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A Survey on Research Activities for Deploying Cell Free Massive MIMO towards Beyond 5G

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SUMMARY 5G service has been launched in various countries, and research for the beyond 5G is already underway actively around the world. In beyond 5G, it is expected to expand the various capabilities of communication technologies to cover further wide use cases from 5G. As a candidate elemental technology, cell free massive MIMO has been widely researched and shown its potential to enhance the capabilities from various aspects. However, for deploying this technology in reality, there are still many technical issues such as a cost of distributing antenna and installing fronthaul, and also the scalability aspects. This paper surveys research trends of cell free massive MIMO, especially focusing on the deployment challenges with an introduction to our specific related research activities including some numerical examples.

key words: *cell free massive MIMO, beyond 5G, deployment, antenna distribution, fronthaul, scalability*

1. Introduction

5G services have launched in many countries around the world and are gradually spreading. At the same time, many research institutes are already working on R&D for beyond 5G or 6G, aiming for commercialization around 2030. In addition, various consortiums and task groups of standardization have been established in various parts of the world to promote the study, and very active studies are underway [1]–[4]. According to these studies, beyond 5G will further expand the communication requirements of 5G, such as high speed and large capacity, high reliability and low latency, and massive connections, while adding new communication requirements such as expanding the communication area beyond the ground and enhancing the power consumption and security level of the entire network. In order to meet these requirements, a wide range of studies including the use of various frequencies and elemental technologies has been conducted.

As one of a candidate elemental technology for beyond 5G, Cell free massive MIMO [5] is getting a lot of attention [8]. In this technology, a large number of antennas are distributed and cooperated, and then removes boundary of cells and eliminates the interference which the current cellular system suffers. In addition, by distributing the large number of antennas, it can obtain macro diversity gain significantly compared to the massive MIMO, of which all the antennas are centralized at an antenna site. This is an also important feature to keep quality especially for higher frequency band such as the millimeter wave, where the effect of the shadowing and blockage of human or foliage and so on, is very severe [6], [7]. By effectively utilizing these features, it is expected to be able to provide a high-quality wireless environment no matter where the user is located [10], and to expand the performance of existing communication systems in many aspects such as enhancing the experienced data rate, ensuring high reliability, and reducing power consumption, without depending on the user's location. Then it can be a platform to operate user centric network, which satisfies diversified user's requirements in everywhere, by controlling the signal processing of the antenna cooperation and network resource management adequately [11].

A great deal of research about cell free massive MIMO including relevant technologies such as coordinated Multi Point (CoMP) and distributed MIMO has been conducted extensively [12], [13]. In addition, some demonstration trials and the product development, which deploys a large number of distributed antennas in a closed area such as an indoor scenario, has been conducted [14]–[16]. On the other hand, in order to deploy this technology to construct a wide service area in reality, there are still technical issues to be solved. In this paper, we focus on the technical issues when actually deploying the cell free massive MIMO from the viewpoint of telecommunication operators, and survey the trends in research toward this end, and outline the research activities that the authors are conducting as concrete relevant examples. Concretely, the cost and time for deploying very large number of antennas at distributed sites and installing their fronthaul with high capacity suitable for the expanding communication bandwidth, and ensuring the scalability for accommodating large number of antennas and users for providing a wider service area are identified as critical issues and the research for them are surveyed. The contribution of this paper is to organize and identify technical issues and effective research activities of cell free massive MIMO from the aspects of real deployment. It is expected to give insights to design a realistic system, and to further accelerate the research and development for practical use towards beyond 5G.

The rest of the paper is organized as follows. Section 2 describe a system model of cell free massive MIMO, and explain its advantage through numerical examples, and classifies its research field. Section 3 surveys research challenges especially for deploying the technologies including concrete introduction of our activities. Section 4 summarizes this sur-

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vey with the future perspectives and expectations.

