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**Effective Channel Gain-Based Access Point Selection in Cell-Free Massive MIMO Systems**

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 **ABSTRACT** In this paper, we investigate the selection problem of access points (APs) in cell-free massivemultiple-input multiple-output (MIMO) systems, where APs equipped with a large number of antennas are geographically distributed over a wide area with no cell border. These APs simultaneously serve many users, which are randomly distributed all over the area. We first derive formulas to calculate two proposed metrics used to measure the effective channel gain from all users to all AP and the channel quality of each user. Moreover, these metrics are only based on large-scale fading coefficients, which change very slowly in time. Next, we propose an algorithm to effectively sort and connect users to each AP in a sequential manner using these proposed metrics. Simulation results show that cell-free massive MIMO systems using proposed scheme have better performance compared to existing schemes.

 **INDEX TERMS** Cell-free, massive MIMO, AP selection, AP-User Association.

|  |  |
| --- | --- |
| **I. INTRODUCTION** | connected to other cell than the current serving cell. |
| Massive multiple-input multiple-output (MIMO) systems | On the other hand, distributed or cell-free massive MIMO |
| where a large number of antennas are equipped on the base | systems have some advantages in comparison to collo- |
| stations (BSs) or access points (APs) to simultaneously serve | cated systems such as more efficient diversity of channels, |
| many users in the same frequency resource, is an emerg- | handover-free, higher probability of coverage, no cost for |
| ing technology for 5G wireless communication systems and | investigating and deploying cells in particular areas, and so |
| future wireless networks [1], [2]. With a large number of | on [8], [9]. The authors of [8] compared cell-free massive |
| AP antennas, small-scale fading, noise and interference from | MIMO with small cell systems. They focused on max- |
| other users are greatly removed by the effects of channel | min power control to provide uniformly good service for |
| hardening and favorable propagation [3]. This helps massive | every user and pilot assignment with the assumption that |
| MIMO systems significantly improve both spectral efficiency | all users are served by all APs at the same time. The au- |
| (SE) and energy efficiency (EE). Moreover, APs use simple | thors of [9] investigated cell-free massive MIMO systems |
| linear signal processing technique for both uplink signal | using an approach called the user centric approach, but APs |
| detection and downlink precoding, such as maximum ratio, | still serve many users simultaneously. In [10], the authors |
| zero forcing and so on, but they still achieve nearly optimal | proposed an energy efficiency maximization scheme using |
| performance [1]- [3]. | power allocation and user-AP selection. They showed that |
| Noticeably, most existing researches on massive MIMO | a fully connected user-AP is not optimal. However, they |
| systems have been based on cellular architectures since they | mainly focused on power allocation and used the results from |
| are well-studied and can be easily managed cell by cell, and | optimization problem to select APs. This selection scheme is |
| have low backhaul resource requirements [4], [5]. However, | very complicated due to the complexity of the optimization |
| some drawbacks of cellular system are cell-edge user perfor- | problem, and many users can be connected to one AP. The |
| mance and user location-related issues [14], [7]. Specifically, | authors of [11] used the AP selection scheme in [10] to |
| an user belongs to a cell but locates in the edge of that | propose a pilot power control design to minimize the mean |
| cell has bad channel quality since the far distance from its | squared errors of the channel estimation using sequential |
| serving cell. That user may have better channel quality if it is | convex optimization. In [12], the authors investigated the |
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energy efficiency in downlink transmission by optimizing power allocation, user-AP association, and antenna activation on each AP in a combinational manner. This algorithm had very high computational complexity since they combined three challenging problems in cell-free massive MIMO into a mixed integer nonlinear problem. Moreover, to solve this problem, the authors need to approximate the original prob-lem two times, and the solution is only a local optimum. In this paper, we focus on AP-user selection problem in a cell-free massive MIMO system. The main contributions of this paper are as follows.

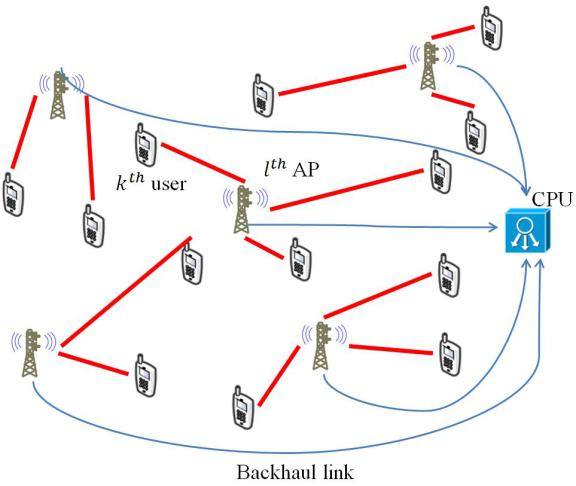
We derive two metrics, one is to measure the channel quality of each user to all APs, and another one is to calculate the effective channel gain between every user and AP in the system. These two metrics are calculated only using large-scale fading coefficients that do not change quickly in time so that we do not need to re-run the algorithm frequently.

