On Energy Efficiency of the Nearest-Neighbor Cooperative Communication in Heterogeneous Networks

Tao Han*, Yu Feng*, Jiang Wang^{†‡}, Lijun Wang[§], Qiang Li* and Yujie Han*

*School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China †Shanghai Research Center for Wireless Communication, Shanghai, China

[‡]Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai, China

[§]Department of Information Science and Technology, Wenhua College, Wuhan, China

Email: *{hantao, m201371739, qli patrick, m201471912}@hust.edu.cn, [†]jiang.wang@wico.sh, [§]wanglj22@163.com

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Abstract—In this paper, we consider a two-dimensional heterogeneous cellular network scenario consisting of one base station (BS) and some mobile stations (MSs) whose locations follow a Poisson point process (PPP). The MSs are equipped with multiple radio access interfaces including a cellular access interface and at least one short-range communication interface. We propose a nearest-neighbor cooperation communication (NNCC) scheme by exploiting the short-range communication between a MS and its nearest neighbor to collaborate on their uplink transmissions. In the proposed cooperation scheme, a MS and its nearest neighbor first exchange data by the short-range communication. Upon successful decoding of the data from each other, they proceed to send their own data, as well as the data received from the other to the BS respectively in orthogonal time slots. The energy efficiency analysis for the proposed scheme is presented based on the characteristics of the PPP and the Rayleigh fading channel. Numerical results show that the NNCC scheme significantly improves the energy efficiency compared to the conventional noncooperative uplink transmissions.¹

Index Terms—Cooperative communication; Poisson point process; heterogeneous cellular network

I. INTRODUCTION

Nowadays many of mobile stations (MSs), e.g, smart cellular phones, tablets and PADs, are equipped with multiple radio access interfaces, e.g, cellular radio access, wireless local area network (WLAN), Bluetooth interfaces and etc.. As multi-mode MSs, they can constitute heterogeneous cellular networks (HCNs) and make it possible to improve the performance of cellular uplinks by serving as a relay to their neighboring MSs. By some of short-range communication methods provided by the multi-mode MSs, they can communicate with each other with significantly high efficiency and quite low cost. Then the MSs can exploit the short-range communication links among them along with the uplinks to the base station (BS) to form the cooperative communication, which can improve the performance of the HCNs with regard to rate, outage probability, coverage, energy efficiency and etc.. This paper focuses on the improvement of the energy efficiency of uplink cellular communications based on cooperation between neighboring MSs in HCNs.

Cooperative diversity has already emerged as a new and effective technique to combat fading and to decrease energy consumption in wireless networks. The nearest neighbor relay scheme that relay is chosen to be the nearest-neighbor to the user towards the BS (access-point) always has been applied in [1], [2]. [1] proposes and analyzes the performance of two schemes: a distributed nearest-neighbor relay assignment in which users can act as relays, and an infrastructure-based relay assignment in which fixed relay nodes are deployed in the network to help the users forward their data. [2] explores the balance between cooperation through relay nodes and aggregated interference generation in large decentralized wireless networks using decode-and-forward by the nearest neighbor relay scheme. [3] proposes an energy-efficient cooperative multicasting scheme by properly selecting relay agents (RAs) based on their location, channel condition and coverage. [4] studies the relay selection schemes to reduce energy consumption, and the optimal number of cooperative is also given. Besides, [5] is based on coded cooperation, which combines cooperation and channel coding together. To save bandwidth and improve the information transmission rate, network coding [6] is often used after the MSs receive each other's information successfully. But based on some criteria, [7] finds more scenarios where network coding has no gain on throughput or energy saving. Further more, many existing works concentrate on the resource allocation in cooperative networks. [8] presents both a centralized and a distributed power allocation schemes to optimize the BER performance of cooperative networks. To maximize the overall throughput, [9] proposes an optimal power allocation. An adaptive coded

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cooperative protocol based on incremental redundancy by a ACK/NACK feedback is proposed in [10].

Many of the above works have presented valuable theories, methods and technologies of cooperative communication. But there are still some improvements left to perform. Zou et al. in [11] investigate user terminals cooperating with each other in transmitting their data packets to the BS, by exploiting the multiple network access interfaces, which is called internetwork cooperation. Given a target outage probability and data rate requirements, they analyze the energy consumption of conventional schemes as compared to the proposed internetwork cooperation. The results show that the inter-network cooperation can significantly improve the energy efficiency of the uplink cellular communications. However in practical view there are some limits of this scheme work. In [11], it is required that the cooperative MSs have the same distances to the BS and know the instantaneous fading coefficients of both the short-range communication channel and each cellular channel to form an orthogonal matrix used in cooperative. In contrast, our paper intends to propose a more general and yet efficient cooperative scheme for HCNs, in which the cooperative MSs do not need to locate at the same distance away from the BS and are able to perform the cooperative communication without knowing the channel status.

The main contributions of this paper are summarized as follows. At first, we present a nearest-neighbor cooperative communication (NNCC) scheme in a HCN consisting of different radio access networks, i.e., a short-range communication network and a cellular network. Then we compare the proposed NNCC scheme to conventional schemes without user cooperation under target outage probability and data rate requirements. Secondly, we derive the energy efficiency of NNCC scheme in a Rayleigh fading environment. Further more, given a target outage probability, data rate requirements and distances between MSs and the BS, we derive the cumulative distribution function (CDF) and the probability density function (PDF) of energy consumption by considering the MSs that follow a Poisson point process (PPP).

The remainder of this paper is organized as follows. Section II presents the network model and the NNCC scheme. In Section III, we present the desired power consumption analysis, then we derive the CDF and the PDF of the system desired power consumption by considering stochastic spatial distribution of cooperative MSs. Section IV gives the numerical results. Finally, Section V concludes the paper.

