



# Coordinated Beamforming Optimization with Interference Suppressing for Massive MIMO Systems

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**Abstract.** To meet the growing demand for high-data rate applications, massive multiple-input multiple-output (MIMO) has been identified to provide better coverage and throughput. Note that the energy efficiency and throughput of massive MIMO system is sensitive to pilot reuse factor, number of antennas and inter-cell interference, which should be accounted when designing a system. In this paper, dynamic division of area coordinated beamforming (DDA-CoBF) algorithm is proposed by suppressing inter-cell interference. Meanwhile, pilot reuse factor, number of antennas and channel state information are investigated for obtaining the optimal energy efficiency and throughput for massive MIMO system. Considering the actual application, we also especially analyze the systems based on imperfect CSI, proving the strong robustness for the proposed DDA-CoBF algorithm. Numerical analysis and simulation indicate that the proposed DDA-CoBF algorithm satisfies the higher energy efficiency and throughput. Moreover, this work provides a potential design scheme for large-scale MIMO multicell systems.

**Keywords:** Coordinated beamforming · Energy efficiency · Imperfect CSI · Interference suppression · Massive MIMO · Throughput

## 1 Introduction

With exponentially growing of mobile-data demand, the capacity of wireless communication networks must be increased, so that it can ensure the quality-of-service (QoS) requirements of the mobile applications [1]. In order to satisfy the various applications of 5G wireless communication systems, massive multiple-input multiple-output (MIMO) has been recognized as a promising technology

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for increasing network capacity and achieving extremely high spectral efficiency [2]. Many antennas can obtain spatial diversity and multiplexing which can be used to improve performance of wireless communication system. Nevertheless, one of the major drawbacks for adopting large-scale antennas is the associated complexity of using a separate RF chain for each antenna, which also results in a significant increase in energy consumption [3]. Therefore, the critical problem and goal is to design the higher energy efficiency (EE) schemes for massive MIMO systems. Whether large-scale system can outperform systems with fewer antennas in terms of EE is a worthwhile and significant research [4].

Coordinated multiple points is a key technology in Long Term Evolution Advanced (LTE-A), which not only can break the limitation of the SE of single-point transmission, but also can reduce inter-cell interference and improve throughput of the cell edge and whole system [5]. Coordinated beamforming (CoBF) is more effective because of only sharing CSI, especially in massive MIMO system [6]. BS allocates resource blocks according to the CSI of the user location and neighboring cells to avoid the interference. Therefore, CoBF can improve the QoS at the inner and outer edges of the cell [7].

Recently, the EE analysis of massive MIMO systems has been well researched. CoBF is more effective and plays an important role in improving EE especially in massive MIMO system. In [8], aiming at optimize EE for the multi-cell massive MIMO system, the authors provided explicit formulas for the optimal number of antennas for BS with conjugate beamforming. In [9], a dual-layer CoBF scheme was proposed to maximize the EE in a multi-cell massive MIMO system while meeting QoS requirements. In [10], a resource allocation scheme was proposed for wireless power transfer in the case of multi-user massive MIMO system with imperfect CSI. In [11], an efficient algorithm for maximizing the ratio between the system-weighted sum rate and the total power consumption was proposed, considering utility function is constrained by QoS and power of each BS. In [12], an CoBF design was proposed as a cascade of the low-complexity analog beam selection mechanism and a robust digital design. In [13], a beamforming scheme was proposed to minimize the transmission power for a large-scale MIMO channel. In [14], a low-complexity power allocation for beamforming and maximizing the EE of massive MIMO system was developed while guaranteeing the requirement of information transmission quality. Many existing CoBF researching focus on minimizing the transmit power, ignoring the static circuit power consumption to improve EE. The total power consumption is assumed to be the radiation transmission power with a constant or neglected circuit power consumption. This model might be very misleading with many RF chains in which circuit power is comparable to the transmit power.

Therefore, in the actual deployment, the circuit power consumption needs to be considered comprehensively, especially massive MIMO system. Moreover, some beamforming for optimal EE was studied in massive MIMO system under the condition fixed cooperative division of areas [15]. In [16], a new full-pilot zero-forcing (ZF) scheme that actively suppresses inter-cell interference in a fully distributed coordinated beamforming was proposed in which partially suppresses strong interference from neighbor cells.

Differing from existing research, we propose dynamic division of area coordinated beamforming (DDA-CoBF) algorithm in which more degrees is adopted to suppress the interference either at all edge users (UEs) in the neighboring cells or UEs close to the BS coverage area. Furthermore, to improve the system EE and throughput, this paper comprehensively considers the influence of the pilot reuse factor, optimal number of antennas and CSI, which are useful insights on the whole optimal system design.

The main contributions are summarized below.

