Multi-user Shared Access Research in Cell-Free Massive MIMO

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Abstract. With the advent of the 5G era, massive device access and explosive data traffic grow rapidly, it is imperative to improve network throughput. As a new network architecture, Cell-Free Massive MIMO can effectively improve network throughput. MUSA (Multi-user shared access), as a kind of NOMA (non-orthogonal multiple access technology), has a great gain in spectrum efficiency. Integrating MUSA's related technologies into the Cell-Free Massive MIMO system can effectively improve the spectrum efficiency and meet the massive access requirements.

In this paper, by using MUSA, the Cell-Free Massive MIMO system is improved. A clustering method is proposed. Each cluster corresponds to a pilot. Users in the cluster use MUSA to distinguish and detect multi-users. For the new model, theoretical analysis and simulation of spectrum efficiency are carried out. The results show that the improved Cell-Free Massive MIMO system has better spectrum efficiency.

Keywords: Cell-free massive MIMO · MUSA · Spectrum efficiency

1 Introduction

The three major business scenarios of 5G include enhanced mobile bandwidth, massive machine communication, ultra-high reliability and low-latency communication. In the application of the Internet of Vehicles, the ultra-high reliability scene is the mainstream.

From the perspective of ultra-high reliability, the current cellular-based network architecture is no longer suitable for the continued evolution and development of the Internet of Vehicles. In the scene of high-speed vehicle movement, the traditional cellular architecture inevitably has the inherent defect of inter-cell handover, which causes the complicated signaling overhead and decrease of reliability. Although technologies such as cooperative communication have been proposed internationally, they can only alleviate the problem of handover between cells to a certain extent. This way of dividing the network into cells, with the massive use of high frequency bands such as millimeter waves in the future, the problem of reliable communication will become more serious. High attenuation is a significant feature of the millimeter wave frequency band. At this time, in order to effectively cover, the layout of outdoor

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wireless network base stations will be denser, and the network coverage of the base stations will also become smaller, which will cause more serious handover problems. From the above analysis, it is not difficult to see that the traditional cellular architecture has seriously affected the application of the scene, and the new Cell-Free network architecture has gradually entered the field of vision of researchers.

In [1], Cell-Free Massive MIMO is proposed as a new type of distributed network architecture, which uses a large number of distributed antenna access points to serve a small number of users distributed in a large area. All units are connected to the central processing unit through the backhaul link, so there is no concept of cell boundaries.

The current research on Cell-Free Massive MIMO mainly focuses on the signal processing part of the Cell-Free system and the performance comparison between Cell-Free Massive MIMO and Cell-Free. The signal processing in the Cell-Free system mainly includes channel estimation and uplink signal. Precoding and power allocation schemes for detection and downlink. For channel estimation, the literature [1] adopts the time division duplex (TDD) mode and uses criterion for channel estimation in the uplink and channel disparity to obtain the channel information of the downlink at the same time. This scheme avoids downlink channel estimation and saves a lot of pilot overhead. However, since the channel hardening characteristics of the Cell-Free system are actually not perfect, this solution has the problem of inaccurate downlink channel estimation. In the literature [2–4], the downlink channel is estimated. Compared with the uplink channel estimation, the spectrum efficiency is indeed improved, but it causes a lot of pilot overhead. Regardless of the uplink channel estimation or the downlink channel estimation, pilot pollution exists and causes certain estimation errors. For uplink signal detection, literature [1] uses matched filtering on each AP for signal detection, which does not require CPU processing and reduces the burden on the backhaul link. Literature [5] uses part or all of the CPU processing, and the results show that the spectrum efficiency can be significantly improved. In the literature [6], four different levels of CPU and AP cooperative processing are compared, and the results show that the higher the degree of CPU processes, the higher the spectral efficiency is. For the precoding and power allocation of the downlink, it is currently mainly divided into CB (conjugate beamforming precoding) and ZF (zero-forcing precoding). The literature [5] compares the performance of CB and ZF. ZF can reduce the interference between users, but increases the data transmission of the backhaul link. Literature [7] proposed an improved conjugate beamforming scheme, which completely eliminates the self-interference in Cell-Free and maintains the simplicity of the original conjugate beamforming.

