

ODMA-Based Cell-Free Unsourced Random Access with Successive Interference Cancellation

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Abstract—We consider the unsourced random access problem with multiple receivers and propose a cell-free type solution. In our proposed scheme, active users transmit their signals to the access points (APs) distributed in a geographical area and connected to a central processing unit (CPU). The transmitted signals are composed of a pilot and a polar codeword, where the latter occupies only a small fraction of the data part of the transmission frame. The receiver operations of pilot detection and channel and symbol estimation take place at the APs, while the actual message bits are detected at the CPU by combining the symbol estimates from different APs. The effect of successfully decoded messages is then subtracted at the APs by successive interference cancellation, and the decoding iterations continue with the residual signal. Numerical examples illustrate that the proposed scheme can support up to 1400 users with high energy efficiency, and the distributed structure decreases the error probability by more than two orders of magnitude.

Index Terms—Cell-free massive MIMO, unsourced random access, on-off division multiple access, polar codes.

I. INTRODUCTION

Unsourced random access (URA) [1] is an emerging paradigm addressing the dense traffic in massive machine-type communications (mMTC). It has been proposed to enable uplink communication of a massive number of users with small payloads. The communication is sporadic, i.e., only a small subset of the users are active at any given time, but they are uncoordinated. This alleviates the problem of delay and signaling overhead that would be prohibitive with a huge number of users. In URA, all devices share the same codebook; hence, the user identities are eliminated, and the receiver aims to recover only a list of the transmitted messages.

In [1], an achievability bound characterizing the core performance of URA over a Gaussian multiple access channel (MAC) is developed. Several low-complexity coding solutions based on slotted transmissions [2], coded compressed sensing

[3], random spreading [4], and on-off division multiple access (ODMA) [5] have since been proposed. Also, the more practical fading MAC with URA is studied over flat [6] and frequency-selective fading [7].

Massive multiple-input multiple-output (MIMO) [8] is a mature technology in 5G that provides high data rates and spatial multiplexing gains due to the significant degrees of freedom. It is also utilized in URA to increase the supported number of active users and energy efficiency [9]–[12]. In cellular MIMO systems, users at the cell edges can suffer from severe path loss. To cope with this issue, a new network paradigm called cell-free massive MIMO [13], [14] has been proposed. In cell-free massive MIMO, each device in the network is served by many access points (APs) simultaneously. The APs distributed in the same geographic area are connected to a central processing unit (CPU) via a fronthaul. In this way, cell boundaries are removed, leading to lower path losses and improved spectral efficiency.

Although it is a promising technology to support a large number of users, cell-free structure is examined in only a few works in the context of URA [15]–[17]. A cell-free URA scheme is proposed in [15], where the users transmit a pilot signal and utilize the random spreading approach in the data part similarly to [9], while *Level 2* cooperation [13] is employed to combine the symbol estimates. On the other hand, the received signals from different APs are jointly processed using variations of approximate message passing (AMP) in [16] and [17].

In this paper, we study a cell-free environment and propose a URA scheme utilizing the ODMA approach [5]. Assuming that the transmission frame is divided into the pilot and data parts, each user first transmits a pilot sequence determined by a part of its message bits. The rest of the bits are encoded by a polar code and modulated prior to being distributed into the data part based on an ODMA pattern. To have a scalable system [14], only a subset of the active users are recovered at each AP, where the active pilot sequences and channel vectors are jointly estimated by orthogonal matching pursuit (OMP) followed by linear minimum mean square

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error (LMMSE) symbol estimation. The symbol estimates are passed to the CPU for joint processing; where *Level 2* cooperation among the APs is assumed. A list decoder is employed at the CPU to recover the transmitted message bits, and the successfully recovered messages are passed back to the APs for successive interference cancellation (SIC). Numerical examples demonstrate that the performance of the proposed scheme is superior to that of [15] by up to 4.5 dB, and it can increase the number of supported active users up to 1400. Furthermore, distributing the receive antennas through the APs can decrease the system per-user probability of error (PUPE) by more than two orders of magnitude compared to a centralized structure.