- Suppress interference and improve the EE are explored with considering the neighboring UEs at the cell edge. Exploring the more degrees to serve UEs with a few spatial dimensions to suppress interference.
- DDA-CoBF algorithm are proposed, and the best division of cooperative areas are obtained.
- Simulation results show that the proposed DDA-CoBF algorithm are superior to some existing CoBF. The performance comparisons are used considering the pilot reuse factor number of antenna and imperfect CSI accounting for the power amplifier power and circuit power.

## 2 System Description

### 2.1 System Model

We consider the downlink of a massive MIMO system. BS is equipped with  $M$  antennas, serving  $K$  ( $K \leq M$ ) single antenna users. Rayleigh small-scale fading and time-division duplexing (TDD) are considered in this work. Therefore, the channels are static within time-frequency coherence blocks of  $U = BT$  symbols, where  $B$  is the coherence bandwidth and  $T$  is the coherence time. A square coverage model is used to facilitate the calculation of interference in this paper, but our proposed algorithm is also applicable to cellular hexagons.

For the sake of ensuring the quality of data transmission and the fairness of the service, we adopted the power distribution to force all users to have the same rate  $R$  in a single-layer homogeneous network. User  $k$  in the cell where BS  $i$  is located can be denoted by  $U_{i,k}^{In} \in \mathbb{R}^2$ . The  $j$  neighbor user of the neighbor cell outside the cell is defined as  $U_{i,j}^{Out} \in \mathbb{R}^2$ . The set of UE physical locations associated with BS  $i$  is denoted by  $U_i \in \mathbb{R}^2$ . It is assumed that the distribution of the UEs in the cell obeys the homogeneous Poisson point process. Since users are deployed through a round-robin [17], the distribution can be distributed randomly with the distribution  $f(x)$ , which determines the distribution shape and density of the user, where  $x$  represents the distance BS to user.

It is assumed that the cell is affected by the interference of 24 external cells and only non-line-of-sight (NLOS) propagation will be considered in the multi-cell model [17]. When a cooperative area is adopted with pilot reuse factor  $F = 1$ . The interference calculation formula is given by

$$I_{jik} = \sum_{j=1, j \neq i}^{24} \frac{\sum_{s=1}^K p_{js} |x_{jik}^H w_{js}|^2}{r_{jik} \|w_{js}\|^2} \quad (1)$$

where  $r_{jik}$  and  $x_{jik}$  is the path loss and small-scale fading vector from BS  $j$  to UE  $k$  in cell  $i$ .  $p_{js} \geq 0$  is the transmission power from BS  $j$  to UE  $s$ . According to (1), we can obtain the interferences from the different color cells are 0.0540, 0.0202, 0.0043, 0.0028, 0.0011. Therefore, 24 neighboring cells is selected because the interference of other further cells is very small and can be ignored.

Since only NLOS propagation is considered, so the closest distance between the UE and the BS is defined as  $d_{\min}^U = 35m$  in a cell.

The BS obtains the CSI of a cooperative user through the training phase, reduces the interference of the local cell to the cooperative user by sacrificing spatial freedom, and improves the rate of the cooperative user. In TDD system, it is assumed that the BS obtains CSI through uplink transmission. Moreover, the user must periodically send relevant information to the BS because of the handover.

## 2.2 Channel Model

It is assumed that the antennas widely separated to avoid mutual coupling when the BS communicates with the user. In this network, we assume that the channels on Rayleigh fading considering the path loss, which is suitable for both large and small arrays. In the single cell, channel vector is defined as  $h_k = [h_{k1}, h_{k2}, \dots, h_{kM}]^T \in C^{M \times 1}$ , where  $\{h_{km}\}$  represents the instantaneous propagation channel between the  $m$ -th antenna and  $k$ -th UE. The channel matrix  $H$  is expressed as  $H = [h_1, h_2, \dots, h_K]$ . Extended to multiple cells, channel vector is defined as  $h_{ijk} = [h_{ijk}^1, h_{ijk}^2, \dots, h_{ijk}^M]^T$ , where  $\{h_{ijk}^m\}$  represents the instantaneous propagation between the  $m$ -th antenna of BS  $i$  and the  $k$ -th user in cell  $j$ . Then, the channel matrix  $H_i$  from BS  $i$  and the related  $K$  UEs can be expressed as

$$H_i = R_i X_i \quad (2)$$

$$X_i = [x_{ii1}, x_{ii2}, \dots, x_{iiK}]^H \quad (3)$$

where  $x_{iik} \sim \mathcal{CN}(0_M, I_M)$  is the small-scale fading vector between the  $i$ -th BS and the  $k$ -th UE in  $i$ -th cell.  $R_i = \text{diag}\{r_{ii1}, r_{ii2}, \dots, r_{iiK}\}$  is the channel fading matrix,  $r_{iik}$  is the path loss from BS  $i$  to the UE  $k$  in cell  $i$ , which is given by

$$r_{iik} = r_{\min} d_{iik}^{-\alpha} \quad (4)$$

where  $d_{iik}$  is the distance from BS  $i$  to the UE  $k$  in cell  $i$ ,  $\alpha$  is the path loss exponent, and  $r_{\min} > 0$  is the channel attenuation at  $d_{\min}^U = 35m$ .

