Evaluation of Uplink Capacity of User-Cluster-Centric Cell-Free massive MIMO

Ryo Takahashi[†], Hidenori Matsuo[†], Sijie Xia[‡], Qiang Chen[†‡], and Fumiyuki Adachi[†]
[†] International Research Institute of Disaster Science, Tohoku University
468-1 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi, 980-8572 Japan
[‡] Department of Communications Engineering, Graduate school of Engineering, Tohoku University
6-6-05 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi, 980-8579 Japan

E-mail: ryo.takahashi.b4@tohoku.ac.jp

2022 IEEE 96th Vehicular Technology Conference (VTC2022-Fall) | 978-1-6654-5468-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/VTC2022-Fall57202.2022.10013011

***Abstract*— To ensure system scalability and to mitigate inter-user interference in cell-free massive MIMO (CF-mMIMO), a user-centric (UC) antenna-clustering approach was investigated. In this UC approach, user-centric antenna-clusters are formed by selecting cooperating antennas for each user, and postcoding is applied by regarding users whose antenna-clusters overlap as interfering users. However, in very high user density environments, since the number of interfering users increases due to increased overlapping of antenna-clusters, the achievable link capacity may degrade. In this paper, we propose a user-cluster-centric (UCC) approach, which groups neighborhood users into a user-cluster and associates the predetermined number of antennas to the user cluster for spatial multiplexing. We evaluate, by computer simulation, the uplink capacity of UCC CF-mMIMO using zero-forcing (ZF) and minimum mean square error (MMSE) based postcoding. We confirm that the proposed UCC approach can provide higher link capacity in a high user density environment.**

Keywords*— *Cell-free massive MIMO, user-centric, user-clustering, user-cluster-centric, ZF, MMSE

I. INTRODUCTION

Cell-free massive MIMO (CF-mMIMO) has recently been attracting attention as an important technology for Beyond 5G and 6G [1]. CF-mMIMO provides uniform, high-quality communications over an entire communication area by aggregating a large number of distributed access points (or distributed antennas) into a central processing unit (CPU) through optical mobile fronthaul for coordinated utilization.

The basic CF-mMIMO system model assumes a fairly large number of antennas and a relatively small number of users who share the same frequency in a wide communication area. In this model, simple complex conjugate beamforming can be applied to obtain high antenna diversity gain while suppressing inter-user interference caused by sharing the same frequency among users in the area. However, the coordinated utilization of a large number of antennas demands prohibitively high computational complexity of signal processing and requires high transmission capacity of the optical mobile fronthaul, thus ensuring the scalability of the system has been an essential challenge. In addition, if interfering users are close to each other (as in the case of highly dense user environment), null steering toward interfering users may be required to improve the communication quality instead of the complex conjugate beamforming.

To address the above challenges, user-centric (UC) antenna-clustering approach was investigated [2]-[4]. In this UC approach, antenna-clusters are formed by selecting antennas to be coordinated for each user. Then, uplink postcoding (or downlink precoding) is applied by regarding the users whose antenna-clusters overlap as interfering users. The above limitation on both the number of cooperating antennas and the number of interfering users to be considered ensures the system scalability while keeping high communication quality. However, in very high user density environments (i.e., the users-to-antennas ratio close to unity), since the number of interfering users increases due to increased overlapping of antenna-clusters, the achievable link capacity may degrade.

In this paper, noticing that as the users-to-antennas ratio increases, the antenna-clusters of neighborhood users tend to become similar, we apply spatial multiplexing idea into CF-mMIMO and propose a user-cluster-centric (UCC) approach. Our proposed UCC approach groups neighborhood users into a user-cluster and associates the predetermined number of antennas to the user cluster for spatial multiplexing. In our preliminary study of UCC approach [5], we derived zero-forcing (ZF) based pre/postcoding and showed the effectiveness of the UCC approach by evaluating link capacity.

