Capacity Analysis of a Multi-Cell Multi-Antenna Cooperative Cellular Network with Co-Channel Interference

Xiaohu Ge, *Senior Member, IEEE,* Kun Huang, Cheng-Xiang Wang, *Senior Member, IEEE,* Xuemin Hong, and Xi Yang

***Abstract*—Characterization and modeling of co-channel interference is critical for the design and performance evaluation of realistic multi-cell cellular networks. In this paper, based on alpha stable processes, an analytical co-channel interference model is proposed for multi-cell multiple-input multi-output (MIMO) cellular networks. The impact of different channel parameters on the new interference model is analyzed numerically. Furthermore, the exact normalized downlink average capacity is derived for a multi-cell MIMO cellular network with co-channel interference. Moreover, the closed-form normalized downlink average capacity is derived for cell-edge users in multi-cell multiple-input single-output (MISO) cooperative cellular networks with co-channel interference. From the new co-channel interference model and capacity formulas, the impact of cooperative antennas and base stations on cell-edge user performance in the multi-cell multi-antenna cellular network is investigated by numerical methods. Numerical results show that cooperative transmission can improve the capacity performance of multi-cell multi-antenna cooperative cellular networks, especially in a scenario with a high density of interfering base stations. The capacity performance gain is degraded with the increased number of cooperative antennas or base stations.**

***Index Terms*—Interference modeling, capacity analysis, multiple-input multiple-output (MIMO), cooperative transmission, co-channel interference.**

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I. Introduction

To achieve high transmission data rates, multi-antenna technology has widely been adopted in the 3rd generation (3G) and 4th generation (4G) mobile communication systems [1]. The multi-antenna technology can improve the system capacity proportionally with the minimum number of antennas at the transmitter and receiver in a single cell communication system [2]. However, the system capacity of multi-cell cellular networks is greatly degraded by the co-channel interference even with multiple antennas at the transmitters and receivers [3], [4]. As a result, co-channel interference modeling and capacity analysis of multi-cell multi-antenna cellular networks are of great importance in the next generation mobile communication systems.

Numerous interference models have been proposed in the literature for wireless communication systems [5]–[11]. Sousa proposed that the infinite aggregated interference from the homogeneous Poisson field of interferers can be modeled by an alpha stable distribution [5]. Furthermore, based on [5], an analytical expression for the instantaneous and second order distributions of the interference was presented in [6]. Salbaroli and Zanella investigated the interference characteristic function in a finite Poisson field of interferers in [7]. The co-channel interference statistics in a Poisson field of interferers was derived from a unified framework in [8]. Whereas, most models proposed in [5]–[8] were constrained to single antenna or single cell communication systems and did not fully consider the complex effects of wireless channels. For example, the interference models proposed in [5], [6] are only suitable for single antenna communication systems without considering shadowing and fading effects in wireless channels. The interference models proposed in [7], [8] did not consider multi-cell multi-antenna systems. Different from these existing models in [5]–[8], in this paper we propose an interference model for multi-cell multi-antenna cellular networks considering the effects of pathloss, shadowing, and small-scale fading in wireless channels. For multi-cell interference statistics, Gulati and Evans introduced a mathematical framework for the characterization of network interference in wireless networks in which interferers are scattered according to a spatial Poisson process and subject to path loss, shadowing, and multi-path fading [9]. Moreover, a unified framework from which the co-channel interference statistics in a Poisson field of interferer distributed on a parametric circular annular region was derived

in [10]. Based on wider range of interferer topologies and Poisson-Poisson cluster field of interferers extended from [10], the applicability of the symmetric alpha stable and Gaussian mixture (with Middleton Class A as a particular form) distributions in modeling co-channel interference signal phase was demonstrated in [11]. In [10], [11], a unified framework for deriving interference models for various wireless network environments was developed and corresponding characteristic functions of interference signal phase models were illustrated. Based on the aforementioned results, we further derive an analytical co-channel interference signal power model for multi-cell multi-input multi-output (MIMO) cellular networks with the Poisson spatial distribution of interferers.

For the capacity analysis of multi-antenna cellular networks, many studies have been carried out [12]–[18]. Telatar and Foschini carried out the initial research for the point-to-point multi-antenna communication system and indicated that the system capacity increases linearly with the minimum number of antennas in the transmitter and receiver over uncorrelated flat Rayleigh fading channels [2], [12]. Furthermore, Webb presented a way of explicitly examining the effect of interference on the MIMO subchannel gains in a mutli-antenna communication system and derived asymptotic lower bounds on capacity with many interferers and in high interference-to-noise ratio [13]. Wang derived an exact closed-form expression of the moment-generating function (MGF) of mutual information of MIMO channels with interference for a cellular network. Then, an exact expression of the MIMO ergodic capacity with the MGF formula of mutual information was proposed for Rayleigh fading channels [14]. Treating interference as noise was shown to be sum capacity achieving for the two-user single-input single-output (SISO) Gaussian interference channel in a low interference regime. Moreover, the low interference regime for the multi-input single-output (MISO) Gaussian interference channel was characterized in [15]. Kwak analyzed the capacity of MIMO channels in the presence of both antenna correlation and co-channel interference [16]. For the special case of separable correlations, Kwak derived analytical expressions for the key statistical properties of the spectral efficiency achievable with an arbitrary input covariance. Under a single cell communication system, Chiani developed an analytical framework to characterize the capacity of MIMO communication systems and derived the ergodic mutual information for MIMO systems in the presence of multiple MIMO co-channel interferers and noise [17]. Based on the mutual information of a MIMO system with co-channel interference, Ye revealed that equal-power interferers give worse performance than unequal-power interferers and a smaller number of interferers each with larger power degrades performance less than a larger number of interferers each with lower power [18].

Cooperative transmission in wireless communications has been studied in the recent literature [19]–[21]. Based on a pathloss channel model, Chen proposed an intuitive method for calculating the system diversity level in the generalized distributed antenna system with cooperative users [19]. Furthermore, a novel channel representation for a two-hop decentralized wireless relay network was proposed and analyzed considering the cooperative transmission [20]. For the cell-edge users, the capacity with beamforming cooperative transmission was investigated for the soft handover region in multi-cell MIMO cellular networks [21].

However, in all the aforementioned capacity studies, only simple scenarios, such as a single cell with finite interfering transmitters, were considered and the underlying channel models were limited to simple flat Rayleigh fading channels. Besides, the exact normalized average capacity of multi-cell MIMO cellular networks with co-channel interference has not been investigated. Moreover, detailed investigation of the analytical co-channel interference model used for multi-cell multi-antenna cellular networks is surprisingly rare in the open literature. Many existing cooperative transmission literature simply treat co-channel interference as noise [19]–[21].

Motivated by the above gaps, in this paper we derive the exact downlink average capacity of multi-cell MIMO cellular network with co-channel interference. The contributions and novelties of this paper are summarized as follows.

1) We propose an analytical co-channel interference model for multi-cell MIMO cellular networks with a Poisson spatial distribution of interfering transmitters, taking into account fading and shadowing effects in wireless channels.
2) From the proposed co-channel interference model, we derive the exact downlink average capacity of multi-cell MIMO cellular networks with co-channel interference.
3) The closed-form normalized downlink average capacity for cell-edge users in multi-cell MISO cooperative cellular networks with co-channel interference is derived for numerical analysis.
4) We study the normalized capacity of the multi-cell MISO cooperative cellular networks in great details and present some interesting observations.

The remainder of this paper is outlined as follows. Section II proposes the new analytical co-channel interference model in multi-cell MIMO cellular networks. In Section III, from the proposed co-channel interference model, the exact downlink average capacity of multi-cell MIMO cellular network is derived. Furthermore, a closed-form normalized downlink average capacity for cell-edge users in a multi-cell MISO cooperative cellular network with co-channel interference is obtained. Simulation results and analysis are presented in Section IV. Finally, conclusions are drawn in Section V.

