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# Location-aided uplink transmission for user-centric cell-free massive MIMO systems: a fairness priority perspective

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## Abstract

In this paper, we investigate the uplink transmission for user-centric cell-free massive multiple-input multiple-output (MIMO) systems. The largest-large-scale-fading-based access point (AP) selection method is adopted to achieve a user-centric operation. Under this user-centric framework, we propose a novel inter-cluster interference-based (IC-IB) pilot assignment scheme to alleviate pilot contamination. Considering the local characteristics of channel estimates and statistics, we propose a location-aided distributed uplink combining scheme to balance the relationship among the spectral efficiency (SE), user equipment (UE) fairness and complexity, in which local partial minimum mean-squared error (LP-MMSE) combining is adopted for some APs, while maximum-ratio (MR) combining is adopted for the remaining APs. A corresponding AP selection scheme based on a novel proposed metric representing inter-user interference is proposed. We also propose a new fairness coefficient taking SE performance into account to indicate the UE fairness. Moreover, the performance of the proposed scheme is investigated under fractional power control and max-min fairness (MMF) power control. Simulation results demonstrate that the channel estimation accuracy of our proposed IC-IB pilot assignment scheme outperforms that of the conventional pilot assignment schemes. It is also shown that compared with the benchmark LP-MMSE combining, the proposed location-aided combining trades 13.45% average SE loss for 26.61% UE fairness improvement and 28.58% complexity reduction when  $\gamma = 0.6$ . And by adjusting the threshold  $\gamma$ , a good trade-off between the average SE, UE fairness and computational complexity can be provided by the proposed scheme. Furthermore, the proposed scheme with fractional power control can better demonstrate the advantages of trade-off performance than MMF power control and full power transmission.

**Keywords:** User-centric cell-free massive MIMO, Pilot assignment, Location-aided distributed uplink combining, Low complexity, Fairness

## 1 Introduction

Cell-free massive multiple-input multiple-output (MIMO) is a promising technique for beyond-5G and 6G networks due to its ability to provide a high spectral efficiency (SE) and tremendous macro-diversity with simple signal processing [1–3]. In cell-free

massive MIMO systems, lots of access points (APs) jointly provide services to all user equipments (UEs) in the same time-frequency resource by utilizing the centralized coordination of the central processing unit (CPU), which is connected to all APs via fronthaul links [4].

The early studies on cell-free massive MIMO assumed that all APs serve all UEs in the network [5, 6]. Unfortunately, this assumption may lead to network-wide fronthaul signaling and data sharing, resulting in huge computational complexity, which is impractical for actual large networks [7]. To overcome this limitation, a user-centric framework has been introduced into cell-free massive MIMO; the main idea of this framework is that each UE is served by a subset of APs with the best channel conditions to improve the service efficiency of the system [8–10].

### 1.1 Motivation

In cell-free massive MIMO, there are two data transmission implementations consisting of the centralized and distributed signal processing, which are characterized by different degrees of cooperation among the APs [11]. Take the uplink as an example, in distributed signal processing, the channel estimation and receive combining are done at the APs, and data detection is done at the CPU, while in centralized processing, all operations mentioned above are done at the CPU, which leads to increased fronthaul load and deployment cost compared with the former. Nowadays, the distributed signal processing has been widely investigated due to its advantages of saving fronthaul overhead and flexible deployment [7, 11, 12]. A representative framework for scalable cell-free massive MIMO exploiting dynamic cooperation cluster concept was proposed in [7], and the uplink/downlink SE performance with maximum-ratio (MR) or local partial minimum mean-squared error (LP-MMSE) combining/precoding was studied, respectively.

These methods mentioned above are fully distributed and widely used in cell-free massive MIMO systems. However, the shortcomings of each scheme are also obvious. For example, the SE performance of MR combining/precoding is poor, although it has low complexity and good fairness among UEs. On the contrary, LP-MMSE combining/precoding outperforms the standard MR method in terms of SE performance at the cost of increased computational complexity. Meanwhile, the UE fairness of these methods cannot be ensured effectively [7, 11]. These motivate us to explore a novel transmission scheme that can make an effective compromise between SE, UE fairness and complexity to improve comprehensive system performance.

Driven by the continuously increasing demands for high system throughput, low latency and improved fairness, location-aware communication for beyond-5G and 6G networks has attracted lots of research interest since location information can be leveraged in wireless network design and optimization to complement existing technological developments [13]. Currently, lots of papers have focused on improving system performance or simplify system design for cellular massive MIMO systems by using location information obtained by means of global positioning system (GPS) or wireless positioning technologies [14], which can be classified into two categories: The first is to investigate pilot assignment schemes for alleviating pilot contamination [15, 16], and the second is devoted to the design of location-aided transmission schemes [17, 18]. Considering in cell-free massive MIMO, user location is closely related to its signal spatial

structure, a natural thought is the following: Can we utilize location information to design and investigate the compromise transmission scheme mentioned above?

## 1.2 Related work

Currently, there are existing researches that have striven to design pilot assignment schemes for cell-free massive MIMO systems using location information [19, 20]. In [19], a structured pilot assignment scheme based on location information was proposed to maximize the minimum distance between UEs assigned to the same pilot by clustering all UEs. And the authors in [20] proposed a location-based greedy (LBG) pilot assignment scheme; the difference between the proposed LBG pilot assignment scheme and the greedy pilot assignment scheme in [1] is that the initial pilot allocation is performed according to the location before applying the greedy algorithm.

On the other hand, there has been a broad amount of work on the design and study the transmission scheme of the cell-free massive MIMO [21–27], where most of them focus on the precoding in downlink. Specifically, in [21], the authors investigated the effect of channel hardening on system performance cell-free massive MIMO and compared the SE performance under the conjugate beamforming (CB) and normalized CB (NCB) schemes. Then, the work in [22, 23] proposed a novel enhanced normalized CB (ECB) precoding scheme for cell-free massive MIMO and studied the performance of NCB under different power allocation schemes. The above CB and its variants greatly boost the channel hardening enabling the UEs, but neglect the impact of interference between UEs. To further improve the SE performance, the authors in [24] proposed two distributed precoding schemes, referred to as local partial zero-forcing (PZF) and local protective PZF (PPZF), which can provide an effective trade-off between suppressing interference and maintaining strong desired signal powers. In [25], a semi-distributed precoding called joint maximum-ratio and zero-forcing (JMRZF) was proposed. The main idea is that part of APs are combined to perform centralized ZF (CZF), while other APs apply simple maximum-ratio transmission (MRT). In [26], the authors investigated the uplink transmission performance based on successive interference cancellation (SIC) for user-centric cell-free massive MIMO systems. The work in [27] was studied based on [24] but for uplink combining and proposed full-pilot ZF (FZF), partial FZF (PFZF), protective weak PFZF (PWPFZF) and local regularized ZF (LRZF) combining schemes, which can be performed in a fully distributed, coordinated and scalable fashion. However, the above schemes can only suppress the self-interference of each AP, and its performance is limited by the interference between APs.

## 1.3 Contributions

Motivated by these observations, we introduce location information of UEs into the design of uplink transmission scheme for user-centric cell-free massive MIMO systems in this paper, which aims to design the transmission scheme to balance the SE, UE fairness and complexity for improving the comprehensive performance of the system. A two-layer decoding method is utilized to mitigate inter-user interference, where each AP computes a local estimate of the data signals in the first layer, and then, the large-scale fading decoding (LSFD) scheme is used to combine these estimates at the CPU in the second layer. In addition, to achieve the user-centric architecture, the

largest-large-scale-fading-based AP selection method is adopted. More specifically, the main contributions are listed as follows.

1. We propose a novel inter-cluster interference-based (IC-IB) pilot assignment scheme for reducing pilot contamination that takes into account the interference of UEs using the same pilot while being served by the same AP.
2. We propose a location-aided distributed uplink combining scheme. In this scheme, a new metric based on location information and the AP inter-cluster interference to indicate the degree of interference between UEs is first proposed to select UEs with more severe interference. Second, the APs that provide service to the above UEs suffering from severe interference adopt LP-MMSE combining, while MR combining is adopted for the remaining APs.
3. We propose a new fairness coefficient that takes SE performance into consideration to compare the UE fairness of each combining scheme more reasonably.
4. We investigate the performance of the proposed combining scheme under different power control schemes. The results demonstrate that the proposed scheme with the fractional power control can further improve the trade-off performance compared with max–min fairness (MMF) and full power transmission.

The remainder of this paper is organized as follows. Section describes the system model. Section presents the proposed IC-IB pilot assignment scheme and the location-aided uplink distributed combining scheme. Additionally, the complexity analysis and the power control schemes are also discussed in this section. Section provides results and discussion. Finally, the conclusions are summarized in Sect. .