In this paper, we derive minimum mean square error (MMSE) based postcoding besides our previously proposed ZF based postcoding. We evaluate, by computer simulation, the uplink capacity of UCC CF-mMIMO using ZF and MMSE based postcoding in a high user density environment. We discuss the noise enhancement brought by ZF postcoding in CF-mMIMO and clarify that MMSE postcoding is effective to suppress the noise enhancement. Furthermore, we compare the link capacities achievable with the UC and UCC approaches and confirm that the proposed UCC approach can provide higher link capacity in a high user density environment.

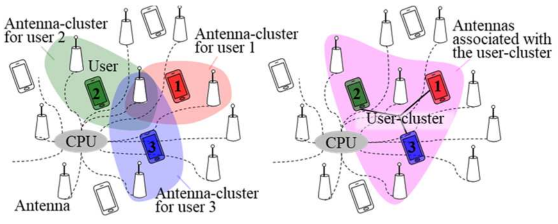
The rest of this paper is organized as follows. Sect. II introduces the CF-mMIMO system model considered in this paper and describes the user-cluster formation and antenna association procedures for the proposed UCC approach. In Sect. III, the uplink transmission model is shown and the ZF and MMSE based postcoding weight vectors are derived, and the comparison of computational complexity of the postcoding weight is made between the UC and UCC approaches. In Sect. IV, the uplink user capacity is evaluated by computer simulation. Sect. V offers some conclusions and future works.

II. CF-mMIMO SYSTEM MODEL

We consider a CF-mMIMO system consisting of A distributed antennas (hereafter simply referred to as antennas) placed at random locations in a communication area and $U(\leq A)$ single-antenna user-equipments (hereafter referred to as users) distributed randomly in the same area. We assume that each antenna is connected with the CPU via an optical

978-1-6654-5468-1/22/$31.00 ©2022 IEEE

mobile fronthaul and that all antennas in the area can be cooperatively utilized. It is also assumed that U users transmit their signals simultaneously using the same radio resource. CF-mMIMO system models using UC approach [2]-[4] and our proposed UCC approaches are illustrated in Fig. 1. Our proposed UCC approach consists of two steps: user-clustering and antenna association.



(a) UC approach (b) UCC approach

Fig. 1. CF-mMIMO system models using UC and UCC approaches for users 1, 2, and 3 of interest.

User-clustering in step 1 uses a constrained K-means algorithm [6] to group neighborhood users into a user-cluster. The constrained K-means algorithm is able to form compact user-clusters so that the sum of the squared distances between the cluster centroid and the user locations in each user-cluster is minimized while constraining the number of users per user-cluster to be less than or equal to a predetermined value (this is an important constraint to make the amount of required multiuser signal processing power to be uniform over all user-clusters). Assuming that the number of users per user-cluster is set to U', U users in the area are grouped into $K(=U/U')$ user-clusters. Let $\mathcal{S}_k \subset \{1,\dots,u,\dots,U\}$ denote the subset of users ($|\mathcal{S}_k| = U'$) belonging to user-cluster k. Since user-clusters do not overlap, $\mathcal{S}_k \cap \mathcal{S}_i = \varnothing$. Note that U' is determined based on the signal processing capability of the CPU.

Antenna association in step 2 of UCC approach selects only a limited number $A' (\ll A)$ of antennas among A antennas to be coordinated for each user-cluster to ensure system scalability. Antenna association is based on the maximum channel gain criterion, and antenna overlap between different user-clusters is allowed. In this paper, we select the top A' antennas with the highest channel gain for each user-cluster (A' and U' are the same for all clusters, respectively). To ensure fair communication quality among users in a user-cluster, we select the top A'/U' antennas with the highest channel gain for each user. If the selected antennas overlap among users in the same user-cluster, the total number of antennas in the user-cluster falls below A'. To avoid this, when the selected antennas overlap among users in the same cluster, the user whose selected antenna has the highest channel gain keeps its antenna preferentially, and the other users select the antenna with the next highest channel gain. Let $\mathcal{M}_k \subset \{1,\dots,a,\dots,A\}$ denote the subset of antennas ($|\mathcal{M}_k| = A'$) belonging to user-cluster k.