II. Co-channel Interference Modeling And Performance Analysis

A. General Interference Model

In this paper, interference analysis is focused on the downlink of cellular networks. A cell of cellular network is analogous to the geometrically based single-bounce macrocell model, where the scatters representing user equipments (UEs) are uniformly distributed within a circle centered at the base stations (BS). To simplify the system model used for interference analysis, we only consider effective interferers in our general interference model. As shown in Fig. 1, there are only two types of nodes. One type of nodes is the signal receiver noted as UE with $N_r \in [1, \cdots, \infty)$ antennas and the other type of nodes is the interfering transmitter, i.e.,

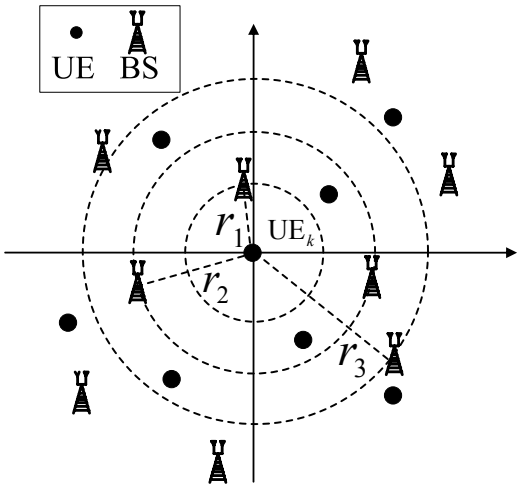

Fig. 1. General interference model.

BS with $N_t \in [1, \cdots, \infty)$ antennas. In idealized cellular networks, the BS locations are assumed to have a regular hexagonal structure. However, in real cellular networks, the BS locations are carefully chosen and optimized to take into account various practical factors such as building heights, user density, terrain features, etc. This typically leads to irregular and seemingly randomized BS locations, which can be well captured by Poisson distributions [22]. This Poisson model has widely been adopted in cellular networks to characterize BS locations [23], [24]. The Poisson model also provides theoretical tractability and scalability. Therefore, in this paper the locations of all BSs are also assumed to follow a Poisson spatial distribution in a two-dimensional infinite plane. Moreover, only one BS is assumed to exist in one cell. This general interference model can be used to describe the interference signals in multi-cell MIMO cellular networks.

B. Interference Model of Multi-cell MIMO Cellular Networks

In the aforementioned general interference model, as illustrated in Fig.1, every signal including the interference signal passes through an independent wireless channel, which means every signal is subject to independent path loss, shadowing, and Nakagami-m fading effect [25]. In general, the shadowing effect can be characterized by lognormal distributions. To simplify the calculation, the PDF of signal with shadowing effect can be approximated by a Gamma distribution [26]:

$$p(x) = \frac{1}{\Gamma(\lambda)}(\frac{\lambda}{\Omega})^{\lambda} x^{\lambda-1} e^{-\frac{\lambda}{\Omega}x}, x > 0 \tag{1a}$$

with

$$\Gamma(\lambda) = \int_0^{\infty} t^{\lambda-1} e^{-t} \mathrm{d}t \tag{1b}$$

$$\Omega = P_r \sqrt{(\lambda+1)/\lambda} \tag{1c}$$

$$\lambda = 1/(e^{(\sigma_{dB}/8.686)^2} - 1) \tag{1d}$$

where σ_{dB} is the shadow spread parameter expressed in decibels whose value usually ranges from 4 to 9 in practice and P_r is the received average signal power at the receiver. Considering that the shadowing effect in the wireless channel is approximated by the Gamma distribution, the wireless channel with Gamma shadowing and Nakagami-m fading can be further approximated by the Generalized-K (K_G) distribution [27].

Without loss of generality, we select one of the users UE_k ($k = 1, \cdots, \infty$) as the signal receiver interfered by interfering transmitters from the given region in Fig. 1. This UE_k receives aggregated interference from the interfering transmitters, i.e., BSs, in the given region. The aggregated interference at UE_k can be expressed as follows

$$P^{RX} = \sum_{b=1}^{\infty} \frac{I_b}{r_b^{\sigma_r}} = \sum_{b=1}^{\infty} \frac{\sum_{i=1}^{N_r} (I_{b,i})}{r_b^{\sigma_r}} = \sum_{i=1}^{N_r} \left(\sum_{b=1}^{\infty} \frac{I_{b,i}}{r_b^{\sigma_r}} \right) \tag{2}$$

where I_b is the interference signal power received by UE_k from the BS b without the path loss effect, $I_{b,i}$ is the interference signal power received by the antenna i of UE_k from the BS b without the path loss effect, $r_b^{-\sigma_r}$ is the path loss variable with path loss coefficient σ_r and path distance r_b from the BS b to the user. The spatial distribution of BSs is a Poisson distribution with a density parameter λ_{BS}. Thus, the distribution of the aggregated interference at UE_k is governed by an alpha stable distribution [8] and expressed by the characteristic function [7],[8].

$$\Phi_{P^{Rx}}(jw) = \exp\left(-|cw|^{\alpha}\left[1 - j\mathrm{sign}(w)\tan\left(\frac{\pi\alpha}{2}\right)\right]\right) \tag{3a}$$

with

$$\mathrm{sign}(w) = \begin{cases} 1, & w > 0 \\ 0, & w = 0 \\ -1, & w < 0 \end{cases} \tag{3b}$$

$$\alpha = \frac{2}{\sigma_r} \tag{3c}$$

$$c = \sqrt[\alpha]{\lambda_{BS} q \mathbb{E}\left(I_b^{\alpha}\right)} \tag{3d}$$

$$q = \begin{cases} \pi\Gamma(2-\alpha)\cos(\pi\alpha/2)/(1-\alpha), & \alpha \neq 1 \\ \pi^2/2, & \alpha = 1 \end{cases} \tag{3e}$$

where $\mathbb{E}(\cdot)$ is the expectation operator, $\Gamma(\cdot)$ is the Gamma function which is defined by (1b), α is the characteristic exponent, and c is the scale parameter.

In Fig. 1, an interfering transmitter, i.e., a BS, with N_t antennas has N_t interference sub-streams from the closed space source and every antenna of UE_k can receive N_t interference sub-streams from a BS. The path loss and shadowing effect for one BS-UE pair is assumed the same across all the antennas. The transmission power of every antenna is assumed to be equal and normalized to 1, i.e., $P_{ant} = 1$. Therefore, in multi-cell MIMO cellular networks, I_b in (3d) is the sum of the interference signal power transmitted by the N_t interference sub-streams from the same BS b without the path loss effect. Furthermore, I_b is expressed by

$$I_b = P_{ant} w_b \left(\sum_{i=1}^{N_r} \sum_{j=1}^{N_t} |z_{b,i,j}|^2 \right) = w_b \left(\sum_{i=1}^{N_r} \sum_{j=1}^{N_t} |z_{b,i,j}|^2 \right) \quad (4)$$

where w_b is a random variable of Gamma shadowing process, which corresponds to the signal passing through the Gamma shadowing channel from the BS b, and $z_{b,i,j}$ is the random variable of Nakagami-m fading process, which corresponds to the signal passing through the Nakagami-m fading channel from the transmitting antenna j of BS b to the receiving antenna i of UE_k.