We propose an effective channel gain-based algorithm to assign users to each AP sequentially to reduce the interference between users and consequently improve the sum rate of the system.

The remainder of this paper is organized as follows. We briefly describe the system model and assumption in Section

1. In Section III, we show the details of proposed metrics and AP-user selection algorithm. Simulation results and dis-cussion are provided in Section IV. Finally, we give our conclusion in Section V.

**II. SYSTEM MODEL**



**FIGURE 1. System model of a cell-free massive MIMO system.**

We consider a multi-user cell-free massive MIMO system containing L geographically distributed APs serving K users in the same time-frequency resource. The system operates in time division duplex (TDD) mode, which means the channels in the uplink and downlink are reciprocal, and we only need to estimate the channel in uplink. Each AP is equipped with

* antennas (MK) while each user has single antenna.

2

Assume that all APs are located without any cell-border and all users are distributed randomly in a wide area. Moreover, all L APs are connected to a central processing unit via a backhaul network as in Fig. (1). The channel vector between the kth user and the lth AP, hkl 2 CM 1, is a combination of two factors, small-scale fading gkl and large-scale fading

kl:

p

hkl = gkl kl; (1)

where elements of gkl are independent and identically dis-tributed (i.i.d) Complex Normal CN (0; 1) random variables (RVs). We further assume block fading where large-scale fading does not change over multiple coherent time intervals and thus can be easily tracked at the BS, while small-scale fading remains unchanged within one coherence interval [1].

With TDD mode, there are three phases within each coher-ence interval: uplink pilot transmission (or training phase), uplink data transmission, and downlink data transmission. In this paper, we focus on the downlink and do not discuss the uplink data transmission. We assume that time duration of each coherent interval is c, in which p is used for the uplink pilot signals, and the remaining c p is used for downlink data transmission.

**A. UPLINK TRAINING & CHANNEL ESTIMATION**

In the training phase, all users simultaneously transmit their pilot signals to APs to estimate channels. A set of mutually orthogonal pilot sequences is assigned randomly to each user. This set contains K pilot sequences with pilot length p; p K, which is shown as

= [ 1; 2; : : : ; K ]T 2 CK p ;

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| H | i = p; | H | (2) |  |
| i | i j = 0; 8i 6=j: |  |

The training pilot signal received at the lth AP is

K

Yl = ppphkl kH + Nl; (3)

X

k=1

where pp is the pilot power, which is the same for all users. Nl 2 CM p presents Gaussian noise at the lthAP with i.i.d zero-mean and unit-variance elements. To estimate the channel vector from the kth user, the received training signal in (3) is correlated with the kth pilot sequence as

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ykl = Yl k = pp |  | hkl + nkl; | (4) |  |
| pp |  |

where nkl = Nl k is the equivalent noise after being correlated with the kth pilot, and its elements follow complex Gaussian distributions with zero-mean. Finally, the MMSE estimated channel [15] between the kth user and the lth AP is calculated as

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ^ | p |  | kl | |  |  |
| pp | (5) |  |
| hkl = |  | | | ykl; |  |
| ppp kl + 1 | | |  |

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Error between true channel and estimated channel is given as

^

kl = hkl hkl. Both estimated channel and estimated error follow complex Gaussian distribution [10]- [12] as follows.

instead of just connecting user to its largest large-scale fading coefficient AP as in [10].

