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System Performance of Cooperative Massive MIMO Downlink 5G Cellular Systems

Chao He and Richard D. Gitlin
Department of Electrical Engineering
University of South Florida
Tampa, Florida 33620, USA
Email: chaohe@mail.usf.edu, richgitlin@usf.edu

***Abstract*— Massive MIMO (multiple-input multiple-output) antenna technology can provide significant performance improvement for cellular systems in terms of both throughput and energy efficiency. It is widely recognized that inter-user interference can be eliminated with a large number of antennas because of the asymptotical orthogonality among users when linear MF (Matched Filter) downlink precoding is used in the eNodeB. Due to the complexity and deployment consideration in practical scenarios at individual eNodeBs, cooperative massive MIMO [CM-MIMO] where multiple base stations cooperate together and form a distributed antenna array to serve multiple users simultaneously is an attractive alternative. Furthermore, cooperative massive MIMO can also help increase the system performance especially for cell edge users because of the cooperative transmission among neighboring cells. In this paper, system level simulation performance for the downlink, based upon current LTE systems, provides an indication of the achievable potential system performance improvement by employing CM-MIMO in future (5G) cellular networks. It is demonstrated that CM-MIMO can improve the system performance of cell edge users significantly even if the cell average performance is very slightly degraded or maintained caused by the power imbalance of received signal from different cooperative neighboring cells.**

***Keywords*—Cooperative Massive MIMO, cooperative transmission, Matched Filter precoding, power imbalance, cell edge system performance.**

I. Introduction

Massive MIMO (multiple-input multiple-output) wireless technology uses a very large number of antennas with an order of magnitude more antennas than current LTE systems and is a leading candidate for inclusion in 5G systems. This will offer significant improvements in both the throughput and energy efficiency. As the number of antennas increases without limit, it is known that the effects of uncorrelated noise and small-scale fading can be removed completely. That means when a large number of user terminals are scheduled simultaneously over the same physical layer resource, the channels of all the terminals are asymptotically orthogonal to each other, and both intra-cell and inter-cell user interference can be eliminated completely through linear signal processing methods, e.g., MF (Matched Filter) precoding or MF detection for the downlink and uplink respectively. That also means each user will be presented with a flat fading channel, meaning that the channel is nearly identical in all subcarriers, so that each user may be scheduled with the full bandwidth, and the MAC (Media Access Control) resource allocation scheduling can be simplified and no control signaling of physical layer resource allocations will be required [1]–[3].

Due to the complexity and deployment consideration in practical scenarios at individual base stations, each base station site cannot be deployed with a large number of antennas. That means with a limited number of antennas, the inter-cell and intra-cell interference still exist if simple non-cooperative linear precoding is used individually in each base station site[4]. Cooperative massive MIMO [CM-MIMO] where multiple base stations cooperate together and form a distributed antenna array to serve multiple users simultaneously is an attractive alternative. In CM-MIMO, user data as well as CSI (channel state information) is shared among base stations that will provide more degrees of freedom for communication. Also, precoding can take into account inter-cell interference and thus mitigate inter-cell interference, which is especially critical for cell edge users that typically suffer more inter-cell interference. Furthermore, CM-MIMO, where multiple base stations coordinate through the backhaul network, the bandwidth of the backhaul link and delay may create additional impairments on the system performance [5], [6].

In this paper, system level simulation performance of cooperative massive MIMO and non-cooperative massive MIMO system performance is compared under the uniform framework of the LTE TDD system. Here MF precoding is adopted for comparison owing to the benefit of low complexity of MF precoding and also in order to reduce the impact on the backhaul since no channel state information needs to be exchanged among base stations. The system level simulation takes into account various numbers of antenna configured in each base station site. This analysis provides insight on the potential system performance that can be achieved by using cooperative massive MIMO.

The rest of the paper is organized as follows. In Section II, massive MIMO systems for both cooperative and non-cooperative implementations are described. Section III presents the system simulation setup and simulation results. Finally, our conclusions are presented in Section IV.

II. NON-COOPERATIVE AND COOPERATIVE SYSTEM

This paper considers a massive MIMO wireless cellular system with L cells denoted as $1,2,\ldots,L$ respectively as shown in Figure 1. Each cell consists of one base station with M antennas and K users equipped with only one antenna for reduced complexity. In this paper, we assume users use orthogonal pilot resources to acquire the Channel State Information [CSI], so pilot contamination is not considered.

