Adaptive Interference Suppressing Multi-User ZF in Cluster-Centric Cell-Free Massive MIMO Systems

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***Abstract*— In this letter, a cluster-centric (CC)-based cell-free massive multiple-input multiple-output (CF-mMIMO) system is considered, which realizes multi-user multiplexing in each user-cluster formed by neighboring users and served by surrounding antennas. Then, the interference suppressing multi-user zero-forcing (IS-MU-ZF) is considered to further eliminate the inter-cluster interference. But the IS-MU-ZF faces a capacity drop problem. Thus, an adaptive interfering user selection method is proposed to flexibly determine the set of interfering users for each user-cluster. It is confirmed by computer simulation that the proposed CC-based CF-mMIMO system utilizing the IS-MU-ZF with the proposed adaptive interfering user selection method outperforms the well-known user-centric (UC)-based CF-mMIMO system in terms of capacity and computational complexity when the accuracy of channel estimation is guaranteed.**

***Index Terms*— Cell-free massive MIMO, user-clustering, zero-forcing, interference suppression.**

I. Introduction

CELL-FREE massive multiple-input multiple-output (CF-mMIMO) systems [1], [2] with a large number of distributed antennas and a powerful central processing unit (CPU), are designed to simultaneously serve a large number of users by conjugate beamforming. However, conjugate beamforming cannot achieve the perfect channel hardening required for eliminating interference between users when the number of accommodated users is large [3]. Furthermore, the prohibitively high fronthaul capacity and signal processing overhead are required, and the scalability issue is concerned. Thus, in [3] and [4], a user-centric (UC) approach was proposed to realize a scalable CF-mMIMO system. In the UC-based CF-mMIMO system, by introducing the interference suppressing (IS) technique based on either zero-forcing (ZF) or minimum mean square error (MMSE) pre/postcoding [5], each user is served only by a set of nearby antennas with high channel gains without relying on the channel hardening effect. A called partial MMSE was proposed in [3], which only considers a part of interfering users in MMSE weight from the perspective of scalability.

The interference becomes severer as the number of users increases and the user capacity of CF-mMIMO systems degrades. To improve the user capacity, we proposed a cluster-centric (CC)-based CF-mMIMO system [6], [7] with the multi-user multiplexing technique. In our proposed CC-based CF-mMIMO system, neighboring users are grouped by a location-based user-clustering method and a certain number of antennas are associated with each user-cluster to perform cluster-wise multi-user spatial multiplexing simultaneously in all user-clusters. It should be noted that, unlike the idea of user-clustering which was utilized in pilot assignment to efficiently reuse the limited pilot resource in CF-mMIMO systems [8], [9], our intention of user-clustering is for applying multi-user spatial multiplexing to improve the user capacity.

We consider partial interference suppressing multi-user ZF (IS-MU-ZF) and IS-MU-MMSE to suppress the dominant interference between user clusters. While the partial IS-MU-ZF is simpler than the partial IS-MU-MMSE because the noise estimation is not required, the achievable user capacity of partial IS-MU-ZF was found to significantly degrade when the number of considered interfering users becomes equal to or close to the antenna degree of freedom (DoF) minus the number of multiplexing users in each user-cluster in [6] and [7]. To solve this problem, in this letter, we investigate the relationship between the user capacity achievable with partial IS-MU-ZF and the number of considered dominant interfering users for the given antenna DoF of each user-cluster. Then, we propose an adaptive interfering user selection method for partial IS-MU-ZF.

The rest of this letter is organized as follows. Section II introduces the transmission model of the CC-based CF-mMIMO system. Then, after giving the problem statement, the proposed adaptive interfering user selection method for partial IS-MU-ZF is described in Section III. In Section IV, the effectiveness of our proposed adaptive interfering user selection method for partial IS-MU-ZF is confirmed by computer simulation. Finally, Section V offers conclusions.