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  | ^ | | |  |  | CN (0; klIM ); | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  | **A. SPECTRAL EFFICIENCY** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  | hkl | | | | |  |  |  |  |  |  | (6) | The received data signal in (9) can be rewritten as | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |
|  | | | | | | | kl CN (0; ( kl | | | | | | | | | | | | | | | | | | | | kl)IM ); | | | | | | | | | |  | | | | | | | |  | | | | |  | H | | | | |  | | | | | | | | | | | | | | | | | | | |  | | | | |  | | H | | | | |  | | | | | | | | | | | | | | | | | |  |
|  | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | |  |
| where kl | | | = | | |  |  |  |  | pp p kl2 | | | | | | |  |  | follows the property of MMSE | | | | | | | | | | | | | | | | | | | uk = Efppdhklwklgdk + (ppdhklwkl | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | | | ppp kl+1 | | | | | | | | | |  | | | Efp | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | jUlj | | | | | |  | | | | | | p | | |  | | | | | | | | | | | | |  |
| estimator in (5). | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | | | | | hklHwklg)dk + | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  | | | hklHwmldm | | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | pd | | | | |  |  |  |  | X | | | | | | 6 | | | |  |  | pd | | |  |
| m | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | =k | | | | |  | | | | | | | | | | | | |  |
| **B. DOWNLINK DATA TRANSMISSION** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | =1;m | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | |  |
|  | | | | | | | | | | | | L |  | | | | | | jUj j p | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| After the training phase, all APs have all estimated channels | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | + | | |  |  |  |  |  |  |  |  |  |  |  |  |  | hH w d | | | | | | | | |  |  |  | + n | | | | | | |  |  |  |  | : | |  |  |  |  |  |  |  |  |  |  |  |  |  |  | (10) |  |
|  |  |  |  |  |  |  |  |  | p | | | d | | | t | | | k | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| from all users and can start transmitting data. In downlink, | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | kl | | | | | | | tj | |  | | | | | | |  | | | | | | | | | | | | | | | | |  |
| =1;j | | | | | | | | | | =tl=1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| we assume that one user can only connect to one AP, but one | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | j | X6 | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| AP can simultaneously serve multiple users. Ul denotes the | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Using lower bounding technique as in [3], the spectral | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| efficiency of kth user is given as (11), which is shown at the | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| set of users served by the lth AP, and the transmitted signal | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| vector from the lth AP is given as | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  | top of the next page, where | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | |  | | | = | | | | | Ef | | | | | p | | | | |  | | | | | | hH w | | | | | | |  | | ; | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  | | | | | | | | | | | | | | | | | | jUlj | | |  | | | | | | | | | | | | | | | | | | | | | k | | | p | | | d | | |  | |  | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | |  | | | | |  | | | | | | | | kl | | | | | | klg | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Zml | | | | | | | | = ppdhklwml; | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  | s |  |  | = | |  |  |  |  | p | | | |  |  | w d ; | | | |  |  |  |  |  |  | (7) |  |  |  |  | Yk | | | | | = p | | | | | | |  | |  | |  | hH wkl | | | | | | | | | | | | | |  | Ef | | | | | | p | | |  | | | |  | hH wkl | | | | | | | | | | | g | ; |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  | l | |  |  |  |  | p | d |  |  |  |  |  |  |  |  |  |  | pd | | | | |  | pd | | | | |  |  |  |  |  |  |  |
|  | | | | | | | | | | | | |  | | | | | | | | | | | kl k | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | kl | | | | | | | | | | | kl | | | | | | | | | | | | | | | | | | |  | | | | | | |  |
|  | | | | | | | | | | | | | | | | | | k=1 | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | |  | | | | H | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| where dk denotes the transmitted data for the kth user with | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  | Ttj = p | | | | | | | | | | | | | |  | | | | hklHwtj: | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | (12) |  |
|  |  |  |  | pd | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Efjdkj2g = 1; pd denotes the transmit data power, which is | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Using properties in (6), we calculate the closed form of | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| same for all users; jUlj is number of elements in set Ul; and | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| user SE as follows. | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| wkl is the precoding vector. In this paper, we use a simple and | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| general maximum ratio transmission precoding technique, | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | jXkj2 = pd | | | | | | | | | | | | | | Ef(h^kl + kl)h^klg | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | 2 | | = M2pd kl2; | | | | | | | | | | | | | | | | | | | |  | (13) |  |
| which is calculated as | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| ^ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | (8) |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| wkl = hkl: | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Y | 2 | g | | = | Efj | | | | | | | p | | |  | | | | hH h^ | | | | | | | | | | | |  | | 2 | | g jEf | | | | | | | |  | | p | | | |  | | | | | hH h^ | | | | | | klgj | | | | 2 | | |  | |  |
| After APs transmit their corresponding data signal to users, | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | p | |  |  |  |  |  |  | p | | | |  |  |  |  |
| Efj | kj |  |  |  |  |  |  | d | |  |  | kl | | | | | |  |  |  |  | klj | | | |  |  |  |  |  |  |  |  |  |  | d |  |  | kl | |  |  |  |  | kl | | |  |