Because the wireless channel with Gamma shadowing and Nakagami-m fading can be approximated by the K_G distribution, the PDF of I_b can be further derived as follows based on the Generalized-K random process theory [26]:

$$f_I(y) = \frac{2\left(\frac{m\lambda}{\Omega}\right)^{\frac{N_t N_r m+\lambda}{2}}}{\Gamma(N_t N_r m)\Gamma(\lambda)} y^{\frac{N_t N_r m+\lambda-2}{2}} K_{\lambda - N_t N_r m}\left(2\sqrt{\frac{m\lambda y}{\Omega}}\right) \quad (5)$$

where m is the Nakagami shaping factor, $K_v(\cdot)$ is the modified Bessel function of the second kind with order v, Ω and λ are defined in (1c) and (1d), respectively.

In order to derive a closed-form expression for the PDF, we can perform an inverse Fourier transform on the characteristic function of (3a). For this purpose, a closed-form expression of (3d) should be first derived. Therefore, from (5) the following transform parameter γ is derived accounting for the transformation in [28]

$$\gamma = c^\alpha = \lambda_{BS} q \left(\frac{m\lambda}{\Omega}\right)^{-\alpha} \frac{\Gamma(\lambda+\alpha)\Gamma(N_t N_r m+\alpha)}{\Gamma(N_t N_r m)\Gamma(\lambda)}. \quad (6)$$

Furthermore, we substitute (6) into (3d) and perform the inverse Fourier transform on the characteristic function of (3a). Ultimately a new PDF expression of the aggregated interference P^{R_X} at the user in the multi-cell MIMO cellular networks is derived as

$$f_{P^{Rx}}(y) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \Phi_{P^{Rx}}(jw) \exp(-2\pi j w y) \mathrm{d}w \quad (7a)$$

where $\Phi_{P^{Rx}}(jw)$ is given by (3a) with

$$c = \left(\lambda_{BS} q \left(\frac{m\lambda}{\Omega}\right)^{-\alpha} \frac{\Gamma(\lambda+\alpha)\Gamma(N_t N_r m+\alpha)}{\Gamma(N_t N_r m)\Gamma(\lambda)} \right)^{\frac{1}{\alpha}}. \quad (7b)$$

When the path loss coefficient is configured as $\sigma_r = 4$ which corresponds to the urban macro-cell with rich scattering environment [25], an analytical interference model is given by

$$f_{P^{Rx}}(y) = \sqrt{\gamma^2/2\pi} \frac{e^{-\gamma^2/2y}}{y^{3/2}}, y > 0 \quad (8a)$$

with

$$\gamma = \lambda_{BS} \sqrt{2}\pi \Gamma\left(\frac{3}{2}\right) \left(\frac{m\lambda}{\Omega}\right)^{-\alpha} \frac{\Gamma(\lambda+\frac{1}{2})\Gamma(N_t N_r m+\frac{1}{2})}{\Gamma(N_t N_r m)\Gamma(\lambda)} \quad (8b)$$

where $\Gamma(\cdot)$, Ω and λ are denoted by (1b), (1c) and (1d), respectively.

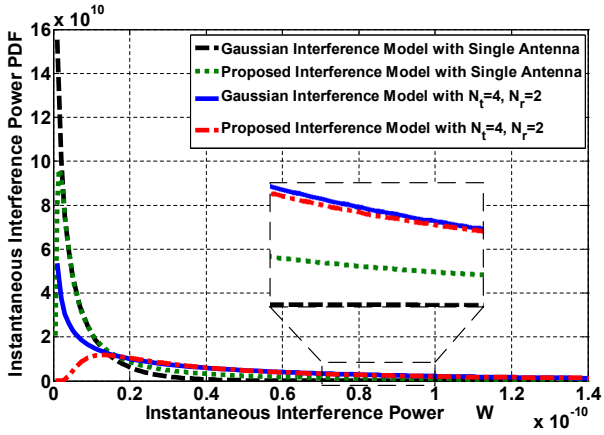

Fig. 2. Comparison of the instantaneous interference power PDFs of the proposed interference model and Gaussian interference model.

C. Performance Analysis

Based on the proposed new interference model, some performance evaluations can be numerically analyzed in detail. In the following analysis, some parameters of the interference model in Fig. 1 are configured as follows: $\sigma_{dB} = 6$, which usually ranges from 4 to 9 in practice [25]; $m = 1$, which usually ranges from 0.5 to 10 in practice [25]; $\sigma_r = 4$, which corresponds to an urban macrocell with a rich scattering environment [25]; $N_t = 4$ and $N_r = 2$ [29]; the effective radius of interfering BS is assumed as 800 meters and the transmission power of interfering BS is assumed as $P_r = 1$ watt; the interfering BSs' density parameter is $\lambda_{BS} = 1/(\pi \times 800^2)$. In the previous work [11], [30], [31], Gaussian interference models were widely used. Based on some default parameters, in Fig. 2 we compare the instantaneous interference power PDFs of the proposed interference model with those of the Gaussian interference model. Both single antenna and multi-antenna scenarios were considered. In the single antenna scenario, the receiver and the interfering transmitters are all equipped with one antenna. In the multi-antenna scenario, the receiver has $N_r = 2$ antennas and the interfering transmitters have $N_t = 4$ antennas. For better visualization, the tail parts of the PDFs of two interference models are enlarged and compared in Fig. 2. It is found that the PDF of the proposed interference model has an obvious heavier tail compared with that of the Gaussian interference model. According to the stable distribution theory [32], [33], the heavy tail characteristic indicates that small probability events or rare events (e.g., interference with high power) may have a non-negligible impact on the alpha stable distribution. Therefore, the aggregate interference in multi-cell MIMO cellular networks can sometimes be dominated by individual high-power interfering signals. Moreover, in Fig. 3 we compare the instantaneous interference power cumulative distribution functions (CDFs) calculated by the numerical method and Monte-Carlo (MC) simulations. A good match is found between the two CDF curves, demonstrating the correctness of our derivations.

Furthermore, we analyze the impact of some parameters on the proposed interference model in Figs. 4–7. In Fig. 4, the probability of instantaneous interference power within the range from 0 to 2.5×10^{-11} watt decreases with the increase

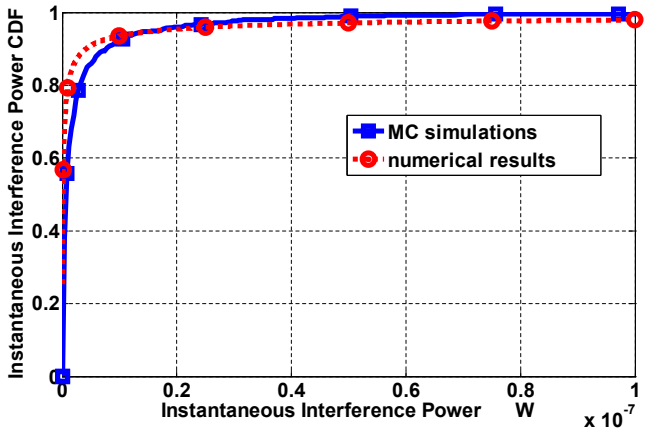

Fig. 3. Comparison of numerical results and MC simulations for the instantaneous interference power CDFs.

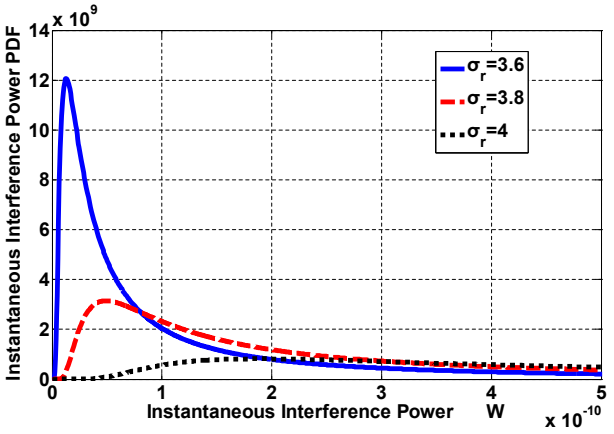

Fig. 5. Impact of the path loss coefficient parameter σ_r on the PDF of the aggregated interference.

