Bernoulli distribution with the parameter $\frac{1}{2}$ independently, and $\mathbf{p}_{k,l}$ is computed using modulo-2 arithmetic which makes $\mathbf{p}_{k,l}$ remain binary. Subsequently, $\mathbf{p}_{k,l}$ is appended to $\mathbf{w}_{k,l}$ to form the fixed-length outer codeword $\mathbf{v}_{k,l} \in \{0, 1\}^{J \times 1}$, where $J = B_l + P_l$, i.e.,

$$\mathbf{v}_{k,l} = [\mathbf{w}_{k,l}^T, \mathbf{p}_{k,l}^T]^T. \quad (5)$$

3.2 Inner Encoding

The inner encoder maps the outer codeword $\mathbf{v}_{k,l}$ to the inner codeword employing the inner codebook $\mathbf{A} \in \mathbb{C}^{R \times 2^J}$, where $\mathbf{A}$ is a Gaussian random matrix with entries following $\mathcal{CN}(0, \frac{1}{R})$ and $R = \frac{N_c N_{\text{sym}}}{L}$

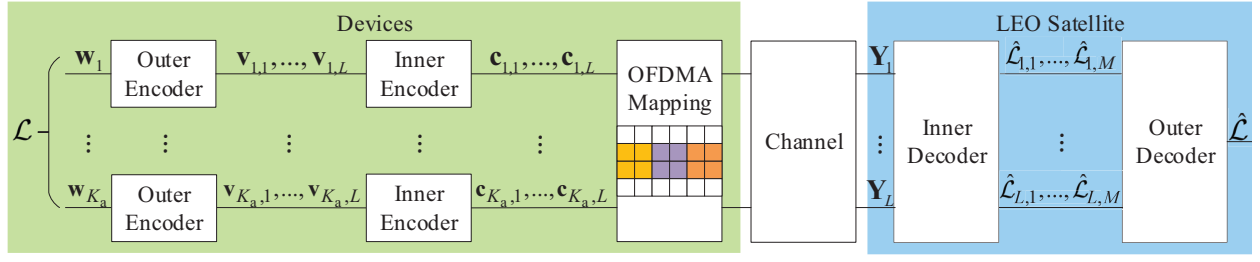


Figure 2. The block diagram of the OFDMA-based CCS URA.

[13]. More precisely, the inner codeword $\mathbf{c}_{k,l} \in \mathbb{C}^{R \times 1}$ of device- k in segment- l is given by

$$\mathbf{c}_{k,l} = \mathbf{A} \mathbf{m}_{k,l}, \quad (6)$$

where $\mathbf{m}_{k,l} \in \{0, 1\}^{2^J \times 1}$ denotes the inner codeword indicator vector with only its $((\mathbf{v}_{k,l})_{b \rightarrow d} + 1)$ -th entry being one, and $(\cdot)_{b \rightarrow d}$ denotes the binary to decimal conversion.

3.3 OFDMA Mapping and Signal Transmission

In the OFDMA mapping process, the inner codewords are mapped to the OFDMA resource elements for being transmitted to the LEO satellite. As illustrated in Figure 3, the inner codeword $\mathbf{c}_{k,l}$ is uniformly divided into $N_s = \frac{R}{N_c}$ fragments, i.e., $\mathbf{c}_{k,l,1}, \mathbf{c}_{k,l,2}, \dots, \mathbf{c}_{k,l,N_s}$, and then $\mathbf{c}_{k,l,t} \in \mathbb{C}^{N_c \times 1}$ is transmitted over the $((l-1)N_s + t)$ -th OFDM symbol.

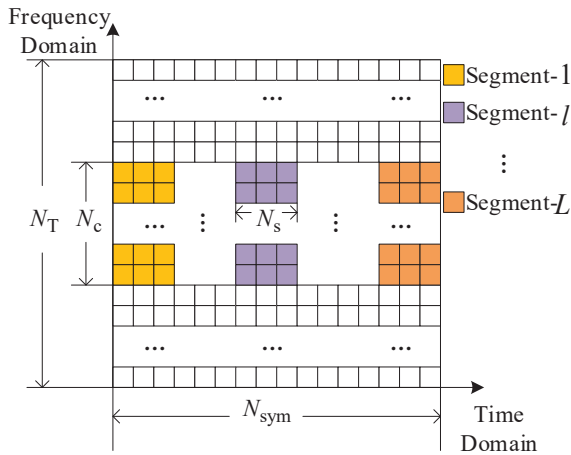


Figure 3. The OFDMA resource elements grid.

In LEO satellite communications, long propagation delay and large Doppler frequency offset can be ameliorated to a certain degree via the pre-compensation

mechanism implemented on the device side. However, for cost-constrained IoT devices, residual timing and frequency offsets persist following the compensation process. Let $\tau_k \in \{0, 1, \dots, \tau_{\max}\}$ and $\epsilon_k \in [-\epsilon_{\max}, \epsilon_{\max}]$ denote the inevitable residual timing and frequency offset coefficients of device- k , respectively. The frequency domain received signals of the l -th segment (specifically, the signals received over the $((l-1)N_s + 1)$ -th to the lN_s -th OFDM symbols) $\mathbf{Y}_l \in \mathbb{C}^{R \times M}$ can be written as [3]

$$\mathbf{Y}_l = \sum_{k \in \mathcal{K}_a} \mathbf{D}_{k,l} \mathbf{c}_{k,l} \mathbf{h}_k^T + \mathbf{Z}_l, \quad (7)$$

where $\mathcal{K}_a$ with the cardinality $|\mathcal{K}_a| = K_a$ represents the active devices set, $\mathbf{Z}_l \in \mathbb{C}^{R \times M}$ represents the noise matrix with its entries independently following $\mathcal{CN}(0, \sigma_z^2)$, $\mathbf{D}_{k,l} \in \mathbb{C}^{R \times R}$ represents the phase shift matrix associated with $\mathbf{c}_{k,l}$, which is given by

$$\mathbf{D}_{k,l} = \text{blkdiag}(\mathbf{D}_{k,l,1}, \mathbf{D}_{k,l,2}, \dots, \mathbf{D}_{k,l,N_s}), \quad (8)$$

the phase shift matrix $\mathbf{D}_{k,l,t} \in \mathbb{C}^{N_c \times N_c}$ associated with $\mathbf{c}_{k,l,t}$ is given by

$$\mathbf{D}_{k,l,t} = \mathbf{W}_{N_c} \mathbf{A}_{k,l,t} \mathbf{Q}_k \mathbf{W}_{N_c}^H, \quad (9)$$