A. Non-cooperative Massive MIMO System

The base station j transmits a $M*1$ precoded vector S_{fj}. The subscript f means forward link and the subscript j denotes the base station index. User k in base station l receives the signal from the transmitted vectors from all the base stations, which is written as:

$$X_{kl} = \sqrt{\rho_f}\sum_{j=1}^{L} G_{jkl}\, S_{fj} + W_{kl} \quad (1)$$

where ρ_f is the signal-to-noise ratio of the forward link, W_{kl} is the complex independent and identically distributed (i.i.d.) white Gaussian noise, and G_{jkl} is the $1*M$ channel matrix between user k in base station l and M antennas in base station j (see Fig. 1). The symbol G_{jkl} comprises the small-scale Rayleigh fading factors H_{jkl} and a large-scale factor $\beta_{jkl}^{1/2}$ that accounts for distance dependent attenuation and shadow fading and is assumed to be the same for all the M antennas in a base station [1].

$$G_{jkl} = H_{jkl}\beta_{jkl}^{1/2} \quad (2)$$

Assume linear MF precoding is used, and precise CSI is available in the base station, then the base station transmits

$$S_{fj} = \sum_{m=1}^{k} G_{jmj}^{*} a_{mj} \quad (3)$$

where G_{jmj} is the $1*M$ channel matrix between user m and M antennas in base station j. The superscript $*$ denotes the

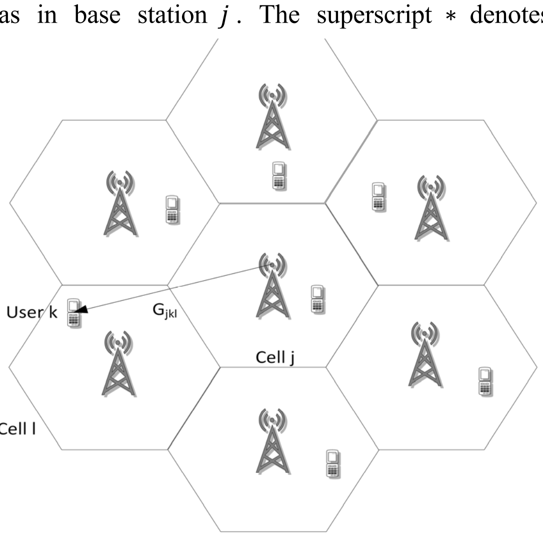

Fig.1. G_{jkl} is channel matrix between user k in base station l and M antennas in base station j.

conjugate transpose. The symbol a_{mj} is the transmitted symbols for user m in base station j.

Substituting (3) into (1), then the received signal for user k in base station l is:

$$X_{kl} = \sqrt{\rho_f}\sum_{j=1}^{L} G_{jkl}\sum_{m=1}^{k} G_{jmj}^{*} a_{mj} + W_{kl} \quad (4)$$

As the number of antennas M is increased to infinity, the channels will be orthogonal to each other, since according to random matrix theory [7]:

$$G_{jkl}G_{jmj}^{*} = \beta_{jkl}^{1/2}\,\beta^{*1/2}_{jmj}\, H_{jkl}H_{jmj}^{*} \rightarrow 0 \text{ when } l \neq j \text{ or } (l = j \text{ and } k \neq m) \quad (5)$$

$$G_{jkl}G_{jmj}^{*} = \beta_{\mathrm{jkl}}\left\|H_{jkl}\right\|^{2} \rightarrow M\beta_{jkl} \text{ when } l = j \text{ and } k = m \quad (6)$$

where $\|\cdot\|$ is the Frobenius norm.

The received signal for user k in base station l becomes:

$$X_{kl} = \sqrt{\rho_f}M\beta_{lkl}a_{kl} + W_{kl} \quad (7)$$

The SINR (signal-to-interference-plus-noise ratio) of user k in base station l becomes:

$$SINR_{kl} = \rho_f M^2\beta_{lkl}^2 \quad (8)$$

In (8), the small-scale fading effects disappear because (5)-(6) are assumed.

When the number of antennas M is asymptotically increased to infinity, the assumptions of (5)-(6) will hold asymptotically, and (7)-(8) are true asymptotically.