| be given as | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | = pd Efj klhklj g + Efkhklk | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | g | |  |  |  | M | |  |  |  |  |
| the received signal at the kth user served by the lth AP can | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | H | | | | | ^ | | | | | | | 2 | | | | | | | | | | | | | ^ | | | | | | | | | 4 | | | | | | | | 2 | | | | 2 | |  |
|  |  | u =p | | |  | | | hH w d + | | | | | | | | | | | | |  |  |  |  | jUlj | | |  | p |  | | hH w d | | | | | |  |  |  |  | = pd M kl( kl | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | kl) + (M2 + M) kl2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | M2 kl2 | |  |
|  |  | p | | |  |  |  |  |  |  |  | 6 | p | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | | k |  | | | d | |  | | kl | |  | | kl | |  | | k | m X | | | | | | | | |  | | d |  | kl ml m | | | | |  | | | | = M pd kl kl; | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | (14) |  |
|  | |  | | |  | |  | |  | |  | | | | | | | | | | | |  |  | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| =1;m | | | | | | | | | | | | | | | | | | | | | | | | | | | | | =k | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| L | | | | | | | | | | | | | | | jUj j | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  | | | + | | |  | | | X6 | | | |  | | X | | | | p |  | | | hH wtjdt + nk; | | | | | | | | | | | |  | | (9) |  | | | | | 2 | |  |  |  | | | | | | | | | | | | | | | | | | | | | |  | H ^ | | | | 2 | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  | | |  | | |  | | pd | | |  | |  | | | | |  | | | | | | | | | | | | | | | | | | | | | |  | | | | H | | | ^ | | | |  | | | | 2 | | |  | | | | | | | | | | |  |
| j | | | | | | | | |  | |  | | | | | | kl | | |  | | | | | | | | | | EfjZmlj g | | | | | | | | | | ^ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | g | | |  |  | | | |  | | | | | | | | | | |  |
|  | | | | | | | =1;j | | | | |  | =tl=1 | | | | | |  | | | | | |  | | | | | | | | | | = pd Efjhklhmlj | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | = pd Efj(hkl + kl) hmlj g | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |
| where nk | | | CNH(0; 1) | | | | | | | | | | | | | |  | is additive noise at k | | | | | | | | | | | | | | | | | | th | user. The |  |  |  |  |  |  |  |  |  |  |  |  | ^ | |  |  |  | 2 |  |  |  |
|  |  |  | | | | | | | | | | | | | | | | | | |  | | | | |  | | | | fj | | | | | ^H | | | ^ | | | | | 2 | | g | | |  | | | | | | | | | fj | | H | | | |  | | | g | |  |
| th | |  | p | |  | d | |  |  | kl | |  |  | kl | |  |  | k |  |  |  |  |  | Ul | | |  |  |  |  |  |  |  | H |  |  |  |  |  |  |  |  |  |  |  |  |  |  | = pd | | | | | | | | E | | | | hklhml | | | | | | | j | |  | + E | | | | | | | | | klhml | | | | | | | | j | |  |
| first | | term | | | p | | | | h | | | w | | | | d | | | is | | | the desired | | | | | | | | | | | signal | | | | from the | | | | | | | | | | | |  | | | | |  | | | | |  | | | | | |  | |  | | | |  |
| k user, the second term | | | | | | | | | | | | | | | | | | | | |  | j j | | | | |  | | p | |  | | h |  | wml is intra- | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  | | pd | | kl |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| m=1;t6=k | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | = pd | | | | | | | |  | | | | M ml( kl | | | | | | | | | | | | | |  | | | | | | | kl) + M ml kl | | | | | | | | | | | | | | | | | | | | | | | |  |  |
| AP interference which | | | | | | | | | | | | | | | | | comes from other users connected | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| P | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |
| to the same lth | | | | | | | | | | AP as | | | | | | | | | the kth user, and the | | | | | | | | | | | | | | | | | | third term | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | (15) |  |
| P | L | P | | jUj j ppdhH wtjdt is inter-AP interference from | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  | = M pd ml kl; | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| j=1;j6=l | | | | t=1 | | | | | | |  | | | kl | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| other APs. In the next section, we will propose an algorithm | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| to select an AP for each user in order to mitigate the effect of | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  | 2 | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | H | ^ | | 2 | | g = M pd tj kj: | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  | (16) |  |
| intra-AP interference. | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | | | | | | | | | | | | | | | | | | | | | |  | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | EfjTtjj g | | | | | | | | |  | = pd Efjhklhtjj | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |
| **III. AP SELECTION SCHEME** | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  | Replace (13), (14), (15) and (16) into (11), we have the | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  | closed-form of SE of kth user as | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| In this section, we derive the SE formula of an user and from | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| that we derive a closed-form of that SE. The closed form of | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  | cp | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | M2pd kl2 | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |
| user SE inspires us to propose two proposed metrics and how | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Sk = | |  | log | | | | |  |  | 1 + | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | : |  |
|  | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  |  | | | | | | | |  |  | |  |  | | L | |  | | | | | | | Uj | | | |  | | | | | | | | | | | | | | | | | | | | |  |
| we use them in the proposed algorithm to effectively select | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |  | | | | c | |  | | | | | | | | | | |  | | | |  | | | | | | | | | | | | |  | | | | | | |  | | | | | | | | | | | | | | | | | | | | |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | j=1 | | |  |  |  |  |  | tj=1j M pd tj kj + 1 | | | | | | | | | | | | | | | | | | | | | | | | | |  |
| an AP for every user in the system to improve the sum SE, | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | P | | | | P | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | (17) |  |
| VOLUME 4, 2016 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 3 |  |