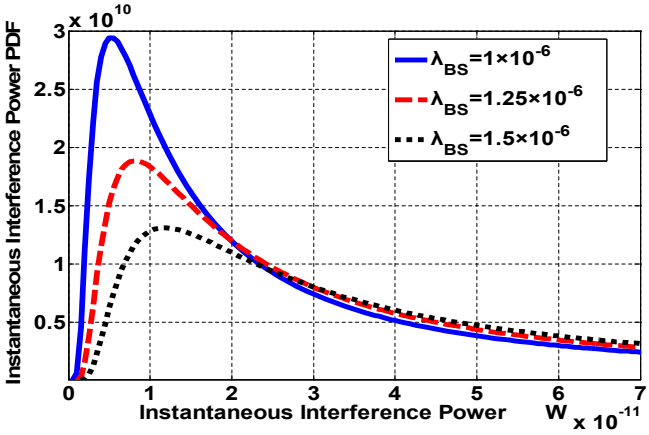

Fig. 4. Impact of the density parameter λ_{BS} of base stations on the PDF of the aggregated interference.

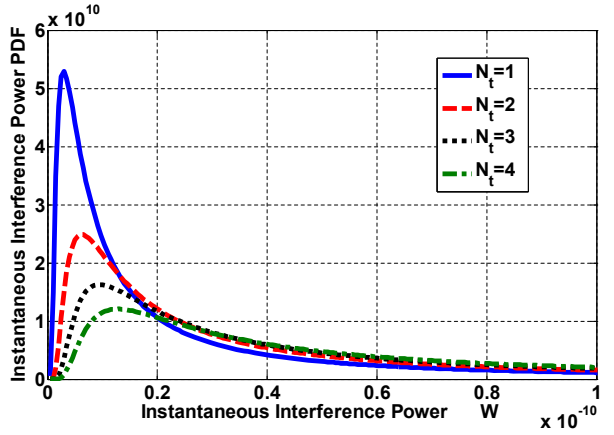

Fig. 6. Impact of the number of transmission antennas per interfering transmitter N_t on the PDF of the aggregated interference.

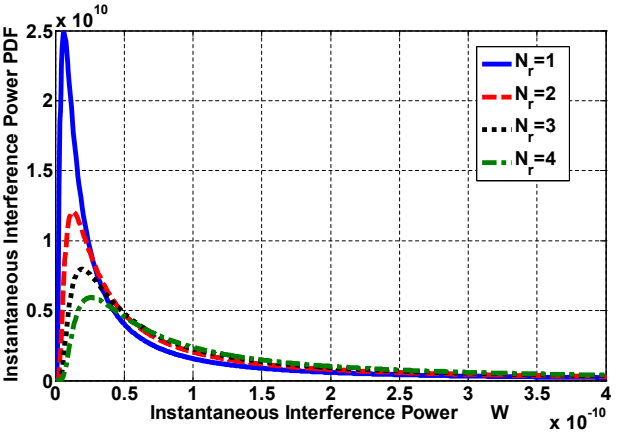

Fig. 7. Impact of the number of receiving antennas per user N_r on the PDF of the aggregated interference.

of the BS density parameter λ_{BS}. When the instantaneous interference power exceeds 2.5×10^{-10} watt, the probability of instantaneous interference power increases with the increase of λ_{BS}. Fig. 5 illustrates that when the instantaneous interference power is less than 0.8×10^{-10} watt, the PDF increases with the increase of the path loss coefficient parameter σ_r. The probability of instantaneous interference power gradually decreases with the increase of σ_r when the instantaneous interference power is larger than 0.8×10^{-10} watt. Fig. 6 demonstrates that the probability of instantaneous interference power decreases with the increase of the number of transmission antennas N_t per interfering transmitter when the instantaneous interference power is less than 0.12×10^{-10} watt. If the instantaneous interference power exceeds 0.12×10^{-10} watt, the trend is reversed. In Fig. 7, the probability of instantaneous interference power decreases with the increase of the number of receiving antennas N_r per user when the instantaneous interference power is smaller than 0.3×10^{-10} watt. After this turning point, the probability of instantaneous interference power gradually increases with the increase of N_r. Based on Figs. 4–7 and the alpha stable process theory [32], [33], we observe that these four parameters can significantly influence the burstiness of the aggregated interference in multi-cell MIMO cellular networks.

III. Capacity of Multi-cell MIMO Cooperative Cellular Networks

A. Cooperative System

Based on the proposed interference model, we further investigate the capacity of a multi-cell MIMO cooperative cellular network. The multi-cell MIMO cellular network considered in this paper is as follows: in the two dimensional given region,

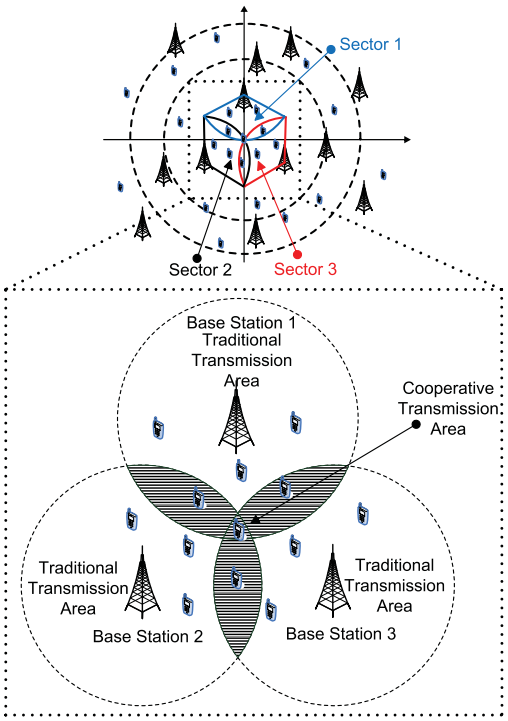

Fig. 8. A cooperative system with co-channel interference.

there are infinite BSs with N_t antennas and user terminals with N_r antennas. The location of interfering BSs is assumed to follow a Poisson spatial distribution. Every cell only has one BS. Without loss of generality, the three closest BSs are selected for cooperative transmission and the three closest BSs are located in a triangle structure. Furthermore, every BS is assumed to have three sectors and three adjacent sectors in different BSs are configured as a hexagon cooperative cluster structure as shown in Fig. 8. Therefore, the three closest BSs are called the cooperative BSs and these three adjacent sectors are called a cooperative cluster. In the following simulations, the number of cooperative BSs is not fixed to three and we further analyze the cooperative transmission performance with the number of cooperative BSs changing from 1 to 3. The cooperative transmission is limited in the overlapping areas of the cells and this area is called cooperative transmission area. The rest of the area is called traditional transmission area. To explicitly describe the cooperative cluster structure, a detailed cooperative cluster structure with three cooperative BSs is zoomed in Fig. 8. To simplify the analysis, our capacity analysis of multi-cell MIMO cellular networks is limited to a cooperative cluster. Perfects channel state information (CSI) in the cooperative cluster is assumed to be available for every cooperative BS [21]. Considering that the interference has great impact on the cell-edge users in the multi-cell MIMO cellular network, this paper focuses on the downlink capacity of cell-edge users in the cooperative transmission area. In the cell-edge overlapping area, K users are assumed to simultaneously receive the desired signal from the cooperative BSs $N_b \in [1,3]$ and the number of other users in this multi-cell MIMO cellular network is denoted as $K^{'}$. In the following numerical analysis, different numbers of cooperative BSs N_b correspond to different cooperative transmission solutions.

