信学技報
IEICE Technical Report
RCS2022-144(2022-10)

A Study on Interference Suppression ZF-based MU-MIMO for Cluster-Centric Cell-Free Massive MIMO Systems

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Abstract Cell-free massive multi-input multi-output (CF-mMIMO), which is recently under extensive study, is considered to be an effective way to provide high-quality services to users by deploying a large number of antennas over a wide area in Beyond 5G systems. However, due to the extremely high computational complexity required for mMIMO, system scalability becomes an important issue for its practical implementation. In our previous study, we proposed a scalable user-cluster-centric (UCC) CF-mMIMO scheme, which employs interference suppression zero-forcing (IS-ZF)-based multi-user MIMO (MU-MIMO) to effectively mitigate the inter-cluster interference. How to identify and select dominant interfering users who give a strong impact on the system capacity is an important issue. In this paper, we will investigate the impact of the number of interfering users considered for the IS-ZF-based MU-MIMO on the system capacity and propose an effective selection method of dominant interfering users. We will show by the computer simulation that the proposed interfering user selection method can approximately reach the upper bound of capacity which is achieved by IS-ZF-based MU-MIMO considering all interfering users.

Keywords Cell-free massive MIMO, ZF, interference suppression, user clustering, beyond 5G systems

1. Introduction

Recently, the cell-free massive multi-input multi-output (CF-mMIMO) currently under extensive study is considered as a significant technology for the Beyond 5G system. Because CF-mMIMO provides a uniform and high quality of service for the users in a wide service area by deploying a large number of antennas over the service area and sharing the communication information through a powerful central processing unit (CPU) [1].

The basic concept of CF-mMIMO system is that a relatively small number of users are provided communication services with quite a large number of antennas simultaneously by sharing the same frequency [1]-[3]. By using a large number of nearby antennas, even the simple complex conjugate beamforming can effectively suppress the inter-user interference (IUI), which is called channel hardening [1], [2]. However, when the user density increases and approaches the antenna density, channel hardening cannot be achieved. In addition, such large-scale antenna coordination requires a large front-haul capacity and furthermore an unacceptable computational complexity for signal transmission processing at the CPU. Thus, the scalable implementation [3] for CF-mMIMO is necessary to make it practical. In our previous work [4], we proposed a user-cluster-centric (UCC) scheme to realize the scalable CF-mMIMO. In the proposed UCC scheme, neighborhood users are grouped as a user cluster and a set of high gain antennas are associated with each user cluster to implement the spatial multiplexing. Since the antenna set of different user clusters may inevitably overlap especially in a high user density environment, the interference suppression zero-forcing (IS-ZF)-based multi-user MIMO (MU-MIMO) transmission [4] is utilized to mitigate both the IUI inside each user-cluster and the inter-cluster-interference (ICI).

However, considering the scalability, how to select the interfering users to be considered in IS-ZF and decide the number of those users are the important issues. In this paper, we will first propose an interfering user selection method, and investigate the impact of the number of interfering users considered for IS-ZF-based MU-MIMO on system capacity. Then, we will propose a conditional selection method of interfering users to further improve the link capacity.

The rest of this paper is organized as follows. In Section 2, we introduce the system model and describe how we construct the user clusters and associate antennas with each user cluster. Then, in Section 3, we present the IS-ZF-based transmission model for the UCC CF-mMIMO and introduce the proposed interfering user selection method. In Section 4, we investigate the impact of the number of interfering users to be considered in the IS-ZF transmission by computer simulation. Then, we demonstrate the validity of our proposed interfering user selection method. Finally, we give some conclusions and future studies in Section 5.

2. System model

We consider a CF-mMIMO system where A distributed antennas in a wide service area connected with the CPU via a mobile front-haul to service U ($U \leq A$) single-antenna users, as illustrated in Fig. 1. We assume that users and antennas are randomly located over the service area and that the channel state information (CSI) between users and antennas and the location information of users and antennas are perfectly known by CPU. The basic concept of CF-mMIMO assumes the extremely high front-haul capacity and computational complexity requirement required for the large-scale antenna coordination and cannot be realistic. Therefore, to make CF-mMIMO scalable and hence, practical, we consider introducing user clustering and to apply spatial multiplexing in each user cluster using a limited number of antennas.