*Notation:* Lowercase boldface symbols  $\mathbf{x}$  and uppercase boldface symbols  $\mathbf{X}$  denote vectors and matrices, respectively.  $(\cdot)^{-1}$ ,  $(\cdot)^T$  and  $(\cdot)^H$  denote the inverse, transpose and conjugate transpose, respectively.  $\lceil \cdot \rceil$  denotes the ceiling function. The expectation and variance operation are denoted as  $\mathbb{E}\{\cdot\}$  and  $\text{Var}(\cdot)$ , respectively.  $|\mathbf{x}|$  and  $\|\mathbf{x}\|$  represent the norm and Euclidean norm, respectively, of vector  $\mathbf{x}$ . We also denote the cardinality and the  $n$ th element of the set  $\mathcal{B}$  by  $|\mathcal{B}|$  and  $\mathcal{B}(n)$ , respectively.

## 2 System model

We consider an user-centric cell-free massive MIMO system with  $N$  APs and  $K$  single-antenna UEs randomly distributed in a large area, where each UE is served by a subset of APs, as shown in Fig. 1. The different colored regions represent AP clusters serving different UEs. Notably, the AP clusters partially overlap, which is a typical feature of a user-centric cell-free architecture. The largest-large-scale-fading-based AP selection scheme in [28] is utilized to reduce the requirement for backhaul connection, where the subset of APs serving UE  $k$  and the predefined threshold for the UE to select APs are denoted by  $\mathcal{M}_k$  and  $\varepsilon$ , respectively. Moreover, each AP is equipped with a uniform linear array (ULA) containing  $M$  antenna elements and connected via an error-free fronthaul link to a CPU, which facilitates data sharing and centralized operation for resource allocation tasks between all APs. The uplink transmission is considered in this paper, and each coherence block consists of  $\tau_c$  samples, where  $\tau_p$  is used for uplink pilots and  $\tau_c - \tau_p$  is used for uplink data transmission.

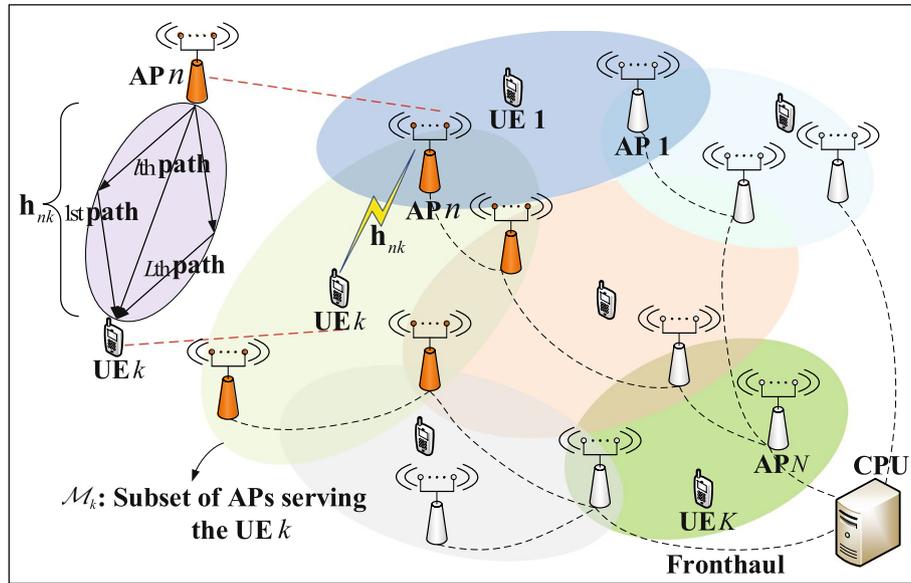


Fig. 1 System model

Then, we assume that there are numerous scatterers in the coverage area, and the propagation of a signal from an AP to a UE is composed of  $L$  paths. From the narrow-band multipath transmission model, the  $M \times 1$  channel vector between the  $n$ th AP and the  $k$ th UE is given by [29, 30]

$$\mathbf{h}_{nk} = \sqrt{\frac{1}{L}} \sum_{l=1}^L \sqrt{\beta_{nk}} \alpha_{nk}^l \mathbf{a}(\theta_{nk}^l), \tag{1}$$

where  $\alpha_{nk}^l$  is the complex gain of the  $l$ th path distributed as  $\alpha_{nk}^l \sim \mathcal{N}_{\mathbb{C}}(0, 1)$  and  $\mathbf{a}(\theta_{nk}^l)$  is the array steering vector for path  $l$ , which can be expressed as

$$\mathbf{a}(\theta_{nk}^l) = \left[ 1, e^{-j\frac{2\pi d}{\lambda} \cos \theta_{nk}^l}, \dots, e^{-j\frac{2\pi(M-1)d}{\lambda} \cos \theta_{nk}^l} \right]^T, \tag{2}$$

where  $\theta_{nk}^l$  is the angle of arrival (AOA) of the  $l$ th path from the  $n$ th AP to the  $k$ th UE,  $\lambda$  is the signal wavelength, and  $d$  denotes the antenna spacing, which is usually assumed to be fixed.  $\beta_{nk}$  is the large-scale fading coefficient.

The main system parameters are summarized in Table 1.

### 3 Methods

#### 3.1 Inter-cluster interference-based pilot assignment and channel estimation

In the uplink pilot training phase, we assume that a set of  $\tau_p$  mutually orthogonal uplink pilot sequences  $\phi_1, \dots, \phi_{\tau_p}$  are assigned to  $K$  UEs, where  $\phi_t \in \mathbb{C}^{\tau_p \times 1}$  and  $\|\phi_t\|^2 = \tau_p$ , for  $t \in \{1, \dots, \tau_p\}$ , with  $\tau_p$  being the number of uplink training samples in each coherence interval. Due to the limited length of the coherence interval, the practical scenario is a large network with  $K > \tau_p$  so that a pilot sequence may be assigned to multiple different UEs. Such pilot reuse among different UEs may lead to a decrease in the channel estimation accuracy, known as pilot contamination. To mitigate pilot

**Table 1** System parameters

|  |                             |
|--|-----------------------------|
| Number of APs                                      | $N$                         |
| Total number of UEs                                | $K$                         |
| Number of antennas per AP                          | $M$                         |
| Coherence block                                    | $\tau_c$                    |
| Number of uplink pilots samples                    | $\tau_p$                    |
| Channel vector for the $n$ th AP and $k$ th UE     | $\mathbf{h}_{nk}$           |
| Number of paths                                    | $L$                         |
| Large-scale fading coefficient                     | $\beta_{nk}$                |
| Small-scale fading coefficient for the $l$ th path | $\alpha_{nk}^l$             |
| Array steering vector for the $l$ th path          | $\mathbf{a}(\theta_{nk}^l)$ |

contamination effect, we propose a novel pilot assignment scheme based on inter-cluster interference. The main idea of this pilot assignment scheme is that orthogonal pilots are assigned to the UEs with large values according to the number of common APs serving UEs, where the number of common APs can indicate the degree of interference between AP cluster. Since the more common serving APs, the interference between UEs is more serious. Subsequently, pilots are assigned to the remaining UEs based on the large-scale fading coefficient and the service relationship between the AP and UE. Specifically, the detailed steps of the proposed IC-IB pilot assignment scheme are presented as follows:

1. The CPU structures a matrix  $\mathbf{S} \in \mathbb{R}^{K \times K}$  that represents the reuse of APs that provide service for different UEs based on  $\{\mathcal{M}_k\}$ , where the element of  $\mathbf{S}$  is given by

$$\mathbf{S}_{ij} = \begin{cases} |\mathcal{M}_i \cap \mathcal{M}_j|, & \text{if } i \neq j \\ \infty, & \text{else} \end{cases}. \quad (3)$$

The non-diagonal elements of  $\mathbf{S}$  represent the number of common APs serving UEs, and  $\mathbf{S}$  is a symmetric matrix; thus, we focus on the  $K(K-1)/2$  entries above the main diagonal.

2. The CPU extracts the upper triangular elements of  $\mathbf{S}$  and sorts them in descending order, denoted as  $\{\tilde{\mathbf{S}}_{ij}^r : i < j, r \in \{1, \dots, K(K-1)/2\}\}$ . According to the sorting results, the corresponding index of UEs can be listed non-repetitively. The first  $\tau_p$  indexes are placed in index set  $\mathcal{F}$ , while the remaining indexes are placed in index set  $\mathcal{S}$ . Then, we assign  $\tau_p$  orthogonal pilots to the UEs whose indices are elements in set  $\mathcal{F}$ .
3. For the remaining UE  $k'$ ,  $k' \in \mathcal{S}$ , when it uses the pilot  $t$ ,  $t \in \{1, \dots, \tau_p\}$  one after another, we first calculate the sum of the average channel gains between the APs serving UE  $k'$  and the UEs that have already been assigned pilot  $t$  and served by these APs. Then, the pilot with the least interference at the APs in the cluster serving UE  $k'$  can be found and assigned to UE  $k'$ .

The IC-IB pilot assignment is summarized in Algorithm 1.

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**Algorithm 1** IC-IB Pilot Assignment Scheme.

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**Require:**  $\{\tilde{\mathbf{S}}_{ij}^r\}, \{\beta_{nk}\}, \mathcal{M}_k, \tau_p, \mathcal{K}, \mathcal{K}_n$ , where  $\mathcal{K}$  and  $\mathcal{K}_n$  denote the set of all UEs and the UEs set served by the  $n$ -th AP, respectively;  
**Ensure:** The pilot index vector,  $\mathcal{I}$ .