Notation: Boldface lowercase letter $\mathbf{x}$ and uppercase letter $\mathbf{X}$ denote vector and matrix, respectively. The $n \times n$ identity matrix and zero matrix are denoted by $\mathbf{I}_n$ and $\mathbf{0}_n$, respectively. $\|\mathbf{A}\|_{\mathrm{F}}$, $\mathbf{A}^T$, $\mathbf{A}^H$, $\mathbf{A}^\dagger$ denote the Frobenius norm,

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transpose, conjugate transpose and pseudo-inverse of matrix $\mathbf{A}$, respectively. $\lceil x \rceil$ and $\lfloor x \rfloor$ denote the ceiling and floor functions, respectively. $|\mathcal{A}|$ denotes the cardinality of set $\mathcal{A}$.

II. System Model

A distributed antennas are assumed to be deployed over the communication area to serve U single-antenna users in a CC-based CF-mMIMO system. K user-clusters are formed, and then distributed antennas are associated with each user-cluster to perform partial IS-MU-ZF in all user-clusters in parallel. As in [9], the time-division-duplex (TDD) mode exploiting the reciprocity of uplink and downlink channels is assumed. Moreover, uplink channel estimation to derive partial IS-MU-ZF weight vector is considered.

A. CC-Based CF-mMIMO System

The neighboring users who may interfere each other severely are grouped into a user-cluster based on their location information. The computational complexity required for IS-MU-ZF increases exponentially with the cluster size [3], [6], and the total computational complexity of the system is mainly determined by the largest user-cluster when the cluster sizes are unequal. For a given K, similar (or perfectly equal) user-cluster sizes can minimize the total computational complexity. Therefore, we utilize the constrained K-means algorithm [6], [10] to restrict the user-cluster size to $U_{\max}$ according to the Euclidian distance metric. The number K of user-clusters is determined as $K = \lceil U/U_{\max} \rceil$, where K and $U_{\max}$ can be flexibly adjusted by the computational complexity affordability of the system. We denote the user set belonging to user-cluster k by $\mathcal{S}_k$ with $|\mathcal{S}_k| = U_k$. For simplicity purpose, in this letter, we assume that U is an integer multiple of $U_{\max}$ so as to form equal-size user-clusters, i.e., $U_k = U_{\max}$ for all k.

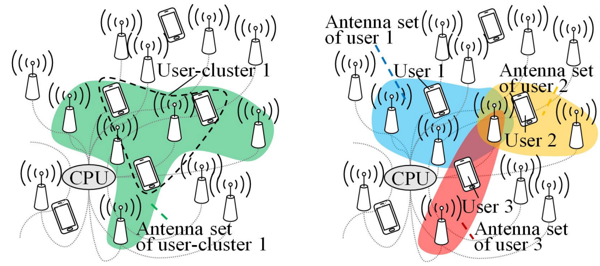
It is assumed that A_k ($\geq U_k$) distributed antennas are associated with user-cluster k after forming user-clusters. To achieve multi-user multiplexing, an exclusive set of $\lfloor A_k/U_k \rfloor$ antennas is selected in ascending order of large-scale propagation loss (path loss plus shadowing loss) for each user in user-cluster k [7], and then, all A_k distributed antennas serve all U_k users in user-cluster k. The antenna association matrix for user-cluster k is defined as $\mathbf{D}_k = \sum_{u \in \mathcal{S}_k} \mathbf{L}_u$, where $\mathbf{L}_u = \text{diag}\,(l_1, \ldots, l_a, \ldots, l_A) \in \mathbb{R}^{A \times A}$ is the antenna selection matrix for user u in user-cluster k with $l_a = 1$ representing that antenna a is selected for user u, otherwise, $l_a = 0$. Note that the distributed antennas associated with different user-clusters are allowed to be overlapped.

UC-based CF-mMIMO system is a special case (i.e., single-user cluster) of our CC-based one. A comparison between CC and UC-based CF-mMIMO systems is shown in Fig. 1.

B. Uplink Transmission Model

The uplink transmission model of partial IS-MU-ZF for user u in user-cluster k is shown in Fig. 2. Then, the uplink received signal after postcoding is expressed for user u as

$$y_u = \mathbf{w}_u \mathbf{D}_k \mathbf{h}_u \sqrt{P} s_u + \sum_{v=1, v \neq u}^{U} \mathbf{w}_u \mathbf{D}_k \mathbf{h}_v \sqrt{P} s_v + \mathbf{w}_u \mathbf{D}_k \mathbf{n}, \tag{1}$$



(a) CC (b) UC

Fig. 1. Comparison between CC and UC-based CF-mMIMO systems.