$\mathbf{W}_{N_c} \in \mathbb{C}^{N_c \times N_T}$ represents the submatrix composed of N_c row vectors extracted from the N_T -point discrete Fourier transform (DFT) matrix indexed by the available subcarriers, $\mathbf{A}_{k,l,t} \in \mathbb{C}^{N_T \times N_T}$ is given by

$$\mathbf{A}_{k,l,t} = e^{\frac{j2\pi\epsilon_k(N_{cp} + ((l-1)N_s + t - 1)(N_{cp} + N_T))}{N_T}} \times \text{diag}(1, e^{\frac{j2\pi\epsilon_k}{N_T}}, \dots, e^{\frac{j2\pi\epsilon_k(N_T - 1)}{N_T}}),$$

N_{cp} represents the length of the cyclic prefix, and

$\mathbf{Q}_k \in \{0, 1\}^{N_T \times N_T}$ represents the τ_k left cyclic shift matrix.

IV. RECEIVER DESIGN

4.1 Inner Decoding

To overcome the path loss challenge in LEO satellite communications, the receiving beamforming technique is often adopted. Given the innate directivity of the UPA-equipped LEO satellite channels, we employ the beamforming method rooted in the extensively utilized DFT beamforming codebook [27]. Denote $\mathbf{F} = \mathbf{F}_x \otimes \mathbf{F}_y$ as the beamforming codebook, where $\mathbf{F}_d \in \mathbb{C}^{M_d \times M_d}$, $d = x, y$, represents the M_d -point DFT matrix. Subsequent to the receiving beamforming process, the angular-frequency domain received signals $\tilde{\mathbf{Y}}_l[:, s] \in \mathbb{C}^{R \times 1}$ of angle- s in segment- l can be written as

$$\begin{aligned} \tilde{\mathbf{Y}}_l[:, s] &= \mathbf{Y}_l \mathbf{F}[:, s]^* \\ &= \sum_{k \in \mathcal{K}_{a,s}} \mathbf{D}_{k,l} \mathbf{c}_{k,l} \mathbf{b}_k[s] + \tilde{\mathbf{Z}}_l[:, s] \\ &= \sum_{k \in \mathcal{K}_{a,s}} \mathbf{D}_{k,l} \mathbf{A} \mathbf{m}_{k,l} \mathbf{b}_k[s] + \tilde{\mathbf{Z}}_l[:, s], \end{aligned} \quad (10)$$

where $\tilde{\mathbf{Z}}_l = \mathbf{Z}_l \mathbf{F}^* \in \mathbb{C}^{R \times M}$, $\mathbf{b}_k = \mathbf{F}^H \mathbf{h}_k \in \mathbb{C}^{M \times 1}$ represents the sparse angular domain channel of device- k , and $\mathcal{K}_{a,s} = \{k | \mathbf{b}_k[s] \neq 0\}$ with $\mathcal{K}_{a,1} \cup \mathcal{K}_{a,2} \cup \dots \cup \mathcal{K}_{a,M} = \mathcal{K}_a$ represents the active devices set corresponding to angle- s .

The role of the inner decoder is to recover the set of the transmitted outer codewords $\mathcal{L}_l = \mathcal{L}_{l,1} \cup \mathcal{L}_{l,2} \cup \dots \cup \mathcal{L}_{l,M}$, where $\mathcal{L}_{l,s} = \{\mathbf{v}_{k,l} | k \in \mathcal{K}_{a,s}\}$. For conventional terrestrial IoT networks, where the phase shift matrix $\mathbf{D}_{k,l}$ can be represented as an identity matrix, the estimation of $\mathcal{L}_{l,s}$ can be obtained employing the direct CS method based on (10) [13]. However, for the LEO satellite-enabled IoT networks, the presence of the unknown $\mathbf{D}_{k,l}$ makes the direct CS method inapplicable. To circumvent this obstacle, we expand the inner codebook $\mathbf{A} = [\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_{2^J}]$ with predefined timing and frequency offsets, and then formulate the inner decoding as a tractable CS problem.

To build the inner decoding model, we postulate that the timing and frequency offsets for the active devices are uniformly distributed within the discrete sets

$\mathcal{T} = \{\eta_1, \eta_2, \dots, \eta_{|\mathcal{T}|}\}$ and $\mathcal{E} = \{\nu_1, \nu_2, \dots, \nu_{|\mathcal{E}|}\}$, respectively. It should be highlighted that this assumption is employed primarily to facilitate building the inner decoding model, rather than representing an inherent property of the timing and frequency offsets. With a little bit of notations abusing, denote $\mathbf{E}_{l,i,j}$ as the phase shift matrix, where the timing and frequency offsets are η_i and ν_j , respectively. In essence, $\mathbf{E}_{l,i,j}$ is obtained by replacing τ_k and ϵ_k in $\mathbf{D}_{k,l}$ with η_i and ν_j , respectively. We expand $\mathbf{A}$ to

$$\mathbf{A}_l^e = [\mathbf{A}_{l,1}^e, \mathbf{A}_{l,2}^e, \dots, \mathbf{A}_{l,2^J}^e] \quad (11)$$

for the l -th segment, where $\mathbf{A}_{l,b}^e \in \mathbb{C}^{R \times |\mathcal{T}| |\mathcal{E}|}$ is given by

$$\mathbf{A}_{l,b}^e = [\mathbf{E}_{l,1,1}, \mathbf{E}_{l,1,2}, \dots, \mathbf{E}_{l,|\mathcal{T}|,|\mathcal{E}|}] \mathbf{a}_b. \quad (12)$$