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**C. PROPOSED AP SELECTION ALGORITHM**

**In this subsection, we propose an effective channel gain-based algorithm to choose the most suitable AP for each user in a sequential way until all users in the system are connected**

**4**

**From (19), we can see that although large-scale fading co-efficient kl is large, which means the channel quality from kth user to lth AP is good, it might not be proper to assign the kth user to connect to the lth AP. Since the other users, which are already connected to the lth AP prior to the kth user, may also have large tl, and it causes large interference to kth user.**

**t=1;t6=k**

**jUlj**

**X**

**Assume that the kth user is assigned to connect to the lth AP, and lth AP already connected to some others users. Clearly, SE of kth user is interfered by these users. As in the denominator of (17), the interference from other users, who are connected to the same AP as kth user, can be roughly measured by tl kl; t 6=k.**

**Eventually, the effective channel gain from the kth user to the lth AP can be measured by its self-channel quality kl2 minuses summation of other users interference, which also are connected to the same AP as kth user. We propose the effective channel quality metric as**

**k is summation of all kl2 from all kth user to all APs and this can help us to roughly evaluate the channel quality of kth user in the system.**

**2) Effective channel quality metric**

**contains only large-scale fading of the intended kth user. Put aside interference from other users in the denominator of SINR in (17), we can define a metric for each user as self price metric using kl2. This metric is used to measure channel quality from that user to all APs, without caring about other user interference. The metric k of the kth user is measured as**

**L**

**X**

**l=1**

**kl = kl2**

**k =**

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Sk = c p log 1+SINRk c

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| = | c | | p | log | 1+ |  |  | jXkj2 | |  |  |  |  |  |  | ; |  |
|  | c |  |  | mj=1j |  | | j=1;j =l | | | tj=1j | E Ttj 2 |  |  |
|  |  |  | | E Yk 2 + | | ;m =kE Zml 2 | + | + 1 | |  |
|  |  |  |  |  |  | fj j g P | Ul | 6 fj j g | P | L |  | P | Uj | fj j g |  |  |  |
|  |  |  |  |  |  |  |  | 6 |  | (11) | |  |

* 1. **PROPOSED METRICS**

1. Self-price metric

From the closed-form SE in (17), we see that the numerator

2

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| of kth user SINR contains 2 | = | pp p kl2 |  | , which |  |
| ppp kl+1 | |  |
| kl |  |  |  |

kl2: (18)

to its AP. The entire process of AP selection is summarized in Algorithm 1 below.

Algorithm 1 Effective Channel Gain-Based AP Selection Algorithm

Initialize: k = 0; kl = 0 8k = 1; 2; :::; K; l = 1; 2; :::L.

1. Calculate k as in (18) 8k = 1; 2; :::; K
2. Sort k 8k = 1; 2; :::; K in descending order.
3. Calculate the effective channel gain kl of each user in order as determined in step 2 as in (19) 8l = 1; 2; :::L.
4. Choose the AP with highest effective channel gain kl and connect this user to that AP.
5. Keep running the process from step 3 until all users have been assigned an AP.

At the beginning of the selection process, there is no user connected to any AP. Thus, steps 1 and 2 are to sort all users in descending order of total channel gain as in (18) to ensure that users with best channel qualities are connected to AP first.