- 1:  $\mathcal{F} \leftarrow \emptyset$
- 2: **for**  $1 \leq r \leq K(K-1)/2$  **do**
- 3:   **if**  $|\mathcal{F}| < \tau_p$  **then**
- 4:      $\mathcal{F} \leftarrow i$  in  $\tilde{\mathbf{S}}_{ij}^r$
- 5:     **if**  $|\mathcal{F}| \geq \tau_p$  **then**
- 6:       break;
- 7:     **else**
- 8:        $\mathcal{F} \leftarrow j$  in  $\tilde{\mathbf{S}}_{ij}^r$
- 9:     **end if**
- 10:   **else**
- 11:     break;
- 12:   **end if**
- 13: **end for**
- 14:  $\{\phi_k : k \in \mathcal{F}\} \leftarrow \{\phi_1, \dots, \phi_{\tau_p}\}$
- 15:  $\mathcal{S} \leftarrow \mathcal{K} \setminus \mathcal{F}$
- 16: **for**  $k' \in \mathcal{S}$  **do**
- 17:   **for**  $1 \leq t \leq \tau_p$  **do**
- $$\tau \leftarrow \arg \min_t \sum_{p \in \mathcal{M}_{k'}, q \in \mathcal{K}_p, t_q = t} \beta_{pq}$$

$$t_{k'} \leftarrow \tau$$
- 18:   **end for**
- 19: **end for**
- 20: **return**  $\mathcal{I}$ .

---

To further mitigate the interference among UEs caused by pilot reuse, we adopt the minimum mean-square-error (MMSE) channel estimation method. According to [31], the MMSE estimate  $\hat{\mathbf{h}}_{nk}$  can be given by

$$\hat{\mathbf{h}}_{nk} = \sqrt{P_k} \mathbf{R}_{nk} \Phi_{nk} \mathbf{y}_{nk}^p, \tag{4}$$

where  $P_k$  denotes the transmit power of UE  $k$ ,  $\mathbf{R}_{nk} = \mathbb{E}\{\mathbf{h}_{nk} \mathbf{h}_{nk}^H\}$  denotes the correlation matrix of channel  $\mathbf{h}_{nk}$ ,  $\mathbf{y}_{nk}^p$  is the inner product of the received signal of AP  $n$  with the pilot  $\phi_k$ , and  $\Phi_{nk} = \left(\sum_{i \in \mathcal{P}_k} P_i \tau_p \mathbf{R}_{ni} + \mathbf{I}_M \sigma^2\right)^{-1}$ , in which  $\mathcal{P}_k$  denotes the set of UEs that uses the same pilot as UE  $k$ , and  $\sigma^2$  is the noise power. Moreover, the estimation error  $\tilde{\mathbf{h}}_{nk} = \mathbf{h}_{nk} - \hat{\mathbf{h}}_{nk}$  has the correlation matrix  $\mathbf{C}_{nk} = \mathbb{E}\{\tilde{\mathbf{h}}_{nk} \tilde{\mathbf{h}}_{nk}^H\} = \mathbf{R}_{nk} - P_k \tau_p \mathbf{R}_{nk} \Phi_{nk} \mathbf{R}_{nk}$ .

### 3.2 Location-aided uplink data transmission

In this subsection, we focus on uplink data transmission and propose a novel location-aided uplink combining scheme, which is described in detail in the following.

#### 3.2.1 Distributed uplink transmission

During uplink data transmission, the received signal  $\mathbf{y}_n^u \in \mathbb{C}^M$  at the  $n$ th AP is given by

$$\mathbf{y}_n^u = \sum_{i=1}^K \mathbf{h}_{ni} s_i + \mathbf{n}_n, \tag{5}$$

where  $s_i$  is the transmitted signal from UE  $i$  with power  $P_i$ , and  $\mathbf{n}_n \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}_M, \mathbf{I}_M \sigma^2)$  is the received noise at the AP  $n$ . The distributed uplink transmission based on a two-layer decoding is considered in this paper. Specifically, in the first layer, AP  $n$  selects the combining vector  $\mathbf{v}_{nk}$  and calculates the local data estimate  $\hat{s}_{nk}$  by using the local channel estimates. Then, in the second layer, the local data estimates  $\hat{s}_{nk}$  are sent to the CPU where they are fused into a final estimate of the UE data by using LSFDF coefficients. Under the user-centric architecture,  $\hat{s}_{nk}$  can be mathematically expressed as

$$\hat{s}_{nk} = \mathbf{v}_{nk}^H \mathbf{D}_{nk} \mathbf{y}_n^u, \tag{6}$$

where  $\mathbf{D}_{nk} = \begin{cases} \mathbf{I}_M, & k \in \mathcal{K}_n \\ \mathbf{0}_M, & k \notin \mathcal{K}_n \end{cases}$  is the matrix denoting which UEs are served by which APs.

Next, the local data estimates of the APs serving UE  $k$  are collected at the CPU, after which the CPU performs the second-layer decoding by computing the LSFDF weighted signal as

$$\begin{aligned} \hat{s}_k &= \sum_{n=1}^N \mu_{nk}^* \hat{s}_{nk} = \sum_{n=1}^N \mu_{nk}^* \mathbf{v}_{nk}^H \mathbf{D}_{nk} \left( \sum_{i=1}^K \mathbf{h}_{ni} s_i + \mathbf{n}_n \right) \\ &= \left( \sum_{n=1}^N \mu_{nk}^* \mathbf{v}_{nk}^H \mathbf{D}_{nk} \mathbf{h}_{ni} \right) s_i + \sum_{i=1, i \neq k}^K \left( \sum_{n=1}^N \mu_{nk}^* \mathbf{v}_{nk}^H \mathbf{D}_{nk} \mathbf{h}_{ni} \right) s_i \\ &\quad + \sum_{n=1}^N \mu_{nk}^* \mathbf{v}_{nk}^H \mathbf{D}_{nk} \mathbf{n}_n, \end{aligned} \tag{7}$$

where  $\mu_{nk}$  is the LSFDF coefficient for AP  $n$  and UE  $k$ . For ease of presentation, we define  $\mathbf{g}_{ki} = [\mathbf{v}_{1k}^H \mathbf{D}_{1k} \mathbf{h}_{1i}, \dots, \mathbf{v}_{Nk}^H \mathbf{D}_{Nk} \mathbf{h}_{Ni}]^T$  as the  $N$ -dimensional vector with the receive-combined channels between UE  $k$  and all APs that serve UE  $k$ . Then, (7) can be expressed as

$$\hat{s}_k = \boldsymbol{\mu}_k^H \mathbf{g}_{kk} s_k + \sum_{i=1, i \neq k}^K \boldsymbol{\mu}_k^H \mathbf{g}_{ki} s_i + \sum_{n=1}^N \mu_{nk}^* \mathbf{v}_{nk}^H \mathbf{D}_{nk} \mathbf{n}_n, \tag{8}$$

where  $\boldsymbol{\mu}_k = [\mu_{1k}, \dots, \mu_{Nk}]^T \in \mathbb{C}^N$  is the LSFDF weighting coefficient vector and  $\{\boldsymbol{\mu}_k^H \mathbf{g}_{ki} : i = 1, \dots, K\}$  denotes the effective channels.

By invoking the arguments as described in [11], the achievable uplink SE of UE  $k$  can be calculated as

$$R_k^u = \frac{\tau_c - \tau_p}{\tau_c} \log_2 (1 + \text{SINR}_k), \tag{9}$$

with  $\text{SINR}_k$  is given by

$$\text{SINR}_k = \frac{P_k |\boldsymbol{\mu}_k^H \mathbb{E}\{\mathbf{g}_{kk}\}|^2}{\boldsymbol{\mu}_k^H \left( \sum_{i=1}^K P_i \mathbb{E}\{\mathbf{g}_{ki} \mathbf{g}_{ki}^H\} - P_k \mathbb{E}\{\mathbf{g}_{kk}\} \mathbb{E}\{\mathbf{g}_{kk}^H\} + \mathbf{F}_k \right) \boldsymbol{\mu}_k}, \tag{10}$$

where  $\mathbf{F}_k = \sigma^2 \text{diag}(\mathbb{E}\{\|\mathbf{D}_{1k} \mathbf{v}_{1k}\|^2\}, \dots, \mathbb{E}\{\|\mathbf{D}_{Nk} \mathbf{v}_{Nk}\|^2\}) \in \mathbb{R}^{N \times N}$ .