The UC approach is a special case of our proposed UCC approach, i.e., the UCC approach with $U'=1$ (a single-user-cluster) becomes the UC approach.

III. Uplink Transmission Model

Fig. 2 shows the uplink transmission model for a CF-mMIMO system with UCC approach. Assuming that user $u(=1,\dots,U)$ belongs to user-cluster $k(=1,\dots,K)$, the uplink received signal $y_u \in \mathbb{C}$ of user u after postcoding is represented as

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

where $\mathbf{w}_u \in \mathbb{C}^A$ is the postcoding weight vector, $\mathbf{h}_u \in \mathbb{C}^A$ is the uplink channel vector, $s_u \in \mathbb{C}$ is the uplink transmit signal (transmit power p_u), and $\mathbf{n} \in \mathbb{C}^A$ is the complex Gaussian noise vector, each element is an independent zero-mean complex Gaussian variable having variance $2\sigma^2$ (note that σ^2 is the noise power). $\mathbf{D}_k = \mathrm{diag}(d_1,\dots,d_a,\dots,d_A) \in \mathbb{C}^{A\times A}$ is the antenna association matrix for user-cluster k, and its diagonal element d_a is given as

$$d_a = \begin{cases} 1 & \text{if } a \in \mathcal{M}_k \\ 0 & \text{if } a \notin \mathcal{M}_k \end{cases}. \tag{2}$$

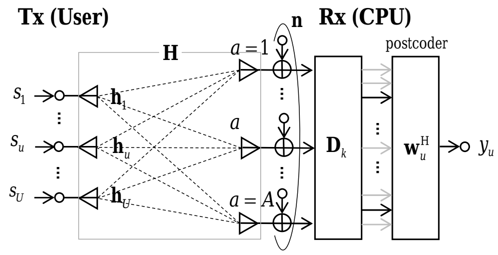


Fig. 2. Uplink transmission model assuming that user u belongs to user-cluster k.

A. ZF-based Postcoding Weight

We start with the postcoding weight matrix of a general multiuser MIMO. Let $\mathbf{H} \in \mathbb{C}^{A\times U}$ and $\mathbf{H}_k \in \mathbb{C}^{A'\times U'}$ denote the uplink channel matrices between U users and A antennas in the entire communication area and between U' users and A' antennas belonging to user-cluster k, respectively. Note that $\mathbf{H}_k$ is a submatrix of $\mathbf{H}$. ZF postcoding weight matrix $\mathbf{W}_k \in \mathbb{C}^{A'\times U'}$ for user-cluster k is given depending on the rank of $\mathbf{H}_k$ as

$$\mathbf{W}_k = \begin{cases} \left(\mathbf{H}_k^{-1}\right)^{\mathrm{H}} & \text{if } A' = U' \\ \mathbf{H}_k \left(\mathbf{H}_k^{\mathrm{H}} \mathbf{H}_k\right)^{-1} & \text{if } U' < A' \\ \left(\mathbf{H}_k \mathbf{H}_k^{\mathrm{H}}\right)^{-1} \mathbf{H}_k & \text{if } A' < U' \end{cases}. \tag{3}$$

If $\mathbf{H}_k$ has full rank (i.e., $A' = U'$), the inverse matrix of $\mathbf{H}_k$ can be used to form perfect nulls toward all interfering users in user-cluster k. If $\mathbf{H}_k$ has full column rank (i.e., $U' < A'$), $\mathbf{W}_k^{\mathrm{H}}$ provides the least square solution; firstly, a complex conjugate beam is formed toward the desired user (i.e., the maximal diversity is achieved) and then, perfect nulls are formed toward all interfering users in user-cluster k. If $\mathbf{H}_k$ has full row rank (i.e., $A' < U'$), the number of interfering users exceeds the antenna degree of freedom, thus $\mathbf{W}_k^{\mathrm{H}}$ provides the minimum norm solution; firstly, a null toward the major interfering signal and then, a complex conjugate beam is formed toward the desired user [7].