As a result, the signal transmission model (10) can be rewritten as

$$\begin{aligned} \tilde{\mathbf{Y}}_l[:, s] &= \sum_{k \in \mathcal{K}_{a,s}} \mathbf{D}_{k,l} \mathbf{A} \mathbf{o}_{k,l} \mathbf{b}_k[s] + \tilde{\mathbf{Z}}_l[:, s] \\ &= \sum_{k \in \mathcal{K}_{a,s}} \mathbf{A}_l^e (\mathbf{o}_{k,l} \otimes \mathbf{e}_{k,l}) \mathbf{b}_k[s] + \tilde{\mathbf{Z}}_l[:, s] \\ &= \mathbf{A}_l^e \mathbf{g}_{l,s} + \tilde{\mathbf{Z}}_l[:, s], \end{aligned} \quad (13)$$

where the timing and frequency offsets indicator vector $\mathbf{e}_k \in \{0, 1\}^{|\mathcal{T}| |\mathcal{E}| \times 1}$ has only one non-zero entry whose index indicates the timing and frequency offsets of device- k , and $\mathbf{g}_{l,s} = \sum_{k \in \mathcal{K}_{a,s}} (\mathbf{m}_{k,l} \otimes \mathbf{e}_{k,l}) \mathbf{b}_k[s] \in \mathbb{C}^{2^J |\mathcal{T}| |\mathcal{E}| \times 1}$ is a sparse vector.

Denote $\mathbf{g}_{l,s} = [\mathbf{g}_{l,s,1}^T, \mathbf{g}_{l,s,2}^T, \dots, \mathbf{g}_{l,s,2^J}^T]^T$ with $\mathbf{g}_{l,s,b} \in \mathbb{C}^{|\mathcal{T}| |\mathcal{E}| \times 1}$. It is important to note that, in our model, " $\mathbf{g}_{l,s,b} \neq \mathbf{0}$ " implies that there exists at least one device from the set $\mathcal{K}_{a,s}$ transmitting $\mathbf{a}_b$ in segment- l . Therefore, the inner decoding is equivalent to the estimation of $\mathbf{g}_{l,s}$ based on (13), which is a traditional CS problem. We resort to the AMP algorithm in [31] to obtain the log-likelihood ratio $\mathbf{r}_{l,s} \in \mathbb{C}^{2^J \times 1}$ with its entry being

$$\mathbf{r}_{l,s}[b] = \ln \frac{p(\mathbf{g}_{l,s,b} \neq \mathbf{0} | \tilde{\mathbf{Y}}_l[:, s])}{p(\mathbf{g}_{l,s,b} = \mathbf{0} | \tilde{\mathbf{Y}}_l[:, s])}. \quad (14)$$

Then, the inner decoding results of angle- s in segment- l (i.e., the estimation $\hat{\mathcal{L}}_{l,s}$ of $\mathcal{L}_{l,s}$), is given

by

$$\hat{\mathcal{L}}_{l,s} = \{ (b-1)_{d \rightarrow b} | \mathbf{r}_{l,s}[b] > 0 \}, \quad (15)$$

where $(\cdot)_{d \rightarrow b}$ represents the decimal to binary conversion.

4.2 Outer Decoding

The outer decoder should stitch the candidate outer codewords from the inner decoders across different segments together for reconstructing the original messages. The traditional tree outer decoder in the CCS URA [13] achieves this task relying solely on the discriminating power of the parity check bits. Nevertheless, such mechanism will end up with incorrect decoding results when the number of active devices K_a exceeds the discriminating power of the parity check bits. The sparsity of the UPA-equipped LEO satellite angular domain channels indicates that the discriminating power of the angles can be employed as an additional tool to stitch the candidate outer codewords. With the discriminating power of the angles, wrong decoding results will only occur when the active devices number $|\mathcal{K}_{a,s}| < K_a$ of angle- s rather than K_a surpasses the discriminating power of the parity check bits. In light of this, we perform the tree outer decoding in the angular domain. Based on $\hat{\mathcal{L}}_{1,s}, \hat{\mathcal{L}}_{2,s}, \dots, \hat{\mathcal{L}}_{L,s}$, the tree outer decoding is performed for getting the outer decoding results $\hat{\mathcal{L}}_s$ of angle- s (i.e., the estimation of $\mathcal{L}_s = \{\mathbf{w}_k | k \in \mathcal{K}_{a,s}\}$). Then, the outer decoding result $\hat{\mathcal{L}}$ (i.e., the estimation of $\mathcal{L} = \{\mathbf{w}_k | k \in \mathcal{K}_a\}$) is obtained by aggregating the results corresponding to all angles i.e., $\hat{\mathcal{L}} = \hat{\mathcal{L}}_1 \cup \hat{\mathcal{L}}_2 \cup \dots \cup \hat{\mathcal{L}}_M$.