For each user from the descending list, we calculate the effective channel gain from it to all APs as in (19) and choose the AP with the highest value, as in steps 3 and 4. A scenario where many users are located closely to a specific AP happens frequently, and it is not good if many users are connected to the same AP. Steps 3 and 4 guarantee that each user is connected to the most suitable AP, not just the AP with the highest large scale fading coefficient, or channel gain. As the proposed algorithm keeps going on, effective channel gain of each user is recalculated and changes since the user set Ul of each AP changes after every time steps 3 and 4 are executed.

It is worth noting that Algorithm 1 has low complexity since it uses only sorting, comparison, and simple mathe-

tl kl: (19) matic operations. Moreover, the proposed algorithm is based

on large scale fading, which does not change in many co-herent intervals so we do not have to re-run the algorithm frequently. Algorithms based on heuristic observations have been proposed in many other researches such as pilot assign-ment based on graph coloring algorithm in [5]- [7], or smart pilot assignment algorithm in [14].

**IV. NUMERICAL RESULTS**

In this section, we evaluate the performance of the proposed AP selection scheme using Monte-Carlo simulations with 500 realizations for each figures. In each realization, APs and users are randomly located on a square area. The coherence length is 200 symbols, system bandwidth is 20 MHz, and

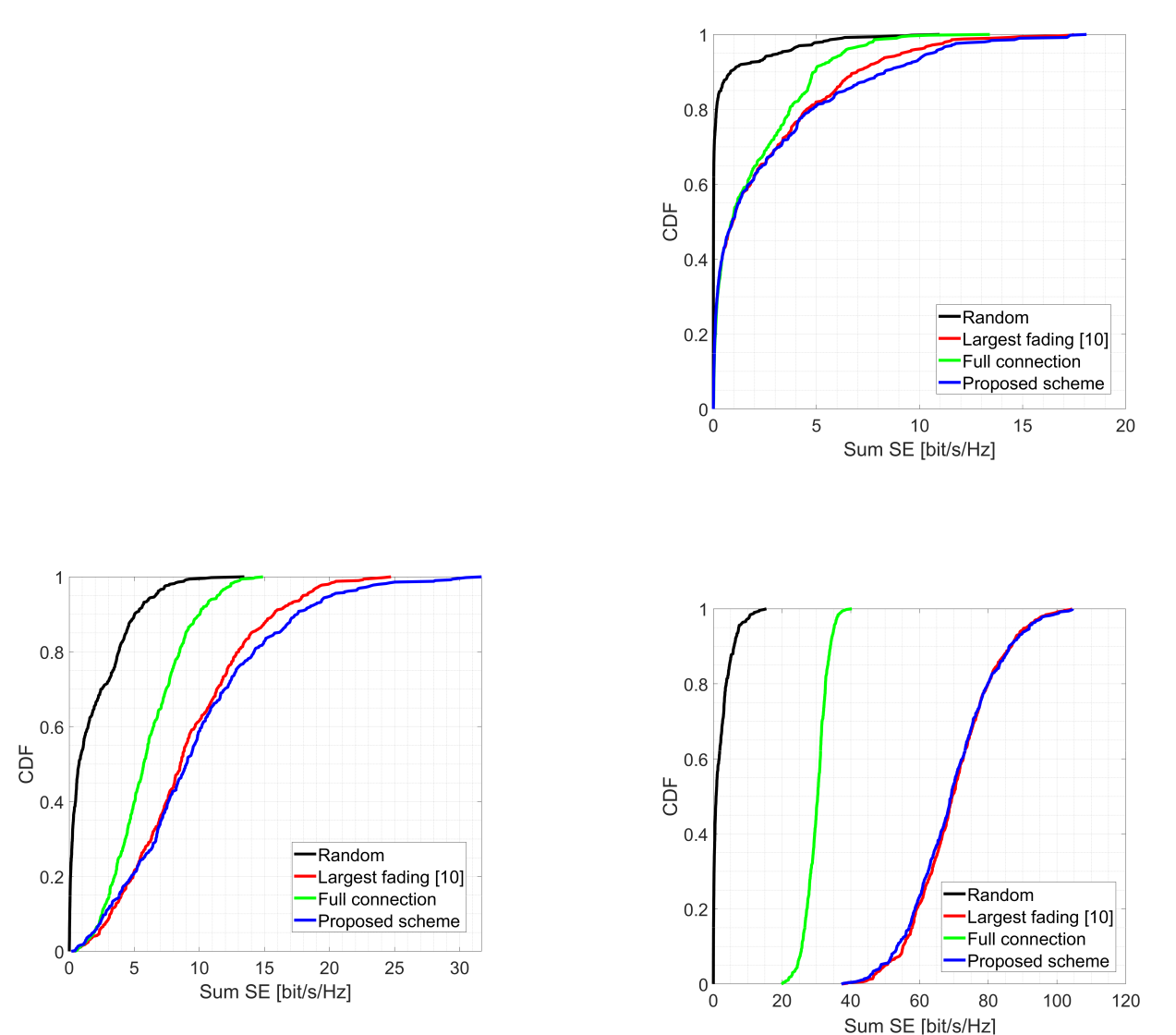
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10.1109/ACCESS.2020.3001270, IEEE Access