The effective SINR in (10) for UE  $k$  can be further maximized by

$$\boldsymbol{\mu}_k = P_k \left( \sum_{i=1}^K P_i \mathbb{E}\{\mathbf{g}_{ki} \mathbf{g}_{ki}^H\} + \mathbf{F}_k + \tilde{\mathbf{D}}_k \right)^{-1} \mathbb{E}\{\mathbf{g}_{kk}\}, \quad (11)$$

where  $\tilde{\mathbf{D}}_k \in \mathbb{R}^{N \times N}$  is the diagonal matrix with the  $(n, n)$ th element being one if  $n \notin \mathcal{M}_k$  and zero otherwise. This leads to the maximum value

$$\text{SINR}_k = P_k \mathbb{E}\{\mathbf{g}_{kk}^H\} \left( \sum_{i=1}^K P_i \mathbb{E}\{\mathbf{g}_{ki} \mathbf{g}_{ki}^H\} - P_k \mathbb{E}\{\mathbf{g}_{kk}\} \mathbb{E}\{\mathbf{g}_{kk}^H\} + \mathbf{F}_k + \tilde{\mathbf{D}}_k \right)^{-1} \mathbb{E}\{\mathbf{g}_{kk}\}. \quad (12)$$

### 3.2.2 Proposed combining scheme

In this subsection, we propose a location-aided combining with an efficient AP selection scheme. The principle of location-aided combining is that only a subset of APs that serves UEs with severe interference performs LP-MMSE combining, while the remaining APs perform MR combining, which can achieve an effective balance between the SE performance, UE fairness and complexity. The operation steps of the proposed combining scheme are as follows:

1. The CPU first calculates the distances  $\{d_{ij} : i, j \in \{1, \dots, K\}, i < j\}$  between the UEs according to the obtained location information.
2. Next, we define a novel metric that indicates the degree of interference between UEs based on the distance and the number of common serving APs:

$$\Lambda_{ij} = \omega/d_{ij} + \mathbf{S}_{ij}, \quad (13)$$

where  $\omega$  denotes the predefined coefficient that balances the relationship between the two metrics. The novel metric described above can be computed and sorted in descending order to obtain the sorted results  $\{\tilde{\Lambda}_{ij}^r : i < j, r \in \{1, \dots, K(K-1)/2\}\}$ .

Then, we define the set  $\mathcal{G} = \emptyset$  in preparation for the following steps.

3. For  $\tilde{\Lambda}_{ij}^r, r = 1, \dots, K(K-1)/2$ , we can find the UE corresponding to  $\tilde{\Lambda}_{ij}^r$  and the APs that provide service to these UEs. Then, the above AP index can be inserted into set  $\mathcal{G}$  one after another until  $|\mathcal{G}| \geq \lceil N\gamma \rceil$  holds, where  $0 \leq \gamma \leq 1$  denotes the predefined threshold.
4. According to the obtained set  $\mathcal{G}$  in the previous step, the APs in set  $\mathcal{G}$  adopt LP-MMSE combining scheme, while the remaining APs adopt MR combining scheme, which can be expressed as

$$\mathbf{v}_{nk}^{\text{LA}} = \begin{cases} \mathbf{v}_{nk}^{\text{LP-MMSE}}, & n \in \mathcal{M}_k, n \in \mathcal{G} \\ \mathbf{v}_{nk}^{\text{MR}}, & n \in \mathcal{M}_k, n \notin \mathcal{G} \end{cases}, \quad (14)$$

where  $\mathbf{v}_{nk}^{\text{LP-MMSE}} = P_k \left( \sum_{i \in \mathcal{K}_n} P_i (\hat{\mathbf{h}}_{ni} \hat{\mathbf{h}}_{ni}^H + \mathbf{C}_{ni}) + \mathbf{I}_M \sigma^2 \right)^{-1} \mathbf{D}_{nk} \hat{\mathbf{h}}_{nk}$  and  $\mathbf{v}_{nk}^{\text{MR}} = \mathbf{D}_{nk} \hat{\mathbf{h}}_{nk}$ ,

respectively.

The location-aided combining is given in Algorithm 2.

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**Algorithm 2** Location-Aided Uplink Combining Scheme.

---

**Require:**  $\{\tilde{\Lambda}_{ij}^r\}$ ,  $\{\mathbf{v}_{nk}^{\text{LP-MMSE}}\}$ ,  $\{\mathbf{v}_{nk}^{\text{MR}}\}$ ,  $\mathcal{M}_k$ ,  $\gamma$   
**Ensure:** The proposed combining vector,  $\mathbf{v}_{nk}^{\text{LA}}$ .

```

1:  $\kappa \leftarrow 0$ 
2:  $\mathcal{G} \leftarrow \emptyset$ 
3: for  $1 \leq r \leq K(K-1)/2$  do
4:    $\tilde{\mathcal{M}}_{ij}^r \leftarrow \mathcal{M}_i \cup \mathcal{M}_j$   $\triangleright i$  and  $j$  are subscripts of  $\tilde{\Lambda}_{ij}^r$ 
5:   for  $1 \leq v \leq |\tilde{\mathcal{M}}_{ij}^r|$  do
6:      $\mathcal{G} \leftarrow \tilde{\mathcal{M}}_{ij}^r(v)$ ,
7:     if  $|\mathcal{G}| \geq \lceil N\gamma \rceil$  then
8:        $\kappa \leftarrow 1$ ,
9:       break;
10:    end if
11:  end for
12:  if  $\kappa = 1$  then
13:    break;
14:  end if
15:  $\mathbf{v}_{nk}^{\text{LA}} \leftarrow \mathbf{v}_{nk}^{\text{LP-MMSE}}, \mathbf{v}_{nk}^{\text{MR}}, \mathcal{G}$   $\triangleright$  Use (14) to calculate  $\mathbf{v}_{nk}^{\text{LA}}$  based on the set  $\mathcal{G}$ 
16: return  $\mathbf{v}_{nk}^{\text{LA}}$ .
```

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For the proposed location-aided combining scheme, the APs that provide service to UEs are divided into two parts, one of which is detected by adopting LP-MMSE combining, while the other by MR combining. Note that the closed form of the expectations in (10) and (12) cannot be computed when the APs using LP-MMSE combining, but the expectations can be obtained by using Monte Carlo simulations easily. However, the expectations in (10) can be computed in closed form when the APs use MR combining, which is derived in the following.

**Corollary** *If the APs adopt MR combining, i.e.,  $\mathbf{v}_{nk} = \mathbf{D}_{nk} \hat{\mathbf{h}}_{nk}$  with  $n \in \mathcal{M}_k, n \notin \mathcal{G}$ , then the expectations in (10) can be given by*

$$[\mathbb{E}\{\mathbf{g}_{ki}\}]_n = \begin{cases} \sqrt{P_k P_i} \tau_p \text{tr}(\mathbf{D}_{nk} \mathbf{R}_{ni} \Phi_{nk} \mathbf{R}_{nk}), & \text{if } i \in \mathcal{P}_k \\ 0, & \text{otherwise} \end{cases}, \quad (15)$$

with  $[\mathbb{E}\{\mathbf{g}_{ki} \mathbf{g}_{ki}^H\}]_{nr} = [\mathbb{E}\{\mathbf{g}_{ki}\}]_n [\mathbb{E}\{\mathbf{g}_{ki}^*\}]_r$ , for  $n \neq r$  and

$$[\mathbb{E}\{\mathbf{g}_{ki} \mathbf{g}_{ki}^H\}]_{nn} = P_k \tau_p \text{tr}(\mathbf{D}_{nk} \mathbf{R}_{ni} \mathbf{R}_{nk} \Phi_{nk} \mathbf{R}_{nk}) + \begin{cases} P_k P_i \tau_p^2 |\text{tr}(\mathbf{D}_{nk} \mathbf{R}_{ni} \Phi_{nk} \mathbf{R}_{nk})|^2, & \text{if } i \in \mathcal{P}_k \\ 0, & \text{otherwise} \end{cases}, \quad (16)$$

while

$$[\mathbf{F}_k]_{nn} = \sigma^2 P_k \tau_p \text{tr}(\mathbf{D}_{nk} \mathbf{R}_{nk} \Phi_{nk} \mathbf{R}_{nk}). \quad (17)$$

*Proof* It follows the similar approach as in [11, 21–23].  $\square$

### 3.3 Complexity analysis

In this subsection, we present complexity analysis for different distributed combining schemes. The complexity of a combining scheme originates mainly from the calculation

of the combining vector. This is because the acquisition of the estimated channel and the second-layer LSFD decoding are the same for each combining scheme, and the computational complexity in this process is not taken into consideration.

Next, we focus on the computational complexity of the combining vector for the proposed combining scheme.

More specifically, recalling that all APs are divided into two parts for the proposed combining scheme, hence the computational complexity of the proposed combining scheme should be analyzed with regard to these two aspects, respectively.

**Proposition** *The computational complexity of the location-aided uplink combining scheme is given by*

$$C^{\text{LA}} = \sum_{n \in \mathcal{G}} \frac{3M^2|\mathcal{K}_n|}{2} + \frac{M|\mathcal{K}_n|}{2} + \frac{M^3 - M}{3}, \quad (18)$$

*Proof* Since the combining vector is computed by using elementary matrix operations, we can calculate the computational complexity with the help of the framework shown in [31]. Only complex multiplications and divisions are considered, while additions and subtractions can be neglected since these are much less complex. Specifically, for the APs  $n \in \mathcal{G}$ , the complexity can be computed resorting to [31, Lemma B.1., B.2.]. On the other hand, for the remaining APs, when the AP serves at least one UE, MR combining is adopted. Since only the channel estimates are used for signal combining in this case, no additional calculations are required. Based on the above analysis, the computational complexity of the proposed scheme in proposition can be easily derived.  $\square$

*Remark* Note that (18) does not consider the calculation of distances between UEs. The main reasons for this are as follows. First, the calculation amount of distances between UEs are smaller than those of the combining vector. Second, the locations of UEs can be treated as unchanged within several or even tens of channel coherence blocks since the channel coherence time is short, whereas the position of a UE and its surrounding environment may not physically change in a comparable period of time. Hence, unlike combining vectors, it is not necessary to frequently calculate the distances between UEs. Based on this, the calculation of distance between UEs is negligible for the complexity of the proposed scheme.