The above documents are rarely research on how to combine Cell-Free Massive MIMO and NOMA in the downlink, and in the literature [8] the author gives the spectral efficiency of Cell-Free Massive MIMO-NOMA in the uplink closed expression. At the same time, the problem of maximizing spectrum efficiency based on the quality of service, power limit and limitation of each user is proposed, and an iterative GP (Geometric Programming) algorithm is proposed to solve this problem. To combine Cell-Free Massive MIMO and MUSA, our research is as follows.

2 Cell-Free Massive MIMO Model

As shown in Fig. 1, this article considers a cell-free network composed of K single-antenna UEs (users) and L APs (wireless access points). Each AP is equipped with an antenna and is arbitrarily distributed in covered area. These APs are connected to the edge cloud processor in any way, called the CPU. This kind of setting can perform consistent joint transmission and reception for the UE in the entire coverage area, and when L and K are relatively large, it is called Cell-Free Massive MIMO; usually assume that L > K, that is, the number of APs is more than the number of users.

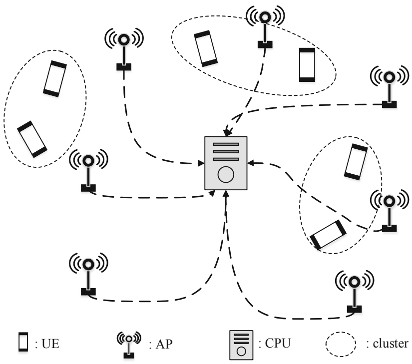

Fig. 1. Cell-free massive MIMO network

For channel estimation, it can be considered that the transmission channel between the AP and the UE is reciprocal, that is, the channel is the same in both directions. In the time division duplex mode, the same frequency resources are used for uplink and downlink transmission. The assumption of reciprocity means that the channel only needs to be characterized in one direction. The uplink channel is a better choice, because the user only needs to send one pilot signal, which is received by all APs. The complexity of channel estimation is proportional to the number of users, rather than the number of antennas in the array. This is very important, because the user may be moving, so channel estimation needs to be performed multiple times. Testing channel information based on the uplink has another great advantage, that is, all channel estimation and signal processing tasks are completed at the base station, rather than at the user end. These tasks are heavy and not suitable for the user end. In the Cell-Free Massive MIMO system, these tasks are all done in the CPU.

It is assumed that the AP and UE perform transmission according to the TDD protocol, where the TDD duplex includes an uplink transmission pilot phase and a downlink data transmission phase for channel estimation. Each coherent block is divided into channels used for uplink pilot, and used for downlink data, so that. The channel between the AP and the UE is denoted by, and the channel parameters of the UE from all APs are denoted by. In each coherent block, assume that the independent Rayleigh fading is, where is the spatial correlation coefficient (assuming the antenna is

1Tx, 1Rx). The Gaussian distribution model is used to model small-scale fading, and large-scale fading is described, including path transmission loss, shadow fading, antenna gain, and spatial channel correlation. Assuming that the channel parameters of different APs are independently distributed, for the channel parameters.

$$\mathbb{E}\left\{h_{kn}(h_{kl})^{\mathrm{H}}\right\} = 0, \quad l \neq n \tag{1}$$

2.1 Pilot Transmission and Channel Estimation

In order to use large-scale antennas more efficiently, in each coherent block, the base station needs to estimate the channel response of all user equipment. In this article, this task is performed by the CPU.