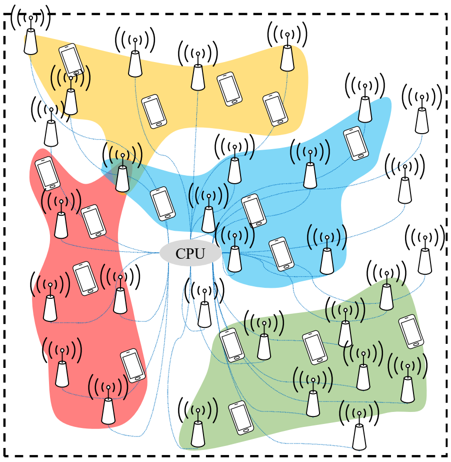


Fig. 1 Concept of UCC CF-mMIMO system.

2.1. User clustering

Since the interference between neighboring users can be considered strong on average, we intuitively group the neighboring users as a user cluster by their location information to implement MU-MIMO ZF and mitigate the IUI inside the cluster. Then, as we noted earlier that all users and antennas are assumed to communicate simultaneously, the number of users, U_k, in a cluster k should not be greater than its number of antennas, A_k, i.e., $U_k \leq A_k$. The computational complexity required for ZF operation in each cluster is related to the 3rd power of A_k or U_k [3],[5], so the cluster size needs to be controlled. The well-known K-means algorithm [6] is an efficient and suitable algorithm for our location-based user clustering, but the number of user clusters, K, needs to be decided in advance and the size of each user cluster cannot be controlled. Consequently, we utilize the constrained K-means algorithm [6],[7] to restrict the size of each user cluster to obtain similar-sized user clusters, so we can set the value of K to $K=\lceil U/U_{\max} \rceil$, where $U_{\max}$ is the upper limit of the user cluster size which is set by considering the allowable signal processing power. For the simplicity purpose, in this paper, we assume that U is an integral multiple of $U_{\max}$ so as to construct equal-size user clusters, i.e., $K=U/U_{\max}$ and $U_k=U_{\max}$ for all k. By denoting the user set $\mathcal{S}_k \subset \{1,\ldots u,\ldots,U\}$ that belongs to the kth user cluster, then, $|\mathcal{S}_k| = U_k$. Moreover, the user clusters are non-overlapped, i.e., $\mathcal{S}_k \cap \mathcal{S}_i = \varnothing$.

2.2. Antenna association

After constructing the user clusters, we associate service antennas for each user cluster. Based on our previous assumption that the number of users within each cluster is equal, the number of antennas associated with each cluster should also be the same, in this paper, we assume that $A_k = 2\times U_k$ (note that sets of antennas of user clusters may be partially overlapped each other). In addition, in order to implement MU-MIMO, each user in any user cluster should be fairly associated with antenna resources, i.e., each user has two ($A_k/U_k=2$) high gain antennas. The antenna selection method we consider in this paper is based on the competition principle, where the first user in the cluster selects its antenna with the highest channel gain, and if there is an overlap in the antenna selection between users, the antenna is associated with the user having the lowest propagation loss (sum of path loss and shadowing loss), while the remaining users select the antenna with the next lowest propagation loss, and so on and so forth until each user in the cluster is associated with one antenna. Then repeat the above procedure until each user in the cluster is associated with two antennas. Similarly, we define the antenna set associated with the user cluster k as $\mathcal{M}_k \subset \{1,\ldots a,\ldots,A\}$ with $|\mathcal{M}_k| = A_k$. It is worth noting that, different from user clustering, sets of antennas associated with different user clusters are allowed to be overlapped.