B. Downlink Capacity of Multi-cell MIMO Cooperative Cellular Network

For analytical tractability, all wireless channels in the multi-cell MIMO cellular network are assumed to be Nakagamim fading channels with path loss. This assumption has been adopted in many wireless communication studies (e.g., [34]–[38]) and a recent study [39] has shown that shadowing effect does not cause major changes in the capacity PDF. Without considering cooperative transmission, the signal y_k received by the cell-edge user UE_k can be expressed as [17]

$$y_k = \sum_{cb=1}^{N_b} \mathbf{h}_{cb,k,c}\mathbf{x}_{cb,k,c} + \sum_{cb=1}^{N_b} \mathbf{h}_{cb,k,c} \sum_{j=1,j\neq k}^{K} \mathbf{x}_{cb,j,c} + \sum_{b=1}^{\infty} \mathbf{h}_{b,k,\overline{c}} \sum_{j=1}^{K^{'}} \mathbf{x}_{b,j,\overline{c}} + \mathbf{n}_0. \tag{9a}$$

On the right side of (9a), the first term is the expected signal for the UE_k, the second term is the aggregated interference signal from the cooperative cluster c, the third term is the aggregated interference signal from the cluster $\overline{c}$, where $\overline{c}$ is the complement cluster of the cluster c, i.e., one of all other clusters excluding the cooperative cluster $\overline{c}$, and the fourth term $\mathbf{n}_0$ is the additive white Gaussian noise (AWGN) in the wireless channel. Where $\mathbf{h}_{cb,k,c}$ is the channel matrix between the cooperative BS cb and the user UE_k in the cooperative cluster c, $\mathbf{x}_{cb,k,c}$ is the signal vector from the cooperative BS cb to the user UE_k in the cooperative cluster c, $\mathbf{h}_{b,k,\overline{c}}$ is the channel matrix between the user UE_k and the interfering BS b in the cluster $\overline{c}$, $\mathbf{x}_{b,k,\overline{c}}$ is the signal vector from the interfering BS b in the cluster $\overline{c}$ to the user UE_k in the cluster c.

Considering the maximum ratio transmission / maximum ratio combining (MRT/MRC) approaches used in multi-cell MIMO cellular networks [40], [41], the interference in the cooperative cluster is eliminated and the signal y_k received by the cell-edge user UE_k can be expressed as

$$y_k = \sum_{cb=1}^{N_b} \mathbf{h}_{cb,k,c}\mathbf{x}_{cb,k,c} + \sum_{b=1}^{\infty} \mathbf{h}_{b,k,\overline{c}} \sum_{j=1}^{K^{'}} \mathbf{x}_{b,j,\overline{c}} + \mathbf{n}_0. \tag{9b}$$

Without changing the nature of the problem, we simply assume that all the weighted coefficients used for receive antennas in the MRT approach are equivalent. Moreover, the aggregated interference from different receive antennas is assumed to be statistically independent. In this case, the interference power from different receive antennas can be simply summed together, as shown in [40]. Therefore, the signal-to-interference-and-noise ratio (SINR) received by the user UE_k can be expressed by

$$\mathrm{SINR}_k = \frac{P_{\mathrm{ant}}\lambda_{\max}\left(\mathbf{H}_{k,c}\mathbf{H}_{k,c}^{H}\right)}{N_0 + \sum_{b=1}^{\infty} I_b} \tag{10a}$$

with

$$\mathbf{H}_{k,c} = [\mathbf{h}_{1,k,c}, \mathbf{h}_{2,k,c}, \cdots, \mathbf{h}_{N_b,k,c}] \tag{10b}$$

where P_{ant} and I_b are the transmission power of each antenna and the sum of the interference signal power transmitted by

the N_t interference sub-streams from the same interfering BS b outside the cooperative cluster c, respectively; $\mathbf{H}_{k,c}$ is the cooperative channel matrix in cooperative cluster c, which is composed by the sub-channel matrix from cooperative BSs to the user UE_k, $\lambda_{max}\left(\mathbf{A}\mathbf{A}^H\right)$ is the maximum singular value of the matrix $\mathbf{A}\mathbf{A}^H$.

Based on the Shannon theory, the capacity of the interference channel linking user UE_k in the multi-cell MIMO cellular network can be expressed by

$$C_k = \mathrm{B_w}\log_2\left[1+\frac{P_{\mathrm{ant}}\lambda_{\max}\left(\mathbf{H}_{k,c}\mathbf{H}_{k,c}^H\right)}{N_0+P_{\mathrm{ant}}\sum\limits_{b=1}^{\infty}\frac{1}{r_b^{\sigma_r}}w_b\left(\sum\limits_{i=1}^{N_r}\sum\limits_{j=1}^{N_t}\left|z_{b,i,j}\right|^2\right)}\right] \tag{11}$$

where $\mathrm{B_w}$ is the bandwidth in the wireless link. Considering that the power of AWGN N_0 can be ignored comparing to the power of the received interference signal [20], the average capacity of multi-cell MIMO cellular network can be given by

$$C_{Aver} \simeq \mathrm{B_w}\int_0^{\infty}\log_2\left(1+\eta\right)f(\eta)\mathrm{d}\eta \tag{12a}$$

with

$$\eta = \frac{S_d}{S_I} = \frac{P_{\mathrm{ant}}\lambda_{\max}\left(\mathbf{H}_{k,c}\mathbf{H}_{k,c}^H\right)}{P_{\mathrm{ant}}\sum\limits_{b=1}^{\infty}r_b^{-\sigma_r}w_b\left(\sum\limits_{i=1}^{N_r}\sum\limits_{j=1}^{N_t}\left|z_{b,i,j}\right|^2\right)} \tag{12b}$$

where S_d and S_I are the powers of the expected signal and aggregated interference signal, respectively. When the power of expected signal and aggregated interference signal are assumed to be statistically independent, the PDF of η is derived as

$$f(\eta) = \int_0^{\infty} f_{P^{Rx}}(z)f_d(\eta z)z\mathrm{d}z \tag{13}$$

where $f_{P^{Rx}}(z)$ is the PDF of aggregated interference signal and $f_d(\eta z)$ is the PDF of expected signal. Considering an urban macro-cell with rich scattering environment, i.e., $\sigma_r = 4$, let us substitute (8a) and (13) into (12a). Finally, a new exact downlink average capacity of multi-cell MIMO cellular network with co-channel interference is derived as

$$C_{Aver} = \mathrm{B_w}\sqrt{\frac{\gamma^2}{2\pi}}\int_0^{\infty}\log_2\left(1+\eta\right) \times\left(\int_0^{\infty}e^{-\gamma^2/2z}z^{-1/2}f_d(\eta z)\mathrm{d}z\right)\mathrm{d}\eta \tag{14a}$$

where γ is given by (8b). If only one BS transmitting expected signals in the cooperative cluster c exists, (14a) is simplified as a downlink average capacity of point-to-point MIMO system with co-channel interference by (14b) and (14c)

$$C_{Aver} = \mathrm{B_w}\int_0^{\infty}\log_2(1+\gamma_k)f(\gamma_k)d\gamma_k \tag{14b}$$

with

$$\gamma_k = \frac{P_{ant}}{P_{ant}\sum\limits_{b=1}^{\infty}r_b^{-\sigma_r}w_b\left(\sum\limits_{i=1}^{N_r}\sum\limits_{j=1}^{N_t}\left|z_{b,i,j}\right|^2\right)}\lambda_{\max}\left(\mathbf{h}_{1,k,c}\mathbf{h}_{1,k,c}^H\right). \tag{14c}$$

C. Closed-form Downlink Capacity of Multi-cell MISO Cellular Network

Because it is easier to integrate multiple antennas into the BSs than the user terminals in practice, in this section we further derive a new closed-form downlink average capacity for cell-edge users in a multi-cell MISO cooperative cellular network with co-channel interference.

