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# Cooperative Energy Efficiency Modeling and Performance Analysis in Co-Channel Interference Cellular Networks

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**Cooperative communication technologies can improve the system throughput energy efficiency and reliability in dynamic wireless networks. For practical multi-cell multi-antenna mobile cellular networks, co-channel interference is a critical issue affecting cooperative transmission (Co-Tx) performance. In this paper, we first derive a cooperative outage probability model and a cooperative block error rate (BLER) model incorporating a binary differential phase shift keying modulation for performance analysis in such cooperative cellular networks. Based on them, a cooperative energy efficiency model is proposed and analyzed under different Co-Tx scenarios, interference levels and wireless channel conditions. As demonstrated by numerical results, our analytical models show that Co-Tx is an effective approach to mitigate co-channel interference and improve the energy efficiency, BLER and overall outage probability performance in multi-cell multi-antenna cooperative cellular networks.**

*Keywords: energy efficiency; co-channel interference; outage probability; block error rate; cooperative transmission*

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## 1. INTRODUCTION

In recent years, cooperative communication technologies have been actively researched and developed to improve system throughput, service coverage, and transmission diversity and reliability in dynamic wireless networks. In the physical layer, cooperative multi-input multi-output (MIMO) technology coordinates multiple distributed antennas at different radio devices to achieve significant performance gains, in terms of spectrum efficiency and service coverage [1]. To enable the accurate design and performance evaluation of cooperative MIMO systems, a comprehensive survey and discussion of cooperative MIMO channel models is provided in [2]. A cooperative transmission (Co-Tx) scheme that makes use of multi-user detection and network coding techniques is developed and studied in [3]. It has high spectral efficiency, diversity order and coding gain, and can offer near optimal bit error rate (BER) performance in an uplink synchronous code division multiple access (CDMA) system. In [4], a two-user cooperation scheme with adaptive power allocations between source, relay and destination nodes is introduced and analyzed. Numerical and simulation results show that it can achieve a maximum cooperative diversity order of 2 and better BER performance than non-cooperative systems. In the medium access control layer, a cooperative scheduling scheme is proposed in [5] for CDMA cellular networks, in order to achieve better fairness and multi-user diversity gain by statistically balancing downlink throughput performance among different users. As demonstrated in [6], cooperative communications enabled by relays can extend the coverage area and improve the spectrum efficiency, compared with a direct transmission scheme. Based on a new multi-hop mesh Co-Tx structure, a novel distributed multi-hop cooperative communication scheme for data dissemination in dense sensor networks is proposed in [7]. The challenges of optimal relay assignment and the potential applications of cooperative communications with relay selection in multi-hop wireless sensor networks are presented in [8].

In addition to cooperative communications, energy efficiency is becoming increasingly important for the design, implementation and operation of next generation mobile communication systems, such as world interoperability for microwave access, and long-term evolution-advanced and international mobile telecommunications-advanced systems [9]. It is envisaged that new energy-efficient system design approaches will greatly reduce not only the overall system energy consumption and operational costs, but also the green-house gas emission and carbon footprint of future mobile communication services and applications. Owing to the limitation of spectrum resource in wireless communication systems, in most cases, high energy efficiency performance should be pursued under a specified spectrum efficiency threshold in cellular wireless networks [10]. In [11], Akhtman and Hanzo discuss the trade-off relationship between energy efficiency and spectrum efficiency in cellular networks and showed that the overall network performance is greatly affected by selected network optimization principles. It is found in [12] different deployment strategies have a significant impact on the energy consumption of cellular networks, e.g. energy saving in deploying micro cells is moderate under full-load scenarios and strongly depends on the offset energy consumption of both macro and micro cells. The energy efficiency in fading channels is analyzed in [13] by considering effective capacity as a measure of the maximum throughput under certain statistical QoS constraints. Numerical results show that strictly higher bit energy values are needed in the wideband regime, especially in the presence of sparse multi-path fading with limited degrees of freedom. Considering frequency selective channels in orthogonal frequency division multiple access systems, a new scheme adapting the overall transmit power and its allocation according to the statuses of all subchannels and circuit power consumption is proposed and analyzed in [14] to maximize energy efficiency performance. Furthermore, an energy-efficient power optimization scheme for interference-limited wireless communication systems is developed in [15] for a simple two-user network with ideal user cooperation. In addition, the impact of co-channel interference on the energy efficiency of multi-cell cellular wireless networks has been studied in [16] under a simple channel model.

In this paper, we consider practical multi-cell multi-antenna cooperative cellular networks with co-channel interference and aim to tackle research challenges in modeling and analyzing the impact of Co-Tx technology on outage probability, block error rate (BLER) and energy efficiency performance. Specifically, the novelties and key contributions of this paper are summarized as follows.

(1) A cooperative outage probability model is derived for performance analysis in wireless fading channels.
(2) Based on a binary differential phase shift keying (BDPSK) modulation, a BLER model is derived for performance analysis.
(3) Regarding some practical requirements on real system deployment and operation, a cooperative energy efficiency model is proposed and its relationships with the number of cooperative base stations (BSs) and instantaneous channel conditions are fully investigated.

The remainder of this paper is organized as follows. In Section 2, a cooperative outage probability model is derived for performance analysis of multi-cell multi-antenna cooperative cellular networks with co-channel interference. In Section 3, a BDPSK modulation is adopted in developing a cooperative BLER model. The impact of Co-Tx schemes on this model and the corresponding BLER performance are studied. In Section 4, a cooperative energy efficiency model with BDPSK modulation is proposed and analyzed under different cooperative scenarios and wireless channel conditions. Some interesting results are presented and discussed. Finally, Section 5 concludes the paper.