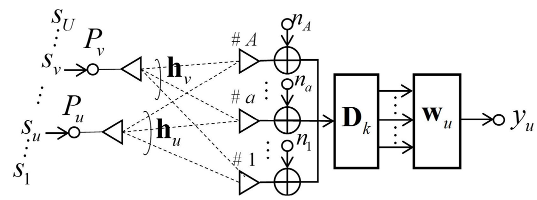


Fig. 2. Uplink transmission model of CC-based CF-mMIMO system.

where $\mathbf{w}_u \in \mathbb{C}^{1 \times A}$, $\mathbf{h}_u = [h_{1,u}, \ldots, h_{a,u}, \ldots, h_{A,u}]^T \in \mathbb{C}^{A \times 1}$, and $\mathbf{n}$ are respectively the partial IS-MU-ZF weight vector of user u, the channel gain vector between user u and all antennas, and the noise vector with each element (n_a) being characterized by zero-mean complex Gaussian random variable with variance σ^2. P_u and S_u are the transmit power and the transmit data symbol with unit variance of user u, respectively. In this letter, the channel between any user and antenna is assumed to be characterized by distance-dependent path loss, log-normally distributed shadowing loss, and Rayleigh fading [9].

The uplink signal-to-interference-plus-noise ratio (SINR) of user u can be derived from (1) as

$$\text{SINR}_u = \frac{P_u |\mathbf{w}_u \mathbf{D}_k \mathbf{h}_u|^2}{\sum_{v=1, v \neq u}^{U} P_v |\mathbf{w}_u \mathbf{D}_k \mathbf{h}_v|^2 + \|\mathbf{w}_u\|_{\text{F}}^2}, \tag{2}$$

where the first and second terms in the denominator are the aggregated interference from all other users and the noise power, respectively. Accordingly, the user capacity of user u can be computed by

$$C_u = \log_2(1 + \text{SINR}_u). \tag{3}$$

C. Partial IS-MU-ZF Weight Vector

The uplink partial IS-MU-ZF weight vector for user u in user-cluster k can be derived as

$$\mathbf{w}_u = P_u \hat{\mathbf{h}}_u^H \mathbf{D}_k \left(\sum_{v \in (\mathcal{S}_k \cup \mathcal{N}_k)} P_v \mathbf{D}_k \hat{\mathbf{h}}_v \hat{\mathbf{h}}_v^H \mathbf{D}_k \right)^{\dagger}, \tag{4}$$

where $\mathcal{N}_k$ is the set of interfering users considered in the IS-MU-ZF for user-cluster k and $\hat{\mathbf{h}}_v$ is the estimated channel gain vector of user u. Assuming that a set of τ ($U \geq \tau \geq U_k$) mutually orthogonal pilots of length τ are used for the well-known least-square channel estimation, the estimated channel between antenna a and user u is

$$\hat{h}_{a,u} = h_{a,u} + \sum_{v \in \mathcal{P}_u, v \neq u} h_{a,v} + \frac{1}{\sqrt{P_u \tau}} \boldsymbol{\phi}_u^H \mathbf{n}_a^p, \tag{5}$$

where $\phi_u \in \mathbb{C}^{\tau\times 1}$ is the pilot sequence of user u with $\|\phi_u\|^2 = \tau$, $\mathbf{n}_a^p \sim \mathcal{CN}\left(\mathbf{0}_\tau, \sigma^2\mathbf{I}_\tau\right)$ is noise vector, and $\phi_u^H\mathbf{n}_a^p \sim \mathcal{CN}\left(\mathbf{0}_\tau, \sigma^2\tau\mathbf{I}_\tau\right)$. Furthermore, $\mathcal{P}_u$ is a set of users who are assigned with same pilot as user u, and the second term in (5) represents the so-called pilot contamination which reduces the channel estimation quality. If a sufficiently large value of τ is used to avoid the pilot contamination, it costs significant overhead due to pilot transmission. Therefore, in this letter, to reduce the impact of pilot contamination while utilizing a relatively small number of orthogonal pilots, we have proposed a pilot assignment method utilizing a graph coloring-based algorithm [11]. In this proposed pilot assignment method, the available orthogonal pilots are divided into different exclusive pilot groups. The relationship among user-clusters is represented by an undirected graph consisting of vertices (cluster centroids) and edges (the relationship between two clusters sharing the same antenna). Then, different pilot groups (colors) are assigned to the neighboring clusters (connected vertices) for channel estimation.