In a cooperative cluster, one user can simultaneously receive the desired signals and interfering signals transmitted from cooperative BSs. To simplify our derivation, the time/frequency division multiple access (T/FDMA) or some such orthogonal strategies are assumed to be used in the cooperative intra-cluster, i.e., the multi-user interference within a single cooperative cluster is assumed to be negligible. Moreover, the power transmitted by every antenna in one BS is normalized to 1, i.e., $P_{\mathrm{ant}} = 1$. To calculate the downlink capacity of multi-cell MISO cellular network, we should first get the signal covariance transmitted to the user UE_k by different BSs in the cooperative cluster c, which has been derived in the Appendix and is expressed by

$$\mathbf{R}_{xx} = P_{\mathrm{ant}}\sum_{cb=1}^{N_b}\sum_{j=1}^{N_t^c}\frac{1}{r_{cb}^{\sigma_r}}\left|z_{cb,j}\right|^2 = \sum_{cb=1}^{N_b}\sum_{j=1}^{N_t^c}\frac{1}{r_{cb}^{\sigma_r}}\left|z_{cb,j}\right|^2 \tag{15}$$

where N_t^c is the number of cooperative antennas transmitting the desired signal and r_{cb} is the distance between the cooperative BS cb and a cell-edge user.

For a single cell MISO cellular network, the downlink capacity of user UE_k is typically presented as follows [42]

$$C_k = \mathrm{B_w}\log_2\left(1+\frac{\mathbf{R}_{xx}}{N_0+P^{R_X}}\right) \tag{16}$$

where P^{R_X} is the aggregated interference.

Based on the assumption in the Appendix, the interfering signals and the desired signals from different cooperative BSs in the cooperative cluster c to the user UE_k are assumed to be uncorrelated. Ideally, the interference within the cooperative cluster can be cancelled completely. Therefore, from the proposed interference model in (2), the aggregated interference in a multi-cell MISO cellular network is further expressed as follows

$$P^{R_X} = P_{\mathrm{ant}}\sum_{b=1}^{\infty}\sum_{j=1}^{N_t}\frac{1}{r_b^{\sigma_r}}\left|z_{b,j}\right|^2 = \sum_{b=1}^{\infty}\sum_{j=1}^{N_t}\frac{1}{r_b^{\sigma_r}}\left|z_{b,j}\right|^2 \tag{17}$$

where r_b is the distance between the interfering BS b and the cooperative cluster and the locations of interfering BSs are governed by the Poisson spatial distribution, $z_{b,j}$ is a random variable following the Nakagami-m distribution and represents a signal passing through the Nakagami-m fading channel from antenna j at interfering BS b.

Furthermore, we substitute (15) and (17) into (16). Considering the path loss coefficient $\sigma_r = 4$ in the urban macro-cell with rich scattering environment, the new downlink capacity of multi-cell MISO cooperative cellular network with co-channel interference is given by

$$C_k = \mathrm{B_w}\log_2\left(1+\frac{\sum_{cb=1}^{N_b}\sum_{j=1}^{N_t^c}\frac{1}{r_{cb}^4}\left|z_{cb,j}\right|^2}{N_0+\sum_{b=1}^{\infty}\sum_{j=1}^{N_t}\frac{1}{r_b^4}\left|z_{b,j}\right|^2}\right). \tag{18}$$

In this paper, we focus on cell-edge users located in cooperative areas of multi-cell MISO cellular network. Therefore the distances r_{cb} between cooperative BSs and cell-edge users can be approximatly treated as equivalent. Furthermore, the path loss between cooperative BSs and users is approximated as a constant. To simplify the notation, we define

$$\eta' = \frac{S_d'}{S_I'} = \frac{\sum_{cb=1}^{N_b}\sum_{j=1}^{N_t^c}\left|z_{cb,j}\right|^2}{\sum_{i=1}^{\infty}\sum_{j=1}^{N_t}\frac{1}{r_i^4}\left|z_{i,j}\right|^2}. \tag{19}$$

Considering that the power of AWGN N_0 can be ignored compared to the power of the received interference P^{R_X} [20], (18) can be concisely expressed as

$$C_k \approx \mathrm{B_w}\log_2\left(1+r_{cb}^{-4}\eta'\right). \tag{20}$$

The Nakagami shaping factor m is configured as $m = 1$ for both desired signals and interfering signals. Each signal passing through the Nakagami fading channel is assumed to follow an i.i.d complex Gaussian distribution with zero mean and variance of 1, i.e., $z_{cb,j} \sim CN(0,1)$. Thus, the PDF of aggregated expected signal S_d' can be simplified as

$$f_d(x) = \frac{x^{N_bN_t^c-1}e^{-x/2}}{(N_bN_t^c-1)!2^{N_bN_t^c}}, x>0. \tag{21}$$

On the other hand, the PDF of aggregated interference S_I' with complex channel coefficients has already been derived in (7a). We assume that the interference signal passes through the same channel condition of the desired signal, i.e. the Nakagami-m fading channels with path loss, thus the PDF of the aggregated interference S_I' can be further simplified as

$$f_{P^{Rx}}(y) = \sqrt{\frac{\gamma^2}{2\pi}}\frac{e^{-\gamma^2/(2y)}}{y^{3/2}}, y>0 \tag{22a}$$

with

$$\gamma = \frac{2\Gamma\left(\frac{3}{2}\right)\pi\lambda_{BS}\Gamma(N_t+\frac{1}{2})}{(N_t-1)!}. \tag{22b}$$

In this paper, the expected signal S_d' and the aggregated interference S_I' are assumed statistically independent. Therefore the PDF of η' is given by

$$f(\eta') = \frac{\sqrt{\frac{\gamma^2}{2\pi}}}{(N_bN_t^c-1)!2^{N_bN_t^c}}\eta'^{N_bN_t^c-1} \times\int_0^{\infty}\exp\left(-\frac{\gamma^2}{2z}-\frac{\eta' z}{2}\right)z^{v-1}\mathrm{d}z. \tag{23}$$

Based on the table of integral in [27], (23) can be simplified as

$$f(\eta') = \frac{\gamma^{v+1}\sqrt{2/\pi}}{(N_bN_t^c-1)!2^{N_bN_t^c}}\eta'^{\frac{v-1}{2}}K_v\left(\gamma\sqrt{\eta'}\right) \tag{24a}$$

with

$$v = N_bN_t^c - \frac{1}{2}. \tag{24b}$$

Based on (24a)–(24b), the average channel capacity can be derived by calculating the expectation of (20). After normalizing the bandwidth $\mathrm{B_w}=1$, the normalized downlink average capacity of multi-cell MISO cooperative cellular network with co-channel interference is derived as

$$\begin{aligned}\overline{C}_{Aver} &= \frac{C_{Aver}}{\mathrm{B_w}}\\ &= p\int_0^{\infty}\log_2\left(1+r_{cb}^{-4}\eta'\right)\eta'^{\frac{v-1}{2}}K_v\left(\gamma\sqrt{\eta'}\right)\mathrm{d}\eta'\end{aligned} \tag{25a}$$

with

$$p = \frac{\gamma^{v+1}\sqrt{2/\pi}}{(N_bN_t^c-1)!2^{N_bN_t^c}} \tag{25b}$$

where v and γ are given by (24a) and (22b), respectively.