## 2. COOPERATIVE OUTAGE PROBABILITY MODELING AND PERFORMANCE ANALYSIS

To investigate the impact of interference on the outage probability of multi-cell multi-antenna cooperative cellular networks, a basic cooperative cellular network system is illustrated in Fig. 1. All BSs are equipped with $N_t$ antennas and distributed in a two-dimensional (2D) plane with a Poisson distribution. All user terminals are equipped with a single antenna and are randomly distributed into this 2D plane. Moreover, every cell has only one BS. Based on a Co-Tx scheme, one user is assumed to simultaneously receive the desired signal from $N_b$ adjacent BSs. In this section, we investigate the interference from BSs and evaluate the impact of interference on the user downlink outage probability with Co-Tx.

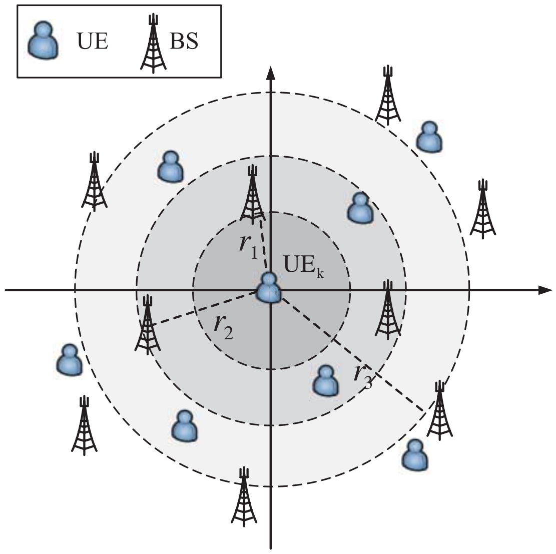


**FIGURE 1.** General background interference system.

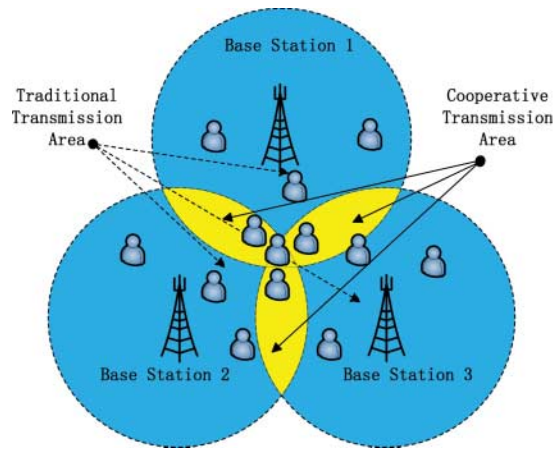


**FIGURE 2.** Co-Tx system structure.

## 2.1. Signal-to-interference ratio of multi-cell multi-antenna cooperative cellular networks

For a traditional single cell single antenna communication system, its capacity or throughput is limited by the signal-to-noise ratio and therefore it is also called the noise limited communication system. However, for a multi-antenna multi-user communication system, the capacity is limited by the signal-to-interference ratio (SIR) [17]. Based on the cooperative communication system in Fig. 1, we first investigate the SIR expression for multi-cell multi-antenna cooperative cellular networks with co-channel interference.

Assume that every subchannel includes the path loss and Nakagami-m fading, and is independent each other. This assumption has been adopted in many wireless communication studies (e.g. [18–20]). To realize the Co-Tx scheme in cooperative cellular networks, a detailed Co-Tx structure is shown in Fig. 2, $N_b = 1, 2, 3$ adjacent BSs can simultaneously transmit the expected signal to a specified user. Without loss of generality, we select one of the users $\mathrm{UE}_k$ ($k = 1, \ldots, \infty$) for detailed analysis. The signal $y_k$ received by the user $\mathrm{UE}_k$ can be expressed as follows [21]:

$$y_k = \sum_{b=1}^{N_b} \mathbf{h}_{b,k}\mathbf{x}_{b,k} + \sum_{\substack{b'=1 \\ b'\neq b}}^{\infty} \mathbf{h}_{b',k} \sum_{i=1}^{K} \mathbf{x}_{b',i} + n_0, \tag{1}$$

where $\mathbf{h}_{b,k}$ and $\mathbf{x}_{b,k}$ are the expected channel matrix and the expected signal vector from the BS $b$ to the user $\mathrm{UE}_k$, respectively, $\mathbf{h}_{b',k}$ is the interference channel matrix between the BS $b'$ and the user $\mathrm{UE}_k$, $\mathbf{x}_{b',i}$ is the interference signal vector between the BS $b'$ and the user $\mathrm{UE}_i$, $K$ is the number of receiving signal users excepting the user $\mathrm{UE}_k$, and $n_0$ is the additive white Gaussian noise (AWGN).

Assume that the maximum rate transmission/maximum rate combining approach is used in this multi-cell multi-antenna cooperative cellular network [22]. The traditional SINR received by the user $\mathrm{UE}_k$ can be expressed by

$$\mathrm{SINR}_k = \frac{P_{\mathrm{ant}}\lambda_{\max}(\mathbf{h}_{b,k}\mathbf{h}_{b,k}^H)}{\mathbf{n}_0 + \sum_{b'=1}^{\infty} I_{b'}}, \tag{2}$$

where $P_{\mathrm{ant}}$ is the transmission power of each antenna, assuming that all the antennas have the same transmission power, $\lambda_{\max}(\mathbf{AA}^H)$ is the maximum singular value of the matrix $\mathbf{AA}^H$ and $I_{b'}$ is the received interference signal power from the BS $b'$.

