Survey on Cell-Free Massive MIMO with Limited Fronthaul

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***Abstract*—User Centric Cell-Free massive MIMO is a technology that ensures uniform service for users located at cell boundaries and interference control when multiple APs are densely deployed to support services. At this time, the Cell-Free MIMO system requires the CPU to control the simultaneous transmission of multiple APs and determine which APs will communicate with each user by estimating channel between the user and the base station. And it greatly increases the bandwidth requirement for fronthaul uplink to deliver state information, resulting in performance constraints according to fronthaul capacity. This paper investigates the research trends in Cell-Free massive MIMO considering fronthaul capacity.**

I. Introduction

Multiple Multiple Input Multiple Output (MIMO), in which APs with multiple antennas serve multiple users simultaneously on the same time-frequency resource, is a radio access technology that can provide high throughput, reliability, and energy efficiency through simple signal processing. The antenna array of the base station may be densely or distributedly deployed. MIMO architectures located in areas where antennas are concentrated have the advantage of low backhaul requirements. In contrast, in a distributed MIMO system, antennas are distributed over a large area. The Cell-Free massive MIMO system has antennas distributed over a wide range of areas and serves a much smaller number of users. These Cell-Free massive MIMO systems combine the concepts of distributed MIMO and massive MIMO. Cell-Free massive MIMO, unlike cellular networks, does not have cell boundaries, and all APs process all users over the same time-frequency resource through Time-Division Duplex (TDD) rather than one base station communicating with the user, making it easier to manage interference. Compared to cellular systems, user capacity who are far from BS are also superior in fairness compared to conventional methods. AP is connected to one central processing unit (CPU), and the link between AP and user is maintained by CPU when the user moves, i.e. no handover occurs. In addition, better results are shown for shaded areas created by structures [1]. Accordingly, Cell-Free massive MIMO is a next-generation network system that replaces cellular networks, and many studies are being conducted as a promising technology in 6G communication. However, there remain topics that need to be addressed, such as clustering problems, pilot corruption problems, and fronthaul constraints that determine which APs the user will communicate with. In fact, fronthaul constraints can be addressed through a star topology with point-to-point links, but this is costly. Therefore, in this paper, we investigated the latest research trends in Cell-Free MIMO systems with fronthaul constraints and several topics.

II. Cell-Free Massive MIMO System

In the Cell-Free massive MIMO system, all APs and users have one antenna, and all APs are connected to the central processing unit through the backhaul network. Essentially, the system utilizes distributed base station antennas to provide evenly good service to all users in the network with a virtual MIMO or distributed antenna system. These Cell-Free systems are very good compared to microcell systems in terms of throughput, and show better results for shadow fading[1].

CF mMIMO systems can controll inter-cell interference through joint transmission of multiple base stations, A major drawback of that is hardware and power costs are high. Also, in terms of implementation complexity, it requires more fronthaul capacity than micro cell systems. To address this, in [2], Zhang et al. improve the overall performance of the system by improving channel conditions by placing RIS around BS and users. By proposing energy efficient hybrid beamforming architecture and examining the effect of transmission power, number of RISs, and size of RIS on energy efficiency, they show that the proposed system achieves higher power efficiency than the existing system.

In [3], Ranasinghe et al propose a GNN-based AP selection algorithm. The AP selection algorithm is used for Dynamic clustering in User centric CF mMIMO, where the GraphSAGE-based GNN algorithm predicts links between nodes. Simulation results show that the computational load is less and more scalable than the AP selection algorithm based on large scale fading coefficient.

Liu et al. [4] presents an efficient pilot allocation method based on Graph coloring to alleviate pilot contamination in a Cell-Free MIMO environment. The AP selection algorithm was used to construct the interference graph, and the interference graph was updated to achieve optimal pilot allocation. Noh et al. [3] combines IRS and Cell-Free MIMO to improve the performance of the MIMO system by reducing cost and power. Previous studies have used optimization algorithms that focus on instant performance and impose high computational complexity and overhead. To address these challenges, authors propose a new two-step algorithm that provides long-term passive beamforming in the IRS using statistical channel state information (S-CSI) and short-term active precoders and provides long-term power allocation at the access point (AP) to maximize the minimum accessible rate. In addition, high power consumption in proportion to the number of APs in configuring a Cell-Free network is a major problem in introduction. To address this, Nguyen et al. [5] develops a new low-complexity power control technique with zero-forcing precoders to maximize the energy efficiency of the Cell-Free massive MIMO system, taking into account the power consumption and incomplete channel state information of the fronthaul network. In [6], Mishra et al. propose a method of combining RSMA with a cell-free mMIMO system for massive machine-type communication. Although pilot contamination occurs due to multiple user's random access, AP with RSMA can robustly transmit using imperfect channel state information caused by pilot contamination. Authors shows that the achievable rate of RSMA cell-free system is significantly increased with various topologies by proposing a new heuristic precoder and max-min pairness algorithm. Le et al. [7] proposes user centric clustering and beamforming techniques to optimize the transmission power of the AP. The clustering technique allocates transmission power through the approximation framework through k means clustering. However, the exchange of channel stae information between all APs and CPUs through the fronthaul increases computational and power consumption overhead. As such, the capacity of fronthaul links reduces the overall performance of the system, and it is important to managing AP clustering and intra handover issues to address these frontfaul limitations.