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| noise variance is 94 dBm. The large-scale fading coefficient | | | | | In fact, if there is only one AP available, all aforementioned |  |
| is simulated using the 3GPP LTE model [16] | | | |  | schemes are the same and any user-AP connection scheme is |  |
|  | kl = 35:3 | log10(dkl) + zkl; | | (20) | useless. Since this extreme case is truism, it is unnecessary to |  |
|  | investigate further. |  |
| where is the path-loss exponent, and 35:3 | | | | denotes the |  |
|  |  |
| average channel gain at 1m reference distance. dkl is the | | | | |  |  |
| distance from the kth user to the lth AP, and zkl is the shadow | | | | |  |  |
| fading that follows a log-normal distribution with a standard | | | | |  |  |
| deviation of 5 dB. Pilot power pp and data power pd are | | | | |  |  |
| 200mW and are the same for all users. | | |  |  |  |  |
| All system parameters are summarized in Table I below. | | | | |  |  |
| **TABLE 1.** System parameters | |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  | Area |  | 1 km2 |  |  |  |
|  | Number of APs L | | 5, 10, 20 |  |  |  |
|  |  | |  |  |  |  |
|  | Number of users K | | 10,20,30 |  |  |  |
|  |  | |  |  |  |  |
|  | Number of AP antennas M | | 100 |  |  |  |
|  |  | |  |  |  |  |
|  | Path loss | | 3.76 |  |  |  |
|  |  | |  |  |  |  |
|  | Bandwidth | | 20MHz |  |  |  |
|  |  | |  |  |  |  |
|  | log normal standard deviation | | 5dB |  |  |  |
|  |  | |  |  |  |  |
|  | Pilot and data power pp; pd | | 200mW |  |  |  |
|  |  |  |  |  | **FIGURE 3. CDF of the sum rate of system with** L= 10; K= 20 |  |



**FIGURE 2. CDF of the sum rate of system with** L= 5; K= 20

**FIGURE 4. CDF of the sum rate of system with** L= 20; K= 30

Our proposed algorithm is compared to three other refer-ence schemes:

Random Selection: each user is randomly connected to one AP. Since there is a chance that some AP will not serve any users, in simulation, we make sure that each AP serves at least one user to be fair in comparison. This scheme is marked as "Random" in figures.

AP selection based on largest fading in [10]: In this scheme, an user is connected to an AP to which this user has the highest large scale fading coefficient. This scheme is marked as "Largest fading [10]" in figures.

Full connection scheme: AP selection in which one user is connected to all APs. This scheme is marked as "Full connection" in figures.

Fig. 2 shows the cumulative distribution function (CDF) of the system’s sum rate with the four aforementioned schemes where L = 5; K = 20. In fig. 1, the proposed algorithm outperforms the others, at nearly 2.5 bit/s/Hz higher than the scheme in [10] at a probability of 0.9. The improvement in our proposed scheme comes from the fact that the largest large-scale fading based scheme only connects an user to its highest largest-scale fading AP, while our proposed scheme smartly chooses a suitable AP instead of the highest large scale fading AP if this AP already connects to too many users prior to the current user. Interestingly, the full connection scheme does not work well in this situation since number of users is 4 times larger than number of APs. This causes

|  |  |
| --- | --- |
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a high intra-AP interference for each user since many users have to be connected to the same AP. Random scheme shows the worst performance since users are randomly connected to APs.

Fig. 3 shows the simulation results when L = 10, and number of users is two times larger than number of APs. In this case, the proposed scheme still outperforms the others, but the gain becomes smaller. Since users have more APs to choose from for connection, the number of users connected to the same AP decreases. Therefore, the scheme in [10] performs better than in the previous situation and produces results closer to those of the proposed scheme.