When the number of antennas M is limited, the assumptions of (5)-(6) will not hold, (7)-(8) cannot be derived. The received signal of user k in base station l becomes:

$$\begin{aligned} X_{kl} = {} & \sqrt{\rho_f}\|G_{lkl}\|^2 a_{kl} \\ & + \sqrt{\rho_f}\sum_{m\neq k}^{k} G_{lkl}G_{lml}^{*}a_{ml} \\ & + \sqrt{\rho_f}\sum_{j\neq l}^{L}\sum_{m=1}^{k} G_{jkl}G_{jmj}^{*}a_{mj} \\ & + W_{kl} \end{aligned} \quad (9)$$

Then residual interference will exist, as (9) shows. The first 3 terms at the right hand of (9) are the signal of user k in base station l, intra-cell interference, and inter-cell interference for user k in base station l respectively.

B. Cooperative Massive MIMO System

As with non-cooperative Massive MIMO system, in cooperative Massive MIMO system, the base station j transmits a $M*1$ precoded vector S_{fj}. What is different is that each cooperative base station precodes the signals of all the $K*L$ users in the cooperative area at the same time:

$$S_{fj} = \sum_{m=1}^{K*L} G_{jmj}^{*} a_{mj} \quad (10)$$

where the parameters in (10) mean the same as those in (3).

Substituting (10) into (1), then the received signal for user k in base station l is:

$$X_{kl} = \sqrt{\rho_f^{'}} \sum_{j=1}^{L} G_{jkl} \sum_{m=1}^{K*L} G_{jmj}^{*} a_{mj} + W_{kl}$$
$$= \sqrt{\rho_f^{'}} \sum_{j=1}^{L} \left\| G_{jkl} \right\|^2 a_{kl} \quad (11)$$
$$+ \sqrt{\rho_f^{'}} \sum_{m=1, m\neq k}^{K*L} \sum_{j=1}^{L} G_{jkl} G_{jmj}^{*} a_{mj} + W_{kl}$$

where $\rho_f^{'}$ is the signal-to-noise ratio for the forward link, and other parameters in (11) mean the same as those in (4).

As the number of antennas M is increased to infinity, (12)-(13) will hold. But the large-scale factor $\beta_{jkl}^{1/2}$ for user k from different cooperative base stations are different, an effect known as power imbalance.

$$\sum_{j=1}^{L} G_{jkl} G_{jmj}^{*} = \sum_{j=1}^{L} \beta_{jkl}^{1/2} \, \beta^{*}{}_{jmj}^{1/2} \, H_{jkl} H_{jmj}^{*} \quad (12)$$
$$\rightarrow 0 \text{ when } k \neq m$$

$$\sum_{j=1}^{L} \left\| G_{jkl} \right\|^2 = \sum_{j=1}^{L} \beta_{\mathrm{jkl}} \left\| H_{jkl} \right\|^2 \rightarrow \sum_{j=1}^{L} M \, \beta_{jkl} \quad (13)$$

The received signal of user k in base station l becomes:

$$X_{kl} = \sqrt{\rho_f^{'}} \sum_{j=1}^{L} M \beta_{jkl} \, a_{kl} + W_{kl} \quad (14)$$

Compared with the non-cooperative case, the SINR of user k will be reduced because the large-scale factor $\beta_{jkl}^{1/2}$ for user k from different cooperative base stations are generally different, the combination gain of the signal power for user k is lower as shown in the first term at the right hand of (14).

When the number of antennas M is limited, the assumptions of (12)-(13) will not hold, inter-user for both intra-cell and inter-cell interference cannot be completely removed. The received signal of user k in base station l is shown in (11).

For cell edge users, because the large-scale factor $\beta_{jkl}^{1/2}$ for user k from different cooperative base stations are similar (e.g., β_{kl}), which equals more transmit antennas with the same large-scale factor, (12)-(13) become:

$$\sum_{j=1}^{L} G_{jkl} G_{jmj}^{*} = \beta_{kl} \sum_{j=1}^{L} H_{jkl} H_{jmj}^{*} \text{ when } k \neq m \quad (15)$$