Specifically, for any angle s : Each outer codewords in $\hat{\mathcal{L}}_{1,s}$ is chosen as a root node. For each root node from $\hat{\mathcal{L}}_{1,s}$, there are $|\hat{\mathcal{L}}_{2,s}|$ candidate outer codewords to be stitched in segment-2, thus forming $|\hat{\mathcal{L}}_{1,s}| |\hat{\mathcal{L}}_{2,s}|$ paths. Then, the valid paths fulfilling (4) are retained. Denote the set of the valid paths in segment-2 as $\hat{\mathcal{P}}_{2,s}$. Accordingly, there exist $|\hat{\mathcal{P}}_{2,s}| |\hat{\mathcal{L}}_{3,s}|$ paths in segment-3. Once more, reserve the valid paths matching (4) to get the set of the valid paths in segment-3, denoted as $\hat{\mathcal{P}}_{3,s}$. This segment-by-segment progression continues up until segment- L . Then, $\hat{\mathcal{L}}_s$ is obtained by extracting the message parts of the valid paths set $\hat{\mathcal{P}}_{L,s}$.

We summarize the proposed decoding algorithms in Section 4.1 and Section 4.2 as Algorithm 1.

Algorithm 1. Proposed decoding.

Input: $\mathbf{Y}_l, \mathcal{T}, \mathcal{E}$.

- 1: **for** $s = 1, \dots, M$ **do**
- 2: **for** $l = 1, \dots, L$ **do**
- 3: Expand $\mathbf{A}$ to $\mathbf{A}_l^e$.
- 4: Apply the AMP to (13) to acquire $\hat{\mathcal{L}}_{1,s}$ (Inner Decoding).
- 5: Compute $\hat{\mathcal{P}}_{l,s}$ with the tree outer decoder (Outer Decoding).
- 6: **end for**
- 7: Extract the message parts of $\hat{\mathcal{P}}_{L,s}$ to get $\hat{\mathcal{L}}_s$.
- 8: **end for**

Output: $\hat{\mathcal{L}} = \hat{\mathcal{L}}_1 \cup \hat{\mathcal{L}}_2 \cup \dots \cup \hat{\mathcal{L}}_M$.

4.3 Joint Inner and Outer Decoding

To further improve the decoding performance and reduce the decoding complexity, we propose the joint inner and outer decoder on the basis of the decoding process proposed in section 4.1 and section 4.2. Based on $\tilde{\mathbf{Y}}_l[:, s]$, the joint inner and outer decoder outputs the estimation $\hat{\mathcal{L}}_s$, and then $\hat{\mathcal{L}}$ is get by combining the results of all angles, i.e., $\hat{\mathcal{L}} = \hat{\mathcal{L}}_1 \cup \hat{\mathcal{L}}_2 \cup \dots \cup \hat{\mathcal{L}}_M$. As depicted in Figure 4, the operation of the inner and outer decoders is orchestrated in an alternating manner. The output of the outer decoder are utilized to reduce the search space of the inner decoder, thus reducing the computational complexity and facilitating the convergence of the inner decoding. For the sake of argument, we will detail the decoding procedure specific to angle- s in segment- $(l+1)$ in the remainder of this section.

Denote the n -th valid path in the valid paths set $\hat{\mathcal{P}}_{l,s}$ of angle- s in segment- l as

$$\hat{\mathcal{P}}_{l,s,n} = \{\mathbf{v}_{l,s,n,i} | i = 1, \dots, l\}, \quad (16)$$

where $\mathbf{v}_{l,s,n,i} \in \{0, 1\}^{J \times 1}$ represents the i -th outer codeword from the inner decoding of segment- i associated with the valid path $\hat{\mathcal{P}}_{l,s,n}$. According to the parity check equation (4), the check components for the transmitted outer codewords of angle- s in segment- $(l+1)$, which can be stitched to the valid path $\hat{\mathcal{P}}_{l,s,n}$, are confined within the check pattern: $\sum_{i=1}^l \mathbf{G}_{l,i} \mathbf{v}_{l,s,n,i} [1 : B_i]$. Consequently, any transmitted inner codeword $\mathbf{a}_b$ of angle- s in segment- $(l+1)$

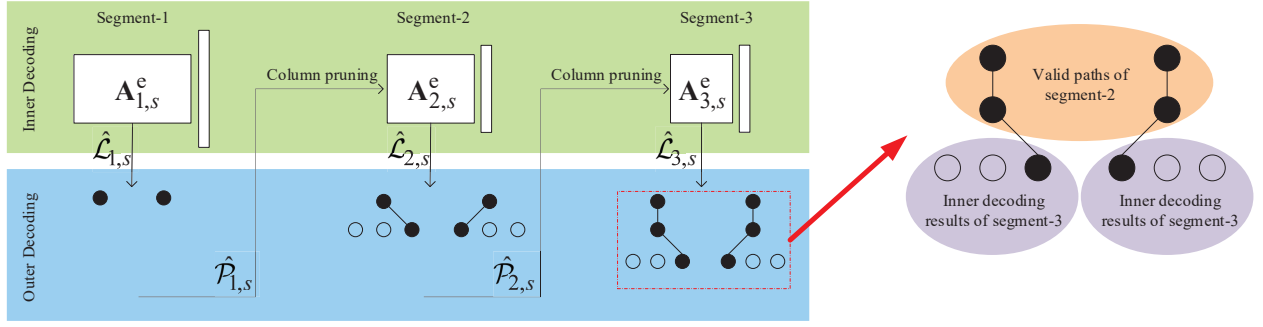


Figure 4. Schematic of the joint inner and outer decoder of angle- s . The circles denote the outer codewords, and the lines composed of solid circles are the valid paths.

must adhere to the condition:

$$\tilde{\mathbf{v}}_b[(B_{l+1} + 1) : J] \in \left\{ \sum_{i=1}^l \mathbf{G}_{l,i} \mathbf{v}_{l,s,n,i} [1 : B_i] \mid n = 1, \dots, |\hat{\mathcal{P}}_{l,s}| \right\}, \quad (17)$$

where $\tilde{\mathbf{v}}_b = (b - 1)_{d \rightarrow b}$.