So far, ZF postcoding weight matrix $\mathbf{W}_k$ for user-cluster k has been derived. Bellow, the weight vector $\mathbf{w}_u^{\mathrm{ZF}} \in \mathbb{C}^A$ of user u belonging to user-cluster k is derived. When taking all antennas (antenna association for cluster k is expressed using $\mathbf{D}_k$) and all interfering users in the communication area in the weight derivation, $\mathbf{w}_u^{\mathrm{ZF}}$ can be derived, by referring to [2] and the full row rank form of Eq. (3), as

$$\mathbf{w}_u^{\mathrm{ZF}} = p_u \left(\sum_{i=1}^{K} \sum_{v \in \mathcal{S}_i} p_v \mathbf{D}_k \mathbf{h}_v \mathbf{h}_v^{\mathrm{H}} \mathbf{D}_k \right)^{\dagger} \mathbf{D}_k \mathbf{h}_u , \tag{4}$$

where the superscript † denotes pseudo-inverse operation and is to address the rank deficiency case. The row rank deficiency happens depending on the result of antenna association and the column rank deficiency happens depending on the number of interfering users. Note that, although the full row rank form is used in Eq. (4), $\mathbf{w}_u^{\mathrm{ZF}}$ becomes full column rank form when the number of interfering users considered is less than the number of selected antennas (i.e., $U < A'$).

The full row rank form of Eq. (4) has two advantages. First, the channel correlation matrix $\mathbf{H}\mathbf{H}^{\mathrm{H}}$ limited by $\mathbf{D}_k$ can be expressed as the sum of the correlation matrices of the users to be considered in the weight calculation (user u and its interfering users). Therefore, the number of interfering users to be considered for determining the weight vector can be flexibly increased or decreased. Second, the pseudo-inverse matrix in Eq. (4) is common to all users in user-cluster k and only the channel vector $\mathbf{D}_k \mathbf{h}_u$ (equivalent to form a complex conjugate receive beam) is unique to user u.

B. MMSE-based Postcoding Weight

The ZF postcoding weight increases the norm of the weight when the channel matrix approaches rank deficiency (the singular values of the channel matrix contain near-zero values) due to channel variations, causing noise enhancement [8]. The MMSE postcoding weight, which takes into account the background noise, solves this problem and is given as

$$\mathbf{w}_u^{\mathrm{MMSE}} = p_u \left(\sum_{i=1}^{K} \sum_{v \in \mathcal{S}_i} p_v \mathbf{D}_k \mathbf{h}_v \mathbf{h}_v^{\mathrm{H}} \mathbf{D}_k + \sigma^2 \mathbf{D}_k \right)^{\dagger} \mathbf{D}_k \mathbf{h}_u . \tag{5}$$

where σ^2 is the noise power. The above MMSE postcoding weight vector improves the received signal-to-interference plus noise power ratio (SINR).

C. Partial ZF/MMSE Postcoding Weight

In Eqs. (4) and (5) (hereafter referred to as full ZF and full MMSE), all users in the communication area are assumed to cause interference to user u. In practice, interference from users far distant from user u can be negligibly weak due to propagation loss. Exploiting this fact, a partial MMSE postcoding weight vector that only considers users who give strong interference to user u was proposed for UC approach [2]. This ensures the system scalability. We apply this idea to our UCC approach. The partial ZF postcoding weight vector and partial MMSE postcoding weight vector for the UCC approach are derived as

$$\mathbf{w}_u^{\mathrm{P\text{-}ZF}} = p_u \left(\sum_{v \in \mathcal{P}_k} p_v \mathbf{D}_k \mathbf{h}_v \mathbf{h}_v^{\mathrm{H}} \mathbf{D}_k \right)^{\dagger} \mathbf{D}_k \mathbf{h}_u , \tag{6}$$