On account of the distance between the UE and the BS is much greater than that between the antennas, the large-scale fading between the antennas of the same user and the BS are assumed to be the same. Because of the system capacity is interference limited for massive MIMO networks [12], the effects of thermal noise are ignored in this paper.

### 2.3 Channel Estimation and Pilot Reuse

Exploiting channel reciprocity, the BS forms an estimate of the channel between the antennas and the UEs in the uplink, and then the BS transmits data to the UE in the downlink. Accurate CSI is necessary to compensate channel-fading during power allocation. CSI can be obtained from the uplink pilot transmission of each time-frequency coherent block. Based on TDD reciprocity, we can obtain the downlink CSI. Meanwhile, the CSI of extended cooperative users outside the cell can be achieved from the training because some resource blocks will be used for pilot transmission training [18].

As the number of users continue to increase, frequency resources increase sharply, and the allocation of pilots also has the problem of shortage. Therefore, it is necessary to divide the cells into multiple sets. The same pilot is used in the cells. The pilot contamination must be further suppressed in massive MIMO systems, so some researchers have proposed pilot-reuse schemes. The most vulnerable users avoid pilot interference by making pilots of neighboring cells orthogonal to each other.

In this paper, we divide 24 neighbor cells into multiple sets, and the number of sets is pilot reuse factor  $F$ . According to the above definition  $U = BT$ , the transmission bandwidth  $B = 180$  kHz and the coherence time is  $T = 10$  ms in the TDD protocol [16].

According to the TDD protocol

$$U = (\tau^{ul} + \tau^{dl})K + (L^{ul} + L^{dl}) \quad (5)$$

where  $\tau^{ul} \geq 1$ ,  $\tau^{dl} \geq 1$  are the respective lengths of the uplink and downlink pilots, to ensure that all users can obtain an orthogonal pilot.  $L^{ul}$  and  $L^{dl}$  are respectively the uplink and downlink data transmission [19].

The more pilots, the less data transmission. Therefore, it is necessary to select an appropriate pilot reuse factor. When the pilot reuse factor is set to  $F = 4$  ( $\tau^{ul} = \tau^{dl} = 4$ ), then 24 neighbor cells are divided into four sets, and the BS of each cell serves more than 100 users simultaneously.

In this paper, the estimated small-scale fading  $\hat{x}_{iik}$  between BS  $i$  and UE  $k$  in cell  $i$  is defined as

$$\hat{x}_{iik} = \sqrt{1 - \beta_{iik}^2} x_{iik} + \beta_{iik} n_{iik} \quad (6)$$

where  $n_{iik} \sim \mathcal{CN}(0_M, I_M)$  is the independent normalized estimation noise, and  $\beta_{iik}^2 \in [0, 1]$  is the error variance, which represents the accuracy of the estimated fading channel  $\hat{x}_{iik}$ , that is,  $\beta_{iik}^2 = 0$  corresponds to ideal CSI, while  $\beta_{iik}^2 = 1$  corresponds to no CSI. By using MMSE estimation, CSI error variance of UE can be written as

$$\beta_{iik}^2 = 1 - \frac{r_{iik}}{\sum_{l \in \Phi} r_{ilk}} \quad (7)$$

where  $\Phi$  represents the set of BSs using the same pilot as UE  $k$  in cell  $i$ . Therefore, the estimated channel matrix at BS  $i$  can be written as

$$\hat{H}_i = R_i \hat{X}_i \quad (8)$$

### 3 Energy Efficiency Optimization

#### 3.1 Cell Association and Cooperative Scheme

In [15], each BS does not suppress the interference of neighboring UEs close to the coverage area. Instead, we specifically target the UEs on the cell edge, which is vulnerable for the neighbor BS. We propose cooperative area division algorithm. The user of a non-local cell in the cooperative range is defined as an extended cooperative user. The extended cooperative users are most vulnerable to interference from the local cell, which are neighbor users outside the cell.

For the proposed DDA-CoBF algorithm, the density function of the distribution can be expressed as

$$f_s(x) = \begin{cases} \frac{1}{4(d_s^2 - d_{\min}^2)}, & d_s \geq x \geq d_{\min} \\ 0, & otherwise \end{cases} \tag{9}$$

where  $d_{\min}$  and  $d_s$  are the nearest distance from the BS to the edge of the cell and from the BS to the edge of the cooperative area.  $x$  represents distance between BS to user.