In segment- $(l + 1)$, we prune the inner codebook $\mathbf{A}$ to $\mathbf{A}_{l+1,s} \in \mathbb{C}^{R \times K_{l+1,s}}$ by only reserve the inner codewords that comply with (17), where the dimension $K_{l+1,s} \leq 2^J$. Following this pruning operation, we expand $\mathbf{A}_{l+1,s}$ to $\mathbf{A}_{l+1,s}^e \in \mathbb{C}^{R \times K_{l+1,s} |\mathcal{T}| |\mathcal{E}|}$ with the predefined timing and frequency offsets to acquire the inner decoding result $\hat{\mathcal{L}}_{l+1,s}$ of angle- s in segment- $(l + 1)$ (See section 4.1.), and then the valid paths set $\hat{\mathcal{P}}_{l+1,s}$ of angle- s in segment- $(l + 1)$ is obtained with the tree outer decoder (See section 4.2.). It is pertinent to note that the search space in segment- $(l + 1)$'s inner decoding of angle- s has been reduced from $2^J |\mathcal{T}| |\mathcal{E}|$ to $K_{l+1,s} |\mathcal{T}| |\mathcal{E}|$.

Remark 1. Given the sparsity of UPA-equipped LEO satellite channels in the angular domain, $|\mathcal{P}_{l,s}|$ is significantly less than $|\mathcal{P}_{l,1} \cup \mathcal{P}_{l,1} \cup \dots \cup \mathcal{P}_{l,M}|$. The result suggests that angle distinctiveness aids in further pruning the inner codebook, thereby reducing the computational complexity and facilitating the convergence of the inner decoding.

The proposed joint inner and outer decoding algorithm is summarized in Algorithm 2.

V. SIMULATION RESULTS

In this section, we provide numerical simulations to evaluate the performance of the proposed OFDMA-

Algorithm 2. Joint inner and outer decoding.

Input: $\mathbf{Y}_l, \mathcal{T}, \mathcal{E}$.

- 1: **for** $s = 1, \dots, M$ **do**
- 2: Apply the AMP to (13) to acquire $\hat{\mathcal{P}}_{1,s}$ (Inner decoding in the first segment).
- 3: **for** $l = 2, \dots, L$ **do**
- 4: Prune $\mathbf{A}$ to $\mathbf{A}_{l,s}$ according to $\hat{\mathcal{P}}_{l-1,s}$.
- 5: Expand $\mathbf{A}_{l,s}$ to $\mathbf{A}_{l,s}^e$.
- 6: Apply the AMP to (13) to acquire $\hat{\mathcal{L}}_{l,s}$ (Inner Decoding).
- 7: Compute $\hat{\mathcal{P}}_{l,s}$ with the tree outer decoder (Outer Decoding).
- 8: **end for**
- 9: Extract the message parts of $\hat{\mathcal{P}}_{L,s}$ to get $\hat{\mathcal{L}}_s$.
- 10: **end for**

Output: $\hat{\mathcal{L}} = \hat{\mathcal{L}}_1 \cup \hat{\mathcal{L}}_2 \cup \dots \cup \hat{\mathcal{L}}_M$.

based CCS URA scheme in the LEO satellite IoT network. The energy per bit to noise power spectral density ratio is given by

$$\frac{E_b}{N_0} = \frac{L}{B \sigma_z^2}. \quad (18)$$

The OFDMA-based CCS URA is configured as follows: The length of original message is $B = 24$, the number of segment is $L = 7$, the length of the outer codeword is $J = 9$, the lengths of the parity check bits are $[P_1, P_2, P_3, P_4, P_5, P_6, P_7] = [0, 5, 5, 5, 6, 9, 9]$, the number of the total subcarriers is $N_T = 2048$, the length of the cyclic prefix is $N_{cp} = 144$, the number of the available subcarriers is $N_c = 72$, the available subcarriers indices are 1001, ..., 1072, and the number of OFDM symbols for transmission is $N_{sym} = 14$. Be-

sides, the channel Rician factor is set as $\kappa = 10\text{dB}$, the physical angle $\phi_k^x, \forall k$ and $\phi_k^y, \forall k$ are uniformly distributed in $(-1, 1]$ [27], devices' timing offsets $\tau_k, \forall k$ and frequency offsets $\epsilon_k, \forall k$ distribute uniformly in $\{0, 1, \dots, \tau_{\max}\}$ and $[-\epsilon_{\max}, \epsilon_{\max}]$, where $\tau_{\max} = 20$ and $\epsilon_{\max} = 0.2$ [32]. In the proposed receiver, we set $\mathcal{T} = \{0, 5, \dots, 20\}$ and $\mathcal{E} = \{-0.2, -0.1, \dots, 0.2\}$.

We compare the following decoding schemes, with their respective computational complexities delineated in Table 1.

Table 1. Computational complexity of different decoding schemes.

Algorithm	Computation Complexity
PD	$\mathcal{O}(R \mathcal{T} \mathcal{E} M2^J L)$
JD	$\mathcal{O}(R \mathcal{T} \mathcal{E} \sum_{l=1}^L \sum_{s=1}^M K_{l,s})$
DOT	$\mathcal{O}(R \mathcal{T} \mathcal{E} M2^J L)$
DOCT	$\mathcal{O}(RM2^J L)$

1. Proposed decoding algorithm in section 4.1 and section 4.2 (**PD**).
2. Joint inner and outer decoding algorithm in section 4.3 (**JD**).
3. Decoding with original tree outer decoder (**DOT**): This method aligns closely with the PD, with the key distinction that the outer decoding in DOT exclusively utilizes the distinguishing capacity of the parity check bits (In essence, it inputs $\hat{\mathcal{L}}_l, l = 1, \dots, L$, to the tree outer decoder to directly get $\hat{\mathcal{L}}.$).
4. Decoding with original inner codebook and original tree outer decoder (**DOCT**): The DOCT is the conventional terrestrial CCS URA decoder [13]. It parallels the DOT, but the inner decoding in DOCT employs the original inner codebook $\mathbf{A}$, as opposed to the expanded inner codebook $\mathbf{A}_l^e$.