The rest of the paper is organized as follows. We present the system model in Section II and the proposed scheme in Section III. We give a set of numerical results in Section IV, and conclude the paper in Section V.

II. SYSTEM MODEL

We consider a cell-free scenario with M APs and a massive number of users, each equipped with a single antenna, while only K_a out of them are active in a given time interval. Active users perform transmission without any coordination during a transmission frame of n symbols. Each AP is equipped with M_r antennas, and connected to a CPU through a high-capacity fronthaul link. An example of such a system with 5 APs connected to a CPU is illustrated in Fig. 1. The received signal at the m -th AP can be written as

$$\mathbf{Y}_m = \sum_{i=1}^{K_a} \mathbf{x}_i \mathbf{g}_{i,m} + \mathbf{Z}_m, \quad (1)$$

where $\mathbf{Y}_m \in \mathbb{C}^{n \times M_r}$, $\mathbf{x}_i \in \mathbb{C}^{n \times 1}$ is the transmitted signal of the i -th user that is obtained by encoding and modulation of $\mathbf{m}_i$, the message of the i -th user, $\mathbf{g}_{i,m} \in \mathbb{C}^{1 \times M_r}$ is the vector of channel coefficients of the i -th user to the m -th AP, and $\mathbf{Z}_m \in \mathbb{C}^{n \times M_r}$ is the circularly symmetric additive white Gaussian noise (AWGN) with independent and identically distributed (i.i.d.) elements, from a zero-mean complex normal distribution with variance σ^2 , $\mathcal{CN}(0, \sigma^2)$. The channel vector $\mathbf{g}_{i,m}$ is defined as [15]

$$\mathbf{g}_{i,m} = \sqrt{\beta_{i,m}} \mathbf{h}_{i,m}, \quad (2)$$

where $\mathbf{h}_{i,m}$ is the small-scale fading channel vector and $\beta_{i,m}$ is the large-scale fading coefficient of the i -th user to the m -th AP. We consider a quasi-static fading channel model, i.e., the fading coefficients remain constant throughout the transmission frame.

The APs are connected to a CPU via a fronthaul, where the aim is to produce a list of transmitted messages using the symbol estimates from the APs. The system performance is measured in terms of the PUPE, P_e , that can be calculated as $P_e = P_{\text{md}} + P_{\text{fa}}$, where P_{md} and P_{fa} are the misdetection and false alarm probabilities, defined as follows:

$$P_{\text{md}} \triangleq \mathbb{E} \left[\frac{1}{K_a} \sum_{i \in \mathcal{K}_a} \mathbb{1}_{\{\mathbf{m}_i \notin \mathcal{L}\}} \right], \quad (3)$$

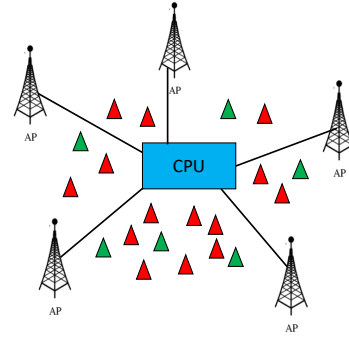


Fig. 1. Illustration of a cell-free system with five access points (APs) and one central processing unit (CPU). Active and inactive users are shown by green and red triangles, respectively.

$$P_{\text{fa}} \triangleq \mathbb{E} \left[\frac{|\mathcal{L} \setminus \{\mathbf{m}_i : i \in \mathcal{K}_a\}|}{|\mathcal{L}|} \right], \quad (4)$$

where $\mathcal{K}_a$ is the set of active users, $\mathcal{L}$ is the list of decoded messages, $\mathbb{1}_{\{\cdot\}}$ is the indicator function, and $|\cdot|$ denotes the cardinality of a set.