2. Cell Free Massive MIMO

2.1 System Model

In this section, a brief system model and advantage of the cell free massive MIMO to the conventional technologies are explained. Figure 1 describes a typical ideal architecture of cell free massive MIMO. A large number of antennas are distributed in a closed target area as access points (APs), and ideally all the APs are served to all the user equipment (UE), and UE shares resources spatially like MU-MIMO. It would be natural to assume total number of antennas are larger than number of spatially multiplexing users and to operate with time and/or frequency division multiplexing. As an ideal architecture, a central processing unit (CPU) is connected to all the APs through fronthaul, and it consolidates the signal processing and access control of uplink and downlink communications and it is also connected to a core network. The signal processing functionality includes the channel estimation among APs and UEs, multiuser detection (MUD) for uplink to detect each user's signals, and precoding for downlink. It is noteworthy that the processing function can be split into AP and CPU by considering processing volume and fronthaul loads, and that is typically selected from options of functional split [17].

There has been two aspects of cell free massive MIMO when comparing it to the conventional schemes. One is comparison to a small cell as discussed in [5]. In a small cell deployment, each user basically connects to a base station with following the cellular network architecture, and the interference among cells is a critical issue that degrades performance severely especially for the users at cell edge. This tends to be much severe if the cells are deployed more densely to increase total network capacity. On the other hand, the cell free massive MIMO can cope with the interference by cooperating the distributed antennas at CPU with large scale signal processing for MU-MIMO by exploiting the degree of freedoms of the large number of antennas, such for the MUD and precoding. The other aspect is comparison to the massive MIMO where the antennas are centralized at an antenna site. In the centralized massive MIMO, it also can exploit the large degree of freedoms, and improves spectral efficiency significantly and has been the important technology especially from 5G [18]–[20]. From a propagation aspect, it can exploit a channel hardening effect and robust to fading by utilizing large number of antennas. However, the UEs experience different pathloss and shadowing, and its wireless quality can be changed depending on the distance from the antenna site and surrounding environment. Contrary, cell free massive MIMO can exploit effect of a macro/site diversity sufficiently because the antennas are distributed around as APs. Therefore, it can be expected that all the UEs can experience the good wireless quality.

In order to show those advantage of cell free massive MIMO, numerical example of uplink performance is shown in Fig. 2, based on the simulation assumption listed in Table 1. It assumes the transmission power of each UE is uniformly set to 23 dBm, and each UE has one antenna. In the figure, CDF of user spectral efficiency for the small cell, massive MIMO, and cell free massive MIMO are plotted. Concretely, in each simulation, the spectral efficiency of each multiplexed users is calculated separately and iterate this operation with setting the position of UEs and APs randomly in a target area, and the curve summarizes its cumulative probability of the corresponding spectral efficiency of the horizontal axis. It assumed that both the small cell and cell free massive MIMO deploys 1 antenna at 256 distributed sites in a target area, whereas massive MIMO centralizes 256 antennas at a 1 site. In addition, it assumes ideal fronthauling without any quantization error for the IQ data transfer from APs to CPU. The results show that cell free

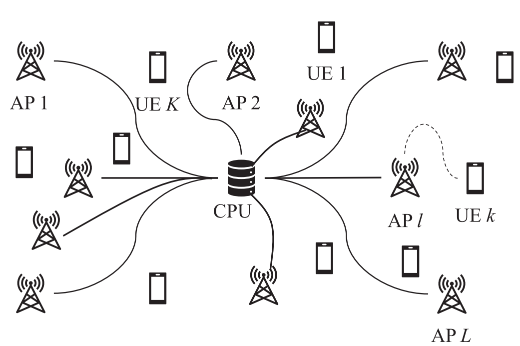

Fig. 1 Typical description of cell free massive MIMO.