#### 3.2 Traditional ZF Precoding

In traditional ZF precoding, all spatial degrees of freedom are used for multiplexing. The estimated channel matrix can be written as

$$\hat{H}_i = [\hat{h}_{ii1}, \hat{h}_{ii2}, \dots, \hat{h}_{iiK}] \tag{10}$$

where  $\hat{h}_{iik}$  is the estimated channel vector between the  $i$ -th BS and the  $k$ -th UE in the cell.

The precoding vector with the  $i$ -th BS for user  $k$  is defined as

$$w_{ik} = (\hat{H}_i^H \hat{H}_i)^{-1} \hat{h}_{iik} \tag{11}$$

Then, the signal  $V_{ik}$  of receiver  $k$  in cell  $i$  is given by

$$V_{ik} = p_{ik} h_{iik}^H w_{ik} + \sum_{s=1, s \neq k}^K p_{is} h_{iik}^H w_{is} + \sum_{j=1, j \neq i}^{24} \sum_{s=1}^K p_{js} h_{jik}^H w_{js} \tag{12}$$

where  $p_{ik} \geq 0$  is the downlink transmission power of the  $i$ -th BS to the  $k$ -th user, and downlink power amplifier (PA) (watts) is defined as the consumption of the PA at the BS.  $h_{iik}$  is defined as the channel matrix between BS  $i$  and the  $k$ -th UE in cell  $i$ . The first item in (12) is the data transmission signal from BS  $i$  to user  $k$ . The second item of  $V_{ik}$  is the signal received by user  $k$  when BS  $i$  transmits to other users in the cell. The third item is the transmission information of the

other 24 neighbor cells received by user  $k$ . Then, the transmission rate of user  $k$  in cell  $i$  is given by

$$R_{ik} = B \log \left( 1 + \frac{p_{ik} \frac{|h_{ik}^H w_{ik}|^2}{\|w_{ik}\|^2}}{\sum_{s=1, s \neq k}^K p_{is} \frac{|h_{is}^H w_{is}|^2}{\|w_{is}\|^2} + I_{jik} + \sigma^2} \right) \quad (13)$$

where  $\sigma^2$  is the noise variance and  $I_{jik}$  is the interference of user  $k$  from cell  $j$  to cell  $i$  in Eq. (1).

### 3.3 Proposed DDA-CoBF

All spatial degrees of freedom are used for user multiplexing in traditional ZF precoding. However, some spatial freedom is used to suppress the interference of cell-edge users in the proposed DDA-CoBF, under which the BS increases the transmission power so that users in the cell cause less interference to neighboring-cell users. Inter-cell interference can be effectively suppressed, and the total EE and throughput of the network are significantly improved with DDA-CoBF algorithm.

Then, the precoding vector between BS  $i$  to the user  $k$  in cell  $i$  is defined as

$$\hat{w}_{ik} = \left( \sum_{l=1}^K \hat{h}_{iil} \hat{h}_{iil}^H + \sum_{\bar{l}=1}^N \hat{h}_{i\bar{l}\bar{l}} \hat{h}_{i\bar{l}\bar{l}}^H \right)^{-1} \hat{h}_{iik} \quad (14)$$

where  $\hat{h}_{iil}$  is the estimated channel matrix between the  $i$ -th BS and the  $l$ -th UE in cell  $i$ ,  $\hat{h}_{i\bar{l}\bar{l}}$  is the estimated channel matrix between the  $i$ -th BS and the  $\bar{l}$ -th neighbor UE outside the cell,  $\bar{l}$  indicates that a user is outside the cell where BS  $j$  is located.  $\hat{h}_{iik}$  is the estimated channel matrix between the  $i$ -th BS and the  $k$ -th UE in cell  $i$ ,  $N$  is the number of users lying in the cooperative area. These users are most vulnerable to interference outside the cell, and they cause the most serious interference to users in the cell. Therefore, the influence of users in the cell of BS  $i$  on the users of other cells can be effectively suppressed after the edge user information is added. After adding an extended cooperative CSI in the precoding vector, the extended cooperative user sets the data in cell  $i$  into zero space to improve the SINR of the extended cooperative users. Meanwhile, BS  $i$  does not transmit data to these extended cooperative users.

Compared with the traditional precoding, the signal  $\hat{V}_{ik}$  at the receiver for user  $k$  in cell  $i$  with the DDA-CoBF algorithm can be written as

$$\begin{aligned} \hat{V}_{ik} &= p_{ik} h_{iik}^H \hat{w}_{ik} + \sum_{s=1, s \neq k}^K p_{is} h_{iik}^H \hat{w}_{is} \\ &+ \sum_{j=1, j \neq i}^{24} \sum_{s=1}^K p_{js} h_{jik}^H \hat{w}_{js} \end{aligned} \quad (15)$$