Considering the path loss and Nakagami-m fading channels, $\lambda_{\max}(\mathbf{h}_{b,k}\mathbf{h}_{b,k}^H)$ can be further extended by [23]:

$$\lambda_{\max}(\mathbf{h}_{b,k}\mathbf{h}_{b,k}^H) = \sum_{b=1}^{N_b}\sum_{j=1}^{N_t^c} \frac{|z_{b,j}|^2}{r_b^{\sigma}}, \tag{3}$$

where $N_t^c$ is the number of cooperative antennas transmitting the expected signal per BS, $r_b$ is the distance between the cooperative BS $b$ and the user $\mathrm{UE}_k$, $\sigma$ is the path loss coefficient in wireless channels and $z_{b,j}$ is the channel coefficient of the Nakagami-m fading channel from the transmission antenna $j$ of BS $b$ to the user $\mathrm{UE}_k$.

Assume that every subchannel is independent of each other. The aggregated interference power of multi-cell multi-antenna cooperative cellular networks can be expressed as follows:

$$\sum_{b'=1}^{\infty} I_{b'} = P_{\mathrm{ant}} \sum_{b'}^{\infty}\sum_{j=1}^{N_t} \frac{|z_{b',j}|^2}{r_{b'}^{\sigma}}, \tag{4}$$

where $r_{b'}$ is the distance between the interfering BS $b'$ and the user $\mathrm{UE}_k$, $z_{b',j}$ is the channel coefficient of the Nakagami-m fading channel from the transmission antenna $j$ of BS $b'$ to the user $\mathrm{UE}_k$.

In this paper, we focus on cell-edge users and the user $UE_k$ is assumed to be located at the cell-edge area of adjacent cooperative BSs. Therefore, distances between the adjacent cooperative BSs abd cell-edge users $r_b$ can be approximated as equivalent and configured as the radius of a cell. Without loss of generality, the path loss coefficient is chosen as $\sigma = 4$, which corresponds to an urban macro-cell with a rich scattering environment. In interference limited communication systems, such as a multi-cell multi-antenna cooperative cellular network, the AWGN power $\mathbf{n}_0$ can be ignored when it is compared with the received interference power $\sum_{b'=1}^{\infty} I_{b'}$. Furthermore, the SIR received by the user $UE_k$ can be expressed as follows:

$$\mathrm{SIR}_k = \frac{S_\mathrm{E}}{S_\mathrm{I}} = \frac{\sum_{b=1}^{N_b}\sum_{j=1}^{N_t^c} |z_{b,j}|^2/r_b^\sigma}{\sum_{b'}^{\infty}\sum_{j=1}^{N_t} |z_{b',j}|^2/r_{b'}^\sigma}, \quad (5)$$

where $S_\mathrm{E}$ is the expected cooperative signal power and $S_\mathrm{I}$ is the aggregated interference signal power.

To simplify the derivation process, the Nakagami shaping factor in wireless channels is configured as 1. Moreover, channel coefficients of Nakagami fading channels are assumed to follow an independent and identically distributed (i.i.d.) complex Gaussian distribution with zero mean and standard variance. Based on the derivation result in the Appendix, the probability density function (PDF) of the expected cooperative signal power $S_\mathrm{E}$ is given by

$$f_\mathrm{E}(x) = \frac{r_b^{4N_bN_t^c} x^{N_bN_t^c-1} e^{-r_b^4 x/2}}{(N_bN_t^c-1)!2^{N_bN_t^c}}, \quad x > 0. \quad (6)$$

Considering that the location of BSs is governed by a Poisson distribution with density parameter $\lambda_\mathrm{BS}$, the PDF of the aggregated interference signal power received by the user $UE_k$ is proved to follow an alpha stable distribution with the following characteristic function [24]:

$$\Phi(jw) = \exp\left(-|cw|^{1/2}\left[1 - j\,\mathrm{sign}(\omega)\tan\left(\frac{\pi}{4}\right)\right]\right) \quad (7a)$$

with

$$\mathrm{sign}(\omega) = \begin{cases} 1, & \omega > 0, \\ 0, & \omega = 0, \\ -1, & \omega < 0, \end{cases} \quad (7b)$$

$$c = \sqrt[0.5]{\lambda_\mathrm{BS} q \mathbf{E}(I_{b'}^{1/2})}, \quad (7c)$$

$$q = \frac{\pi}{2}\Gamma\left(\frac{3}{2}\right)\cos\left(\frac{\pi}{4}\right), \quad (7d)$$

$$\Gamma(x) = \int_0^\infty t^{\lambda-1} e^{-t}\, dt \quad (7e)$$

where $\mathbf{E}(\cdot)$ is the expectation operator and $c$ is the scale parameter in alpha stable distributions.

Based on the transformation in [25] and the inverse Fourier transform on the characteristic function of (7a), we can derive a new PDF expression of the aggregated interference signal power $S_\mathrm{I}$ as follows:

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

with

$$\gamma = \frac{2\pi\Gamma(3/2)\lambda_\mathrm{BS}\Gamma(N_t+1/2)}{(N_t-1)!}. \quad (8b)$$

In this paper, the expected cooperative signal power $S_\mathrm{E}$ and the aggregated interference signal power $S_\mathrm{I}$ are assumed to be statistically independent. Based on the transformation in [25], ultimately the PDF of the SIR received by the user $UE_k$ can be derived and given by

$$\begin{aligned} f_\mathrm{SIR}(y) &= \int_0^\infty f_\mathrm{I}(x) f_\mathrm{E}(yx) x\, dx \\ &= \frac{r_b^{2N_bN_t^c+1}\gamma^{v+1}\sqrt{2/\pi}}{(N_bN_t^c-1)!2^{N_bN_t^c}} y^{(v-1)/2} K_v(r_b^2\gamma\sqrt{y}) \end{aligned} \quad (9a)$$

with

$$v = N_bN_t^c - \tfrac{1}{2}, \quad (9b)$$

where $K_v(\cdot)$ is the modified Bessel function of the second kind with order $v$.