Suppose there are p mutually orthogonal pilot signals of length τ_p, where τ_p is a constant independent of K. When UEs access the network, they are allocated to UEs. When these UEs send pilots, the received signal at the AP is

$$\mathbf{y}_{tl}^{\text{pilot}} = \sum_{i \in \mathcal{S}_t} \sqrt{\tau_p p_i}\mathbf{h}_{il} + \mathbf{n}_{tl} \tag{2}$$

Using the above formula, the MMSE (Minimum Mean Square Error) of this channel is obtained as

$$\widehat{\mathbf{h}}_{kl} = \sqrt{p_k \tau_p}\mathbf{R}_{kl}\mathbf{\Psi}_{tl}^{-1}\mathbf{y}_{tl}^{\text{pilot}} \tag{3}$$

where

$$\mathbf{\Psi}_{tl} = \mathbb{E}\left\{\mathbf{y}_{tl}^{\text{pilot}}\left(\mathbf{y}_{tl}^{\text{pilot}}\right)^{\mathrm{H}}\right\} = \sum_{i \in \mathcal{S}_t} \tau_p p_i \mathbf{R}_{il} + \sigma^2 \mathbf{I}_N \tag{4}$$

is the correlation matrix. Similar to the situation in traditional Massive MIMO, mutual interference generated by multi-user pilot sharing UE will cause pilot pollution, thereby reducing system performance. There are two main consequences of pilot contamination. First, it will reduce the estimation quality, thereby reducing the efficiency of coherent transmission; Second, the estimated values $\widehat{\mathbf{h}}_{kl}$ are correlated with each other, which leads to additional interference. Both of these effects will affect the performance of the UE.

After using the MMSE criterion for channel estimation in the uplink, the channel reciprocity can be used to obtain the downlink channel information at the same time. This scheme avoids downlink channel estimation and can save a lot of pilot overhead.

2.2 Downlink Data Transmission

Let $\mathrm{w}_{il} \in \mathbb{C}^N$ denote the precoding allocated to the UE by the AP. During the downlink transmission, the received signal at the UE is

$$y_k^{\mathrm{dl}} = \sum_{l=1}^{L} \mathrm{h}_{kl}^{\mathrm{H}} \sum_{i=1}^{K} \mathrm{w}_{il}\zeta_i + n_k = \mathrm{h}_k^{\mathrm{H}} \sum_{i=1}^{K} \mathrm{w}_i\zeta_i + n_k \tag{5}$$

Where $\zeta_i \in \mathbb{C}$ is the unit power data signal used for the UE i. The system model is mathematically equivalent to a downlink single-cell massive MIMO system with correlated fading.

Therefore, the achievable downlink spectrum efficiency in Cell-Free Massive MIMO can easily be derived from the massive MIMO literature with related fading.

3 MUSA Improvement of Cell-Free Massive MIMO

3.1 Cell-Free Massive MIMO Cluster Model

Pilot pollution often greatly reduces the performance of Cell-Free Massive MIMO, and the cause of pilot pollution is that multiple users share the same pilot. In order to reduce pilot pollution and make full use of the limited pilot resources, this paper proposes a solution for user clustering, that is, users in a cluster share one pilot, and different clusters use different pilots. Non-orthogonal multiple access technology to distinguish users. In this way, the influence of pilot pollution is effectively avoided, and the spectrum efficiency is improved.

As shown in Fig. 1, we divide users into K clusters, tentatively there are two users in each cluster. There are three clustering schemes, namely random clustering, closest clustering and farthest clustering. In this paper, the first scheme is randomly clustered for modeling, and the other two schemes are waiting for in-depth study later.

3.2 Spectrum Efficiency Research

Because the channel hardening phenomenon is a reasonable assumption. Therefore, users use channel statistics instead of instantaneous CSI to perform serial interference cancellation (SIC), relying on the average value of the effective channel gain as an estimate of the channel gain. Suppose that in the cluster l, the user l_1 has the best received signal, so it can decode other user information, but l_{k} is the weakest signal. It can only decode on its own and cannot decode other user signals. In other words, MUSA is only used in each cluster, not between clusters. When users can use instantaneous CSI, users in each cluster can be sorted according to their effective channel gain. In order to successfully implement SIC at stronger users to decode weaker user signals, the following necessary conditions should be met:

$$\mathbb{E}\left\{\log_2\left(1 + \mathrm{SINR}_{mj}^{mk}\right)\right\} \geq \mathbb{E}\left\{\log_2\left(1 + \mathrm{SINR}_{mk}^{mk}\right)\right\}, \forall j < k, \forall m \tag{6}$$

That is, in the same cluster, user j with high SNR can decode the user k's signal.