The transmission rate of user  $k$  is given by

$$\hat{R}_{ik} = B \log \left( 1 + \frac{p_{ik} \frac{|h_{iik}^H \hat{w}_{ik}|^2}{\|\hat{w}_{ik}\|^2}}{\sum_{s=1, s \neq k}^K p_{is} \frac{|h_{is}^H \hat{w}_{is}|^2}{\|\hat{w}_{is}\|^2} + \hat{I}_{jik} + \sigma^2} \right) \quad (16)$$

where  $\hat{R}_{ik}$  is the rate of user  $k$  in the cell  $i$ ,  $\hat{I}_{jik}$  is the inter-cell interference and can be written as

$$\hat{I}_{jik} = \sum_{j=1, j \neq i}^{24} \frac{\sum_{s=1}^K p_{js} |x_{jik}^H \hat{w}_{js}|^2}{r_{jik} \|\hat{w}_{js}\|^2} \quad (17)$$

If the  $k$ -th user in cell  $j$  is an extended cooperative user of other cells, then the  $k$ -th user sets the data transmission information of the other cells in a null space at the downlink data receiving. Since the calculation of inter-cell interference is too complicated in a massive MIMO multi-cell system, we treat CSI error as noise during SINR calculation. Then, the transmission rate [19] can be rewritten as

$$\hat{R}_{ik} = B \log \left( 1 + \frac{\rho^2 K \tau (M - K)}{1 + \rho K + \rho K \tau} \right) \quad (18)$$

where  $\tau$  is the uplink pilot of user  $k$ ,  $M$  is the number of antennas of the cell, and  $K$  is the number of UEs in cell  $j$ .  $\rho \geq 0$  is proportional to SINR. Then, SINR [20] can be expressed as

$$SINR = \rho (M - K) \quad (19)$$

### 3.4 Energy Efficiency and Throughput Analysis

In this section, we analyze the downlink data rates and the EE of a massive MIMO system. The power consumption model at the BS in each channel can be expressed as

$$P_{BS} = P_{TX}^{(dl)} + P_{CP} \quad (20)$$

where  $P_{TX}^{(dl)}$  is the power consumed by the power PAs, and  $P_{CP}$  is the circuit power. Then,

$$P_{BS} = P_{TX}^{(dl)} + P_{FIX} + P_{TC} + P_{CE} + P_{C/D} + P_{BH} + P_{LP} \quad (21)$$

where  $P_{FIX}$  is constant accounting for the fixed power consumption required for site-cooling, control signaling, and load-independent power of backhaul infrastructure and baseband processors.  $P_{TC}$ ,  $P_{CE}$ ,  $P_{C/D}$ ,  $P_{BH}$  and  $P_{LP}$  are power consumption of transceiver chains, channel estimation, coding and decoding, backhaul, and linear processing, respectively. Taking every part of the circuit power consumption into consideration, we can finally get

$$P_{CP} = a + bM + c \log(1 + \rho(M - 1)) \quad (22)$$

where  $a$ ,  $b$ ,  $c$  are constants,

$$a = 2P_{syn} + P_{lna} + P_{mix} + P_{ifa} + P_{filr} + P_{adc} \quad (23)$$

$$b = P_{dac} + P_{mix} + P_{filt} \quad (24)$$

$$c = P_{cod} + P_{dec} + P_{bt} \quad (25)$$

where  $P_{syn}$ ,  $P_{lna}$ ,  $P_{ifa}$ ,  $P_{filr}$ ,  $P_{adc}$ ,  $P_{dac}$ ,  $P_{mix}$ ,  $P_{filt}$ ,  $P_{cod}$ ,  $P_{dec}$ ,  $P_{bt}$  are the power consumption values for the frequency synthesizer, the low-noise amplifier, the intermediate frequency amplifier, the active filters at the receiver side, the ADC, the DAC, the mixer, the active filters at the transmitter side, coding, decoding, and backhaul traffic, respectively. Then, EE can be written as

$$EE = \frac{\sum_{k=1}^K R_k^{dl}}{P_{TX}^{dl} + P_{CP}} \quad (26)$$

where  $R_k^{dl}$  is the downlink users rate.

Most of the literature define  $P_{CP} = P_{FIX}$ . However, the system model with constant circuit power is not accurate. The more antennas, the higher the user rate and system EE for fixed PA power. Then we consider a more complete circuit power model to solve the problem, and obtain the best antenna deployment for massive MIMO systems.

Throughput is also an important measure of system performance in massive MIMO multi-cell systems. In this paper, the throughput is defined as

$$R_t = \frac{\sum_{k=1}^K R_k^{dl}}{4d_{\min}^2} \quad (27)$$

where  $d_{\min}$  is the closest distance from the BS to the edge of the cooperative area.