III. PROPOSED SCHEME

A. Encoding

Let $\mathbf{m}_i \in \{0, 1\}^B$ denote the B -bit message of user i . Each user splits its message as $\mathbf{m}_i = [\mathbf{m}_i^p \mathbf{m}_i^d]$, where the first $\mathbf{m}_i^p$ are mapped to a pilot sequence of length n_p . Pilot sequences are selected from a common non-orthogonal pilot codebook $\mathbf{A} \in \mathbb{C}^{n_p \times N}$ consisting of $N = 2^{B_p}$ pilot sequences. Each column of $\mathbf{A}$ is normalized to have a Euclidean norm of $\sqrt{n_p P_p}$, where P_p is the average symbol power of the pilot sequences. The received signal $\mathbf{Y}_{p,m} \in \mathbb{C}^{n_p \times M_r}$ at the m -th AP during pilot transmission is given by

$$\mathbf{Y}_{p,m} = \sum_{i=1}^{K_a} \mathbf{a}_i \mathbf{g}_{i,m} + \mathbf{Z}_{p,m}, \quad (5)$$

where $\mathbf{a}_i$ is the pilot sequence of the i -th user, and $\mathbf{Z}_{p,m}$ is the matrix of first n_p columns of $\mathbf{Z}_m$.

The remaining $B - B_p$ bits are appended with r cyclic redundancy check (CRC) bits, encoded by a $(n_c, B - B_p + r)$ polar code, and then modulated by quadrature phase shift keying (QPSK) to obtain the symbol sequence $\mathbf{c}_i$ of length $n_d = n_c/2$, where n_c is the code length. The elements of $\mathbf{c}_i$ are QPSK symbols in $\{\sqrt{P_d/2}(\pm 1 \pm j)\}$ where P_d is the average symbol power of the data part. The modulated sequence $\mathbf{c}_i$ is then distributed across the data part of the frame utilizing ODMA, i.e., its elements are placed in n_d out of $n - n_p$ symbols based on an ODMA transmission pattern determined by the first B_p message bits. The transmission patterns are selected independently from the transmission pattern matrix $\mathbf{P} \in \mathbb{R}^{(n-n_p) \times N}$ with n_d non-zeros in each column, denoting where the codeword elements will be placed (active indices). The received signal $\mathbf{Y}_{d,m} \in \mathbb{C}^{(n-n_p) \times M_r}$ in the data part at the m -th AP can be written as

$$\mathbf{Y}_{d,m} = \sum_{i=1}^{K_a} s_d(\mathbf{c}_i, \mathbf{m}_i^p) \mathbf{g}_{i,m} + \mathbf{Z}_{d,m}, \quad (6)$$

where $s_d(\cdot)$ is a mapping distributing the modulated polar codeword of the i -th user, $\mathbf{c}_i \in \mathbb{C}^{n_d}$, across the $n - n_p$ data symbols, and $\mathbf{Z}_{d,m}$ is the matrix consisting of the last $n - n_p$ rows of $\mathbf{Z}_m$.

B. Receiver Operation at AP

At each AP, the received signal is processed to recover the selected pilot sequences, estimate the channel vectors, and estimate the transmitted data symbols using the channel vector estimates. The symbol estimates are then passed to the CPU via the fronthaul links, where the final decisions are made. To keep the system scalable, only K_m users are recovered at each AP. In the following, we explain these processes in detail.

First, we jointly estimate the active pilot sequences and the corresponding channel coefficients using the greedy iterative OMP algorithm [19]. In OMP, the element of the measurement matrix that has the highest correlation with the received signal is found at each iteration, and its effect is subtracted by using its projection onto the signal space. First, we calculate the correlation between the candidate pilots and the received signal at the m -th AP as

$$\mathbf{R}_m = \mathbf{A}^H \mathbf{Y}_{\text{OMP},m}^{(k)}, \quad (7)$$

where $\mathbf{R}_m \in \mathbb{C}^{N \times M_r}$, $\mathbf{Y}_{\text{OMP},m}$ is an auxiliary variable that is initialized as $\mathbf{Y}_{\text{OMP},m}^{(1)} = \mathbf{Y}_{p,m}^{(j)}$, where $\mathbf{Y}_{p,m}^{(j)}$ is the residual received pilot signal at the m -th AP in the j -th decoding iteration (iteration between the APs and CPU), and $\mathbf{Y}_{\text{OMP},m}^{(k)}$ is the residual of $\mathbf{Y}_{\text{OMP},m}$ at the k -th OMP iteration. The decision metric of each pilot is obtained by calculating the Euclidean metric of the corresponding row, and the pilot index with the highest decision metric is added to the output list $\hat{\mathcal{I}}_m$. Then, the effect of the detected pilots is subtracted as