Based on the above conditions, the achievable rate of the first user can be written as:

$$R_{lk}^{lk,\text{final}} = \min\left(\mathbb{E}\left\{\log_2\left(1+\text{SINR}_{lj}^{lk}\right)\right\}, \mathbb{E}\left\{\log_2\left(1+\text{SINR}_{lk}^{lk}\right)\right\}\right), \forall l, k \quad (7)$$

That is, the user with the worst channel condition in the cluster can be detected by other users. We should take the smaller rate. The reason is that when the formula is not satisfied, that is to say, when the SINR calculated by the user with poor channel gain is larger than the previous user, it is necessary to consider reducing the data transmission rate of this user to facilitate the detection on the user.

Based on the above analysis, the spectrum efficiency of the improved Cell-Free Massive MIMO system can be derived:

$$\text{SE}_{mk} = \left(1 - \frac{\tau_p}{\tau_c}\right)\log_2\left(1+\text{SINR}_{mk}\right) \quad (8)$$

With the aid of conjugate beamforming, the achievable SINR of the user is obtained. Then we use MUSA's SIC detection scheme, in which users with higher received power first detect their signals, then we demodulate them, and subtract the corresponding signals from the composite received signal, thus leaving the lower power users without interference.

With the previous assumptions, users are sorted according to their channel quality. MUSA uses the code domain to send multiple signals on the same resource, and performs SIC at the receiver to decode the corresponding signals.

3.3 System Performance Analysis

We set up a scenario in which L APs and K UEs are independently and randomly distributed in a square area of km^2, assuming that the APs and UEs in the area have only a single antenna. Specific configuration parameters are shown in Table 1.

Table 1. Simulation parameter configuration

Simulation parameter	Configuration
Channel condition	Rayleigh
Channel estimation	MMSE
AP number	400
UE number	0–400
Antenna configuration	1Tx, 1Rx
Uplink power	1 W
Downlink power	100 mW
Resource block length	200
Precoding scheme	MR

First, compare the spectrum efficiency between the improved Cell-Free Massive MIMO system and the improved system before. It should be noted that the default clustering method in this article is that there are two users in each cluster, and random clustering is used to pair users. Figure 2 is a study of the spectrum efficiency distribution of the Cell-Free Massive MIMO system before and after the improvement in the scenario of 400 APs and 100 users. The improved system contains 50 clusters, each of which contains two users.

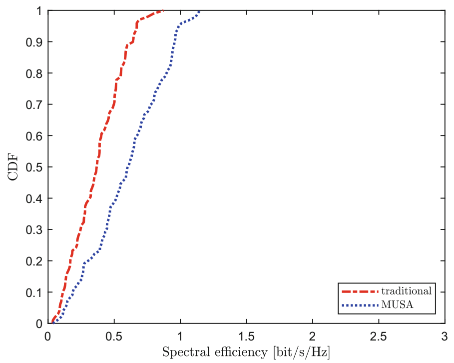

Fig. 2. CDF of spectrum efficiency

It can be seen from Fig. 2 that the improved Cell-Free Massive MIMO system has a greater improvement in spectrum efficiency compared to the previous system. The reason is that the existence of clustering improves the utilization rate of pilots, thereby increasing the resources used for downlink data transmission, thereby effectively improving the spectrum efficiency of the Cell-Free Massive MIMO system. The existence of MMSE precoding and SIC suppresses the interference between users of multiple users in the same cluster, thereby improving the overall signal-to-interference and noise ratio of the user receiving end, and also has a great effect on enhancing the spectrum efficiency.