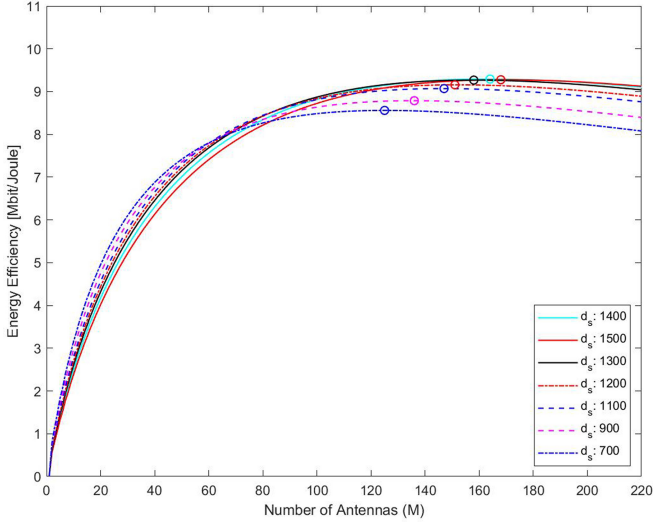
The parameters involved in Eq. (21) are given in Table 1.

**Table 1.** Key parameters.

Parameter	Value
The power dissipation from a DAC: $P_{DAC}$	15.6 mW
The power dissipation from a transmission filter: $P_{FIT}$	20 mW
The power dissipation from a mixer: $P_{MIX}$	30.3 mW
The power dissipation from the frequency synthesizer: $P_{syn}$	50 mW
Power required for the active filters at the transmitter side: $P_{filt}$	2.5 mW
Power required for the active filters at the receiver side: $P_{filr}$	2.5 mW
Power required for backhaul traffic: $P_{bt}$	0.25 W/(Gbit/s)
Power required for decoding: $P_{dec}$	0.8 W/(Gbit/s)
Power required for coding: $P_{cod}$	0.1 W/(Gbit/s)

## 4 Numerical Results and Discussion

This section presents numerical simulations to verify the accuracy of our analysis of the proposed DDA-CoBF algorithm. First, the performance of the DDA-CoBF algorithm and the traditional algorithm are simulated and compared.

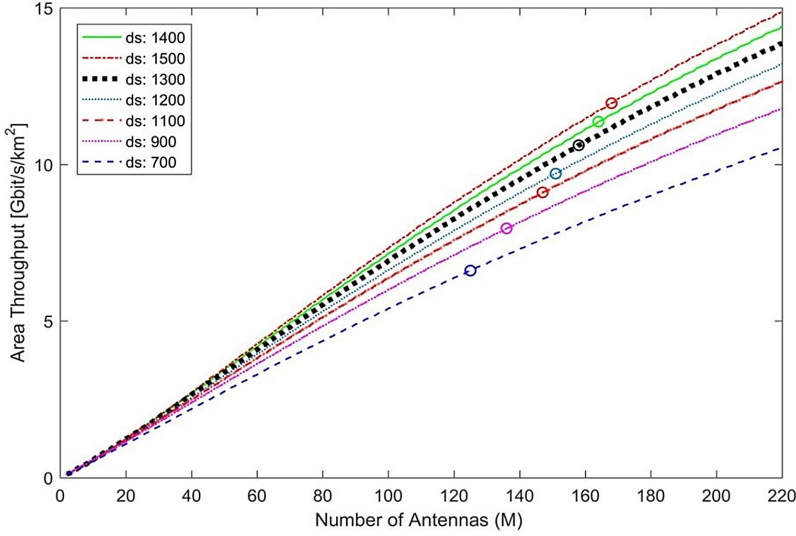


**Fig. 1.** Energy efficiency for different numbers of BS antennas and different cooperative areas.

Afterwards, the proposed DDA-CoBF algorithm based on cooperative areas is studied respectively. Meanwhile, the respective cooperative area division algorithm for the best EE and throughput are obtained, and the algorithm are compared and discussed. Finally, we analyze the robustness of the DDA-CoBF algorithm, considering the impact of CSI error and pilot reuse factor.

This paper assumes that the number of antennas  $M$ , the number of users  $K$ , and the rate  $R$  in each cell are the same. At the same time, the cell shape and signal propagation conditions are also the same according to the principle of symmetry, which means that the interference in the uplink and downlink is consistent. Suppose that each cell is a cell coverage of  $5 \times 10^2 \times 5 \times 10^2$  m<sup>2</sup>, the neighbors are the surrounding 24 cells, pilot reuse factor  $F = 4$ . In this system, under the condition of satisfying  $M > K$ , antenna arrays ( $M = 220$ ) are deployed at the BS.

Figure 1 shows the EE comparison with different cooperative areas for the DDA-CoBF algorithm. We can see that the EE only slightly increases after the side length of the cooperative area exceeds 1100 m, which reaches the optimum when the side length is 1400 m. The EE does not increase in proportion to the length of the cooperative area, due to the non-uniform user deployment and hardware circuit power limitations. In Fig. 1, the optimal EE of DDA-CoBF algorithm with the longer edge of the cooperative area is relatively low, and not as high as 1400 m, since the inter-cell interference is relatively small when the number of antennas and users are low, the power consumption at the BS is greater than the user gain.