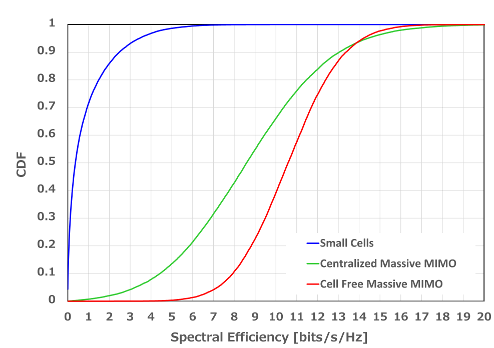

Fig. 2 Comparison of cell free massive MIMO to small cell and massive MIMO.

Table 1 Assumption for comparison with conventional schemes.

Target Area Size	2km x 2km
Center Frequency	3.5 GHz
Bandwidth	100 MHz
Transmission Power	23 dBm
Noise Figure	7 dB
Number of multiplexing UEs	64
Number of antennas per site, number of sites	- 1, 256 (small cell) - 256, 1 (massive MIMO) - 1, 256 (cell Free massive MIMO)
Multiuser detection	MMSE
Channel Estimation	LMSE

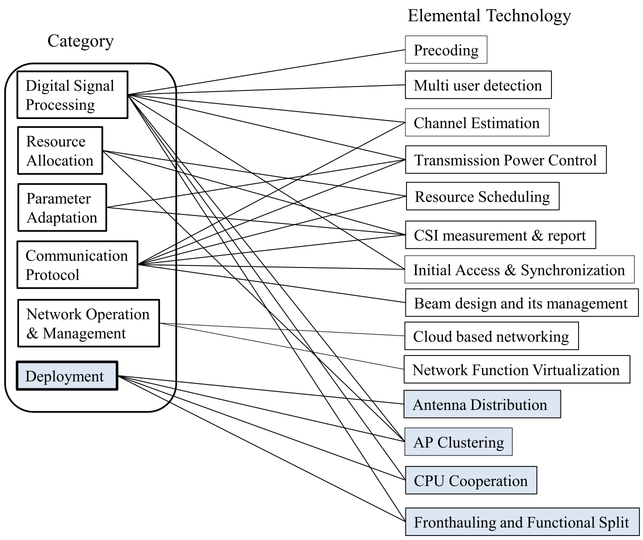

Fig. 3 Elemental technologies of cell free massive MIMO.

massive MIMO can improve the spectral efficiency drastically comparing to small cell by the use of large number of antennas and reduce the interference significantly. In addition, it also shows that it can improve spectral efficiency especially at lower %-tile from massive MIMO sufficiently. For example, it improves 5%tile spectral efficiency 2.1 times. This characteristic is very important to provide great service quality to all the UEs.

2.2 Classification of the Research Topics

For realizing the cell free massive MIMO, various technologies are required and extensive research has been conducted all over the world. Figure 3 classifies its elemental technologies, which has been researched, into field categories.

As a digital signal processing for cell free massive MIMO, downlink precoding, uplink MUD and channel estimation schemes have been well researched [21]–[25]. For the channel estimation, the pilot signal allocation suitable for the cell free architecture have been researched [26]–[29]. Transmission power control (TPC) has been also researched widely for both downlink and uplink respectively, and it is considered with the signal processing schemes to derive the optimization problem [30]–[33]. The signal processing schemes are also considered with AP clustering scheme, that limit the number of APs for the signal processing per users or group of users to reduce the total complexity efficiently [34]–[39]. In addition, most of the research assumes the simultaneous spatial multiplexing UEs are already scheduled, but some papers reveal the performance can be enhanced with considering a resource scheduling [40], [41].