Next, we summarize expressions for the computational complexity of other different combining schemes, obtained using the same methodology as the above analysis and shown in Table 2 at the top of the next page, where  $\mathcal{S}_n$  and  $\mathcal{W}_n$  represent the strong UEs set and weak UEs set in PWPZF combining scheme, respectively, and  $\tau_{\mathcal{S}_n}$  denotes the number of different pilots used by the UEs  $k \in \mathcal{S}_n$ . Besides,  $\mathbb{I}(E)$  is the indicator function, and it is equal to one if the logic statement E is true.

### 3.4 Power control

Pragmatic power control is needed in practical implementations of cell-free massive MIMO systems. In the following, we introduce two power control schemes which are widely used in cell-free massive MIMO.

**Table 2** Computational complexity

| Combining scheme   | Number of complex multiplications  |
|--------------------|--|
| MR                 | 0  |
| FZF                | $\sum_{n=1}^N \left( \frac{3\tau_p^2 M}{2} + \frac{\tau_p M}{2} + \frac{\tau_p^3 - \tau_p}{3} \right) \times \mathbb{I}(\mathcal{K}_n \neq \emptyset)$   |
| PWPFZF             | $\sum_{n=1}^N \left[ \left( \frac{3\tau_{S_n}^2 M}{2} + \frac{\tau_{S_n} M}{2} + \frac{\tau_{S_n}^3 - \tau_{S_n}}{3} \right) \times \mathbb{I}(\mathcal{S}_n \neq \emptyset) \right. \\ \left. + 2(\tau_p - \tau_{S_n})\tau_{S_n} M \times \mathbb{I}(\mathcal{W}_n \neq \emptyset) \right]$ |
| LRZF               | $\sum_{n=1}^N \left( \frac{3M^2  \mathcal{K}_n }{2} + \frac{M \mathcal{K}_n }{2} + \frac{M^3 - M}{3} \right) \times \mathbb{I}(\mathcal{K}_n \neq \emptyset)$  |
| LP-MMSE            | $\sum_{n=1}^N \left( \frac{3M^2  \mathcal{K}_n }{2} + \frac{M \mathcal{K}_n }{2} + \frac{M^3 - M}{3} \right) \times \mathbb{I}(\mathcal{K}_n \neq \emptyset)$  |
| Proposed combining | $\sum_{n \in \mathcal{G}} \frac{3M^2  \mathcal{K}_n }{2} + \frac{M \mathcal{K}_n }{2} + \frac{M^3 - M}{3}$   |

### 3.4.1 Max-min fairness power control

MMF power control consists in optimizing the SE achieved by the weakest UE to provide uniform service throughout the network [1, 5]. The MMF power control problem can be formulated as:

$$\begin{aligned} \max_{P_k} \min_{k \in \{1, \dots, K\}} R_k^u \\ \text{s.t. } 0 \leq P_k \leq P_{\max}, k = 1, \dots, K, \end{aligned} \tag{19}$$

where  $P_{\max}$  denotes the maximum transmit power of UE. Without loss of generality, the problem given in (19) can be rewritten by introducing an auxiliary variable  $w$ :

$$\begin{aligned} \max_{w, P_k} w \\ \text{s.t. } \text{SINR}_k \geq w, k = 1, \dots, K \\ 0 \leq P_k \leq P_{\max}, k = 1, \dots, K. \end{aligned} \tag{20}$$

Then, to improve the convergence rate, we equivalently replace the problem in (20) with a problem having the same constraints but where the total power is minimized, which is similar to [5], given by

$$\begin{aligned} \min_{P_k} \sum_{k=1}^K P_k \\ \text{s.t. } \text{SINR}_k \geq w, k = 1, \dots, K \\ 0 \leq P_k \leq P_{\max}, k = 1, \dots, K. \end{aligned} \tag{21}$$

Finally, if  $w$  is fixed, (21) is a convex program, which can be solved by using bisection search method with the help of the CVX toolbox [11].

### 3.4.2 Fractional power control

Fractional power control is a classical heuristic in the cell-free massive MIMO systems, which utilizes the local long-term channel statistics to balance performance for

UEs with different channel gain [24]. In this paper, we also consider the distributed fractional power control scheme, which the power of UE  $k$  is given by [11]

$$P_k = P_{\max} \frac{\left(\sum_{n \in \mathcal{M}_k} \beta_{nk}\right)^\chi}{\max_{i \in \mathcal{K}} \left(\sum_{n \in \mathcal{M}_i} \beta_{ni}\right)^\chi}, \tag{22}$$

where  $\chi$  denotes the power control behavior. Specifically, if  $\chi = 0$ , the fractional power control degenerates to full power transmission scheme, i.e.,  $P_k = P_{\max}, \forall k \in \mathcal{K}$ .

#### 4 Results and discussion

In this section, we evaluate the performance of the proposed IC-IB pilot assignment scheme in comparison with that of the existing pilot assignment schemes, and we present simulation results to investigate the performance of the location-aided uplink combining scheme in terms of the SE performance, UE fairness and computational complexity, respectively. We consider a simulation scenario where all APs and UEs are randomly distributed in  $300 \times 300 \text{ m}^2$ . The large-scale fading coefficient  $\beta_{nk}$  models the path loss and shadow fading, as follows

$$\beta_{nk} = \text{PL}_{nk} \cdot 10^{\frac{\sigma_{sh} z_{nk}}{10}}, \tag{23}$$

where  $\text{PL}_{nk}$  denotes the path loss, and  $10^{\frac{\sigma_{sh} z_{nk}}{10}}$  represents the log-normal shadow fading with standard deviation  $\sigma_{sh}$  and  $z_{nk} \sim \mathcal{N}_{\mathbb{C}}(0, 1)$ . The path loss follows the 3GPP Urban Micro-cell model in [24, 32], which assumes a 2 GHz carrier frequency, and is given by

$$\text{PL}_{nk} [\text{dB}] = -30.5 - 36.7 \log_{10} \left( \frac{d_{nk}}{1 \text{ m}} \right), \tag{24}$$

where  $d_{nk}$  denotes the distance between AP  $n$  and UE  $k$  including AP and UE's heights. The shadow fading accounts for spatial correlations between APs and between UEs and follows

$$z_{nk} = \sqrt{\vartheta} a_n + \sqrt{1 - \vartheta} b_k, \tag{25}$$

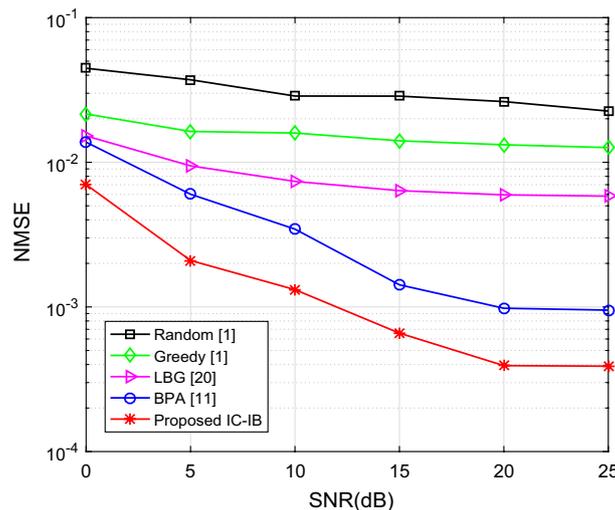
where  $a_n \sim \mathcal{N}_{\mathbb{C}}(0, 1)$  and  $b_k \sim \mathcal{N}_{\mathbb{C}}(0, 1)$  are independent random variables modeling the shadow fading impact on the channels from AP  $n$  to all the UEs and from UE  $k$  to all the APs, respectively, and  $\vartheta$  is the weighting parameter. The shadowing terms are correlated as

$$\mathbb{E}\{a_n a_i\} = 2^{\frac{d_{ni}^{\text{AP}}}{9 \text{ m}}}, \quad \mathbb{E}\{b_k b_j\} = 2^{\frac{d_{kj}^{\text{UE}}}{9 \text{ m}}}, \tag{26}$$

where  $d_{ni}^{\text{AP}}$  is the distance between AP  $n$  and AP  $i$ ,  $d_{kj}^{\text{UE}}$  is the distance between UE  $k$  and UE  $j$ , and 9 meters is the decorrelation distance [24]. The standard deviation is set to  $\sigma_{sh} = 4 \text{ dB}$ , and the heights of AP and UE are set as 10 m and 1.6 m, respectively. The channel bandwidth  $B = 20 \text{ MHz}$ . The ULA antenna spacing is  $d = \frac{\lambda}{2}$ . Each coherence block contains  $\tau_c = 100$  samples. Unless specified, the fractional power control is utilized for transmission, where  $\chi = -0.3$ . Furthermore, the AP selection threshold and