### 2.2. Cooperative outage probability model

From the PDF in (9a), we can now evaluate the outage probability in multi-cell multi-antenna cooperative cellular networks subjecting to Co-Tx and co-channel interference. The outage occurs when the received SIR falls below a given threshold $P_\mathrm{th}$. The cooperative outage probability $P_\mathrm{out}$ is given by

$$\begin{aligned} P_\mathrm{out}(y_\mathrm{th}) &= \int_0^{y_\mathrm{th}} f_\mathrm{SIR}(y)\, dy \\ &= \int_0^{y_\mathrm{th}} \frac{r_b^{2N_bN_t^c+1}\gamma^{v+1}\sqrt{2/\pi}}{(N_bN_t^c-1)!2^{N_bN_t^c}} y^{(v-1)/2} \\ &\quad \times K_v(r_b^2\gamma\sqrt{y})\, dy. \end{aligned} \quad (10)$$

Utilizing the transformation in [25], a new analytical cooperative outage probability model of multi-cell multi-antenna cooperative cellular networks is derived as

$$\begin{aligned} P_\mathrm{out}(y_\mathrm{th}) &= 2^v \frac{r_b^{2N_bN_t^c+1}\gamma^{v+1}\sqrt{2/\pi}}{(N_bN_t^c-1)!2^{N_bN_t^c}} y_\mathrm{th}^{1/2}(r_b^2\gamma)^{-v}\pi^{1/2} \\ &\quad \times \Gamma\left(v+\frac{1}{2}\right)[K_v(r_b^2\gamma y_\mathrm{th}^{1/2})L_{v-1}(r_b^2\gamma y_\mathrm{th}^{1/2}) \\ &\quad + L_v(r_b^2\gamma y_\mathrm{th}^{1/2})K_{v-1}(r_b^2\gamma y_\mathrm{th}^{1/2})] \end{aligned} \quad (11a)$$

with

$$L_v(x) = \frac{2(x/2)^v}{\sqrt{\pi}\Gamma(v+1/2)}\int_0^{\pi/2}\sinh(x\cos\varphi)(\sin\varphi)^{2v}\, d\varphi,$$
$$\mathrm{Re}(v) > -\frac{1}{2}, \quad (11b)$$

where $L_v(x)$ is the modified struve function and $\mathrm{Re}(v)$ is the real part of function $v$.

### 2.3. Performance analysis

Based on the proposed cooperative outage probability model, some performance evaluation can be numerically analyzed in detail. In the following analysis, some parameters of the cooperative cellular network system in Fig. 1 are configured as default values:$N_b \in [1, 3]$, $y_{\text{th}} = 0.1$, the radius of cell is 500 m, i.e. $r_b = 500$, and $\lambda_{\text{BS}} = 1/(\pi \times r_b^2)$. Every BS has no more than four antennas used for Co-Txs. In the default Co-Tx method, every BS just uses two antennas for signal Co-Tx per user. To simplify numerical analysis, Co-Txs among BSs are assumed as the aggregation of desired signals transmitted by multi-antennas from different BSs, i.e. desired signals are accumulated directly by numerical calculation.

In Fig. 3, the impact of the number of Co-Tx antennas per cooperative BS on the cooperative outage probability is analyzed. The number of cooperative BSs is noted as CBS. Without cooperative BSs, i.e. CBS = 1, the cooperative outage probability decreases from 0.66 to 0.33 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 cooperative outage probability decreases from 0.48 to 0.22 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 cooperative outage probability is increased from 0.38 to 0.18 when the number of Co-Tx antennas per cooperative BS increases from 1 to 4. Therefore, with increasing the number of cooperative BSs and Co-Tx antennas per cooperative BS, the performance of the cooperative outage probability is improved.

In Fig. 4, the impact of SIR threshold $y_{\text{th}}$ on the cooperative outage probability is analyzed. Without cooperative BSs, i.e. CBS = 1, the cooperative outage probability increases from 0.48 to 0.91 when the SIR threshold is increased from 0.1 to 1. With two cooperative BSs, i.e. CBS = 2, the cooperative outage probability increases from 0.33 to 0.8 when the SIR threshold is increased from 0.1 to 1. With three cooperative BSs, i.e. CBS = 3, the cooperative outage probability increases from 0.26 to 0.7 when the SIR threshold is increased from 0.1 to 1. Therefore, with increasing the SIR threshold, the cooperative outage probability is correspondingly increased. But with increasing the number of cooperative BSs, the cooperative outage probability is decreased.