Current 3GPP standard of 5G NR and LTE support joint transmission and reception scheme as one transmission scheme of CoMP, operating with distributed antennas deployed at different site. It can be regarded as one example of cell free massive MIMO, when distributing the massive number of antennas in an area to operate them synchronously for MU-MIMO. However, its scale and performance would be limited since the current standard is not optimized for the cell free operation. Hence, it is expected to embody communication protocols suitable for operating cell free massive MIMO effectively in a communication system towards beyond 5G by around 2025. One critical example is number of ports of demodulation reference signal (DMRS) that limits the number of spatial multiplexing UEs. Currently, maximum number of multiplexing UE for MU-MIMO is 12 [42], but it will not be sufficient when distributing the antenna widely and large number of UEs are connecting. Straightforward strategy to increase DMRS ports is to increase DMRS symbols in a time slot, but it increases overhead and reduce spectral efficiency. Hence it will be expected to establish strategy to increase number of multiplexing UEs. In 3GPP Rel.18, mechanisms to increase the number of the DMRS ports up to 24 will be studied for enhancing MU-MIMO [43]. In addition, the framework to facilitate aforementioned effective pilot allocation schemes [26]–[29] will also be required to further enhancing multiplexing of cell free massive MIMO. There can be various other functionalities to improve from the protocol aspects including its mechanism for establishing initial access [44], channel state information (CSI) measurement and report from UE for resource scheduling, and beam management of each AP especially for mm wave frequency band [45], from standardization aspects. It is also important to design beams themselves suitable for cell free massive MIMO [46].

For 5G network operation and management, the network function virtualization (NFV) and the software defined network (SDN) have been considered for the core network as a key technology for its flexibility and efficiency. It will also be expected to apply them to radio access network (RAN) functionalities, and have been actively researched and developed recently [47]. For example, RAN slicing has been considered, using SDN and NFV technologies to build logical networks that meet the quality requirements of users. In O-RAN alliance, the RAN functionalities and RAN controller interfaces have been standardized on the assumption that SDN and NFV are applied. In [48], an implementation of the cell free massive MIMO based on the cloud baseband architecture is introduced. It is expected that the cell free massive is operated flexibly for satisfying the diversified communication requirements by utilizing the degrees of freedom of the large number of distributed antennas and the computing resource efficiently with such the platform [49], [50].

Besides these aspects, it will also be important to identify issues to deploy cell free massive MIMO in reality, and requires to establish technologies to solve these issues. In the next section, the issues for deploying cell free massive MIMO are identified and surveys focusing on the relevant technologies toward them.

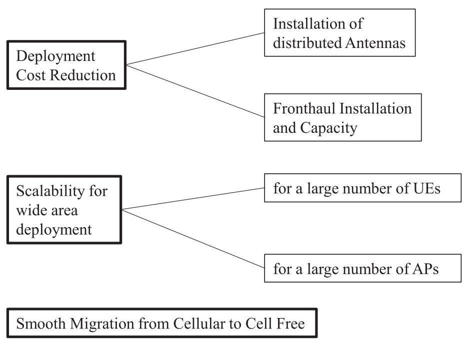

Fig. 4 Technical issues for deploying cell free massive MIMO.

3. Technical Issues and Challenges for Deploying Cell Free Massive MIMO

The technical issues for deploying cell free massive MIMO can be classified into three categories as shown in Fig. 4.

One is mainly cost reduction for deploying a large number of APs. This includes installation of the large number of distributed antennas and that of fronthaul among CPU and APs and those capacity. The deployment of the distributed large number of antennas in the real sites are one of a critical issue for operators because of its time and effort to determine the sites including the negotiation of the building owners in addition to the cost in reality. The issue for the fronthaul also includes its cost, and time to install optical fibers. Especially towards beyond 5G, the cost-effective methodologies to accommodate signals with much wider bandwidth and the large number of antennas are desirable.

Another issue is scalability for wide area deployment. As shown in Fig. 1 in a typical ideal cell free massive MIMO, it assumes all the antennas are connected to CPU and all antennas are assumed to serve to all users. In the closed specific area, such as a stadium, a shopping center or in a building, the assumption would be valid. However, as deploying cell free massive MIMO in a further wider area including outdoor service area, number of APs for connecting CPU and UEs grows with expanding the service area, and then the complexity of the CPU, for cooperative signal processing of a large number of antennas for all UEs and resource management, increases prohibitively higher. For example, the MIMO signal processing schemes like MMSE or ZF with all antennas of APs to separate all the UEs, the required computational complexity is the 3rd order of the numbers. Hence, it is desirable to accommodate APs in wider with less computation complexity without severe performance degradation even if the number of APs and/or UEs grows.