**Table 3** Parameters setup

| Parameters                                       | Value   |
|--|---------|
| Number of scattering paths, $L$                  | 10      |
| Noise power, $\sigma^2$                          | -96 dBm |
| Single-side angle spread                         | 4°      |
| Maximum uplink transmit power, $P_{\max}$        | 100 mW  |
| Number of random realizations of AP/UE locations | 100     |
| Number of random channel realizations            | 1000    |



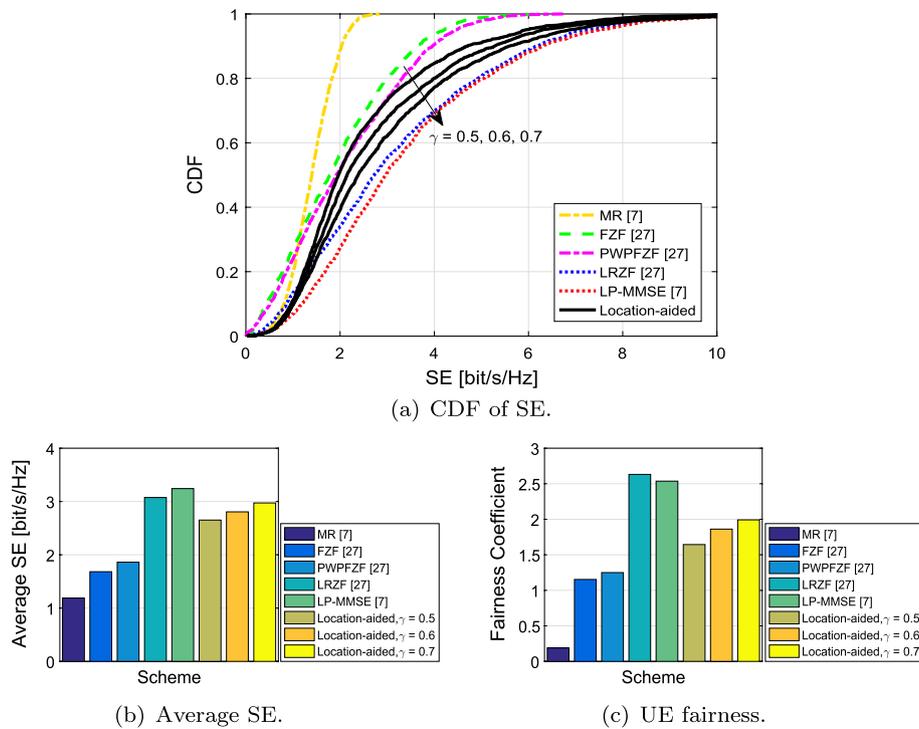
**Fig. 2** NMSE of channel estimation with various received signal-to-noise ratio (SNR) for different pilot assignment schemes with  $M = 8, N = 30, K = 20$  and  $\tau_p = 10$

the predefined coefficient are set to  $\varepsilon = 90\%$  and  $\omega = 1000$ , respectively. The other specific parameters are summarized in Table 3.

Then, we use the normalized mean-squared error (NMSE) to evaluate the performance of channel estimation. Considering the user-centric framework adopted in this paper, the expression of NMSE can be given by [33]

$$\text{NMSE} \triangleq \frac{1}{K} \sum_{k=1}^K \frac{\sum_{n \in \mathcal{M}_k} \|\mathbf{h}_{nk} - \hat{\mathbf{h}}_{nk}\|^2}{\sum_{n \in \mathcal{M}_k} \|\mathbf{h}_{nk}\|^2}. \tag{27}$$

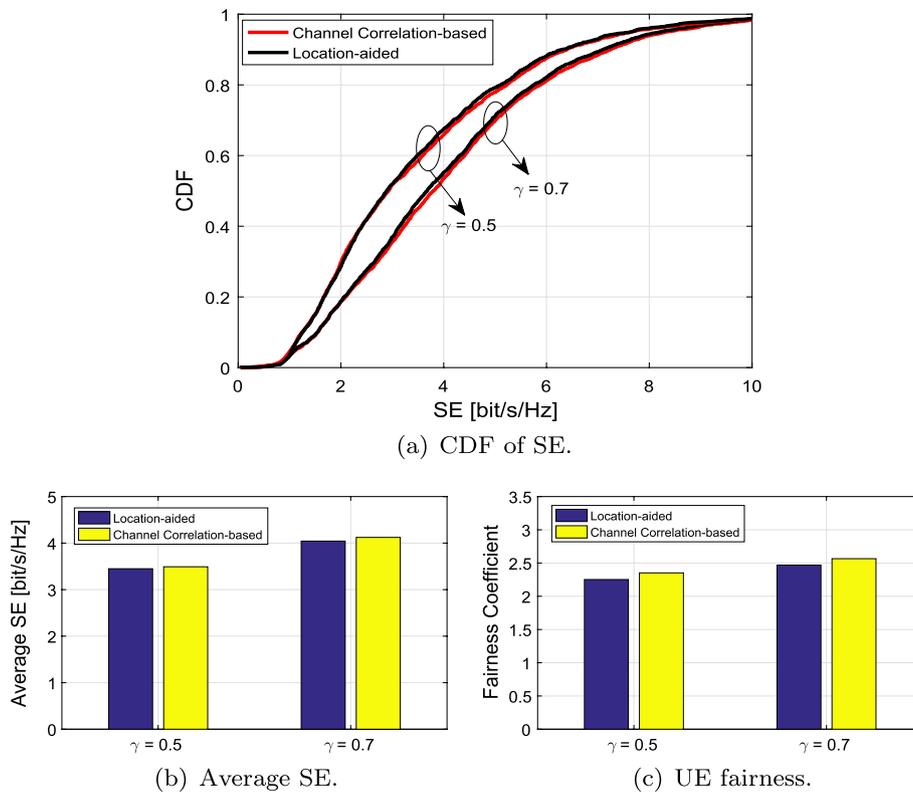
Figure 2 compares the NMSE of the channel estimation performance versus SNR with different pilot assignment schemes. Clearly, the proposed IC-IB pilot assignment scheme is superior to the existing pilot assignment schemes such as random, greedy, LBG and basic pilot assignment (BPA) schemes. There are two reasons for this superiority. First,  $\tau_p$  mutually orthogonal pilots are assigned to  $\tau_p$  UEs with severe potential interference, rather than randomly. Second, for the UEs remaining after these orthogonal pilots are assigned, we consider the interference between the corresponding UE and the UEs served by the common APs that use the same pilot, and the interference



**Fig. 3** The comparison of per-UE uplink SE, average SE and UE fairness of the proposed combining scheme with other combining schemes under different thresholds  $\gamma$ , where  $M = 8, N = 30, K = 40, \tau_p = 5$ , and  $\gamma = 0.5, 0.6, 0.7$

relationship between UEs is used to assign pilots to the maximum extent under the user-centric framework. Furthermore, the NMSE performance is improved with the increase of SNR for all schemes and we can improve the channel estimation accuracy by increasing SNR appropriately.

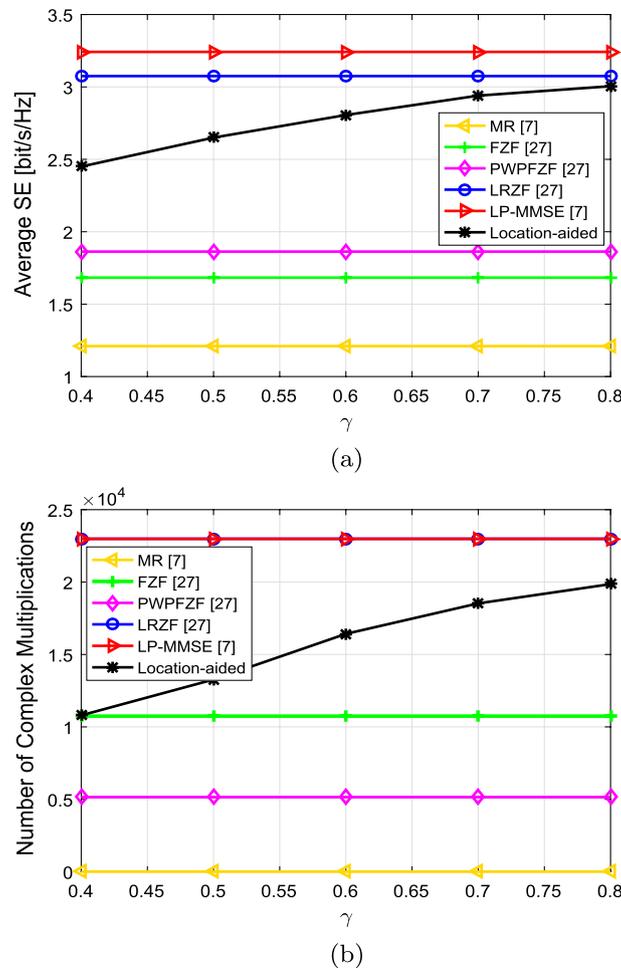
Figure 3 depicts the comparison of per-UE uplink SE, average SE and UE fairness of the proposed combining scheme with other combining schemes under different thresholds  $\gamma$ , where the UE fairness is measured by the proposed fairness coefficient, which is inspired by [34] and taken the average SE into account, and defined as  $\text{Var}(R_k^u) / \sqrt{\mathbb{E}\{R_k^u\}}$ . FZF, PWPZF and LRZF adopt the same random pilot assignment as [27]. And MR and LP-MMSE utilize the same BPA as [7]. While regarding the proposed location-aided combining scheme, we adopt the IC-IB pilot assignment scheme. From Fig. 3a, we observe that the per-UE uplink SE of our proposed location-aided combining is improved with the increase of  $\gamma$ . This is intuitive since a larger threshold  $\gamma$  means that more APs use LP-MMSE combining to suppress inter-user interference. We can also observe in Fig. 3a that the location-aided combining gives a comparable 95%-likely SE to LP-MMSE, and higher than that of MR, FZF, PWPZF and LRZF. As shown in Fig. 3b, c, in terms of average SE, the proposed scheme is inferior to LP-MMSE and LRZF, but better than MR, FZF and PWPZF, while on the aspect of UE fairness, the above result is reversed. Take the LP-MMSE among five benchmarks as an example, when  $\gamma = 0.6$ , the proposed scheme trades 13.45% average SE loss for 26.61% UE fairness improvement compared with LP-MMSE combining. These observations indicate that