In the computer simulation, we model the communication service area as a 1×1 square area which can be scaled to any physical area (e.g., 1km ×1km square area). An example of antenna association of our proposed UCC approach is shown in Fig. 2. Here, users and antennas are represented by circles and triangles, respectively. The specific physical location of the CPU can be anywhere in the service area or in the cloud and thus, is omitted from this figure. For a clearer understanding of our proposed

UCC approach, users and antennas in different clusters are indicated by different colors and are linked to their cluster centroids using solid and dashed lines. In Fig. 2, there are 8 users and 16 antennas in each cluster, and each user is given two antennas equally.

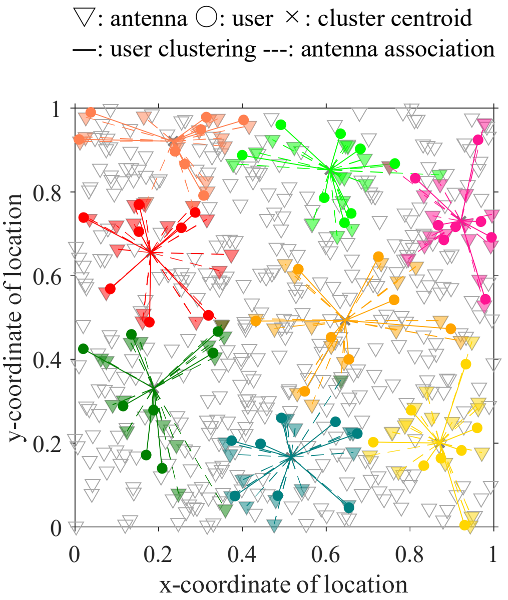


Fig. 2 An example of formed user clusters with antenna association (A=512, U=64, K=8, A_k=16).

3. IS-ZF-based MU-MIMO transmission model

In this section, we present the IS-ZF-based MU-MIMO transmission scenario for the UCC CF-mMIMO. Fig. 3 shows the uplink transmission model of the UCC approach. As illustrated in this figure, the uplink received signal expression after postcoding of the user u belonging to cluster k is

$$y_u = \sum_{i=1}^{K} \sum_{v \in \mathcal{S}_i} \mathbf{w}_u \mathbf{D}_k \mathbf{h}_v \sqrt{P_v} s_v + \mathbf{w}_u \mathbf{D}_k \mathbf{n}_u , \qquad (1)$$

where, $\mathbf{h}_u$, $\mathbf{w}_u$, P_u, s_u, and $\mathbf{n}_u$ are the uplink channel between all the antennas to the user u, postcoding vector of the user u, transmit power of the user u, transmit signal of the user u, and noise vector at service antennas of the user u, respectively. The MIMO channel is composed of path loss, log-normal shadowing loss, and Rayleigh fading as in the well-known propagation model. Thus, $\mathbf{h}_u = \mathbf{l}_u \circ \mathbf{g}_u$, where $\mathbf{l}_u$, $\mathbf{g}_u$, and $\circ$ represent the large-scale propagation loss, Rayleigh fading gain, and Hadamard product, respectively. In (1), $\mathbf{D}_k \in \mathbb{C}^{A \times A} = diag(d_1,\ldots,d_a,\ldots,d_A)$ is the antenna association matrix of the cluster k, where d_a=1 indicates the antenna a is associated with the cluster k, otherwise, d_a=0. Then, the uplink channel between antennas associated with cluster k to the user u can be expressed by $\mathbf{D}_k \mathbf{h}_u$.

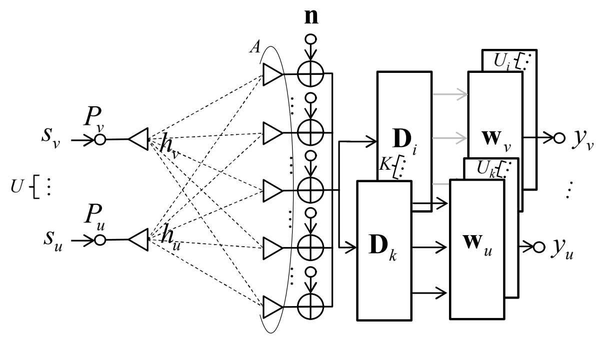


Fig. 3 Uplink IS-ZF transmission model.