Note that IS-MU-MMSE weight vector [7] is obtained if the effect of noise is considered as a diagonal matrix $\sigma^2\mathbf{D}_k$ in the pseudo-inverse matrix in (4). As in [3], full IS-MU-ZF, which tries to mitigate interference from all users outside the user-cluster k, is not scalable. Hence, in partial IS-MU-ZF, $\mathcal{N}_k$ consists of only the dominant interfering users, i.e.,

$$\mathcal{N}_k = \{v : \mathbf{D}_k\mathbf{D}_i \neq \mathbf{0}_A, v \in \mathcal{S}_i, i \neq k\}. \quad (6)$$

It can be understood that $\mathbf{w}_u$ in (4) is given as a cascade connection of conjugate beamforming for user u of interest and nulling to eliminate interferences from other users in $\mathcal{S}_k$ and $\mathcal{N}_k$. The number of complex multiplications required for weight calculation in (4) is given as

$$N_{\mathrm{cm}} = \frac{A_k^2 + A_k}{2}|\mathcal{N}_k| + A_k^2 + \frac{A_k^3 - A_k}{3}, \quad (7)$$

which has approximately an order of $O(A_k^3)$ [3].

III. Adaptive Interference User Selection Method for Partial IS-MU-ZF

A. Problem Statement

It was shown in our preliminary study [6], [7] that, compared with IS-MU-MMSE, the user capacity of IS-MU-ZF significantly decreases when the antenna DoF of cluster is exhausted for interfering suppression, regardless of full or partial IS. This can be clearly seen in Fig. 3, where the user capacity at 50% level of the cumulative distribution function (CDF) is plotted as a function of the total number U of users.

In capacity evaluation, the Monte Carlo simulation is carried out following the settings described in Table I. To compare the two systems under the same total computational complexity, A_k is set to $A_k = \left\lfloor \sqrt[3]{U_k} \times A_u \right\rfloor$, since total computational complexity required for CC and UC-based systems are around $K \times A_k^3$ and $U \times A_u^3$, respectively, from (7). Here, the transmit power for each user is represented by the normalized transmit signal-to-noise ratio (SNR) γ_{tx}, which is defined as the received SNR when the transmitter-receiver distance is equal to the side length of the communication area of 1×1. We set $\gamma_{\text{tx}} = -30$ dB (equivalent to 0.4W in [3]) to guarantee that the received SNR at a distance equal to the average distance between immediate neighbor antennas is sufficiently high (17.4 dB) to perform cluster-wise multi-user spatial multiplexing.

TABLE I

Simulation Settings

Parameter	Value
Communication area size	Normalized 1×1
Antenna and user distribution	Random
No. of antennas (A)	512
No. of users (U)	{8, 16, 32, 64, 128, 256, 512}
No. of user location generation for each U	1000
No. of antennas for each user in UC (A_u)	8
Cluster size ($U_{\max}$) in CC	8
No. of antennas for each cluster in CC (A_k)	16
Path loss exponent	3.5
Standard deviation of shadowing loss	8 dB
Normalized transmit SNR (γ_{tx})	-30 dB
No. of orthogonal pilot sequences (τ)	32 (4 pilot groups)

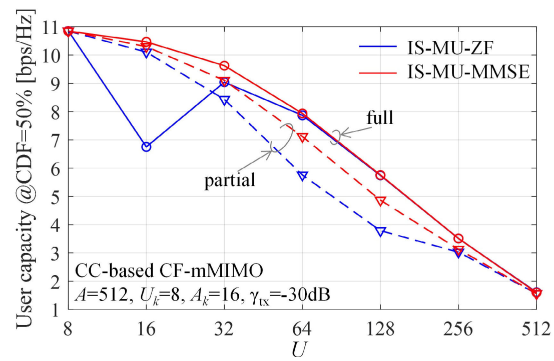


Fig. 3. Comparison between full/partial IS-MU-ZF and MMSE.