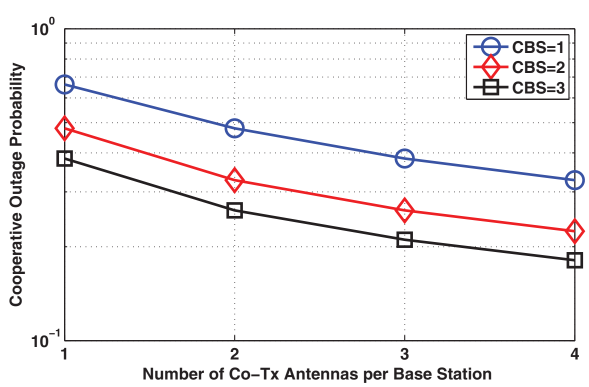


**FIGURE 3.** The impact of the number of Co-Tx antennas per cooperative BS on the cooperative outage probability.

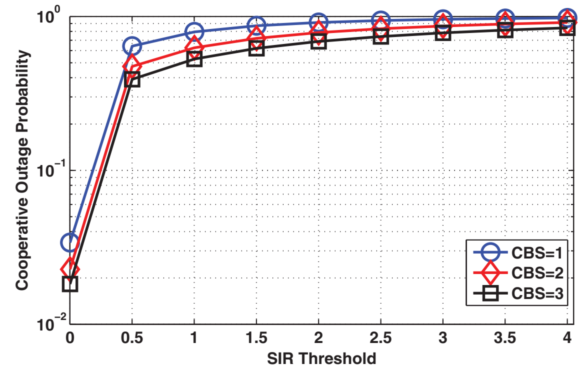


**FIGURE 4.** The impact of SIR threshold on the cooperative outage probability.

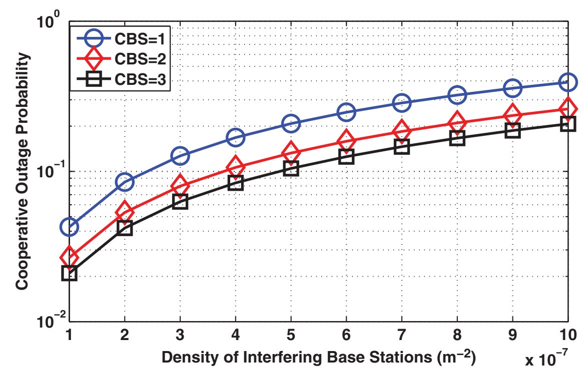


**FIGURE 5.** The impact of the density of interfering BSs on the cooperative outage probability.

In Fig. 5, the impact of the density parameter of interfering BSs $\lambda_{\text{BS}}$ on the cooperative outage probability is analyzed. Without cooperative BSs, i.e. CBS = 1, the cooperative outage probability increases from 0.04 to 0.4 when the density of interfering BSs is increased from $1 \times 10^{-7}$ to $1 \times 10^{-6}\,\text{m}^{-2}$. With two cooperative BSs, i.e. CBS = 2, the cooperative outage probability increases from 0.03 to 0.26 when the density of interfering BSs is increased from $1 \times 10^{-7}$ to $1 \times 10^{-6}\,\text{m}^{-2}$. With three cooperative BSs, i.e. CBS = 3, the cooperative outage probability increases from 0.02 to 0.2 when the density of interfering BSs is increased from $1 \times 10^{-7}$ to $1 \times 10^{-6}\,\text{m}^{-2}$. Therefore, the cooperative outage probability increases with the density of interfering BSs. Moreover, the cooperative outage probability decreases with the number of cooperative BSs.

## 3. COOPERATIVE BLER MODELING AND PERFORMANCE ANALYSIS

In the practical communication engineering, the BLER is one of the most important performance indexes. A block error occurs when a received block contains at least one error symbol. The evaluation of BLER is often associated with a specific modulation method. Without loss of generality, the BDPSK modulation [26], which is widely used in wireless communication systems, is selected for the cooperative BLER modeling.

### 3.1. Cooperative BLER modeling based on BDPSK modulation

Based on the Kullback–Leibler divergence [27], the aggregated interference governed by an alpha stable distribution in (8a) can be accurately approximated by a circularly symmetric complex Gaussian process with the same variance as (8a). Furthermore, the BER with BDPSK modulation used in cooperative cellular networks is calculated by [28] as follows:

$$P_{\text{BER\_BDPSK}}(y) = \frac{1}{2}e^{-y}, \tag{12}$$

where $y$ is a random variable of SIR in (9a) and the aggregated interference in (9a) is substituted by a circularly symmetric complex Gaussian process.

Under the Gray encoded BDPSK modulation assumption, the symbol error rate (SER) of cooperative cellular networks can be approximated by

$$P_{\text{SER\_BDPSK}}(y) = P_{\text{BER\_BDPSK}}(y)\log_2 M, \tag{13}$$

where $M$ is the number of points in the constellation with the specified modulation method. For the BDPSK modulation method, $M$ is configured as 2. Assuming that every symbol in a BDPSK block is statistically independent, the instant BLER can be simplified as [29]

$$P'_{\text{BLER}}(y) = 1 - (1 - P_{\text{SER\_BDPSK}}(y))^N, \tag{14}$$

where $N$ is the length of the BDPSK block.

To perform integration on (14), a new average cooperative BLER model is derived and given by

$$\begin{aligned} P_{\text{BLER}}(y) &= \int_0^\infty f_{\text{SIR}}(y)P'_{\text{BLER}}(y)\,dy \\ &= \int_0^\infty \left(1-\left(1-\frac{1}{2}e^{-y}\right)^N\right)\frac{r_b^{2N_bN_t^c+1}\gamma^{v+1}\sqrt{2/\pi}}{(N_bN_t^c-1)!2^{N_bN_t^c}} \\ &\quad \times y^{(v-1)/2}K_v(r_b^2\gamma\sqrt{y})\,dy. \end{aligned} \tag{15}$$

### 3.2. Performance analysis

Based on the proposed cooperative BLER model of a multi-cell multi-antenna cooperative cellular network with co-channel interference, the impact of the number of cooperative BSs and modulation parameters on the cooperative BLER model is numerically analyzed in detail. In this section, some parameters of the cooperative cellular network in Fig. 1 are configured as default values: $N_b \in [1, 3]$, the radius of cell is 500 meters, i.e. $r_b = 500$, and $\lambda_{\text{BS}} = 1/(\pi \times r_b^2)$. Every cooperative BS has two antennas used for Co-Tx. Every BDPSK symbol block has no more than six symbols, i.e. the maximum length of the block is 6. Similarly, the detailed Co-Tx scheme among cooperative BSs is illustrated in the Part C of Section II.