3.1. IS-ZF postcoding weight

Next, we present the postcoding weight $\mathbf{w}_u$ as

$$\mathbf{w}_u = P_u \mathbf{h}_u^H \mathbf{D}_k \left(\sum_{v \in \mathcal{N}_k} P_v \mathbf{D}_k \mathbf{h}_v \mathbf{h}_v^H \mathbf{D}_k \right)^{\dagger} , \qquad (2)$$

where, $\mathbf{A}^{\dagger}$ denotes the Moore–Penrose inverse of matrix $\mathbf{A}$, and $\mathcal{N}_k$ is the user set to be considered in the ZF weight calculation for the cluster k. The size of $\mathcal{N}_k$ is a key point of discussion in this paper. If $\mathcal{N}_k$ only contains the users within the same cluster, the interference between clusters cannot be eliminated and we call it non-IS-ZF, and conversely if $\mathcal{N}_k$ also contains interfering users outside the cluster and is called full or partial IS-ZF respectively depending on whether it contains all users, i.e.,

$$\begin{cases} \mathcal{N}_k = \{1,\ldots u,\ldots,U\}, & \text{full IS-ZF} \\ \mathcal{S}_k \subset \mathcal{N}_k \wedge \mathcal{N}_k \subset U, & \text{partial IS-ZF} \\ \mathcal{N}_k = \mathcal{S}_k, & \text{non IS-ZF} \end{cases} . \qquad (3)$$

We can see that the dimension of the part of the pseudo-inverse matrix in (2) is $A_k \times A_k$, which makes it easy to adjust the size of $\mathcal{N}_k$, and the required computational complexity remains unchanged once the antenna association has been done.

3.2. Interfering user selection method for partial IS-ZF

In this paper, we determine the members of $\mathcal{N}_k$ in the case of partial IS-ZF by setting a threshold G_{th}. When the difference between the sum of channel gains from a user v to all antennas in the cluster k and the minimum value of the sum of channel gains from users in the cluster k to all antennas is equal or lower than G_{th}, the user v is considered as the interfering user for the cluster k. That is

$$\mathcal{N}_k = \left\{ v : 10 \times \log_{10} \left(\frac{\min_{u \in \mathcal{S}_k} \left(\|\mathbf{D}_k \mathbf{l}_u\|_F^2 \right)}{\|\mathbf{D}_k \mathbf{l}_v\|_F^2} \right) \le G_{th} \right\} , \qquad (4)$$

where $\|\mathbf{A}\|_F$ denotes the Frobenius norm of the matrix $\mathbf{A}$.

3.3. Conditional interfering user selection (CIUS) method for partial IS-ZF

However, simply selecting the interfering users as described above will result in a situation where the sum of the number of multiplexed and interfering users considered in the ZF weight is the same as the number of associated antennas in a cluster, and the available capacity will drop significantly as the antenna degree of freedom is exhausted (we will expand on the details of this part in Section 4).

Consequently, to avoid this problem, we propose to sort the previously selected interfering users by the channel gain between these users and the antennas in the cluster in descending order, and only select the appropriate number of interfering users (first M_k selected users after sorting) for the weight calculation, to avoid the worst performance of ZF and further improve the transmission performance. We use the following constrained number of considered interfering users (M_k):

$$M_k = \begin{cases} \min(4, |\mathcal{N}_k|), & |\mathcal{N}_k| \leq 16 \\ |\mathcal{N}_k|, & 16 < |\mathcal{N}_k| < 40 \\ 40, & 40 \leq |\mathcal{N}_k| \end{cases}. \tag{5}$$

The reason for introducing the above constraint is described in Section 4.