$$\begin{aligned} \hat{\mathbf{G}}_{m,t}^{(k)} &= \left(\mathbf{A}_{\hat{\mathcal{I}}_m^{(k)}}^H \mathbf{A}_{\hat{\mathcal{I}}_m^{(k)}} + N_0 \mathbf{I}_{|\hat{\mathcal{I}}_m^{(k)}|} \right)^{-1} \mathbf{A}_{\hat{\mathcal{I}}_m^{(k)}}^H \mathbf{Y}_{\text{OMP},m}^{(1)}, \\ \mathbf{Y}_{\text{OMP},m}^{(k+1)} &= \mathbf{Y}_{\text{OMP},m}^{(1)} - \mathbf{A}_{\hat{\mathcal{I}}_m^{(k)}} \hat{\mathbf{G}}_{m,t}^{(k)}, \end{aligned} \quad (8)$$

where $\mathbf{A}_{\hat{\mathcal{I}}_m^{(k)}}$ is the set of the columns of $\mathbf{A}$ specified by $\hat{\mathcal{I}}_m^{(k)}$, $\hat{\mathcal{I}}_m^{(k)}$ is the set of detected pilot indices up to the k -th OMP iteration, $\hat{\mathbf{G}}_{m,t}^{(k)}$ is the matrix of temporary channel vector estimates corresponding to $\mathbf{A}_{\hat{\mathcal{I}}_m^{(k)}}$ obtained by LMMSE, and $\mathbf{I}$ denotes the identity matrix. Note that since the ODMA patterns in the data part are also determined by the first B_p bits, they are recovered in this step as well. After K_m OMP iterations, the estimated channel vectors become

$$\hat{\mathbf{G}}_m = \left(\hat{\mathbf{A}}_m^H \hat{\mathbf{A}}_m + N_0 \mathbf{I}_{K_m} \right)^{-1} \hat{\mathbf{A}}_m^H \mathbf{Y}_{p,m}, \quad (9)$$

where $\hat{\mathbf{G}}_m \in \mathbb{C}^{K_m \times M_r}$, and $\hat{\mathbf{A}}_m = \mathbf{A}_{\hat{\mathcal{I}}_m^{(K_m)}} \in \mathbb{C}^{n_p \times K_m}$ denotes the detected set of active pilot sequences at the m -th AP. Note that here and in (11), to simplify the notation, we omit the decoding iteration index, and the equation is presented for the first decoding iteration; however, the same operation can be carried out with the residual pilot and data signals in subsequent decoding iterations.

Given the channel vector estimates, an LMMSE solution is employed to estimate the transmitted symbols in the data part. To do that, first, the LMMSE matrix can be calculated as

$$\mathbf{W}_m = \left(\hat{\mathbf{G}}_m^H \hat{\mathbf{G}}_m + \frac{\sigma^2}{P_d} \mathbf{I}_{M_r} \right)^{-1} \hat{\mathbf{G}}_m^H. \quad (10)$$

Then, the symbol estimates at the m -th AP, $\hat{\mathbf{C}}_m$, are obtained by taking the symbols at the active indices at each row of

$$\hat{\mathbf{C}}'_m = \mathbf{Y}_{d,m} \mathbf{W}_m, \quad (11)$$

where $\hat{\mathbf{C}}'_m \in \mathbb{C}^{(n-n_p) \times K_m}$. The set of estimated symbols are passed to the CPU without estimated large-scale fading channel coefficients; namely, we consider *Level 2* cooperation between the APs as in [15]. The active pilot indices are also passed since they are required to combine the symbol estimates belonging to the same user coming from different APs.