$$\mathbf{w}_u^{\mathrm{P\text{-}MMSE}} = p_u \left(\sum_{v \in \mathcal{P}_k} p_v \mathbf{D}_k \mathbf{h}_v \mathbf{h}_v^{\mathrm{H}} \mathbf{D}_k + \sigma^2 \mathbf{D}_k \right)^{\dagger} \mathbf{D}_k \mathbf{h}_u , \tag{7}$$

where $\mathcal{P}_k$ is the set of users to be considered as interfering users in weight computation (i.e., sum of users in user-cluster k (multiplexing users) and those in neighborhood user-clusters (interfering users)). The set of users is expressed as $\mathcal{P}_k = \bigcup_{v \in \mathcal{S}_k} \mathcal{P}_v$ for the UCC approach, while $\mathcal{P}_v = \{ i : \mathbf{D}_v \mathbf{D}_i \neq \mathbf{0}_A \}$ (i.e., users whose antenna-clusters overlap with that of the vth user antenna-cluster) for the UC approach (i.e., $k \to v$, $U' = 1$) [2]. Note that Eq. (7) is equivalent to the weight vector of the UC approach in [2] if $U' = 1$.

D. Computational Complexity of Postcoding Weight

The inverse matrix operation of the channel correlation matrix has a significant impact on the computational complexity of the postcoding weight, and the order of computational complexity is $O(A'^3)$ [2]. In the UCC approach, antennas associated with the same user-cluster are used in common to multiplex all users in that cluster. Because of this, the pseudo-inverse matrix in Eq. (4) only needs to be calculated once for each user-cluster. Therefore, if the computational complexity required for obtaining the inverse matrix for the UCC approach is made equal to the UC approach, the number A'_{UCC} of antennas in each user-cluster for the UCC approach can be increased to

$$A'_{\mathrm{UCC}} = \left\lfloor \sqrt[3]{U'_{\mathrm{UCC}}} A'_{\mathrm{UC}} \right\rfloor , \tag{8}$$

where A'_{UC} is the number of antennas in each user-cluster for the UC approach, U'_{UCC} is the number of users in each user-cluster for the UCC approach, and $\lfloor \bullet \rfloor$ is the floor function. Compared to the UC approach, the UCC approach can increase the number of antennas in each user-cluster, it is made possible to generate the nulls toward more interfering users as well as improve the antenna diversity gain. This is an advantage of the UCC approach.

IV. Computer Simulation

A. Comparison of ZF and MMSE Postcoding

To clarify the suppression effect of noise enhancement by MMSE postcoding, we evaluated the uplink user capacities achievable with ZF and MMSE postcoding in CF-mMIMO using the UCC approach by computer simulation.

We considered the following simulation settings. $A = 512$ antennas were randomly placed in a 1×1 normalized communication area. To evaluate the impact of user density, $U = \{8, 16, 32, 64, 128, 256, 512\}$ users were randomly generated in the area. The number of users for each user-cluster was constrained to $U'_{\mathrm{UCC}} = 8$, thereby forming a total of $K = U/8$ user-clusters. Then, $A'_{\mathrm{UCC}} = 16$ antennas were associated with each user-cluster. The transmit power for each user was represented by the normalized transmit SNR, which is defined as the received SNR when the transmitter-receiver distance equals to the normalized distance of 1. To investigate the impact of transmit power on the achievable link capacity, we considered the normalized transmit SNR of {-60, -50, -40, -30} dB, which provides the received SNR of about 58dB higher, i.e., {-2, 8, 18, 28} dB when the transmitter-receiver distance is half the average distance between the two neighborhood antennas. The propagation channel was assumed to be characterized by distance-dependent pathloss with pathloss exponent of 3.5, log-normally distributed shadowing loss with standard deviation of 8 dB, and Rayleigh fading. The perfect knowledge of MIMO channels and user/antenna locations was assumed.