III. Limited Fronthaul Analysis In Cell-Free mMIMO System

Wireless networks are changing their paradigm from cellular networks limited by inter-cell interference to User Centric Cell-Free Massive MIMO with additional diversity and processing of interference [8]. This is likely to be an important component in a 6G environment characterized by low complexity, high throughput, ultra reliability, and low latency, with high spectral efficiency due to Channel Hardening and Favour Propagation, just like MIMO. As the number of APs increases, the increase in fronthaul traffic is a major limitation in the deployment of Cell-Free systems due to channel information exchange between APs and CPUs. So the scalability is one of the most important parts of recent Cell-Free studies.

In [9], Guenach et al. propose a power control and AP scheduling algorithm to improve performance while meeting fronthaul bandwidth constraints. To reduce the complexity of common power and scheduling optimization problems, a low-complexity algorithm was developed by dividing it into two sub-problems, which provide near-optimal performance while minimizing the requirement for fronthaul bandwidth. In order to formulate fronthaul capacity constraints, Parida et al. [10] model the locations of APs and users into two independent Poisson point processes. Authors prove that for cell-free architectures where each base station serve all users, the achievable rate becomes zero as the network size increases. They also formulate the fronthaul load in the User Centric approach to present the achievable percentage of users under the fronthaul constraints and prove that the energy efficiency of the system is a concave function to the number of antennas at the base station. These existing studies conclude that joint transmission in Cell-Free system outperforms cellular methods when fronthaul links have no capacity limitations. However, in order to show whether this conclusion holds if there is a capacity limitation, [11] compares the performance of each transmission system by formulating the energy efficiency maximization problem for it. This shows that joint transmission is heavily influenced by cluster size and the number of antennas at the base station, and in many cases, non-coherent transmission achieve higher energy efficiency. And they suggests the appropriate number of antennas and cluster size according to fronthaul capacity limitations. In [12], Ibrahim et al. investigate the uplink performance of the Cell-Free mMIMO system supported by the mmWave-fronthaul network. In fact, using wired fronthaul links in star topology is optimal, but practically impossible. Authors show that utilizing large bandwidth in millimeter wave to support fronthaul links can increase the performance of Cell-Free mMIMO systems. They also show that network deployment needs to be adjusted according to the bandwidth of the fronthaul and the density of the AP. In particular, it shows that increasing the density of APs beyond a certain level no longer improves UL data rate, and increasing the number of antennas per AP results in system performance degradation. Rajapaksha et al. [13] propose a resource allocation algorithm utilizing deep learning in a massive MIMO network with transceiver hardware impairments. The proposed deep neural network (DNN), PowerNet, provides a simple and scalable solution to power control and allocation problems. In addition, model training is also simple because it is not necessary to know the optimal resource allocation during model training by using unsupervised learning methods. Simulation results show better sum rate performance compared to existing benchmarks, and scalability is also good depending on the number of users and APs. Also cell-free mMIMO system has advantages of wide coverage and flexible arrangement, but its performance is affected by a limitation of front hole capacity. In [14], Rui et al. propose a co-user clustering and AP selection scheme that reduces fronthaul link load. First, they derive the uplink spectral efficiency for the Rician fading channel, and based on this, propose an AP selection algorithm and a clustering algorithm by optimizing power control. Simulation results show that the proposed algorithm reduces the fronthaul link load.

Although these works try to improve performance for user centric cell-free mMIMO, there are several challenges such intra-handover problem, dynamic power control, and clustering interference left.

IV. CONCLUSION

In this paper, we investigated various research to measure the performance of the Cell-Free mMIMO system when fronthaul link is limited. In future work, we suggest a optimization scheme and resource allocation for user-centric mMIMO with fronthaul links.

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