The other issue is smooth migration from cellular to cell free system. For deploying the cell free massive MIMO, 2 scenarios can be considered depending the operating frequency band. For frequency bands where the 5G has already been operated, the important issue will be how to migrate from cellular systems to a cell-free system with keeping service continuity. In the service area where centralized RAN (C-RAN) is deployed, it is considered possible to build a cell-free area partially by rewriting or adding the baseband software in some extent. However, it is necessary to establish a concrete methodology for gradually expanding that area scale including distributed RAN (D-RAN) area for smooth migration, and it is expected the that the research for this issue will be proceeded. On the other hand, there are no such migration issues for frequency bands that are not currently in use.

3.1 Installation of Distributed Antennas

Based on the aforementioned background, it is desired to distribute and install the antennas efficiently as much as possible with keeping the performance. For the purpose, performance analysis of distributed antennas systems from the aspect of the antenna distribution have been made through computer simulations in [51], [52] and with field experiments in outdoor [53], and indoor [54], respectively. Each analysis evaluates system performance of distributed antenna systems by comparing various combination of the number of antennas per antenna site and number of antenna sites, by keeping the total number of deploying antennas. Some papers show the user throughput is not always improved by completely distributing antenna sites. Effect of the number of antennas at each antenna site is also discussed from the propagation property aspects such as channel hardening and favorable propagation, especially for MRC type signal processing, and it also indicate that characteristics [55].

For clarifying efficient antenna deployment strategy, our paper [56] evaluates the impact of the antenna distribution on the spectral and energy efficiency comprehensively with various TPC and MUD algorithms, and show that the possibilities to reduce the number of antenna sites by concentrating some antennas at each antenna site without severe degradation. Figure 5 and Fig. 6 show exemplified results of the CDF of the spectral and energy efficiency of uplink with the simulation condition listed in Table 2. For the analysis, performances with different number of antenna sites L, under the condition where the total number of antennas are constant as 256 by changing number of antennas N in each antenna site, are compared. The energy efficiency is defined as spectral efficiency per consumed transmission power. The transmission power of each UE was assumed to be controlled with Max-Min criteria of spectral efficiency, that maximizes the minimum spectral efficiency of UE, and with constraints of its maximum as 23 dBm.

From both the spectral and energy efficiency, $L = 64$ is the best antenna distribution and $L = 16$ can still obtain superior performance to $L = 256$ in this situation in at the most of the cumulative probabilities. This means the number of antenna sites can be reduced with performance improvement (without degradation) comparing to fully distributed situation. This motivates to concentrate several antennas at each

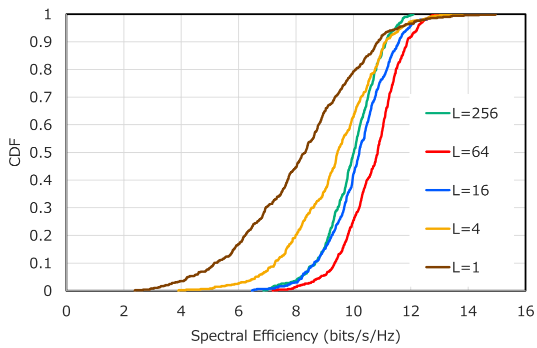

Fig. 5 Uplink spectral efficiency comparison.