The cumulative distribution function (CDF) of the uplink user capacity for a fixed antenna layout was obtained as follows. The uplink capacity C_u [bps/Hz] of user u was calculated for the given set of pathloss (i.e., user distribution), shadowing loss, and Rayleigh fading, using

$$C_u = \log_2(1+\mathrm{SINR}_u)\,, \tag{9}$$

where SINR_u is the SINR of user u, given from Eq. (1) as (assuming that user u belongs to user-cluster k)

$$\mathrm{SINR}_u = \frac{p_u\left|\mathbf{w}_u^{\mathrm{H}}\mathbf{D}_k\mathbf{h}_u\right|^2}{\sum_{v=1,v\neq u}^{U} p_v\left|\mathbf{w}_u^{\mathrm{H}}\mathbf{D}_k\mathbf{h}_v\right|^2+\sigma^2\mathbf{w}_u^{\mathrm{H}}\mathbf{w}_u}\,. \tag{10}$$

By changing the user distribution 100 times, and changing the shadowing loss and Rayleigh fading once for each user distribution, a total of $100\times U$ user capacity samples was obtained, from which the CDF of the user link capacity was obtained. Hereafter, the user link capacity at which the cumulative probability becomes 50% is called the user capacity at the CDF = 50%.

The uplink user capacities at the CDF = 50% achievable with ZF and MMSE postcoding are plotted as a function of the total number of users, U, in Fig. 3 with the normalized transmit SNR as a parameter. As for the ZF/MMSE postcoding, we considered full ZF/MMSE (which takes all interfering users in the area into the weight calculation) given by Eqs. (4) and (5) and partial ZF/MMSE (which takes only the strong interfering users in the weight calculation) given by Eqs. (6) and (7).

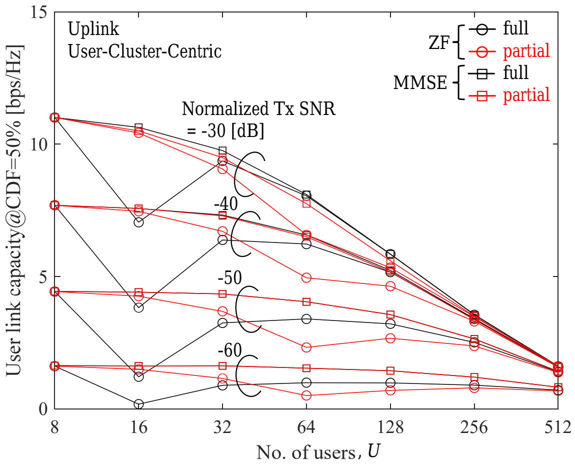


Fig. 3. User capacities achievable with ZF and MMSE postcoding.

It can be seen from Fig. 3 that user capacity decreases as U increases. This is because, as U increases, the distance between users gets closer and hence, the number of interfering users increases. Also seen from Fig.3 is that the decreasing rate gets steeper with higher normalized transmit SNR. This is because, as the transmit power increases, more distant users cause strong interference.

It can be seen from Fig. 3 that full MMSE always provides higher capacity than full ZF. This is because full MMSE tries to improve the received SINR which directly affects the achievable link capacity, while full ZF tries to improve the received SIR. The similar result can be seen between partial ZF and partial MMSE. Furthermore, it can be seen from Fig. 3 that partial MMSE can achieve the user capacity very close to full MMSE although it limits the number of interfering users in weight calculation and hence, it can be considered practically attractive because of reduced computational complexity.

It is interesting to notice that significant drop of the achievable capacity happens at U = 16 and 64 for full ZF and partial ZF, respectively. This significant capacity drop is due to the noise enhancement which is unique to ZF. When U = 16, full ZF fully utilizes the antenna degree of freedom obtained at $A'_{\mathrm{UCC}}=16$ to generate nulls toward all of 8 $(=U-U'_{\mathrm{UCC}})$ interfering users as well as toward 7 $(=U'_{\mathrm{UCC}}-1)$ users in the user-cluster of interest and as a consequence, severe noise enhancement is produced. In partial ZF, we examined the actual number of interfering users taken in the weight calculation and found that the probability of 8 interfering users being taken in the weight calculation becomes highest when U = 64.