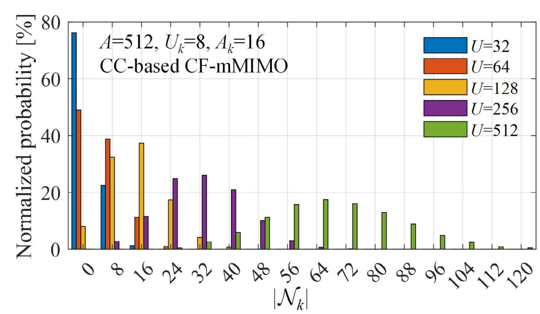


Fig. 4. Probability of $|\mathcal{N}_k|$ in partial IS-MU-ZF.

Fig. 3 shows that, for full IS-MU-ZF, the user capacity drops obviously when $U = 16$. At this time, in each cluster, $|\mathcal{N}_k| = R_k$ ($R_k = A_k - |\mathcal{S}_k|$ is called the remaining antenna DoF, hereafter). When $|\mathcal{N}_k| = R_k$, the well-known noise enhancement [7], [12] is produced which leads to the capacity drop. $|\mathcal{N}_k|$ determined in (6) for partial IS-MU-ZF varies according to changes in the propagation condition and the user-cluster structure and becomes a random variable. Fig. 4 plots the probability of $|\mathcal{N}_k|$ and indicates that when $U =$ 32, 64, and 128, the probability of $|\mathcal{N}_k| = R_k = 8$ (since $A_k = 16$ and $|\mathcal{S}_k| = U_k = 8$) is larger, and accordingly, the user capacity of partial IS-MU-ZF degrades noticeably compared with partial IS-MU-MMSE as seen in Fig. 3.

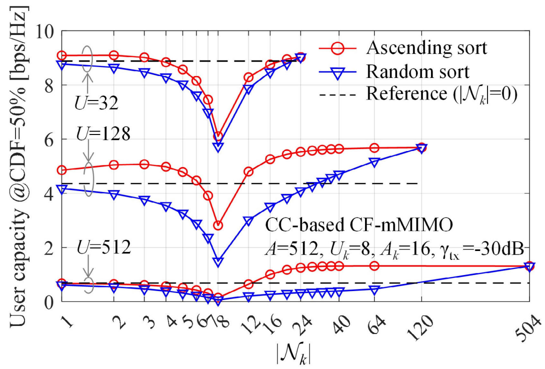


Fig. 5. Impact of $|\mathcal{N}_k|$ in partial IS-MU-ZF weight on user capacity.

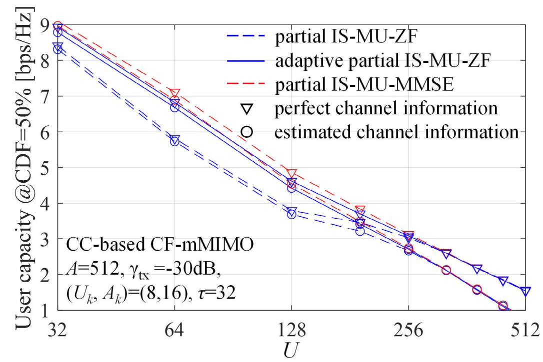


Fig. 6. Uplink user capacity of CC-based CF-mMIMO systems.

B. Proposed Adaptive Interfering User Selection Method

The impact of $|\mathcal{N}_k|$ in partial IS-MU-ZF weight on the user capacity is plotted in Fig. 5, where the user capacity of non-IS-MU-ZF (i.e., $|\mathcal{N}_k| = 0$) is also plotted as a dashed line for comparison. In Fig. 5, $\mathcal{N}_k$ are not determined by using (6) but through two sorting methods: one is to sort the interfering users in the ascending order of the sum of large-scale propagation loss between each interfering user and A_k antennas in each user-cluster and the other is a random sorting.