In Figure 5, we assess the PUPE performance for various algorithms under the assumption of zero timing and frequency offsets. The result validates the effectiveness of the baseline DOCT approach. Additionally, in the absence of the timing and frequency offsets, the performance of DOCT is equivalent to that of DOT. Figures 6 through 8 illustrate the performance of the proposed OFDMA-based CCS URA under conditions involving timing and frequency offsets. In Figure 6, the decoding performance of several algorithms is

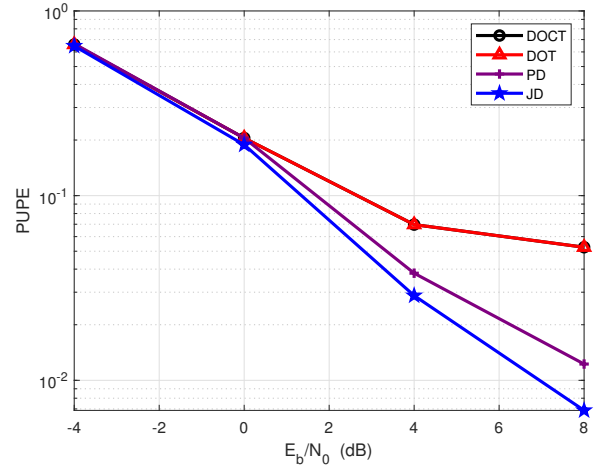


Figure 5. The PUPE of different decoding schemes versus $\frac{E_b}{N_0}$, where $K_a = 50$ and $M_x = M_y = 4$.

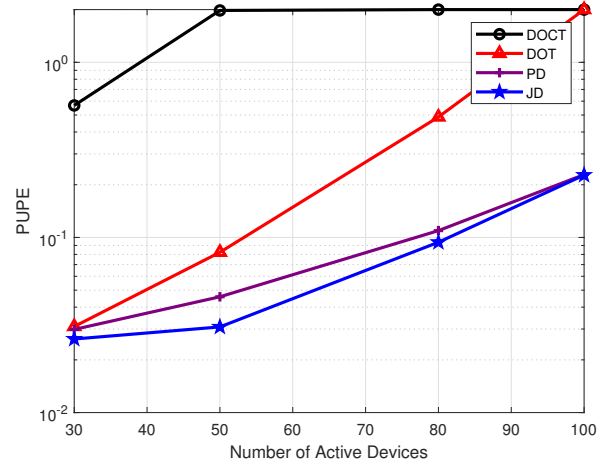


Figure 6. The PUPE of different decoding schemes versus the number of active devices K_a , where $\frac{E_b}{N_0} = 5\text{dB}$ and $M_x = M_y = 4$.

investigated against the variation in the number of active devices. We can observe that the DOCT is almost ineffectual. All the algorithms manifest degradation in performance with the increase of the number of active devices. Comparing the DOT and the DOCT, it can be inferred that the expanded inner codebook significantly mitigates the effects of timing and frequency offsets. Moreover, the distinguishing capacity of the angles enables the PD to outperform the DOT. Due to the reduced search space which expedites the convergence of the inner decoding, the JD with lower computational complexity, demonstrates superior performance compared to the PD. Figure 7 shows the perfor-

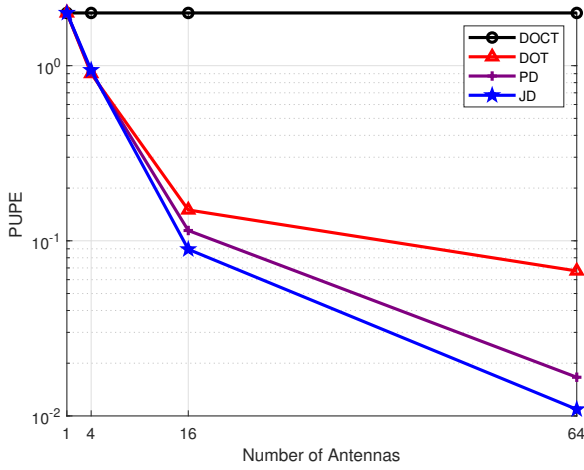


Figure 7. The PUPE of different decoding schemes versus the number of antennas M , where $M_x = M_y = \sqrt{M}$, $\frac{E_b}{N_0} = 3\text{dB}$, and $K_a = 50$.

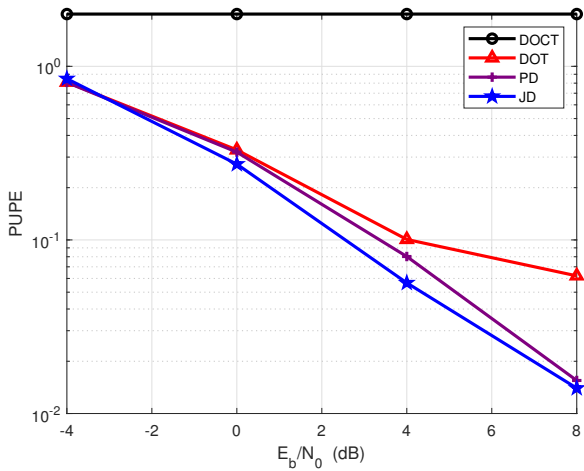


Figure 8. The PUPE of different decoding schemes versus $\frac{E_b}{N_0}$, where $K_a = 50$ and $M_x = M_y = 4$.

mance of different algorithms with respect to the number of antennas. As the number of antennas escalates, the distinguishing power of the angles is progressively augmented. This results in a widening performance gap between the DOT and the proposed algorithms PD and JD. Figure 8 illustrates the decoding performance of several algorithms against the $\frac{E_b}{N_0}$. The proposed algorithms PD and JD outstrip the baseline algorithms across an extensive $\frac{E_b}{N_0}$ range. Furthermore, consistent with previous observations, the proposed JD algorithm achieves the optimal performance.