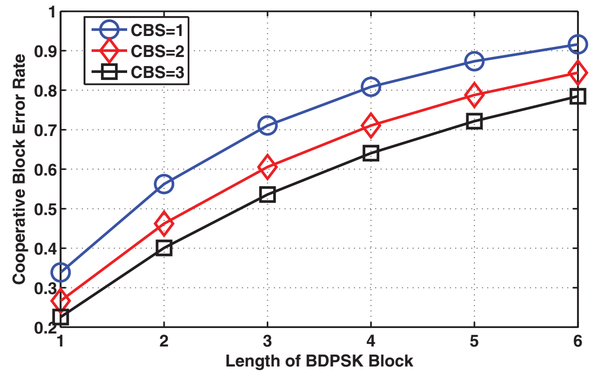


**FIGURE 6.** The impact of the length of the BDPSK block on the cooperative BLER.

In Fig. 6, the impact of the length of the BDPSK block on the cooperative BLER model is analyzed. Without cooperative BSs, i.e. CBS = 1, the cooperative BLER increases from 0.34 to 0.82 when the length of the BDPSK block is increased from 1 to 6. With two cooperative BSs, i.e. CBS = 2, the cooperative BLER increases from 0.26 to 0.69 when the length of the BDPSK block is increased from 1 to 6. With three cooperative BSs, i.e. CBS = 3, the cooperative BLER increases from 0.23 to 0.6 when the length of the BDPSK block is increased from 1 to 6. Therefore, we can find that the cooperative BLER increases with the length of the BDPSK block, but the cooperative BLER decreases with the number of cooperative BSs.

In Fig. 7, the impact of the density of interfering BSs $\lambda_{\text{BS}}$ on the cooperative BLER model is analyzed. Without cooperative BSs, i.e. CBS = 1, the cooperative BLER increases from 0.06 to 0.47 when the density of interfering BSs is increased from $1 \times 10^{-7}$ to $10 \times 1^{-6}\,\text{m}^{-2}$. With two cooperative BSs, i.e. CBS = 2, the cooperative BLER increases from 0.04 to 0.36 when the density of interfering BSs is increased from $1 \times 10^{-7}$ to $10 \times 1^{-6}\,\text{m}^{-2}$. With three cooperative BSs, i.e. CBS = 3, the cooperative BLER increases from 0.03 to 0.3 when the density of interfering BSs is increased from $1 \times 10^{-7}$ to $10 \times 1^{-6}\,\text{m}^{-2}$. Therefore, the cooperative BLER linearly increases with the density of interfering BSs. But the cooperative BLER decreases with the number of cooperative communication BSs, especially in the high density of interfering BSs scenarios. Hence, Multi-BS Co-Tx can provide more BLER performance gain than that of the single BS transmission.

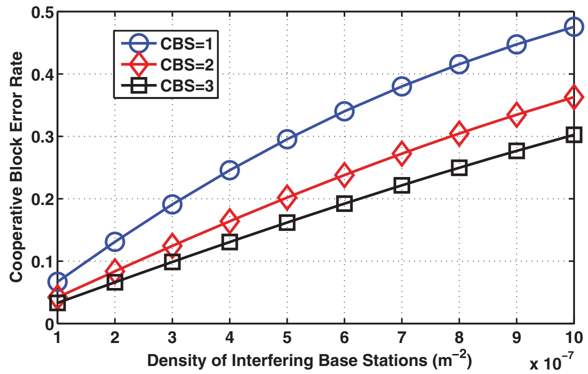


**FIGURE 7.** The impact of the density of interfering BSs on the cooperative BLER.

## 4. COOPERATIVE ENERGY EFFICIENCY MODELING AND PERFORMANCE ANALYSIS

In the traditional studies on the energy efficiency of wireless communication systems, the energy efficiency is defined as the ratio of the wireless channel capacity to the transmission power consumption. However, in practical wireless communication engineering, users and service providers have great interest in the average throughput over wireless links. It means that the calculation of the effective energy efficiency should be based on the average throughput over wireless links. In this case, users and service providers can evaluate how much energy is consumed for transmitting the correct data. Therefore, in this section we investigate the cooperative energy efficiency accounting for the average throughput with BDPSK modulation.

### 4.1. Cooperative energy efficiency modeling

Compared with the traditional energy efficiency of cellular networks, the cooperative energy efficiency of cellular networks is evaluated by accounting for the average throughput with BLER loss over wireless links. Without loss of generality, the BDPSK modulation is used for calculating the BLER loss over wireless links in this paper. As the demand for higher data rates increases, the distributed power control algorithms for maximizing the network throughput have attracted significant research attention [30]. Based on the multi-cell multi-antenna cooperative cellular network in Fig. 1, a new cooperative energy efficiency model with BDPSK modulation is defined by

$$EE = \frac{T_{\text{throughput}}}{E}, \tag{16}$$

where $T_{\text{throughput}}$ is the average throughput with BDPSK modulation and $E$ is the total transmission power of all cooperative BSs.

For a single link in wireless communication systems, the instant throughput with BDPSK modulation from substream $i$ is expressed by Catreux *et al.* [31] as follows:

$$T_i = \log_2 M \times (1 - P'_{\text{BLER}}(y)), \tag{17}$$

where $M$ is the number of points in the constellation with the specified modulation method. For the BDPSK modulation method, $M$ is equal to 2.

In a multi-cell multi-antenna cooperative cellular network of Fig. 1, a cell-edge user $\text{UE}_k$ can simultaneously receive $N_b \times N_t^c$ substreams from adjacent $N_b$ cooperative BSs with $N_t^c$ transmitting antennas. In this case, the instant energy efficiency throughput of user $\text{UE}_k$ is expressed by

$$EE' = \frac{T'_{\text{throughput}}}{E} = \frac{\sum_{i=1}^{N_b \times N_t^c} T_i}{\sum_{i}^{N_b \times N_t^c} E_i}, \tag{18}$$

where $T'_{\text{throughput}}$ is the instant throughput with BDPSK modulation received by the user $\text{UE}_k$, $E_i$ is the transmission power of substream $i$ and the transmission power of every substream is assumed equivalent.