**Fig. 4** The comparison of per-UE uplink SE, average SE and UE fairness of the proposed combining scheme with the channel correlation-based combining under different thresholds  $\gamma$ , where  $M = 8, N = 30, K = 25, \tau_p = 5$ , and  $\gamma = 0.5$  and  $0.7$

the proposed scheme can provide a good trade-off between the UE fairness and average SE.

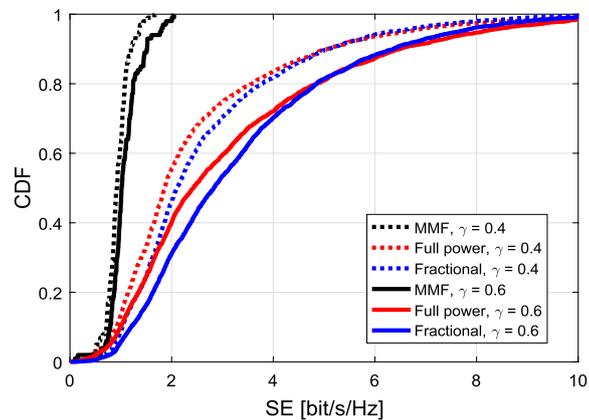
Figure 4 compares the per-UE uplink SE, average SE and UE fairness of the proposed location-aided combining scheme with another benchmark for different thresholds  $\gamma$ , where the difference between the benchmark and the proposed scheme lies in the metric used to select APs. Specifically, similar to (13), we define a metric  $\Omega_{ij,n} = \mathbb{E}\{\mathbf{h}_{ni}^H \mathbf{h}_{nj}\}, i \neq j$  based on the channel correlation, which represents the degree of interference between different UEs relative to AP  $n$ . The subsequent AP selection process is the same as the proposed scheme except for the selection metric. For convenience of expression, this benchmark can be called the channel correlation-based combining scheme. As shown in Fig. 4a, the proposed combining scheme can provide a comparable per-UE uplink SE to the channel correlation-based combining regardless of  $\gamma = 0.5$  or  $\gamma = 0.7$ . From Fig. 4b, c, the proposed scheme is also comparable to the channel correlation-based combining in terms of average SE, while in terms of UE fairness, the channel correlation-based combining is even slightly inferior to the proposed scheme. The AP selection metric proposed in (13) not only considers the distance between UEs, but also considers the common AP service situation determined by the largest-large-scale-fading-based AP selection scheme. From this point of view, the proposed location-aided scheme also takes the impact of large-scale fading into



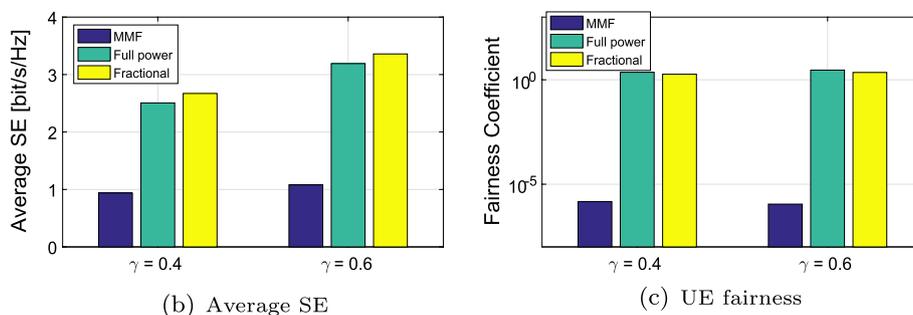
**Fig. 5** Average SE and the number of complex multiplications versus the threshold  $\gamma$  for different combining schemes, where  $M = 8, N = 30, K = 40$  and  $\tau_p = 5$

account. Moreover, the metric of AP selection for the channel correlation-based combining needs to be obtained through long-term observation and calculation, which requires more time and computational overhead compared to the acquisition of location information and common AP situation in the proposed scheme. Based on the above analysis, the proposed location-aided combining scheme is reasonable and meaningful.

Figure 5 shows the average SE and the number of complex multiplications of different combining schemes versus  $\gamma$ . Similarly, the random pilot assignment is adopted for FZF, PWPFZF and LRZE, the BPA is adopted for MR and LP-MMSE, while the IC-IB scheme is used for the proposed location-aided combining. As shown in Fig. 5a, b, both average SE and the number of complex multiplications of proposed scheme grow linearly with the increase of  $\gamma$ , whereas those of the five other schemes remain unchanged. Specifically, compared with LP-MMSE combining scheme, the proposed scheme can reduce the complexity by 28.58% at the cost of average SE only losing 13.45% when  $\gamma = 0.6$ , while  $\gamma = 0.5$ , the SE loss is 18.2%, and the complexity can be greatly reduced by 42.28%. Therefore, the proposed combining scheme can select an



(a) CDF of SE.



**Fig. 6** The comparison of per-UE uplink SE, average SE and UE fairness with different power control schemes for the proposed location-aided combining scheme, where  $M = 8, N = 30, K = 30$  and  $\tau_p = 5$

appropriate  $\gamma$  to balance the uplink SE and computational complexity according to the actual requirements of the network.

Figure 6 compares per-UE uplink SE, average SE and UE fairness with different power controls for proposed combining scheme. We use the proposed IC-IB pilot assignment as before. In Fig. 6a, we can see that when  $\gamma = 0.4$  or  $\gamma = 0.6$ , the SE distribution with fractional power control both outperforms the MMF power control and full power transmission in terms of 95%-likely SE. This is because that fractional power control allows UEs with worse channel conditions to transmit with higher power when  $\chi = -0.3$ . In addition, the MMF power control can provide the best uniformly service than the other two schemes and thus can achieve best UE fairness, as shown in Fig. 6c. However, we can observe in Fig. 6b that the average SE of the proposed scheme with MMF power control is much less than the other schemes. Moreover, regardless of the value of  $\gamma$ , the fractional power control outperforms the full power transmission in both average SE and UE fairness, which verifies the advantages of fractional power control for the proposed location-aided combining scheme.

### 5 Conclusion

This paper investigates the uplink transmission of cell-free massive MIMO systems based on a user-centric topology. The largest-large-scale-fading-based AP selection method is adopted, and a novel pilot assignment scheme based on the inter-cluster interference

is proposed to reduce pilot contamination. Based on the location information of UEs and the service relationship of AP-UE pairs, we design a new metric to represent the degree of interference between UEs. Then, we propose a location-aided distributed uplink combining scheme that includes a novel proposed AP selection to select the APs served by UEs with large inter-user interference to adopt LP-MMSE combining, while MR combining is adopted for the remaining APs. A new fairness coefficient that takes SE performance into account is proposed to characterize UE fairness. Furthermore, the performance of the proposed combining scheme is investigated under different power control schemes. Simulation results show that the proposed IC-IB pilot assignment scheme achieves better channel estimation performance than the existing pilot assignment schemes. Moreover, our proposed location-aided uplink combining scheme effectively compromises between the average SE, UE fairness and complexity by adjusting the threshold  $\gamma$ , which has obvious advantages when considering the comprehensive performance of the above three metrics in comparison with the existing combining schemes. Finally, applying fractional power control can further improve the trade-off performance compared with MMF power control and full power transmission.