C. Symbol Combining and Decoding at CPU

At the CPU, the symbol estimates of the users are obtained by combining the symbol estimates from different APs belonging to the same pilot index as follows

$$\hat{\mathbf{c}}_i = \frac{1}{n_i} \sum_{m=1}^M \mathbb{1}_{\{i \in \hat{\mathcal{I}}_m\}} \hat{\mathbf{C}}_m[:, f_m(i)], \quad \forall i \in [N], \quad (12)$$

where $n_i \triangleq |\{m : i \in \hat{\mathcal{I}}_m\}|$ is the number of APs that have detected the pilot sequence with index i , and $f_m(i)$ is a function mapping the pilot index i to the corresponding column index of $\hat{\mathbf{C}}_m$. Note that each pilot index estimate is matched to a user ignoring the collisions, as the number of pilot sequences can be set such as to make the collision probability small. Then, the log-likelihood ratio (LLR) values corresponding to symbol estimates are extracted and fed to a single-user polar decoder employing successive cancellation list decoding (SCLD). The decoded sequence is added to the output list if the CRC check is satisfied.

D. Successive Interference Cancellation (SIC)

After the operation at the CPU is completed, the successfully recovered message bits are passed back to the APs with their active pilot indices via the backhaul and re-encoded and modulated prior to SIC. Without loss of generality, the SIC at the m -th AP is performed as follows

$$\mathbf{Y}_m^{(j+1)} = \mathbf{Y}_m^{(j)} - \sum_{i=1}^{|\hat{\mathcal{D}}^{(j)}|} \mathbb{1}_{\{\text{ind}(\hat{\mathbf{a}}_i) \in \hat{\mathcal{I}}_m\}} \hat{\mathbf{x}}_{\hat{\mathcal{D}}^{(j,i)}} \hat{\mathbf{g}}_{i,m}, \quad (13)$$

where $\mathbf{Y}_m^{(j)}$ is the residual of the received signal at the m -th AP, $\hat{\mathcal{D}}^{(j)}$ is the set of successfully decoded messages, $\text{ind}(\hat{\mathbf{a}}_i)$ is the index of the estimated pilot sequence of the i -th user, $\hat{\mathbf{x}}_{\hat{\mathcal{D}}^{(j,i)}}$ is the re-constructed transmitted signal of the i -th user at the j -th decoding iteration, and $\hat{\mathbf{g}}_{i,m}$ is its estimated channel vector. The decoding iterations continue until no new user message can be decoded successfully in the current iteration or n_{dec} iterations are reached. The decoding procedure of the proposed scheme is illustrated in Fig. 2.

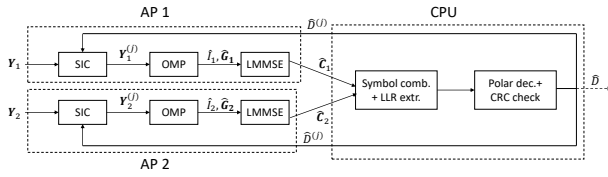


Fig. 2. An illustration of the decoding process of the proposed scheme with two APs, comprising of an orthogonal matching pursuit (OMP) based joint pilot and channel estimation, followed by a linear minimum mean square error (LMMSE) based symbol estimation APs. Assuming a *Level 2* cooperation, the symbol estimates are combined at the CPU, and the recovered bits are fed back to APs for successive interference cancellation (SIC).

E. Complexity Analysis

In this subsection, we provide a computational complexity analysis of the proposed scheme in terms of the number of multiplications in decoding operations. The complexity of joint pilot and channel estimation is dominated by the matrix multiplication in (7) with a complexity of $\mathcal{O}(Nn_pM_r)$, where $\mathcal{O}(\cdot)$ denotes the standard big-O notation. The complexity of symbol estimation is $\mathcal{O}(n_dM_rK_m)$, and SIC has a complexity of $\mathcal{O}((n_d + n_p)K_mM_r)$, that are determined by the matrix multiplications in (11) and (13), respectively.