Furthermore, the average throughput with BDPSK modulation for the user $\text{UE}_k$ is derived as

$$\begin{aligned} T_{\text{throughput}} &= \int_0^{\infty} f_{\text{SIR}}(y)(1 - P'_{\text{BLER}}(y))\, dy \\ &= 1 - P_{\text{BLER}}(y). \end{aligned} \tag{19}$$

Substituting (19) into (16), an analytical cooperative energy efficiency model with BDPSK modulation is derived by

$$\begin{aligned} EE = \frac{1}{E}\Bigg(1 - \int_0^{\infty}\left(1 - \left(1 - \frac{1}{2}e^{-y}\right)^N\right) \\ \times \frac{r_b^{2N_bN_t^c+1}\gamma^{v+1}\sqrt{2/\pi}}{(N_bN_t^c - 1)!2^{N_bN_t^c}}\, y^{(v-1)/2}K_v(r_b^2\gamma\sqrt{y})dy\Bigg) \end{aligned} \tag{20}$$

### 4.2. Numerical results and discussions for cooperative MISO channels

This section aims to numerically evaluate the proposed cooperative energy efficiency model with BDPSK modulation. Specifically, we focus on the impact of the interference, modulation parameters, transmission power per BS and average distance between cooperative BSs on the cooperative energy efficiency model. In the following analysis, some parameters of a cooperative cellular network in Fig. 1 are configured as default values: $N_b \in [1, 3]$, the radius of cell is 500 m, i.e. $r_b = 500$, and $\lambda_{\text{BS}} = 1/(\pi \times r_b^2)$. Every cooperative BS uses two antennas for Co-Txs. Every BDPSK symbol block has no more than six symbols, i.e. the maximum length of the block is 6. But in the default BDPSK modulation method, the length of the BDPSK symbol block is configured as 2. Similarly, the Co-Tx among BSs is configured and illustrated in the Part C of Section II.

In Fig. 8, the impact of the density of interfering BSs $\lambda_{\text{BS}}$ on the cooperative energy efficiency model is analyzed.

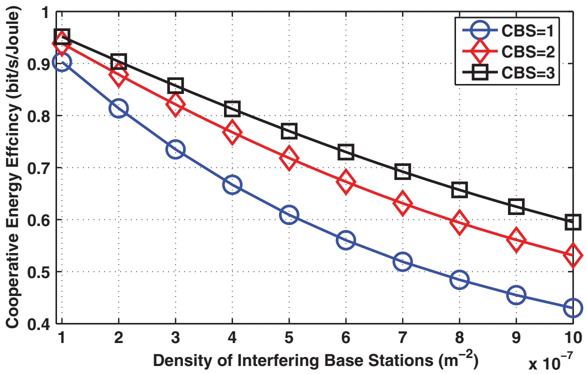


**FIGURE 8.** The Impact of the density of interfering BSs on the cooperative energy efficiency.

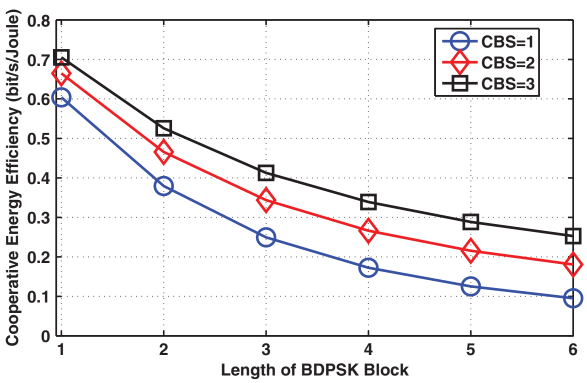


**FIGURE 9.** The impact of the length of the BDPSK block on the cooperative energy efficiency.

Without cooperative BSs, i.e. CBS = 1, the cooperative energy efficiency decreases from 0.9 to 0.42 when the density of interfering BSs is increased from $1 \times 10^{-7}$ to $1 \times 10^{-6}\,\mathrm{m}^{-2}$. With two cooperative BSs, i.e. CBS = 2, the cooperative energy efficiency decreases from 0.92 to 0.52 when the density of interfering BSs is increased from $1 \times 10^{-7}$ to $1 \times 10^{-6}\,\mathrm{m}^{-2}$. With three cooperative BSs, i.e. CBS = 3, the cooperative energy efficiency decreases from 0.93 to 0.6 when the density of interfering BSs is increased from $1 \times 10^{-7}$ to $1 \times 10^{-6}\,\mathrm{m}^{-2}$. Based on the above results, we can find that the co-channel interference can obviously decrease the cooperative energy efficiency with the density of interfering BSs. However, the Co-Tx is an effective approach to improve the cooperative energy efficiency performance in the high density of interfering BSs scenarios.

In Fig. 9, the impact of the length of the BDPSK block on the cooperative energy efficiency model is investigated. Without cooperative BSs, i.e. CBS = 1, the cooperative energy efficiency decreases from 0.6 to 0.1 when the length of the BDPSK block is increased from 1 to 6. With two cooperative BSs, i.e. CBS = 2, the cooperative energy efficiency decreases from 0.68 to 0.18 when the length of the BDPSK block is

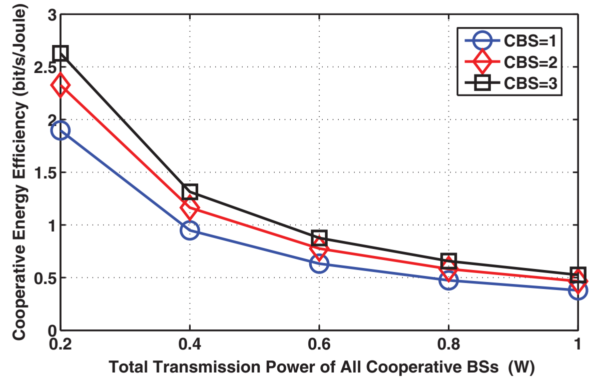


**FIGURE 10.** The impact of the total transmission power of all cooperative BSs on the cooperative energy efficiency.

increased from 1 to 6. With three cooperative BSs, i.e. CBS = 3, the cooperative energy efficiency decreases from 0.7 to 0.25 when the length of the BDPSK block is increased from 1 to 6. Therefore, the cooperative energy efficiency decreases with the length of the BDPSK block. Moreover, in the case of the same length of the BDPSK block, the cooperative energy efficiency performance increases with the number of cooperative BSs.