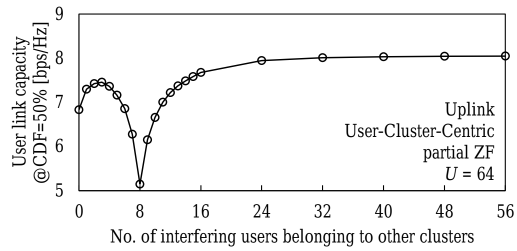


Fig. 4. Impact of the number of interfering users to be taken in the weight calculation of partial ZF.

How the achievable user capacity varies according to the change in the number of interfering users to be taken in the weight when U = 64 is shown in Fig. 4. The interfering users were selected in order of the highest sum of channel gains observed at antennas of user-cluster of interest. It can be seen from Fig. 4 that the user capacity drops when choosing 8 interfering users. This is because, as discussed earlier, the antenna degree of freedom of 16 $(=A'_{\mathrm{UCC}})$ is fully utilized to form nulls toward 8 interfering users in addition to 7 $(=U'_{\mathrm{UCC}}-1)$ users in the user-cluster of interest. From Fig. 4, the local maximum capacity is obtained when $A'_{\mathrm{UCC}}=16$, the number of nulls which can be generated without causing severe noise enhancement is only 10 and accordingly, the user capacity can be locally maximized when the number of interfering users is 3. Although nulls can be formed for the fourth and subsequent users, these users are further away from the own cluster, and thus their channel matrices are closer to the rank deficiency, causing a strong noise enhancement. The noise enhancement is most significant for the case of 8 users, which is the same as the antenna degrees of freedom. In contrast, it can be seen from Fig. 4 that the capacity gradually improves as the number of interfering users taken in the weight calculation increases beyond 8. This is because when the number of interfering users taken in the weight calculation exceeds the antenna degree of freedom, the weight is switched to improve the SINR instead of SIR, thereby mitigating the problem of noise enhancement.

B. Comparison of UC and UCC Approaches

To confirm the effectiveness of the proposed UCC approach, we evaluated the uplink user capacities achievable with the UC and UCC approaches by computer simulation.

The simulation setting was the same as in Sect. IV A. In the UC approach ($U'_{UC}=1$), the number of antennas in each antenna-cluster was set to $A'_{UC}=8$ to make the inverse matrix computational complexity in the weight calculation equal to that in the UCC approach (see Eq. (8)). Partial MMSE was used for both UC and UCC approaches.

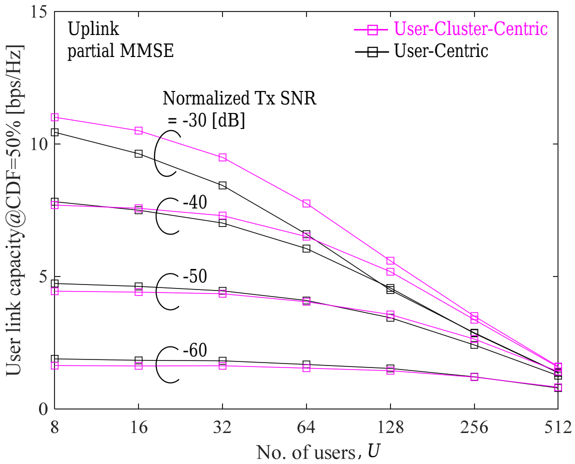


Fig. 5. User capacities achievable with the UC and UCC approaches.