For comparison, the complexity of the pilot detection and channel estimation of the scheme in [15] is similar to that of our proposed scheme. On the other hand, the complexity of symbol estimation [15] is $\mathcal{O}(L^3M_r^3n_d)$, which is much higher than the complexity of the symbol estimation in our method, where L is the length of the spreading sequence in [15].

IV. NUMERICAL RESULTS

We evaluate the performance of the proposed scheme through Monte Carlo simulations. We set $n = 3200$ and $B = 100$. We assume that the APs are randomly located in a $D \times D$ m^2 area according to a binomial point process, where $D = 550$. We employ Gaussian sequences as pilots, each element is selected from a zero-mean standard normal distribution. We utilize 5G polar codes with a code length of 1024, set the CRC length to 16, and the list size of the polar decoder to 8.

For the path loss, we utilize the urban micro-cell propagation model in [18] with a center frequency of 2 GHz similar to [13], [15]. Hence, the large-scale fading coefficient $\beta_{i,m}$ can be written as

$$\beta_{i,m}[dB] = -30.5 - 36.7 \log_{10} d_{im} + F_{im}, \quad (14)$$

where d_{im} is the distance between the i -th user and the m -th AP, and F_{im} is the shadow fading. We utilize the shadow fading model in [15], namely, $F_{im} \sim \mathcal{CN}(0, 16)$, and it is correlated from an AP to different users as [18]

$$\mathbb{E}[F_{im}F_{kj}] = \begin{cases} 16 \times 2^{-d'_{ik}/9} & \text{if } m = j \\ 0, & \text{if } m \neq j \end{cases} \quad (15)$$

where d'_{ik} is the distance between the i -th and k -th user. The small-scale fading coefficients are generated by assuming a uniform linear array (ULA) at the APs with half-wavelength

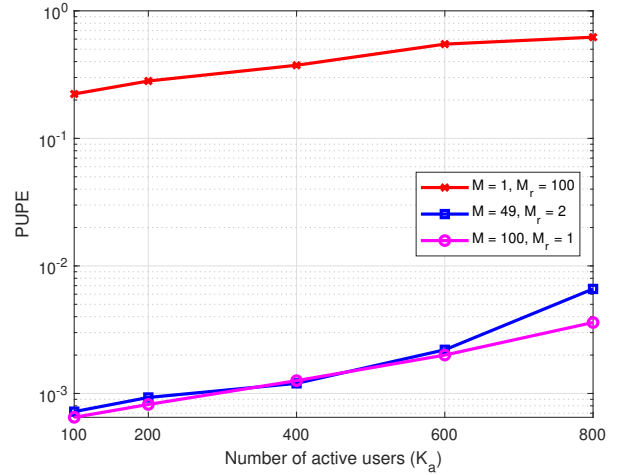


Fig. 3. Comparison of PUPE versus the number of active users for different AP configurations.

antenna spacing and using the spatial correlation matrix provided in (2.23) in [8]. (See Sections 2.2 and 2.6 in [8] for further details on correlated fading).

We assess the effect of distributing the receive antennas in Fig. 3 for $K_m = 7$ by evaluating the PUPE of the proposed scheme for $M = 1$ and $M_r = 100$, i.e., the centralized scenario, and compare it with that of the two distributed scenarios: 1) $M = 49$ and $M_r = 2$, and 2) $M = 100$ and $M_r = 1$. We set the average symbol power to 10 mW and $\sigma^2 = -84$ dBm. The results in Fig. 3 show that distributing the antennas across the area through the APs significantly improves the performance, namely, the PUPE decreases by more than two orders of magnitude as the system becomes more robust to large-scale fading.

We also investigate the effect of cooperation between the APs in Fig. 4, where we set $K_a = 200, 800$, $M = 100$ and $M_r = 1$, and compare the proposed scheme with the scenario that there is no cooperation between the APs, namely, each AP tries to recover the message of K_m users without passing the symbol estimates to CPU. As expected, the AP cooperation improves the performance considerably even if only the symbol estimates are passed to the CPU.