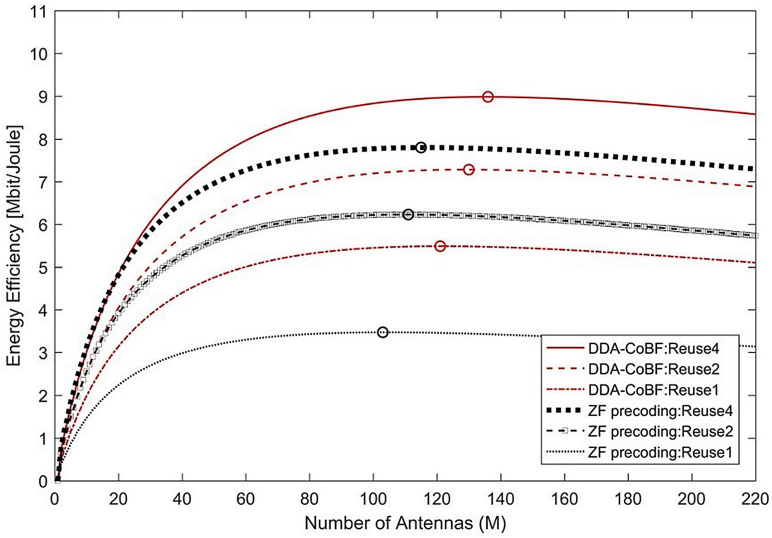


**Fig. 2.** Area throughput for different numbers of BS antennas with different cooperative areas.

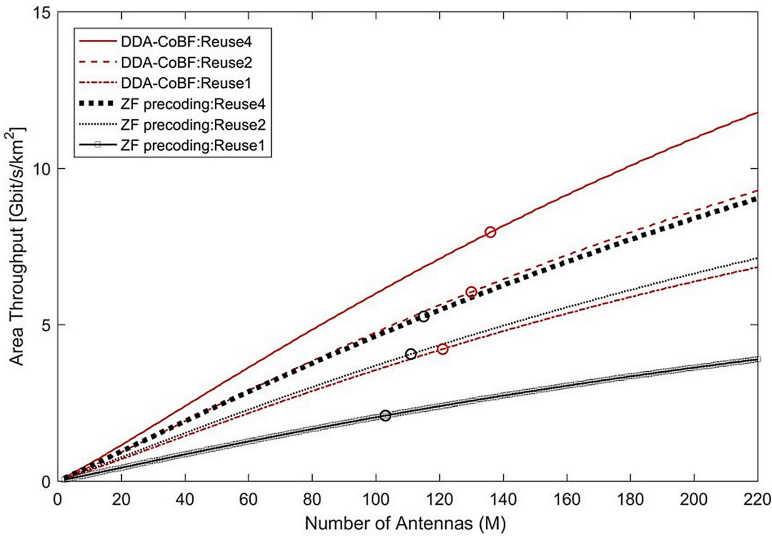
Figure 2 shows the throughput with different cooperative areas and numbers of antennas on the BS. Different from the trend of EE, the throughput increases as the side length of the cooperative area. This is because the proposed algorithm suppresses the interference at the cost of increasing the total PA power, so the EE cannot increase indefinitely. However, the user rate continuously increases without considering the energy consumption, so the throughput of the system gradually increases as the side of the cooperative area from 700 to 1500 m. Therefore, it is not possible to enlarge the cooperative area without limit, because the PA power will increase by a multiple, and the overall EE will be greatly reduced. Therefore, a larger cooperative area should be selected to increase the throughput with the similar EE to further improve the system performance.

The pilot contamination caused by the shortage of frequency bands in massive MIMO systems have a serious impact on system performance. Therefore, we analyze the performance of the cooperative area is set as  $9 \times 10^2 \times 9 \times 10^2$  m<sup>2</sup> in the case of pilot contamination. Figure 3 illustrates the EE varying with the number of antennas under different pilot reuse factors (1, 2 and 4). Note that the influence of pilot contamination is serious, as shown in Fig. 3. However, the DDA-CoBF algorithm maintains the higher EE than the traditional algorithm. Moreover, the more serious the pilot contamination is, the more obvious the improvement.

Figure 4 shows the variation of system throughput under different pilot reuse factors. It can be seen the throughput of the system is reduced obviously when the pilot reuse factor is reduced, especially for the traditional algorithm. However, the system throughput of the proposed DDA-CoBF algorithm is always



**Fig. 3.** EE under the influence of pilot reuse factor.



**Fig. 4.** Area throughput with DDA-CoBF algorithm under the influence of pilot reuse factor.

higher than ZF precoding regardless the pilot reuse factor. Meanwhile, the proposed algorithm also can obviously improve throughput when the pilot reuse factor is 2 or 4.