#### Abbreviations

|         |  |
|---------|--|
| MIMO    | Massive multiple-input multiple-output   |
| AP      | Access point                             |
| IC-IB   | Inter-cluster interference-based         |
| SE      | Spectral efficiency                      |
| UE      | User equipment                           |
| LP-MMSE | Local partial minimum mean-squared error |
| MR      | Maximum ratio                            |
| MMF     | Max-min fairness                         |
| CPU     | Central processing unit                  |
| GPS     | Global positioning system                |
| LOS     | Line of sight                            |
| LBG     | Location-based greedy                    |
| CB      | Conjugate beamforming                    |
| NCB     | Normalized CB                            |
| ECB     | Enhanced normalized CB                   |
| PZF     | Partial zero-forcing                     |
| PPZF    | Protective PZF                           |
| JMRZF   | Joint maximum-ratio and zero-forcing     |
| CZF     | Centralized ZF                           |
| MRT     | Maximum-ratio transmission               |
| SIC     | Successive interference cancellation     |
| FZF     | Full-pilot ZF                            |
| PFZF    | Partial FZF                              |
| PWPFZF  | Protective weak PFZF                     |
| LRZF    | Local regularized ZF                     |
| LSFD    | Large-scale fading decoding              |
| ULA     | Uniform linear array                     |
| AOA     | Angle of arrival                         |
| MMSE    | Minimum mean square error                |
| NMSE    | Normalized mean-squared error            |
| BPA     | Basic pilot assignment                   |

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#### Author contributions

All authors made contributions in the discussions, analyses and implementation of the proposed solution. CW contributed to writing the manuscript. All authors read and approved the final manuscript.

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#### Availability of data and materials

Not applicable.

#### Declarations

##### Competing interests

The authors declare that they have no competing interests.

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#### References

- H.Q. Ngo, A. Ashikhmin, H. Yang, E.G. Larsson, T.L. Marzetta, Cell-free massive MIMO versus small cells. *IEEE Trans. Wirel. Commun.* **16**(3), 1834–1850 (2017)
- G. Interdonato, E. Björnson, H.Q. Ngo, Pål. Frenger, E.G. Larsson, Ubiquitous cell-free massive MIMO communications. *EURASIP J. Wirel. Commun. Netw.* **2019**(197), 1–13 (2019)
- J. Zhang, E. Björnson, M. Matthaiou, D.W.K. Ng, H. Yang, D.J. Love, Prospective multiple antenna technologies for beyond 5G. *IEEE J. Sel. Areas Commun.* **38**(8), 1637–1660 (2020)
- Ö. Özdogan, E. Björnson, J. Zhang, Performance of cell-free massive MIMO with Rician fading and phase shifts. *IEEE Trans. Wirel. Commun.* **18**(11), 5299–5315 (2019)
- M. Bashar, K. Cumanan, A.G. Burr, M. Debbah, H.Q. Ngo, On the uplink max-min SINR of cell-free massive MIMO systems. *IEEE Trans. Wirel. Commun.* **18**(4), 2021–2036 (2019)
- P. Liu, K. Luo, D. Chen, T. Jiang, Spectral efficiency analysis of cell-free massive MIMO systems with zero-forcing detector. *IEEE Trans. Wirel. Commun.* **19**(2), 795–807 (2020)
- E. Björnson, L. Sanguinetti, Scalable cell-free massive MIMO systems. *IEEE Trans. Commun.* **68**(7), 4247–4261 (2020)
- S. Buzzi, C. DAndrea, Cell-free massive MIMO: user-centric approach. *IEEE Wirel. Commun. Lett.* **6**(6), 706–709 (2017)
- S. Buzzi, C. DAndrea, A. Zappone, C. DiElia, User-centric 5G cellular networks: resource allocation and comparison with the cell-free massive MIMO approach. *IEEE Trans. Wirel. Commun.* **19**(2), 1250–1264 (2020)
- C. Wei, K. Xu, X. Xia, Q. Su, M. Shen, W. Xie, C. Li, User-centric access point selection in cell-free massive MIMO systems: a game-theoretic approach. *IEEE Commun. Lett.* (2022). <https://doi.org/10.1109/LCOMM.2022.3186350>
- Ö.T. Demir, E. Björnson, L. Sanguinetti, Foundations of user-centric cell-free massive MIMO. *Found. Trends<sup>®</sup> Signal Process.* **14**(3–4), 162–472 (2021)
- E. Björnson, L. Sanguinetti, Making cell-free massive MIMO competitive with MMSE processing and centralized implementation. *IEEE Trans. Wirel. Commun.* **19**(1), 77–90 (2020)
- R. Taranto, S. Muppirisetty, R. Raulefs, D. Slock, T. Svensson, H. Wymeersch, Location-aware communications for 5G networks: how location information can improve scalability, latency, and robustness of 5G. *IEEE Signal Process. Mag.* **31**(6), 102–112 (2014)
- Z. Shen, K. Xu, X. Xia, 2D fingerprinting-based localization for mmWave cell-free massive MIMO systems. *IEEE Commun. Lett.* **25**(11), 3556–3560 (2021)
- N. Akbar, S. Yan, N. Yang, J. Yuan, Location-aware pilot allocation in multicell multiuser massive MIMO networks. *IEEE Trans. Veh. Technol.* **67**(8), 7774–7778 (2018)
- L.S. Muppirisetty, T. Charalambous, J. Karout, G. Fodor, H. Wymeersch, Location-aided pilot contamination avoidance for massive MIMO systems. *IEEE Trans. Wirel. Commun.* **17**(4), 2662–2674 (2018)
- Y. Xu, X. Xia, K. Xu, Y. Wang, Three-dimension massive MIMO for air-to-ground transmission: location-assisted precoding and impact of AoD uncertainty. *IEEE Access* **5**, 15582–15596 (2017)
- K. Xu, Z. Shen, Y. Wang, X. Xia, Location-aided mMIMO channel tracking and hybrid beamforming for high-speed railway communications: an angle-domain approach. *IEEE Syst. J.* **14**(1), 93–104 (2020)
- M. Attarifar, A. Abbasfar, A. Lozano, Random vs structured pilot assignment in cell-free massive MIMO wireless networks, in *Proceedings of IEEE International Conference on Communications* (2018), pp. 1–6
- Y. Zhang, H. Cao, P. Zhong, C. Qi, L. Yang, Location-based greedy pilot assignment for cell-free massive MIMO systems, in *Proceedings of IEEE 4th International Conference on Computer Communications* (2018), pp. 392–396
- A.Á. Polegre, F.R. Palou, G. Femenias, A.G. Armada, New insights on channel hardening in cell-free massive MIMO networks, in *Proceedings of IEEE International Conference on Communications Workshops (ICC Wkshps)* (2020), pp. 1–7
- G. Interdonato, H.Q. Ngo, E.G. Larsson, Enhanced normalized conjugate beamforming for cell-free massive MIMO. *IEEE Trans. Commun.* **69**(5), 2863–2877 (2021)
- G. Interdonato, S. Buzzi, Conjugate beamforming with fractional-exponent normalization and scalable power control in cell-free massive MIMO, in *Proceedings of IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)* (2021), pp. 396–400
- G. Interdonato, M. Karlsson, E. Björnson, E.G. Larsson, Local partial zero-forcing precoding for cell-free massive MIMO. *IEEE Trans. Wirel. Commun.* **19**(7), 4758–4774 (2020)
- L. Du, L. Li, H.Q. Ngo, T.C. Mai, M. Matthaiou, Cell-free massive MIMO: joint maximum-ratio and zero-forcing precoder with power control. *IEEE Trans. Commun.* **69**(6), 3741–3756 (2021)

26. S. Buzzi, C. D'Andrea, C. DiElia, User-centric cell-free massive MIMO with interference cancellation and local ZF downlink precoding, in *Proceedings of IEEE International Symposium on Wireless Communication Systems (ISWCS)* (2018), pp. 1–5
27. J. Zhang, J. Zhang, E. Björnson, B. Ai, Local partial zero-forcing combining for cell-free massive MIMO systems. *IEEE Trans. Commun.* **69**(12), 8459–8473 (2021)
28. H.Q. Ngo, L. Tran, T.Q. Duong, M. Matthaiou, E.G. Larsson, On the total energy efficiency of cell-free massive MIMO. *IEEE Trans. Green Commun. Netw.* **2**(1), 25–39 (2018)
29. A. Abdallah, M.M. Mansour, Efficient angle-domain processing for FDD-based cell-free massive MIMO systems. *IEEE Trans. Commun.* **68**(4), 2188–2203 (2020)
30. J. Qiu, K. Xu, Z. Shen, Cooperative fingerprint positioning for cell-free massive MIMO systems, in *Proceedings of International Conference on Wireless Communications, Signal Processing* (2020), pp. 1–6
31. E. Björnson, J. Hoydis, L. Sanguinetti, Massive MIMO networks: spectral, energy, and hardware efficiency. *Found. Trends® Signal Process.* **11**(3-4), 154–655 (2017)
32. Further advancements for E-UTRA physical layer aspects (release 9). 3GPP, document TS 36.814 (2017)
33. X. Zheng, A. Liu, V. Lau, Joint channel and location estimation of massive MIMO system with phase noise. *IEEE Trans. Signal Process.* **68**, 2598–2612 (2020)
34. J. Choi, Power allocation for max-sum rate and max-min rate proportional fairness in NOMA. *IEEE Commun. Lett.* **20**(10), 2055–2058 (2016)

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