VI. CONCLUSION

In this paper, we combined the CCS URA and the LEO satellite communication in the framework of the OFDMA to serve massive devices in remote areas. With the presence of the inevitable timing and frequency offsets, we formulated the inner decoding of the CCS URA as a solvable CS problem, and proposed the angular domain outer decoding algorithm. Then, the joint inner and outer decoding algorithm was proposed to reduce the computational complexity and further improve the system performance. Simulations revealed the effectiveness of the proposed scheme.

ACKNOWLEDGEMENT

This work was supported by the National Key R&D Program of China under Grant 2023YFB2904703, the National Natural Science Foundation of China under Grant 62341110, 62371122 and 62322104, the Jiangsu Province Basic Research Project under Grant BK20192002, and the Fundamental Research Funds for the Central Universities under Grant 2242022k30005 and 2242023K5003.

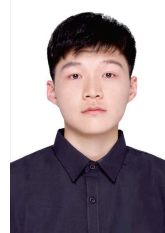
References

- [1] A. Zanella, N. Bui, *et al.*, "Internet of things for smart cities," *IEEE Internet of Things journal*, 2014, vol. 1, no. 1, pp. 22–32.
- [2] X. Chen, D. W. K. Ng, *et al.*, "Massive access for 5g and beyond," *IEEE Journal on Selected Areas in Communications*, 2020, vol. 39, no. 3, pp. 615–637.
- [3] G. Sun, Y. Li, *et al.*, "Massive grant-free ofdma with timing and frequency offsets," *IEEE Transactions on Wireless Communications*, 2021, vol. 21, no. 5, pp. 3365–3380.
- [4] Technical Specification Group Radio Access Network, "Study on new radio (nr) to support non terrestrial networks (release 15)," 3GPP, Technical Report TR 38.811, 2018.
- [5] Y. Zhu, G. Sun, *et al.*, "Ofdm-based massive grant-free transmission over frequency-selective fading channels," *IEEE Transactions on Communications*, 2022, vol. 70, no. 7, pp. 4543–4558.
- [6] G. Sun, Y. Li, *et al.*, "Ofdma based massive grant-free transmission in the presence of timing offset," in *2021 13th International Conference on Wireless Communications and Signal Processing (WCSP)*. IEEE, 2021, pp. 1–6.
- [7] Y. Zhu, G. Sun, *et al.*, "Massive grant-free receiver design for ofdm-based transmission over frequency-selective fading channels," in *ICC 2022 - IEEE International Conference on Communications*. IEEE, 2022, pp. 2405–2410.
- [8] Z. Gao, K. Ying, *et al.*, "Grant-free random access in massive mimo based leo satellite internet of things," in *2021*

IEEE/CIC International Conference on Communications in China (ICCC). IEEE, 2021, pp. 700–705.