The integral in (25a) will cause some difficulties in the practical engineering calculation. To simplify the expression, we will utilize a special function, the so-called Meijer's G-function, which is defined as [43]

$$\begin{aligned}&G_{p,q}^{m,n}\left(x\left|\begin{array}{c}a_1,\cdots a_p\\ b_1,\cdots b_q\end{array}\right.\right)\\ &=\frac{1}{2\pi\Im}\int_0^{\infty}\frac{\prod_{j=1}^{m}\Gamma(b_j-s)\prod_{j=1}^{n}\Gamma(1-a_j+s)}{\prod_{j=m+1}^{q}\Gamma(1-b_j+s)\prod_{j=n+1}^{p}\Gamma(a_j-s)}x^s\mathrm{d}s\end{aligned} \tag{26}$$

where $0\le m\le q$, $0\le n\le p$, and $\Im=\sqrt{-1}$. The $\log_2(\cdot)$ and $K_v(\cdot)$ functions can be expressed as a special form of Meijer's G-function. So, (25a) can be expressed by a new form with Meijer's G-functions

$$\begin{aligned}\bar{C}_{Aver} = \frac{p}{2\ln 2}\int_0^{\infty}&\eta'^{\frac{v-1}{2}}G_{2,2}^{1,2}\left(r_{cb}^{-4}\eta'\left|\begin{array}{c}1,1\\1,0\end{array}\right.\right)\\ &\times G_{0,2}^{2,0}\left(\begin{array}{c}\\ \frac{v}{2},-\frac{v}{2}\end{array}\left|\frac{\gamma^2\eta'}{4}\right.\right)\mathrm{d}\eta'.\end{aligned} \tag{27}$$

Based on the table of integral in [28], (25a) can be further simplified as follows by eliminating the integral calculation and parameter simplification

$$\bar{C}_{Aver} = \frac{p}{2\ln 2}r_b^{2(v+1)}G_{2,4}^{4,1}\left(\begin{array}{c}-\frac{v+1}{2},\frac{1-v}{2}\\ -\frac{v}{2},\frac{v}{2},-\frac{v+1}{2},-\frac{v+1}{2}\end{array}\left|\frac{\gamma^2r_b^4}{4}\right.\right) \tag{28}$$

where p, v and γ are given by (25b), (24a) and (22b), respectively.

IV. Simulation Results and Discussions For MISO System Capacities

Based on the normalized downlink average capacity of the multi-cell MISO cellular network with co-channel interference derived in Section III, the effect of various system parameters on the capacity will be analyzed and compared by numerical calculations and MC simulations in this section. In what follows, some parameters of the capacity model are configured as follows: $\sigma_{dB} = 7$, $m = 1$, $\sigma_r = 4$, $\sigma^2 = 1$, $\lambda_{BS} = 1/(\pi * 500^2)$, and $r_{cb} = 500$ m. Every BS has no more than four antennas used for cooperative transmission, but in the default cooperative transmission scheme, every cooperative BS just uses two antennas. To simplify numerical analysis, the cooperative transmission among BSs is assumed as the aggregation of desired signals transmitted by the multi-antennas from different BSs, i.e., desired signals are accumulated directly by numerical calculation. The detailed cooperative transmission scheme, e.g., the joint pre-coding scheme [16], is not included in this paper for conciseness.

In Fig. 9, we first analyze the impact of the number of cooperative transmission (Co-Tx) antennas per cooperative BS on the normalized downlink average capacity. The number of cooperative BSs is noted as CBS. In numerical calculations, we obtain the following results. Without cooperative BSs, i.e., $CBS = 1$, the capacity is improved by 209% when the number of Co-Tx antennas per cooperative BS is increased from 1 to 4. With two cooperative BSs, i.e., $CBS = 2$, the capacity is improved by 173% when the number of Co-Tx antennas per cooperative BS is increased from 1 to 4. With three cooperative BSs, i.e., $CBS = 3$, the capacity is improved by 153% when the number of Co-Tx antenna per cooperative BS is increased from 1 to 4. When only one antenna per cooperative BS is used to transmit expected signals, the capacity is improved by 80.99% when CBS is increased from 1 to 2; the capacity is improved by 37.88% when CBS is increased from 2 to 3. When four antennas per cooperative BS is used to transmit expected signals, the capacity is improved by 50.9% when CBS is increased from 1 to 2; the capacity is improved by 27.62% when CBS is increased from 2 to 3. Therefore, with the increasing number of antennas or cooperative BSs, the capacity performance is improved, but the increment of capacity performance is decreased. Compared with results from MC simulations, these numerical results are validated.

In Fig. 10, the impact of the density parameter of interfering BSs λ_{BS} on the normalized downlink average capacity is analyzed by numerical calculations and MC simulations. Based on numerical calculations, the following results are analyzed. Without cooperation BSs, i.e., $CBS = 1$, the capacity decreases by 94.86% when the density parameter of interfering BSs is increased from $0.5 \times 10^{-6}\mathrm{m}^{-2}$ to $3.5 \times 10^{-6}\mathrm{m}^{-2}$. In the case of two cooperative BSs, i.e., $CBS = 2$, the capacity decreases by 93.40% when the density parameter of interfering BSs is increased from $0.5 \times 10^{-6}\mathrm{m}^{-2}$ to $3.5 \times 10^{-6}\mathrm{m}^{-2}$. In the case of three cooperative BSs, i.e., $CBS = 3$, the capacity decreases by 92.22% when the density parameter of interfering BSs is increased from $0.5 \times 10^{-6}\mathrm{m}^{-2}$ to $3.5 \times 10^{-6}\mathrm{m}^{-2}$. These results indicate that the density parameter of interfering BSs

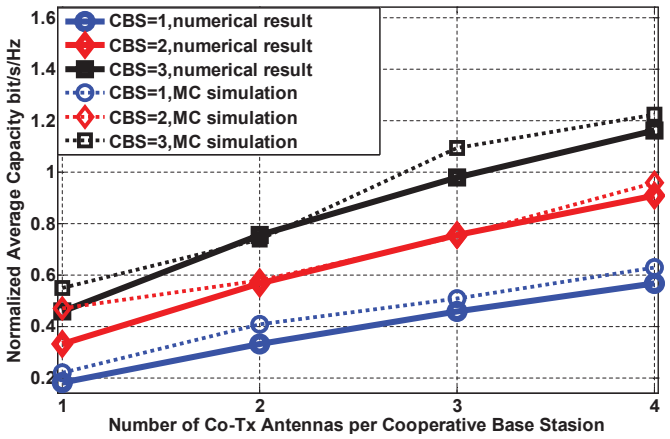

Fig. 9. Impact of the number of Co-Tx antennas per cooperative BS on the normalized downlink average capacity of multi-cell MISO cellular networks.

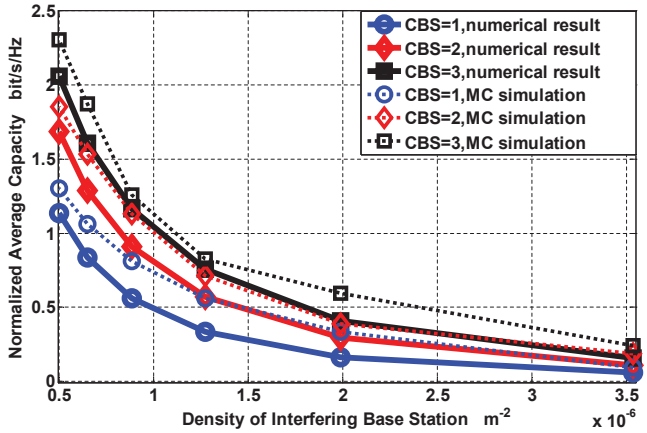

Fig. 10. Impact of the density of interfering BSs on the normalized downlink average capacity of multi-cell MISO cellular networks.

can obviously decrease the capacity performance in a multi-cell MISO cellular network. When the density parameter of interfering BSs is configured as $0.5 \times 10^{-6}\mathrm{m}^{-2}$, compared with the capacity of one BS, the average capacity of two cooperative BSs improves by 48.76%; compared with the average capacity of two cooperative BSs, the average capacity of three cooperative BSs improves by 21.99%. Hence, with the specified density of interfering BSs, the cooperative transmission can improve the capacity performance, but this gain of capacity performance is decreased with the increasing number of cooperative BSs. When the density of interfering BSs is configured as $3.5 \times 10^{-6}\mathrm{m}^{-2}$, compared with the capacity of one BS, the average capacity of two cooperative BSs improves by 90.98%; compared with the average capacity of two cooperative BSs, the average capacity of three cooperative BSs improves by 43.81%. Therefore, compared with the capacity performance in the small density of interfering BSs, the cooperative transmission can obviously improve the capacity performance with a high density of interfering BSs. From MC simulations, we can obtain consistent results with numerical calculations.