It can be seen from Fig. 5 that, as $|\mathcal{N}_k|$ increases from 1, the user capacity tends to decrease and becomes minimal when $|\mathcal{N}_k| = R_k$, because the remaining antenna DoF is used to eliminate the gradually increasing interference of $\mathcal{N}_k$, resulting in a reduction of target signal strength and noise enhancement by ZF weight calculation. But, the capacity starts to increase when $|\mathcal{N}_k|$ gets larger than R_k because the effect of channel hardening is gradually achieved in the summation of correlation matrices in (4) as $|\mathcal{N}_k|$ increases. Also seen from Fig. 5 is that the user capacity achievable with large-scale propagation loss-based sorting method is noticeably higher compared with the random sorting method.

Based on the above observation, we propose an adaptive interfering user selection method to avoid the capacity drop by dynamically selecting the appropriate number of dominant interfering users to be considered in partial IS-MU-ZF weight. In the proposed adaptive interfering user selection method, firstly $|\mathcal{N}_k|$ interfering users determined by (6) are sorted according to large-scale propagation loss-based sorting method mentioned above, and then only the first M_k dominant interfering users are selected from $\mathcal{N}_k$. The computational complexity of our adaptive interfering user selection algorithm is that of the sorting algorithm typically as $O(|\mathcal{N}_k| \log |\mathcal{N}_k|)$ [13] in terms of compare and swap of two values, and is negligible compared to $O(A_k^3)$ of (4).

It is understood from Fig. 5 that M_k needs to be adjusted so as to always maximize the user capacity according to the change of $|\mathcal{N}_k|$ which is determined by (6). Considering the case of $U = 128$, M_k is set to be the smaller of 4 and $|\mathcal{N}_k|$, when $|\mathcal{N}_k| \leq 12$, since 4 interfering users is enough for sufficient interfering suppression. On the other hand, if $|\mathcal{N}_k|$ is between 12 and 40, no adjustment is necessary. Finally, if $|\mathcal{N}_k|$ is larger than or equal to 40, $M_k = 40$ strongest interfering users are taken out of $|\mathcal{N}_k|$ interfering users. Moreover, the above adjustment of M_k by segmentation of $|\mathcal{N}_k|$ can be applied to different values of U, because the trend of capacity changing with $|\mathcal{N}_k|$ is almost unchanged by the value of U. It should be noted that the boundaries of the segmentation of $|\mathcal{N}_k|$ are proportional to R_k, but they may be affected by the antenna distribution and the propagation channel characteristics. Accordingly, we propose to adjust M_k as the following:

$$M_k = \begin{cases} \min(\lfloor b_1 R_k \rfloor, |\mathcal{N}_k|), & \text{if } |\mathcal{N}_k| \leq b_2 R_k \\ |\mathcal{N}_k|, & \text{if } b_2 R_k < |\mathcal{N}_k| < b_3 R_k \\ \lfloor b_3 R_k \rfloor, & \text{if } b_3 R_k \leq |\mathcal{N}_k|, \end{cases} \tag{8}$$

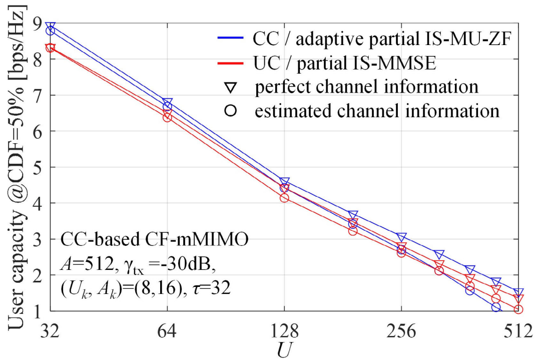
where three coefficients (b_1, b_2, b_3) are introduced to determine the segmentation boundaries of $|\mathcal{N}_k|$, and are set to (0.5, 1.5, 5) according to the results obtained in Fig. 5, in this letter.