TABLE I SYSTEM SIMULATION CONFIGURATION

Parameters	Assumption
Cellular layout	Hexagonal grid, 7 cell sites, 1 sector per site wrap around
Cell radius	500 meters
Path loss model	3GPP 36.942 urban model
Lognormal Shadowing	Fading mean: 0 dB Standard deviation: 10 dB Shadowing corrlelation between sites: 0.5
Antenna pattern	Omni-directional
eNodeB antennas	ULA 15, 25, and 50 antennas
UE antennas	1 antenna
Carrier frequency/Duplex mode	TDD 2GHz
System bandwidth	20 MHz
Channel model	ITU Typical Urban (TU)
Receiver noise figure	9 dB
UE speed	30 km/h
Total BS TX power	46 dBm
Number of UEs	10 full buffer UEs in each cell
Scheduler	All-user Full bandwidth scheduling

$$\sum_{j=1}^{L} \left\| G_{jkl} \right\|^2 = \beta_{\mathrm{kl}} \sum_{j=1}^{L} \left\| H_{jkl} \right\|^2 \quad (16)$$

From (15)-(16), we can observe that for cell edge users, where the power imbalance is less significant, the asymptotical properties will be more asymptotically true. That means, (15) will be more asymptotically zero, and (16) will be more asymptotically approaching to $ML\beta_{jkl}$. Therefore, compared with the non-cooperative case, the SINR will be higher because the combination gain of the signal power for cell edge users as shown in (16) is higher and inter-user for both intra-cell and inter-cell interference is lower as shown in (15).

However, for cell center users, it is the opposite and system performance may be degraded because power imbalance is more significant, the combination gain of the signal power is small and inter-user interference still exists, as can be verified in the system simulation in next section.

So cooperative massive MIMO can achieve a more uniform data rate among all users, improving the system performance for cell edge users and degrading the system performance for cell center users. The overall cell average system performance depends upon both the performance gain for cell edge users and the degradation for cell center users.

III. SYSTEM LEVEL SIMULATION

A. System Level Simulation Setup

The system level simulation is run using Matlab [8]. The system simulation configuration is partly based upon LTE macro-cell system simulation baseline parameters [9] as shown in Table I. Seven omni-directional sites are simulated with 10 single-antenna UEs in each site equipped with 15, 25, and 50 transmit antennas with ULA (Uniform Linear Array) configurations respectively. The path loss model of 3GPP 36.942 urban model is used [10]. The TDD duplex mode is

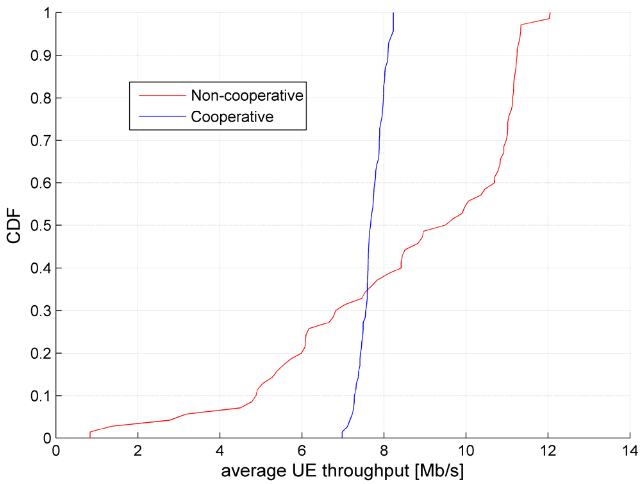

Fig.2. UE throughput CDF for non-cooperative and cooperative massive MIMO with 15 transmit antennas.

assumed, where the downlink channel matrix can be obtained through TDD channel reciprocity from the uplink channel matrix. A system bandwidth of 20 MHz and all-user full bandwidth scheduling are used, which means all 10 users in each cell are scheduled at the same time to the full bandwidth. In the simulation, for simplification of illustration, we assume that all the system bandwidth is available for downlink data transmission in each subframe. The net system throughput for a specific TDD uplink-downlink configuration [11] can be easily derived. In the simulation downlink MF precoding is utilized.

B. 15 Transmit Antennas

Figure 2 shows the UE throughput CDF (Cumulative Distribution Function) for non-cooperative and cooperative massive MIMO with 15 transmit antennas deployed in each eNodeB. Table II also summarizes the 5% user throughput and cell average throughput for both non-cooperative and cooperative massive MIMO. It is observed that 5% user throughput is increased significantly from about 2.7 to 7.2 Mbps, whereas median user throughput is decreased from about 9 to 7.8 Mbps, and the cell average throughput is decreased from about 86.3 to 77.1 Mbps.