In Fig. 10, the impact of the total transmission power of all cooperative BSs on the cooperative energy efficiency is analyzed. Without cooperative BSs, i.e. CBS = 1, the cooperative energy efficiency decreases from 1.9 to 0.4 when the total transmission power of all cooperative BSs is increased from 0.2 to 1 W (Watt). With two cooperative BSs, i.e. CBS = 2, the cooperative energy efficiency decreases from 2.3 to 0.45 when the total transmission power of all cooperative BSs is increased from 0.2 to 1 W. With three cooperative BSs, i.e. CBS = 3, the cooperative energy efficiency decreases from 2.6 to 0.5 when the total transmission power of all cooperative BSs is increased from 0.2 to 1 W. Therefore, the cooperative energy efficiency decreases with the total transmission power of all cooperative BSs. Moreover, the cooperative energy efficiency performance increases with the number of cooperative BSs when the total transmission power of all cooperative BSs is fixed. However, the cooperative energy efficiency gain obtained from the number of cooperative BSs is obviously decreased when the total transmission power of all cooperative BSs is large.

## 5. CONCLUSIONS

This paper has derived a cooperative outage probability model and a cooperative BLER model incorporating a BDPSK modulation for performance analysis of multi-cell multi-antenna cooperative cellular networks. Further, a cooperative energy efficiency model has been proposed and analyzed under different Co-Tx scenarios, interference levels and wireless channel conditions. Based on these models and their numerical results in performance analysis, we found that Co-Tx is an effective approach to improve the energy efficiency, overall outage probability and BLER performance in such cooperative cellular networks. Our future work is to extend these analytical models to more complex wireless channel models and cooperative communication schemes.

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## APPENDIX

In this appendix, we derive the PDF expression of expected cooperative signal power $S_{\mathrm{E}}$ in multi-cell multi-antenna cooperative cellular networks. To simplify the complexity of derivation, we first define the following random variable:

$$S_{\mathrm{X}} = \sum_{b=1}^{N_b} \sum_{j=1}^{N_t^c} |z_{b,j}|^2. \tag{A.1}$$

Based on the cumulative distribution function (CDF) definition, we can get, respectively, the CDF of $S_{\mathrm{X}}$ and $S_{\mathrm{E}}$:

$$F_{\mathrm{X}}(x) = P(S_{\mathrm{X}} \le x), \tag{A.2a}$$

$$F_{\mathrm{E}}(x) = P(S_{\mathrm{E}} \le x), \tag{A.2b}$$

where $P(\cdot)$ is the probability function. Based on (A.2a) and (A.2b), we can derive the CDF of $S_{\mathrm{E}}$ as follows:

$$\begin{aligned} F_{\mathrm{E}}(x) &= P(S_{\mathrm{E}} \le x) = P\left(\frac{S_{\mathrm{X}}}{r_b} \le x\right) \\ &= P(S_{\mathrm{X}} \le r_b x) = F_{\mathrm{X}}(r_b x). \end{aligned} \tag{A.3}$$

Furthermore, the PDF expression of the expected cooperative signal power $S_{\mathrm{E}}$ can be derived and given by

$$\begin{aligned} f_{\mathrm{E}}(x) &= \frac{dF_{\mathrm{E}}(x)}{dx} = \frac{dF_{\mathrm{X}}(r_b x)}{dx} \\ &= r_b \frac{dF_{\mathrm{X}}(r_b x)}{d(r_b x)} = r_b f_{\mathrm{X}}(r_b x). \end{aligned} \tag{A.4}$$

Assume that the Nakagami shaping factor in wireless channels is configured as 1. Moreover, each signal passing through Nakagami fading channels is assumed to follow an i.i.d. complex Gaussian distribution with zero mean and standard variance, i.e. $z_{b,j} \sim CN(0,1)$. In this case, $S_{\mathrm{X}}$ is governed by Bithas *et al.* [32]:

$$\left[ S_{\mathrm{X}} = \sum_{b=1}^{N_b} \sum_{j=1}^{N_t^c} |z_{b,j}|^2 \right] \sim \mathcal{G}(N_b N_t^c, 2), \tag{A.5}$$

where $\mathcal{G}(\alpha, \beta)$ is a Gamma distribution. The PDF of Gamma distribution is expressed as follows:

$$f_{\mathrm{X}}(x) = \frac{1}{\Gamma(\alpha)\beta^{\alpha}} x^{\alpha-1} e^{-x/\beta}, \quad x > 0. \tag{A.6}$$

Substituting (A.5) and (A.6) into (A.4), the PDF of the expected cooperative signal power $S_{\mathrm{E}}$ can be expressed by

$$f_{\mathrm{E}}(x) = \frac{r_b^{4N_b N_t^c} x^{N_b N_t^c - 1} e^{-r_b^4 x/2}}{(N_b N_t^c - 1)! 2^{N_b N_t^c}}, \quad x > 0. \tag{A.7}$$

This completes the derivation.