The simulation results when number of users is only 1.5 times higher than number of APs with L = 20; K = 30 are shown in fig. 4. Obviously, the proposed algorithm performs similarly to the scheme in [10]. In conclusion, our proposed scheme performs very well in a scenario where the ratio of number of users to number of APs is high.

**V. CONCLUSION**

In cell-free massive MIMO research, full connection is com-monly assumed between users and APs. Another common assumption is connection of an user to its highest large-scale fading AP. However, both these schemes cannot have good performance when the number of APs are much fewer than the number of users. Motivated by that, in this paper, we propose two metrics to measure the channel quality of users and the effective channel gain between users and APs. After that, we propose an effective channel gain-based algorithm to smartly select AP for each user to be connected in a cell-free massive MIMO system using these metrics. Compared to existing schemes, our proposed algorithm offers better performance when the ratio of number of users to number of APs is high. Practically, our proposed scheme should be applied to cell-free massive MIMO system which is deployed in crowed area where the number of user is much higher than number of APs.

**REFERENCES**

1. T. L. Maezetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas,” IEEE Trans. Wireless Commun., vol. 9, no. 11, pp. 3590–3600, Nov. 2010.
2. L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, “An overivew of massive MIMO: Benefits and challenges,” IEEE J. Sel. Top. Signal Process., vol. 8, no. 5, pp. 742–758, Oct. 2014.
3. E. Bjornson, J. Hoydis, and L. Sanguinetti, Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency. NOW Publisher, 2017.
4. X. Zhu, L. Dai, and Z. Wang, and X. Wang, “Soft pilot reuse and multicell block diagonalization precoding for massive MIMO systems,” IEEE Trans. Veh. Technol., vol. 65, no. 5, pp. 3285–3298, May 2016.
5. X. Zhu, L. Dai, Z. Wang, and X. Wang, “Weighted-graph-coloring-based pilot decontamination for multicell massive MIMO systems,” IEEE Trans. Veh. Technol., vol. 66, no. 3, pp. 2829–2834, Mar. 2017.
6. Z. Wang, P. Zhao, C. Qian et al., “Location-aware channel estimation enhanced TDD based massive MIMO,” IEEE Access, vol. 4, pp. 7828–7840, Nov. 2016.
7. H. T. Dao and S. Kim, “Vertex graph-coloring-based pilot assignment with location-based channel estimation for massive MIMO systems,” IEEE Access, vol. 6, pp. 4599–4607, Jan. 2018.

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1. H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta,“Cell-free massive MIMO versus small cells,” IEEE Trans. Wireless Commun., vol. 16, no. 3, pp. 1834–1850, Mar. 2017.
2. S. Buzzi and C. D. Andrea, “Cell-free massive MIMO: User-centric ap-proach,” IEEE Wireless Commun. Lett., vol. 6, no. 6, pp. 706–709, Dec. 2017.
3. H. Q. Ngo, A. L. N. Tran, T. Q. Duong, M. Mathaiou, and E. G. Larsson,“On the Total Energy Efficiency of Cell-Free Massive MIMO,” IEEE Trans. Green Commun. Netw., vol. 2, no. 1, pp. 25–39, Mar. 2018.
4. T. C. Mai, M. Egan, and T. Q. Duong,“Pilot Power Control for Cell-Free Massive MIMO,” IEEE Trans. Veh. Technol., vol. 67, no. 11, pp. 11264– 11268, Nov. 2018.
5. G. Dong, H. Zhang, S. Jin, and D. Yuan,“Energy-Efficiency-Oriented Joint User Association and Power Allocation in Distributed Massive MIMO Systems,” IEEE Trans. Veh. Technol., vol. 68, no.6, pp. 5794–5808, Jun. 2019.
6. Z. Gao, L. Dai, D. Mi, Z. Wang, M. A. Imran, and M. Z. Shakir, “Mmwave massive-MIMO-based wireless backhaul for the 5G ultra-dense network,” IEEE Wireless Commun., vol. 22, no. 5, pp. 13–21, Oct. 2015.
7. X. Zhu, Z. Wang, L. Dai, and C. Qian, “Smart pilot assignment for massive MIMO,” IEEE Commun. Lett., vol. 19, no. 9, pp. 1644–1647, Sept. 2015.
8. S. M. Kay, Fundamentals of Statistical Signal Processing: Estimation Theory, Upper Saddle River, NJ, USA: Prentice-Hall, 1993.
9. Further advancements for E-UTRA physical layer aspects (Release 9), 3GPP TS 36.814, 2010.



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