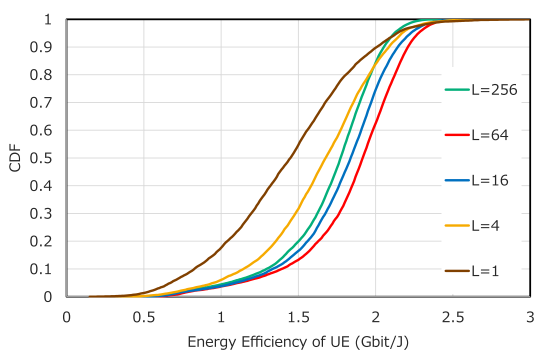

Fig. 6 Uplink energy efficiency comparison.

Table 2 Simulation condition for analyzing the effect of antenna distribution.

Target Area Size	1km x 1km
Center Frequency	3.5 GHz
Bandwidth	20 MHz
Maximum Transmission Power	23 dBm
Noise Figure	7 dB
Number of multiplexing UEs	64
Number of antenna sites (L) and antennas per site (N)	(L,N) = (256,1), (64, 4), (16, 16), (4, 64), (1, 256)
Multiuser detection algorithm	Zero Forcing
Channel Estimation	Ideal
Transmission Power Control	Max-Min SE Algorithm

antenna site to obtain performance without increasing the number of antenna sites as required. It is noteworthy that the installation point of view, the increasing the number of antennas may increase space, weight and receiving wind load, and it should also be considered that fact.

3.2 Fronthauling

Currently, a digitized radio over fiber (DRoF) transmission with common public radio interface (CPRI) [57], that transfers digitized radio signals as I/Q samples, have been employed as a typical fronthaul. In DRoF, resolution of ADCs and quality of the signals through fronthaul is a fundamental trade-off. Hence, the effect of the quantization error generated for the fronthaul to the total performance of cell free massive MIMO has been analyzed [58]–[60], and suitable functional split [61], signal processing scheme [62], and TPC algorithm [63] under the constraint have been discussed. Although such the scheme is effective, the cost will be increased as the bandwidth of the wireless system and number of antennas increases if a certain signal quality is guaranteed, because the more fiber installation is required. Especially, for the beyond 5G, which is expected further wideband transmission, it will be critical.

As an alternative to DRoF, analog RoF (ARoF), which achieves large capacity by converting analog RF waveform to the optical signal, has been attracted much attention of its applicability to further wideband transmission including beyond 5G [64]. In [65], it is revealed that the cost of the fiber infrastructure can be reduced by more than 93% by employing ARoF schemes. It is noteworthy that such the ARoF schemes do not require ADC/DAC at each AP site, and it is also beneficial to reduce power consumption and implementation scale of each site and then it might relax the installation requirements at a site. As one type of ARoF, intermediate frequency over fiber (IFoF) have been researched [64]–[67]. In this scheme, the analog RF waveform is converted to the IF and then converted to optical signals, and at AP side the optical signal is converted to IF and converted to RF signal. If applying different IF to convert each signal streams for MIMO transmission it can be multiplexed by FDM in a single optical fiber, and improves efficiency [68]. In [69], it is demonstrated that 24 streams of 400 MHz bandwidth 5G NR signals are successfully transmitted, and achieved 34.2 Gbps throughput with 9.12 GHz bandwidth over 20 km links. However, the number of the streams corresponding antennas is limited depending on the supporting bandwidth of the devices such as the electrical to optical (E/O) converter and optical to electrical (O/E) converter. To further increase capability to accommodate more antennas into a single optical fiber, it can be considered to utilize with other multiplexing schemes with other granularities and domains, such as core multiplexing, wavelength multiplexing and so on. For applying the ARoF technologies to the cell free massive MIMO, such the multiplexing scheme is very beneficial to transmit them to the vicinity of the antenna sites with a single fiber for reducing the number and length of optical fibers required to be installed as shown in Fig. 7. In addition, cost of the E/O and O/E converter are high for mm wave frequency and it can save the device cost. Such the concept of multiplexing in an optical fiber for applying cell free massive MIMO has been demonstrated in [70]. In the demonstration experiment, a millimeter-wave (28 GHz) wireless communication environment was established in an anechoic chamber as shown in Fig. 8. The 5G base station simulator (signaling tester) and multiple antennas at different position, regarded as APs, are connected with a single multicore optical fiber, and transmitting the wireless signals from each antenna of AP through the IFoF-based mobile fronthaul. In the communication tests, we have confirmed that the following effects can be obtained by cooperating the distributed antennas with commercial 5G terminals.
(1) Stable throughput can be obtained by mitigating the effects of a tree blockage.