In addition, the minimum mean square error (MMSE) that considers SINR maximization can also avoid the worst case of ZF to guarantee higher link capacity. The difference with ZF is just adding the noise factor in the inverse matrix in (2), as

$$\mathbf{w}_u^{\mathrm{MMSE}} = P_u \mathbf{h}_u^H \mathbf{D}_k \left(\sum_{v \in \mathcal{N}_k} P_v \mathbf{D}_k \mathbf{h}_v \mathbf{h}_v^H \mathbf{D}_k + \mathbf{I}_A \mathbf{D}_k \right)^{\dagger}. \tag{6}$$

4. Computer simulation

In this section, by Monte Carlo simulation, we evaluate the impact of the number of interfering users, which is considered in the ZF weight calculation, on the link capacity. Assuming a specific but representative randomly generated antenna location pattern, we randomly change the user pattern 100 times, then randomly generate the shadowing losses and the Rayleigh fading gains between users and antennas for each user location pattern. After that, under the same user clustering and antenna association condition, three types of ZF transmission, i.e., full, partial, and non IS-ZFs, are performed. Then, we calculate the user capacity (in (7)) and sum capacity (in (8)) under these three types of ZF as the samples of cumulative distribution function (CDF).

$$C_u = \log_2\left(1 + \mathrm{SINR}_u\right) \tag{7}$$

$$C_{\mathrm{sum}} = \sum_u C_u \tag{8}$$

In (7), assuming the power spectral density of transmit signals is unity, the signal-to-interference plus noise power ratio (SINR) of user u can be derived as

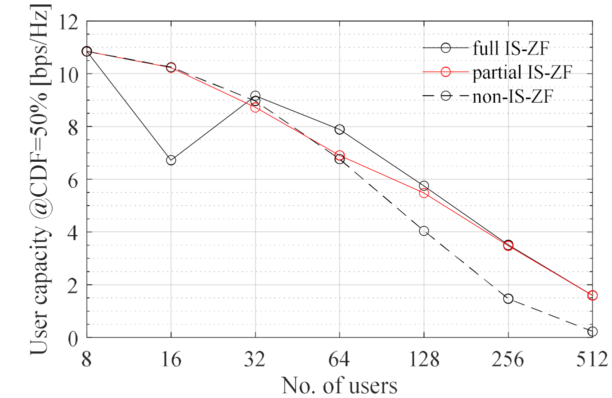
$$\mathrm{SINR}_u = \frac{P_u \left| \mathbf{w}_u \mathbf{D}_k \mathbf{h}_u \right|^2}{\sum_{v=1, v \neq u}^{U} P_v \left| \mathbf{w}_u \mathbf{D}_k \mathbf{h}_v \right|^2 + \left\| \mathbf{w}_u \right\|_{\mathrm{F}}^2}. \tag{9}$$

Moreover, the transmit power is assumed to be equal for all users and is represented by the normalized transmit signal-to-noise ratio (SNR) which is defined as the received SNR when the transmitter-receiver distance is equal to the side length of the normalized 1×1 service area. The concrete parameter setting is shown in Table. 1.

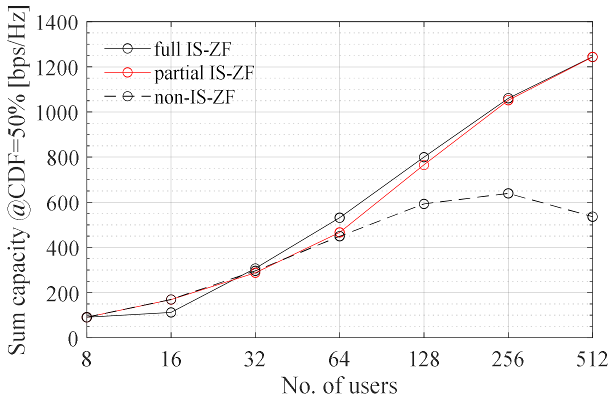
Table. 1

Number of antennas (A)	512
Number of users (U)	8, 16, 32, 64, 128, 256, 512
No. of users per cluster (U_k)	8
Number of clusters (K)	U/8
No. of antennas per cluster (A_k)	16
Number of times of user location generations	100
Path loss exponent	3.5
Log-normal shadowing standard deviation [dB]	8
Fading type	Rayleigh
Transmit SNR per user (P) [dB]	-30
Threshold of interfering user selection (G_{th}) [dB]	20