Finally, we evaluate the energy efficiency of our proposed scheme by calculating the required E_b/N_0 for a target PUPE of 0.05 in a wide range of number of active users and compare it with the energy efficiency of the scheme in [15] (CEFURA) for $K_m = 10$. The required transmit energy-per-bit of the system can be calculated as

$$\frac{E_b}{N_0} = \frac{n_p P_p + n_d P_d}{B \sigma^2}. \quad (16)$$

Note that the receive signal-to-noise ratio is much lower compared to transmit energy-per-bit due to the severe path-loss and shadowing. The results in Fig. 5 demonstrate that the proposed scheme outperforms CEFURA for a maximum of 4.5 dB for $K_a \leq 400$ for $M = 100$ and $M_r = 1$, and 1.5

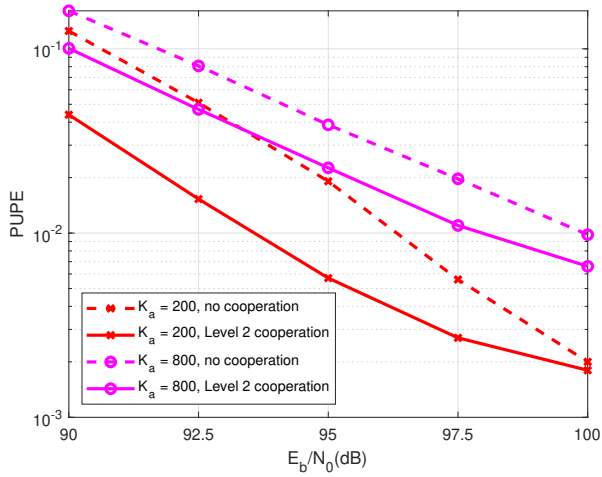


Fig. 4. PUPE comparison of different cooperation levels.

dB for $K_a \leq 200$ for $M = 49$ and $M_r = 2$. Moreover, it can support up to 1400 active users, depending on the configuration. Furthermore, its complexity is two orders of magnitude less than that of the scheme in [15] for practical system parameters.

We believe that the main reason for the superior performance of the proposed scheme compared to CEFURA is the highly efficient SIC block, which is a crucial step in URA schemes to cope with the heavy multiuser interference. Moreover, ODMA has potential advantages compared to random spreading in [15] in high active user loads thanks to the sparsification, resulting in decreased multiuser interference.

V. CONCLUSIONS

We investigated URA in cell-free massive MIMO systems, and proposed an ODMA-type solution combining OMP-based joint pilot and channel estimation followed by symbol estimation by LMMSE at the APs. Symbol estimates are combined at the CPU assuming *Level 2* cooperation, and the recovered bits are fed back to APs for SIC. Numerical results show that the cell-free structure considerably improves the system performance, and the proposed scheme offers excellent performance. In this work, we study one cooperation level between the APs. A deeper investigation of the cooperation levels and an analysis of the effects of unquantified estimation errors on the system performance are left for future investigations.

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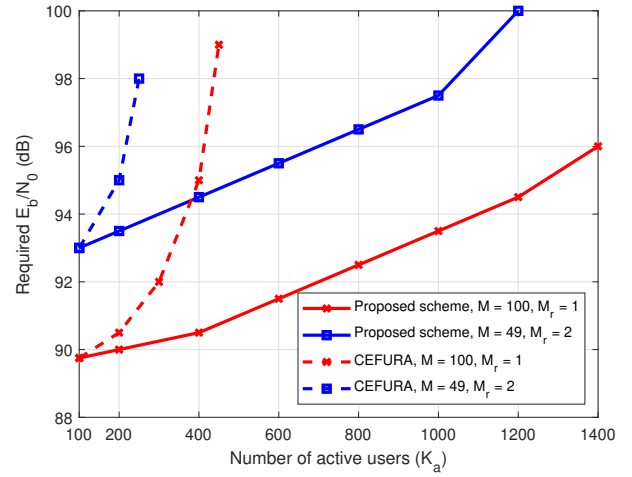


Fig. 5. Comparison of the required E_b/N_0 versus the number of active users for PUPE $P_e \leq 0.05$.

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