Considering the influence of interference between users, this article also explores the user service carrying capacity of this hypothetical scenario. The specific method is: still keep the number of APs at 400, and the length of related resource blocks at 200. On this basis, the total number of users accessed is adjusted, and the number of users per cluster is still two. Count the spectrum efficiency of all users.

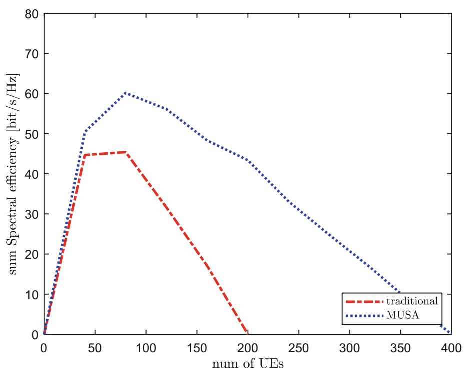

Fig. 3. Total spectrum efficiency with number of users changing

It can be seen from Fig. 3 that as the number of users access increases, the total spectrum efficiency of the Cell-Free Massive MIMO system has a tendency to increase first and then decrease to zero. This is because when the number of users is appropriate, the sum rate of the system increases as the number of users increases, and the corresponding inter-user interference is not enough to reduce the total spectrum efficiency due to the small number of users. However, when the number of connected users reaches a peak, there will be users accessing again, which will cause the spectrum efficiency of the system to decrease. This is because the spectrum efficiency is also related to the effective correlation time. An increase in the number of users will lead to an increase in the number of pilots. Thereby reducing the time of data transmission. Therefore, it can be concluded that the number of users that the Cell-Free Massive MIMO system can access has a certain limit, and blindly increasing user access will only cause the loss of system performance. In order to specifically analyze the changes in the spectrum efficiency under each user number scenario, this paper also studies the average spectrum efficiency. Keep the number of users in each cluster at two and change the total number of users connected. As shown in Fig. 4.

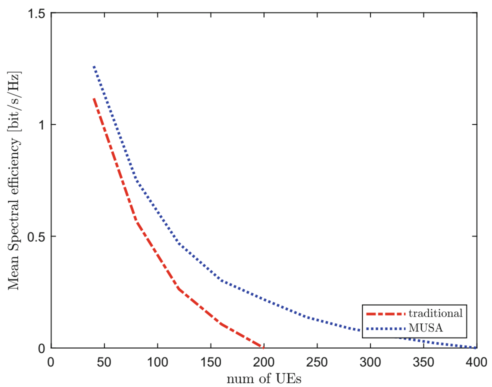

Fig. 4. Average spectrum efficiency

It can be seen from Fig. 4 that the average spectral efficiency of all users will gradually decrease as the number of users increases, until it decreases to zero. Compared with the system before the improvement, the average spectrum efficiency of the system after the improvement decreases more slowly, and the number of users reaching 0 is also more than that before the improvement. It shows that the improved system has greater user carrying capacity. Because the relevant resource blocks are limited and the number of users contained in each cluster is fixed, both of which are two. Therefore, the increase of the number of users will increase the total number of clusters in the area, thereby increasing the resources occupied by the pilot and compressing the resources for downlink data transmission. As a result, the spectrum efficiency will gradually decrease as the number of users increases. The improved Cell-Free Massive MIMO system has better user bearing capacity because the clustering algorithm improves the utilization of pilots.

4 Conclusion

In this paper, the Cell-Free Massive MIMO system is improved on the MUSA non-orthogonal multiple access technology, and a clustering method is proposed. Users in the same area are divided into clusters according to random matching. Each cluster contains two users. Users in each cluster share the same pilot and different clusters uses different pilot, thereby improving the utilization rate of the pilot. Users in the same cluster use MUSA to distinguish code domains and use MMSE-SIC to detect multi-user information. The result shows that the improved Cell-Free Massive MIMO system has better spectrum efficiency. In the future, we plan to change the number of users in each cluster, which may improve the spectrum efficiency and consider different clustering methods.

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