The uplink user capacities at the CDF = 50% achievable with UC and UCC approaches are plotted in Fig. 5. It can be seen from Fig. 5 that the UCC approach provides higher capacity when the normalized transmit SNR is set to -30 dB and -40 dB (i.e., relatively high transmit powers). The reason for this is discussed below. At a high transmit power, since distant users cause severe interference, nulls need to be formed toward even distant users, otherwise the user capacity degrades. In the UC approach, the antennas close to a user of interest are selected to form an antenna-cluster and thus, nulls can only be formed for interfering users close to the user of interest, but not toward distant users. On the other hand, in the UCC approach, neighborhood users form a user-cluster and thus, antennas associated with each user-cluster are more spatially distributed than in the UC case, thereby able to form nulls toward distant users. It can be seen from Fig. 5 that the UC approach provides slightly higher capacity when the normalized transmit SNR is set to -50 dB and -60 dB (i.e., low transmit powers). This is because, in the UC case, antennas of an antenna-cluster are close to a user of interest, thus enabling inter-antenna coordination even at low transmit power. However, when U is larger, the UCC approach provides slightly higher capacity. This is because user-clusters become more compact (i.e., the inter-antenna distance becomes shorter), thus enabling inter-antenna coordination even at low transmit power. It can also be seen that the UC approach provides a slightly higher capacity in the case of U = 128 when the normalized transmit SNR is set to -40dB than when it is set to -30dB. The reason for this is given below. Since, in partial MMSE, the number of interfering users considered in the weight calculation is limited, the unconsidered interference becomes stronger by increasing the normalized transmit SNR from -40dB to -30 dB.

V. Conclusion

In this paper, we proposed the UCC approach for the CF-mMIMO and evaluated the link capacities achievable with ZF and MMSE postcoding by computer simulation. The suppression effect of noise enhancement by MMSE postcoding was clarified. From the simulation results, we found that if taking interfering users within the antenna degrees of freedom, only those close to the user-cluster of interest should be chosen to mitigate the noise enhancement brought by ZF postcoding. We also found that if interfering users exceeding the antenna degrees of freedom are taken in the ZF postcoding weight calculation, the weight is switched to improve the SINR.

We also compared the link capacities achievable with the UC and UCC approaches by computer simulation and confirmed the effectiveness of the UCC approach at high transmit power and high user density. Dense deployment of antennas would be able to keep the transmit power low enough because of the closer distance between antennas.

The impacts of channel/location estimation error, computational complexity, overhead for pilot signal transmission, and non-uniform distribution of users on the link capacity achievable with UCC based CF-mMIMO are left as our future study. In this paper, we proposed location-based user-clustering. Our future study is to consider another approach based on channel state information.

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.

References

[1] H. I. Obakhena, A. L. Imoize1, F. I. Anyasi and K. V. N. Kavitha, “Application of cell-free massive MIMO in 5G and beyond 5G wireless networks: A survey,” J. Eng. Appl. Sci., Vol. 68, No. 13, Oct. 2021.

[2] E. Björnson and L. Sanguinetti, “Scalable Cell-Free Massive MIMO Systems,” IEEE Trans. Commun., Vol. 68, Issue 7, pp. 4247 - 4261, July 2020.

[3] K. Yamazaki, T. Ohseki, Y. Amano, H. Shinbo, T. Murakami and Y. Kishi, “Proposal for a User-Centric Ran Architecture Towards Beyond 5G,” 2021 ITU Kaleidoscope: Connecting Physical and Virtual Worlds (ITU K) , pp. 1-7, 2021.

[4] K. Ando, H. Iimori, T. Takahashi, K. Ishibashi and G. T. F. De Abreu, “Uplink Signal Detection for Scalable Cell-Free Massive MIMO Systems With Robustness to Rate-Limited Fronthaul,” in IEEE Access, vol. 9, pp. 102770-102782, 2021.

[5] S. Xia, C. Ge, R. Takahashi, Q. Chen and F. Adachi, “Incorporation of MU-MIMO Technology into User-centric Cell-Free mMIMO System,” IEICE Technical Report, vol. 122, No. 49, RCS2022-14, pp. 7-12, May 2022.

[6] P. Bradley, K. Bennett and A. Demiriz, “Constrained K-means clustering”, Microsoft Research Technical Report, May 2000.

[7] NTT DoCoMo, “Further Development of LTE/LTE-Advanced -LTE Release 10/11 Standardization Trends-,” NTT DOCOMO Technical Jounal, Vol.15, No.2, pp. 27-30, Oct. 2013.

[8] A. Goldsmith, “Wireless Communications,” Cambridge University Press, 2005.