Fig. 4 plots the user capacity and the sum capacity at the CDF of 50% as a function of the number of users. As the benchmark, the results of non IS-ZF are indicated by dashed lines, and the partial and the full IS-ZF are represented by red and black solid lines, respectively. As we can see from the figures, the non IS-ZF provides a reduced capacity due to residual ICI as only the IUI within each cluster is eliminated, which makes its achievable capacity the lowest among the three. In contrast, the capacity of full and partial IS-ZFs which consider other cluster interference users in the weight calculation perform much better, and the capacity improvement over the non IS-ZF gets higher as U increases and reaches a maximum at U=256 (the user capacity improvement of full IS-ZF over non IS-ZF reaches a maximum of about 2bps/Hz). Although the capacity improvement is reduced when U=A=512, the full and partial achieve 1.6bps/Hz while non IS-ZF achieves a user capacity of only 0.2bps/Hz. The capacity improvement can be more clearly seen in the sum capacity comparison in Fig. 4 (b). The above observation suggests that it is necessary to consider inter-cluster interference in calculating the ZF weights in the case of a high-density user environment to obtain a high link capacity in CF-mMIMO. In addition, it is important to mention that the user capacity difference between partial and full IS-ZFs is not large, which also proves that our proposed interfering user selection method effectively identifies the dominant interfering users.



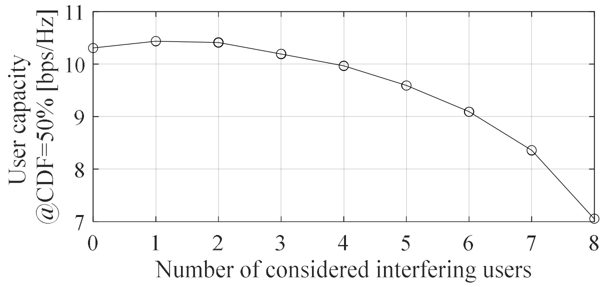
(a) user capacity



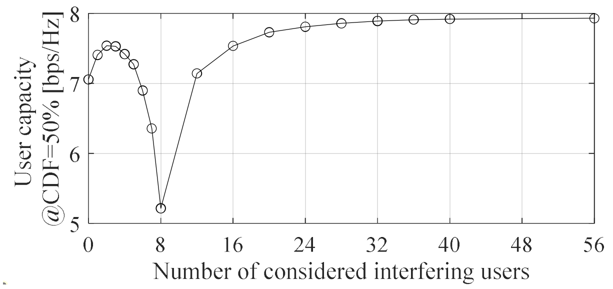
(b) sum capacity

Fig. 4 Comparison of three types of ZF in terms of user capacity and sum capacity.

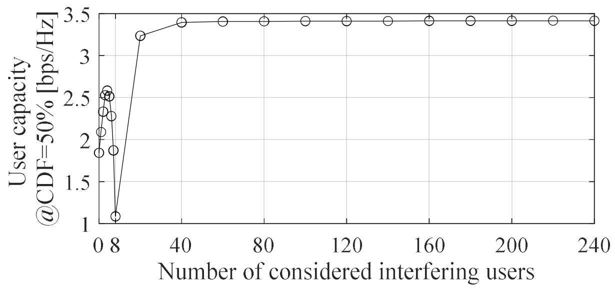
From Fig. 4 (a), we note that a severe drop of the user capacity is caused for full IS-ZF when U=16 (user capacity of full IS-ZF becomes significantly lower than that of non IS-ZF) while a slight capacity drop for partial IS-ZF when U=32. These capacity drops are caused when the number of users (interfering users and desired users to be spatially multiplexed) considered in weight calculation becomes the same as that of antennas. For full IS-ZF, this happens when U=16. On the other hand, for partial ZF, this happens ($|\mathcal{N}_k| = A_k = 16$)with a high probability when U=32 [4]. In the ZF scenario, the degree of freedom of antennas is all used to generate $|\mathcal{N}_k|-1$ nulls, and thus, the received signal power for the desired users is reduced. Next, we analyze the impact of the number of interfering users considered in weight calculation on the user capacity and modify the proposed interfering user selection method to avoid the capacity drop. Here, we plot the relationship between the number of interfering users considered in ZF weight calculation and the user capacity in Fig. 5 based on one user location and channel pattern. It should be noted that, in Fig. 5, the interfering users are selected in descending order of the sum of channel gains observed at associated antennas in each user cluster. From Fig. 5 (b), we find that the capacity drop happens when the number of interfering users considered in weight calculation becomes 8. Figs. 5 (a) and (c) of U=16 and 256 also support the above discussion.