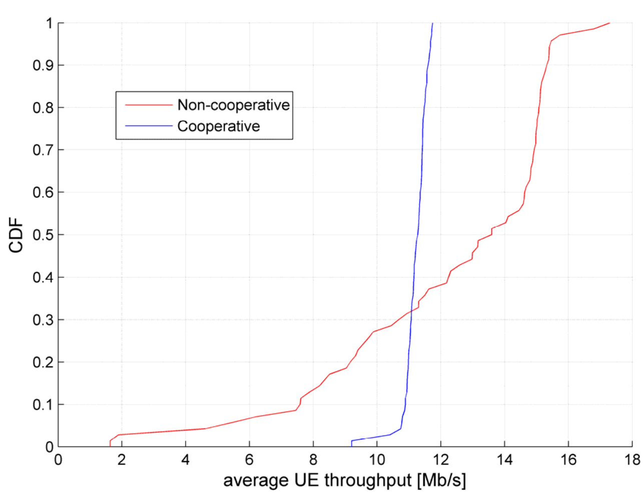

Fig.3. UE throughput CDF for non-cooperative and cooperative massive MIMO with 25 transmit antennas.

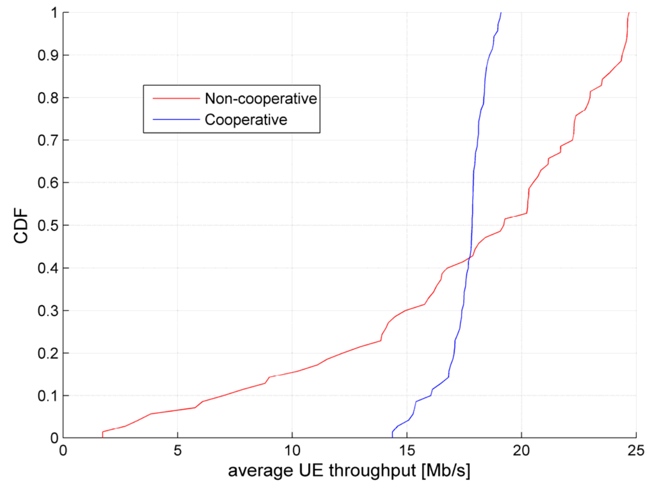

Fig.4. UE throughput CDF for non-cooperative and cooperative massive MIMO with 50 transmit antennas.

C. 25 Transmit Antennas

Figure 3 shows the UE throughput CDF for non-cooperative and cooperative massive MIMO with 25 transmit antennas deployed in each eNodeB. It is observed from Fig. 3 and Table II that 5 % user throughput is increased significantly from about 4 to 10.5 Mbps, whereas median user throughput is decreased from about 13.5 to 11 Mbps, and the cell average throughput is decreased from about 123.0 to 112.2 Mbps.

D. 50 Transmit Antennas

Figure 4 shows the UE throughput CDF (Cumulative Distribution Function) for non-cooperative and cooperative massive MIMO with 50 transmit antennas deployed in each eNodeB. It is observed from Fig 4 and Table II that 5 % user throughput is increased significantly from about 4 to 15.2 Mbps, whereas median user throughput is decreased from about 19 to 17.5 Mbps, and the cell average throughput is slightly increased from about 175.5 to 175.9 Mbps.

The above three cases demonstrate that the cooperative massive MIMO can significantly improve cell edge users' system performance, whereas the cell average system performance is slightly degraded or maintained.

IV. CONCLUSIONS

In this paper, system level simulation performance of non-cooperative and cooperative massive MIMO systems for downlink performance is presented based upon current LTE systems considering different numbers of antennas deployed in

TABLE II SYSTEM SIMULATION PERFORMANCE

Cases		**5 % User Throughput (Mbps)**	**Cell average Throughput (Mbps)**
15 Antennas	Non-cooperative	2.7	86.3
	Cooperative	7.2	77.1
25 Antennas	Non-cooperative	4	123.0
	Cooperative	10.5	112.2
50 Antennas	Non-cooperative	4	175.6
	Cooperative	15.2	175.9

the base station. It is shown that through cooperation among base stations, system performance of cell edge users can be significantly improved, whereas cell average throughput is slightly degraded or maintained owing to the power imbalance for the cell center users. The system simulations presented in this paper provide a view of the potential system performance that can be achieved by cooperative massive MIMO technologies in practical 5G systems. Future research will be on system performance evaluation of cooperative massive MIMO only for cell edge users based upon 3D channel models.

V. ACKNOWLEDGMENT

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