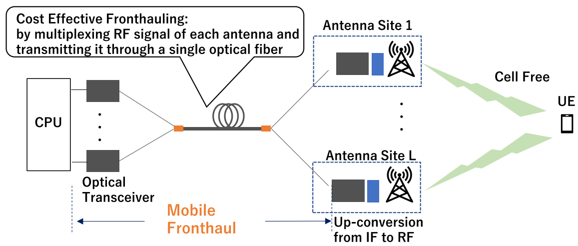

Fig. 7 Concept of IFoF for cell free massive MIMO.

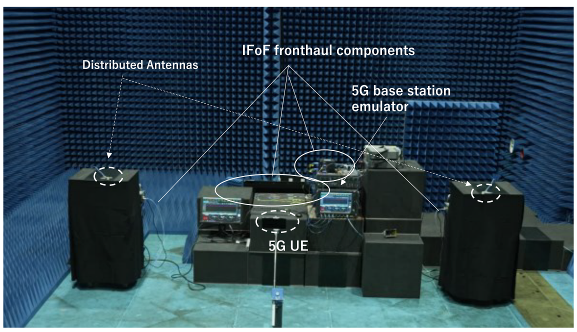

Fig. 8 Demonstration environment.

(2) Higher wireless communication quality can be maintained even when the distribution patterns of the antennas are changed.

As another fronthaul architecture, called as radio stripe, has been emerging [71]. In this architecture, APs are connected serially and transfers fronthaul data to the neighbor AP with sequential signal processing [72], and only the APs at edge connect to the CPU. This serialized architecture is very different from general architecture as shown in Fig. 1, where the CPU connect to all APs parallelly, and might be an effective solution especially for the closed specific area.

3.3 Scalability for Wide Area Deployment

The scalability issues have been viewed from 2 aspects. One is from the large number of connecting users, and the other is from a large number of APs, and research has been conducted from each or both aspects.

When the number of UEs grows, the efficient scheme to reduce the complexity of the total signal processing for all UE is to make cluster with limited number of APs, and the signal processing is operated in cluster-wise. Basically, it is natural to select APs that is close to each UE, and this is called as user centric clustering [34]. The researches that assume to apply such the clustering scheme are increasing [35]–[39], [41], [44]. Most of the signal processing algorithm suitable for the clustering assumes that each AP have some number of antennas, and it combines the signals as partial local processing, for such MUD or precoding, only for UEs that is responsible by the clustering. Then the CPU combines them for each UE according to the AP cluster information.

In addition, if a large number of users connect the net-

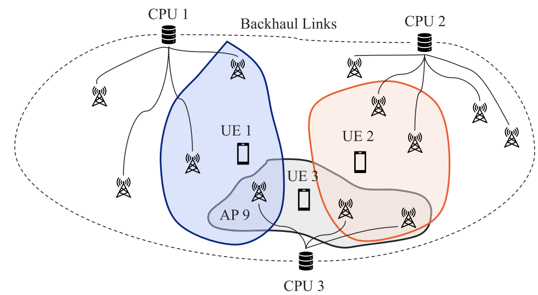

Fig. 9 Cell free massive MIMO with multiple CPUs.

work and are spatially multiplexed, the overhead of pilot sequence for channel estimation would be a critical issue, because it decreases spectral efficiency. Hence it would be natural to reuse the pilot sequence with some extent in a target wide area. However, it causes pilot contamination, that degrades performance of the channel estimation, and it also decrease the spectral efficiency. Then the efficient pilot assignment scheme has been considered. That is supposed to allocate the same pilot sequence to the users with large separation distance for reducing the interference for channel estimation [26]–[29]. As another approach, pilot decontamination [73], [74], that improves channel estimation accuracy even if the pilot is contaminated, has been considered and applied it to the cell free massive MIMO with the user centric clustering [75].