(a) U=16



(b) U=64



(c) U=256

Fig. 5 Impact of number of considered interfering users on user capacity.

We can see from Fig. 5 that as the number of interfering users considered in weight calculation increases, the user capacity firstly increases and approaches a local maximum.

This local maximum of capacity happens when the number of interfering users considered in weight calculation equals around half of the remaining antennas in the user cluster, i.e., $(A_k\text{-}U_k)/2=4$. The number of interfering users considered in weight calculation further increases beyond 8, the capacity increases again and approaches the upper bound which is obtained when all interfering users are considered in weight calculation, i.e., full IS-ZF. We find that the capacity difference between partial IS-ZF with 40 interfering users and full IS-ZF is almost negligibly small. Meanwhile, the capacity performance until the number of considered interfering users rises to 16 is similar to the result of considering only 4 interfering users. As a result, we propose to control the number of interfering users for partial IS-ZF as shown in (5).

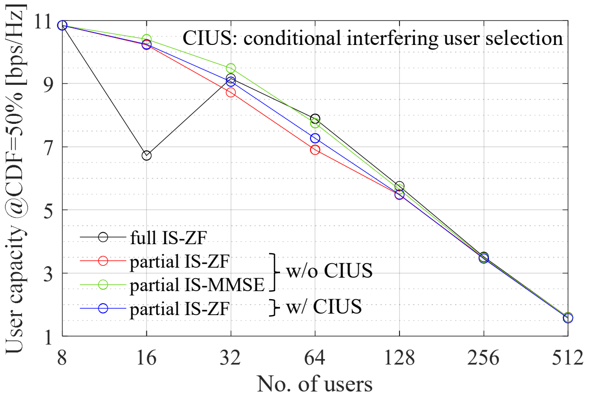


Fig. 6 User capacity comparison of full and partial IS-ZF schemes and partial IS-MMSE scheme.

Next, in Fig. 6, we evaluate the user capacities achievable by the proposed partial IS-ZF with conditional interfering user selection and partial IS-MMSE and compare them with those achievable by the original partial and full IS-ZFs. Note that the capacity degradation caused by using the ZF technique can be indeed avoided by using the MMSE technique. The partial IS-MMSE achieves the highest user capacity in the case of low user density (U<64) and consistently maintains a similar capacity performance to full IS-ZF under high user density. Meanwhile, our proposed method of limiting the number of interfering users (presented by blue line in Fig. 6) is slightly lower than the partial IS-MMSE (represented by green line), but the maximum capacity difference is lower than 0.5bps/Hz. Our proposed conditional interfering user selection method can also effectively improve the decreased user capacity in partial IS-ZF and keep the user capacity similar as in partial IS-MMSE case. Furthermore, the algorithm of the proposed conditional interfering user selection is simple and can be easily done with the knowledge of CSI without additional operation like noise power estimation necessarily in MMSE.

5. Conclusion

In this paper, we proposed the effective interfering user selection method for IS-ZF-based UCC CF-mMIMO system. Through the computer simulation, we pointed out the impact of the number of considered interfering users in ZF weight calculation and verified the effectiveness of our proposed interfering user selection method compared with the full IS-ZF and partial IS-MMSE. The proposed method can effectively avoid the capacity degradation problem in partial IS-ZF when degree of freedom of antenna in a cluster are all used for generating nulls. And the proposed method can be simply used in partial IS-ZF obtaining the achievable capacity similar to that of partial IS-MMSE without noise power estimation.

How to effectively select the threshold for the interfering user selection is left as our future work.

Acknowledgment

A part of this work was conducted under "R&D for further advancement of the 5th generation mobile communication system" (JPJ000254) commissioned by the Ministry of Internal Affairs and Communications in Japan.

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