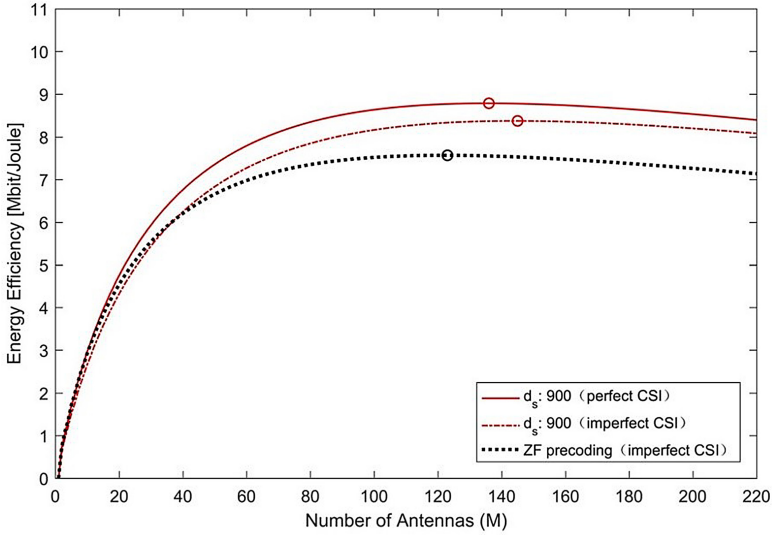


Fig. 5. EE under the influence of imperfect CSI.

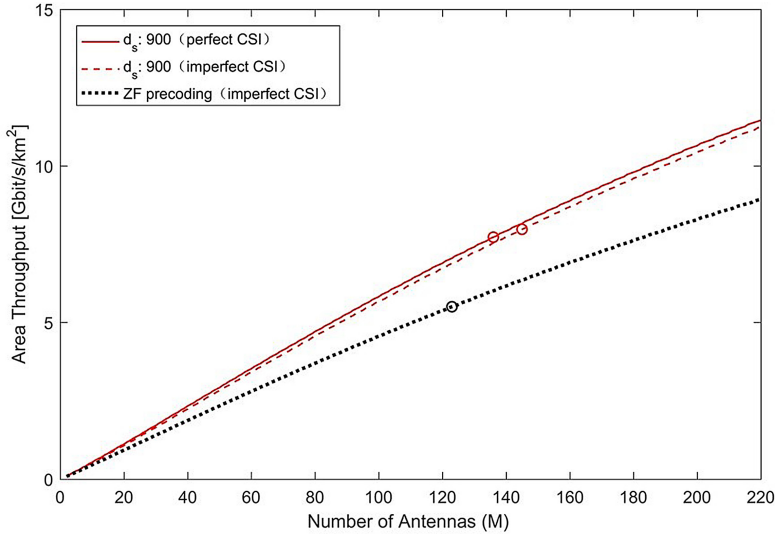


Fig. 6. Area throughput with DDA-CoBF algorithm under the influence of imperfect CSI

Figure 5 depicts the effect of imperfect CSI on the EE with the traditional algorithm and the proposed DDA-CoBF algorithm, which as the function of the number of BS antennas. We can see that the system EE has declined for both the traditional algorithm and DDA-CoBF algorithm. Furthermore, the system

with imperfect CSI can also effectively improve the optimal EE when BS antennas are deployed more than 40 with the proposed DDA-CoBF algorithm. The more antennas are deployed, the more obvious the advantages for the proposed algorithm. Therefore, the proposed DDA-CoBF algorithm is particularly well adapted in the massive MIMO systems.

Figure 6 shows the change in system throughput as the number of antennas with and without CSI errors. The system throughput with the proposed DDA-CoBF algorithm slightly decreases with the influence of an imperfect CSI, that is, the CSI error has a relatively small influence on the system throughput than EE. Furthermore, the system with the proposed DDA-CoBF algorithm has a very stable throughput, so the proposed algorithm exhibits greater robustness under the influence of CSI error.

## 5 Conclusions

In this paper, the proposed DDA-CoBF algorithm by suppressing interference is proposed. This paper analyzes how to select the cooperative area to maximize the EE in multi-user massive MIMO systems. In contrast to existing work, we suppressed the interference of cell-edge users to improve network performance by exploiting and using the spatial degrees of the massive MIMO systems. The algorithm focuses mainly on users at the edge of a cell that are most vulnerable to interference, that is, suppressing the interference of extended cooperative users. By adjusting the cooperative area, we have obtained the optimal EE and throughput with the proposed DDA-CoBF algorithm. Therefore, we can deploy the BS antenna according to the number of served users and improve the performance of the system by selecting an appropriate cooperative scheme and cooperative regions. Finally, we explored the effect of pilot reuse factor and CSI error on the system performance. Numerical results show that the proposed DDA-CoBF algorithm is more robust to pilot contamination and CSI errors, and more suitable for massive MIMO systems.

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