- [9] X. Zhou, K. Ying, *et al.*, “Active terminal identification, channel estimation, and signal detection for grant-free noma-otfs in leo satellite internet-of-things,” *IEEE Transactions on Wireless Communications*, 2023, vol. 22, no. 4, pp. 2847–2866.
- [10] B. Shen, Y. Wu, *et al.*, “Random access with massive mimo-otfs in leo satellite communications,” *IEEE Journal on Selected Areas in Communications*, 2022, vol. 40, no. 10, pp. 2865–2881.
- [11] Z. Zhang, Y. Li, *et al.*, “User activity detection and channel estimation for grant-free random access in leo satellite-enabled internet of things,” *IEEE Internet of Things Journal*, 2020, vol. 7, no. 9, pp. 8811–8825.
- [12] Y. Polyanskiy, “A perspective on massive random-access,” in *2017 IEEE International Symposium on Information Theory (ISIT)*. IEEE, 2017, pp. 2523–2527.
- [13] V. K. Amalladinne, J. Chamberland, *et al.*, “A coded compressed sensing scheme for unsourced multiple access,” *IEEE Transactions on Information Theory*, 2020, vol. 66, no. 10, pp. 6509–6533.
- [14] A. Fengler, S. Haghighatshoar, *et al.*, “Non-bayesian activity detection, large-scale fading coefficient estimation, and unsourced random access with a massive mimo receiver,” *IEEE Transactions on Information Theory*, 2021, vol. 67, no. 5, pp. 2925–2951.
- [15] F. Tian, X. Chen, *et al.*, “Massive unsourced random access over rician fading channels: Design, analysis, and optimization,” *IEEE Internet of Things Journal*, 2022, vol. 9, no. 18, pp. 17 675–17 688.
- [16] Y. Su and J. Zheng, “Index modulation multiple access for unsourced random access,” *IEEE Wireless Communications Letters*, 2023, vol. 12, no. 5, pp. 794–798.
- [17] O. Ordentlich and Y. Polyanskiy, “Low complexity schemes for the random access gaussian channel,” in *2017 IEEE International Symposium on Information Theory (ISIT)*. IEEE, 2017, pp. 2528–2532.
- [18] X. Xie, Y. Wu, *et al.*, “Massive unsourced random access: Exploiting angular domain sparsity,” *IEEE Transactions on Communications*, 2022, vol. 70, no. 4, pp. 2480–2498.
- [19] V. Shyianov, F. Bellili, *et al.*, “Massive unsourced random access based on uncoupled compressive sensing: Another blessing of massive mimo,” *IEEE Journal on Selected Areas in Communications*, 2020, vol. 39, no. 3, pp. 820–834.
- [20] J. Che, Z. Zhang, *et al.*, “Unsourced random massive access with beam-space tree decoding,” *IEEE Journal on Selected Areas in Communications*, 2022, vol. 40, no. 4, pp. 1146–1161.
- [21] X. Shao, X. Chen, *et al.*, “Cooperative activity detection: Sourced and unsourced massive random access paradigms,” *IEEE Transactions on Signal Processing*, 2020, vol. 68, pp. 6578–6593.
- [22] J. Jiang and H. Wang, “A fully bayesian approach for massive mimo unsourced random access,” *IEEE Transactions on Communications*, 2023, vol. 71, no. 8, pp. 4620–4635.
- [23] Z. Han, X. Yuan, *et al.*, “Receiver design for mimo unsourced random access with sparse kronecker-product coding,” *IEEE Wireless Communications Letters*, 2023, vol. 12, no. 1, pp. 45–49.
- [24] T. Li, Y. Wu, *et al.*, “Joint device detection, channel estimation, and data decoding with collision resolution for mimo massive unsourced random access,” *IEEE Journal on Selected Areas in Communications*, 2022, vol. 40, no. 5, pp. 1535–1555.
- [25] V. K. Amalladinne, J. Chamberland, *et al.*, “An enhanced decoding algorithm for coded compressed sensing,” in *ICASSP 2020 - 2020 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. IEEE, 2020, pp. 5270–5274.
- [26] 3GPP, “3GPP TR 38.821 V16.1.0 Study on scenarios and requirements for next generation access technologies,” 3rd Generation Partnership Project (3GPP), Technical report (TR) 38.212, 2021.
- [27] L. You, K. Li, *et al.*, “Massive mimo transmission for leo satellite communications,” *IEEE Journal on Selected Areas in Communications*, 2020, vol. 38, no. 8, pp. 1851–1865.
- [28] K. Li, L. You, *et al.*, “Downlink transmit design for massive mimo leo satellite communications,” *IEEE Transactions on Communications*, 2022, vol. 70, no. 2, pp. 1014–1028.
- [29] Huawei, HiSilicon, *et al.*, “Discussion on doppler compensation, timing advance and rach for ntn,” in *R1-1908049 3GPP TSG RAN WG1 Meeting #98*, 2019.
- [30] Thales, “Considerations on doppler shift and doppler pre-post compensation mechanism,” in *R1-1908229 3GPP TSG RAN WG1 Meeting #98*, 2019.
- [31] L. Liu and W. Yu, “Massive connectivity with massive mimo—part I: Device activity detection and channel estimation,” *IEEE Transactions on Signal Processing*, 2018, vol. 66, no. 11, pp. 2933–2946.
- [32] W. Wang, Y. Tong, *et al.*, “Near optimal timing and frequency offset estimation for 5g integrated leo satellite communication system,” *IEEE Access*, 2019, vol. 7, pp. 113 298–113 310.

Biographies



access and XL-MIMO communications.

Jiaqi Fang received the B.E. degree in information science and engineering from Southeast University, Nanjing, China, in 2021, where he is currently pursuing the M.E. degree with the National Mobile Communications Research Laboratory. His research interests include wireless communications and signal processing, with the current emphasis on unsourced random



Gangle Sun received the B.E. degree in communication engineering from Tianjin University, Tianjin, China, in 2019. He is currently pursuing the Ph.D. degree with the National Mobile Communications Research Laboratory, Southeast University, Nanjing, China. From 2022 to 2023, he was a visiting Ph.D. student with the Department of Information Technology and Electrical Engineering, ETH Zurich, Zurich, Switzerland. His research interests include compressive sensing theory, optimization theory, artificial intelligence, and their applications in massive connectivity and massive MIMO communications.



Wenjin Wang received the Ph.D. degree in communication and information systems from Southeast University, Nanjing, China, in 2011. From 2010 to 2014, he was with the School of System Engineering, University of Reading, Reading, U.K. He is currently a Professor with the National Mobile Communications Research Laboratory, Southeast University. His research interests include advanced signal processing for future wireless communications and satellite communications. He was awarded the Best Paper Award at IEEE WCSP'09. He was also awarded the First Grade Technological Invention Award of the State Education Ministry of China in 2009.



Li You received the B.E. and M.E. degrees from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2009 and 2012, respectively, and the Ph.D. degree from Southeast University, Nanjing, in 2016, all in electrical engineering. From 2014 to 2015, he has conducted a Visiting Research at the Center for Pervasive Communications and Computing, University of California Irvine, Irvine, CA, USA. Since 2016, he has been with the Faculty of the National Mobile Communications Research Laboratory, Southeast University. His research interests lie in the general areas of communications, signal processing, and information theory, with the current emphasis on massive MIMO and XL-MIMO communications.

Dr. You received the National Excellent Doctoral Dissertation Award from the China Institute of Communications (CIC) in 2017, the Young Elite Scientists Sponsorship Program (2019–2021) by the China Association for Science and Technology (CAST), and the URSI Young Scientist Award in 2021. He is the Wireless Communications Symposium Co-Chair of IEEE ICC 2023 and the Satellite Communications Symposium Co-Chair of IEEE WCSP 2022.



Rui Ding received the B.S. and Ph.D. degrees in electronics and telecommunications from Southeast University, Nanjing, China, in 2001 and 2011, respectively. He is currently a Professor with the China Academy of Space Technology, Beijing, China. His research interests include satellite communication, integrated satellite-terrestrial communications networks, and satellite system design.