Fig. 11 shows the normalized downlink average capacity without and with AWGN, computed by means of numerical calculations and MC simulations, respectively. In the most

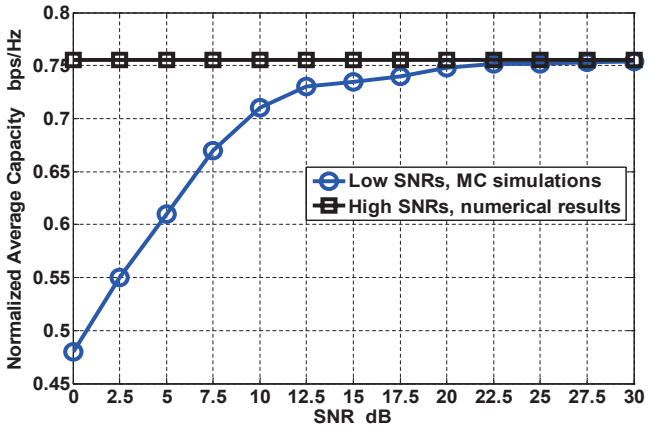

Fig. 11. Impact of the AWGN on the normalized downlink average capacity of multi-cell MISO cellular networks.

cases, the power of AWGN N_0 can be ignored comparing with the power of the received interference signal [20] in multi-cell MISO cellular networks. Based on this assumption, a closed-form normalized downlink average capacity of multi-cell MISO cooperative cellular networks i.e., (28) is derived. This result can be used in high signal-to-noise ratio (SNR) scenarios. However, in some special cases, the power of AWGN N_0 can not be ignored in multi-cell MISO cellular networks. Hence, the capacity performance with low SNR in multi-cell MISO cooperative cellular networks is analyzed by MC simulations. Based on default parameters in this section, we compare the normalized downlink average capacity without or with AWGN in Fig. 11. From Fig. 11, the AWGN has great impact on the normalized downlink average capacity when the SNR is less than or equal to 12.5 dB; however, the AWGN has little impact on the normalized downlink average capacity when the SNR is larger than 12.5 dB.

V. Conclusions

In this paper, we have derived the exact downlink average capacity of multi-cell MIMO cellular network with co-channel interference. Furthermore, the analytical closed-form normalized downlink average capacity for cell-edge users in a multi-cell MISO cooperative cellular network with co-channel interference has been derived and analyzed numerically. To derive this downlink capacity model, an analytical co-channel interference model has been proposed for multi-cell MIMO cellular networks. Based on the proposed closed-form normalized downlink average capacity of multi-cell MISO cooperative cellular network with co-channel interference, simulation results have shown that the cooperative transmission can improve the capacity performance in most cases, but the capacity gains diminish with the increasing number of cooperative BSs or antennas. Our analysis indicates that the cooperative transmission can efficiently enhance the capacity performance, especially in scenarios with high densities of interfering BSs. For our future work, we will explore the impact of different cooperative transmission schemes on the system capacity.

Appendix A
Derivation of (15)

In this appendix, we derive the covariance of expected signals at the user UE_k. In one cooperative cluster, one cell-edge user can receive expected signals and unexpected signals transmitted from different cooperative BSs. To simplify the complex of derivation, expected signals and unexpected signals from different cooperative BSs in the same cooperative cluster c received by the user UE_k are assumed to be uncorrelated, which can be expressed as follows

$$\mathbb{E}\left[\mathbf{x}_{cb,k,c}\left(\mathbf{x}_{cb',k,c}\right)^H\right] = 0, \forall cb \neq cb' \tag{29}$$

where $\mathbb{E}(\cdot)$ is the expectation calculation operator, $\mathbf{x}_{cb,k,c}$ is the expected signal transmitted to the user UE_k by BS cb in the cooperative cluster c, $\mathbf{x}_{cb',k,c}$ is the unexpected signal transmitted to the user UE_k by the BS cb' in the cooperative cluster c. Moreover, the expected signal $\mathbf{x}_{cb,k,c}$ is assumed to have i.i.d. complex Gaussian entries with zero mean and unit variance. Therefore, the covariance of the expected signal $\mathbf{Q}_{cb,k,c}$ can be given by

$$\mathbf{Q}_{cb,k,c} = \mathbb{E}\left[\mathbf{x}_{cb,k,c}\mathbf{x}_{cb,k,c}^H\right] = P_{\mathrm{ant}}\mathcal{I} \tag{30}$$

where $\mathcal{I}$ is the unite matrix. Furthermore, in the scenario of multi-cell MISO cooperative cellular network, the signal covariance transmitted to the user UE_k by different BSs in the cooperative cluster c can be expressed by

$$\begin{aligned} R_{xx} = {} & \mathbb{E}\left(\sum_{cb=1}^{N_b}\mathbf{h}_{cb,k,c}\mathbf{x}_{cb,k,c}\left(\mathbf{x}_{cb,k,c}\right)^H\left(\mathbf{h}_{cb,k,c}\right)^H\right) \\ & + \mathbb{E}\left(\sum_{cb=1}^{N_b}\sum_{\substack{cb'=1 \\ cb'\neq cb}}^{N_b}\mathbf{h}_{cb,k,c}\mathbf{x}_{cb,k,c}\left(\mathbf{x}_{cb',k,c}\right)^H\left(\mathbf{h}_{cb',k,c}\right)^H\right) \end{aligned} \tag{31}$$

where $\mathbf{h}_{cb,k,c}$ and $\mathbf{h}_{cb',k,c}$ are the channel matrices from the BS cb and BS cb' to the user UE_k in the cooperative cluster c, respectively. Base on (29) and (30), we only consider the Nakagami-m fading effect and (31) can be further simplified as

$$\begin{aligned} R_{xx} &= \mathbb{E}\left(\sum_{cb=1}^{N_b}\mathbf{h}_{cb,k,c}\mathbf{x}_{cb,k,c}\left(\mathbf{x}_{cb,k,c}\right)^H\left(\mathbf{h}_{cb,k,c}\right)^H\right) \\ &= \sum_{cb=1}^{N_b}\left[\mathbf{h}_{cb,k,c}\mathbf{Q}_{cb,k,c}\mathbf{h}_{cb,k,c}^H\right] \\ &= P_{ant}\sum_{cb=1}^{N_b}\left\|\mathbf{h}_{cb,k,c}\right\|_F^2 \\ &= P_{ant}\sum_{cb=1}^{N_b}\sum_{j=1}^{N_t^c}\left|\mathbf{h}_{cb,j}\right|^2 \\ &= P_{ant}\sum_{cb=1}^{N_b}\sum_{j=1}^{N_t^c}\frac{1}{r_{cb}^{\sigma^r}}\left|z_{cb,j}\right|^2. \end{aligned} \tag{32}$$

This completes the derivation.

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