IV. Performance Evaluation

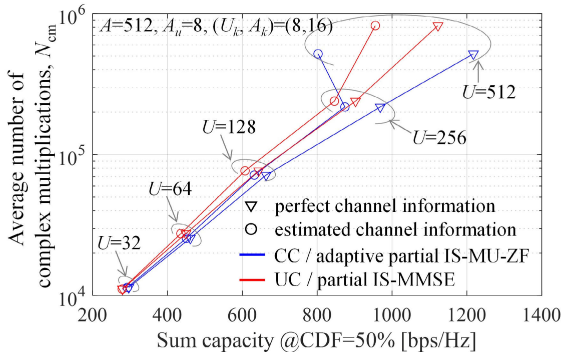
Below, partial IS-MU-ZF with our proposed adaptive interfering user selection method is called adaptive partial IS-MU-ZF for simplicity. Monte Carlo simulation, mentioned in Section III, is implemented to verify the effectiveness of adaptive partial IS-MU-ZF and to compare CC and UC-based CF-mMIMO systems in terms of the user capacity, the sum capacity, and the total computational complexity required for weight calculation.

A. Effectiveness of Adaptive Partial IS-MU-ZF

In Fig. 6, adaptive partial IS-MU-ZF, partial IS-MU-ZF, and partial IS-MU-MMSE for CC-based CF-mMIMO system are compared in terms of user capacities at CDF=50% achievable for the cases of perfect and estimated channel information. It can be seen that although the use of estimated channel information reduces the capacity compared to the perfect channel information case, the user capacity achievable for adaptive partial IS-MU-ZF has a significant improvement compared with that of partial IS-MU-ZF and approaches that of partial IS-MU-MMSE. Note that the simulation results under other settings (e.g. $(U_k, A_k) = (4, 12)$) also obtained the same conclusion as mentioned above, confirming the effectiveness of adaptive partial IS-MU-ZF.



(a) User capacity



(b) Sum capacity versus computational complexity

Fig. 7. Comparison between CC and UC-based CF-mMIMO systems.

B. Comparison Between CC and UC-CF-mMIMO Systems

In Fig. 7, CC-based CF-mMIMO system using adaptive partial IS-MU-ZF is compared with UC-based CF-mMIMO system using partial IS-MMSE [3] in the cases of perfect and estimated channel information. It can be seen from Fig. 7(a) that, irrespective of the value of U, CC-based CF-mMIMO system always achieves a higher user capacity compared with UC-based one in the case of perfect channel information. On the other hand, the CC-based one outperforms the UC one when U is less than approximately 256 (half of A), due to our proposed pilot assignment method effectively suppressing the impact of pilot contamination on IS-MU-ZF weight calculation.

At last, the relationship between averaged computational complexity (number of complex multiplications, i.e, N_{cm} in (7)) and the sum capacity at CDF=50% is plotted in Fig. 7(b), where $\gamma_{\mathrm{tx}} = -30$ dB is assumed. It can be seen from Fig. 7(b) that the CC-based CF-mMIMO system using adaptive partial IS-MU-ZF achieves higher sum capacity with lower computational complexity than the UC-based CF-mMIMO system using partial IS-MMSE when U is lower than 256 even with the estimated channel information.

In summary, CC-based CF-mMIMO system using adaptive partial IS-MU-ZF is superior to UC-based CF-mMIMO system using partial IS-MMSE in terms of user capacity, sum capacity, computational complexity when the normalized transmit SNR is sufficiently high and the accuracy of channel estimation is guaranteed.

V. Conclusion

In this letter, we proposed an adaptive interfering user selection method for partial IS-MU-ZF to avoid the capacity drop problem due to noise enhancement unique to ZF signal processing in a CC-based CF-mMIMO system. It was confirmed by computer simulation that the proposed adaptive partial IS-MU-ZF provides a similar capacity performance as partial IS-MU-MMSE. Furthermore, it is confirmed that CC-based CF-mMIMO system has advantages in link capacity, and computational complexity compared with the UC-based CF-mMIMO system when the accuracy of channel estimation is guaranteed.

Finally, it is worth mentioning that several interesting future studies remain to be done for CC-based CF-mMIMO system. They include theoretical analysis of achievable user capacity, capacity improvement of multiple-antenna user case, machine-learning-based interfering user selection method, enhanced pilot assignment and channel estimation methods, etc.

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