For the scalability when the number of the APs grows as deploying wider area, multiple CPU cooperation can be considered as an effective solution. The paper [76]–[78] have focused on this issue and shows its architecture for dividing computation into multiple CPUs as shown in Fig. 9. With this topology, UE connect to either of the one CPU, and only the user's data signals and PHY layer information of the APs across the CPU are shared among APs. Then it can divide the UEs to each CPU to have a scalability of the core network functionalities. In addition, each CPU partially demodulate the signals of target UEs and the partially demodulated signals are shared among CPUs through backhaul as required, and the signals are combined to decode for each UE in a CPU. Hence the dimension of the MUD at each CPU can be reduced compared to single CPU architecture because the number of APs for processing at each CPU is reduced, and the computational complexity can also be reduced significantly. It can employ the user centric clustering that construct cluster for each UE and it is effective for reducing the complexity of the CPUs by reducing number of APs. By the CPU cooperation, user throughput can be maintained even if the UEs are located at boundary of the CPUs as shown in the same figure. For clarifying the effectiveness of the CPU cooperation with assumption where the backhaul link do not ideally share information, [79] evaluates the throughput with taking the backhaul loads into account, and clarifies its effectiveness through the comparison without CPU cooperation. Figure 10 shows the example of the simulation results for the assumption listed in Table 3, and it shows effectiveness of the cooperation. The transmis-

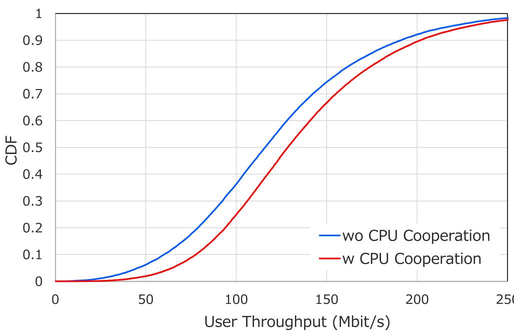

Fig. 10 Effectiveness for cooperation of CPUs through backhaul.

Table 3 Simulation assumption for verifying CPU cooperation.

Target Area Size	1km x 1km
Center Frequency	2.0 GHz
Bandwidth	20 MHz
Transmission Power	23 dBm
Noise Figure	7 dB
Number of multiplexing UEs	25
Number of CPUs	4
Number of antennas per CPU	25
Multiuser detection	MMSE
Channel Estimation	Ideal

sion power of each UE was assumed to be set to 23 dBm uniformly. It can improve throughput especially for 5%tile throughput because it can establish the cluster efficiently even at the boundary area of the CPUs, and with this kind of cooperation schemes cell free massive MIMO can divide the processing to multiple CPUs to keep the scalability of the signal processing.

4. Conclusion and Future Perspectives

This paper surveys research for cell free massive MIMO, especially for the issues to deploy it in reality over a wide area. Concretely, research topics for reducing the cost for installing a large number of antennas and its fronthaul, and for keeping the scalability are introduced including our activities.

In the future, it will be expected to establish the deployment methodologies with employing intelligent reflecting surface (IRS) to reduce the number of APs by optimizing the wireless area [80], and the rapid area deployment by applying wireless relay technologies such as integrated access and backhaul as a fronthaul. In addition, optimization of the entire network operation, including RRC state management, clustering formation, resource allocation, and parameter control, will be required to accommodate each user with different communication requirements. It will also be expected to establish a method to apply these tasks with a feasible amount of computation using machine learning [81].

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