II. SYSTEM MODEL

In this section, we first present a two-dimensional network model of a HCN environment. Then, we propose a NNCC scheme by exploiting the short-range network to assist cellular uplink transmissions.

A. Network Model

Consider a HCN consisting of a BS and some MSs whose locations follow a homogeneous Poisson point process (PPP) with density ρ . The MSs are assumed to equip with multiple



Fig. 1. System Model

radio access interfaces including at least a short-range communication interface and a cellular access interface. The MSs can communicate with their neighboring MSs by the short-range communication. The packet size of data is assumed to be the same across cellular communication link and all short-range communication links between MSs. Without loss of generality, we consider the BS is located at the origin of coordinate, and a specific MS U1 located at coordinate $(r_0, 0)$ intends to communicate with the BS. Our model is shown in Fig. 1, U1 will choose its nearest neighboring MS, denoted by U2, to cooperatively communicate with the BS. According to the properties of the homogeneous PPP, the distance r between U1 and U2 satisfies the following PDF [12]

$$f_r(r) = 2\pi\rho r \exp\left(-\pi\rho r^2\right),\tag{1}$$

then the coordinate of U2 can be obtained as $(r_0 + r \cos \theta, r \sin \theta)$, where θ follows a uniform distribution between $-\frac{\pi}{2}$ and $\frac{3\pi}{2}$. Denote the distance between U1 and the BS by r_1 . The distance r_2 between the MS U2 and BS can be obtained as

$$r_2^2 = r^2 + r_1^2 + 2r_1 r \cos\left(-\theta\right) = r^2 + r_1^2 + 2r_1 r \cos\theta.$$
 (2)

We consider a general channel model that incorporates the radio frequency, path loss and fading effects in characterizing wireless transmissions, i.e.,

$$\mathcal{P}_{\mathrm{R}} = \mathcal{P}_{\mathrm{T}} \left(\frac{\lambda}{4\pi d}\right)^2 G_{\mathrm{T}} G_{\mathrm{R}} \left|h\right|^2, \qquad (3)$$

where \mathcal{P}_{R} is the received power, \mathcal{P}_{T} is the transmitted power, λ is the carrier wavelength, d is the transmission distance, G_{T} is the transmit antenna gain, G_{R} is the receive antenna gain, and h is the channel fading coefficient. In this paper, we consider a Rayleigh fading model to characterize the channel fading, i.e., $|h|^2$ is modeled as an exponential random variable.

B. The NNCC Scheme

In the NNCC scheme, when MS U1 and its nearest neighbor MS U2 intend to send data D_1 and D_2 to the BS, respectively,



Fig. 2. In NNCC scheme, transmissions happen in short range network channel in time slot 1, and in cellular network channel in time slot 2 (and time slot 3).

they cooperate with each other according to the following steps:

- 1) U1 and U2 exchange their data over the short-range communication network in time slot 1.
- 2) If both U1 and U2 succeed in decoding the data from each other, defined as the case $\delta = 0$, both of them will send their own data as well as the data received from the other side to the BS in time slot 2 and time slot 3, respectively, i.e., they send both D_1 and D_2 to the BS over two orthogonal cellular uplink channels. Otherwise, defined as the case $\delta = 1$, U1 and U2 will send only their own data to the BS separately in time slot 2, just like a conventional non-cooperation communication.

Assuming that the short-range channels among MSs and the cellular channels to the BS are orthotropic and there is no interference at the BS among the MSs' signals, we only consider the channel noise when analyzing the performance of the scheme. Considering that Ui transmits D_i to Uj with the signal power \mathcal{P}_{ij}^{NC} , we can obtain the received signal-to-noise-ratio (SNR) between MSs by NNCC scheme as

$$\gamma_{\rm ij}^{\rm NC} = \frac{\mathcal{P}_{\rm ij}^{\rm NC}}{N_0 B_{\rm s}} \left(\frac{\lambda_{\rm s}}{4\pi r}\right)^2 G_{\rm U1} G_{\rm U2} \left|h_{\rm ij}\right|^2,\tag{4}$$

where i = 1 or 2, j = 2 or 1, $i \neq j$, λ_s is the carrier wavelength of the short-range communication, G_{U1} is the antenna gain at U1, G_{U2} is the antenna gain at U2, and h_{ij} is the fading coefficient of the channel from Ui to Uj. The noise is modeled as N_0B_s , where N_0 is the noise power spectral density and B_s is the channel bandwidth.

In step 2, MSs will transmit the data to the BS, and the received SNR at the BS from MS U1 or U2 over the cellular channel can be obtained as

$$\gamma_{\rm ib} = \frac{\mathcal{P}_{\rm ib}}{N_0 B_{\rm c}} \left(\frac{\lambda_{\rm c}}{4\pi r_i}\right)^2 G_{\rm Ui} G_{\rm BS} \left|h_{\rm ib}\right|^2,\tag{5}$$

where i = 1 or 2, λ_c is the cellular carrier wavelength, B_c is the cellular spectrum bandwidth, G_{BS} is the receive antenna gain at BS, and h_{ib} is the fading coefficient of channel from Ui to BS.

III. ENERGY EFFICIENCY ANALYSIS OF NNCC SCHEME

In this section, we analyze the energy efficiency of the proposed NNCC scheme compared to the conventional scheme without cooperation, under the requirements of target outage probability P_{out} and data rate R.

A. Energy Consumption in the NNCC scheme

Theorem 1. Under the situation that the BS succeeds in receiving the complete data from both MSs, the power consumption for the NNCC scheme can be obtained as

$$\mathcal{P}^{\rm NC} = \mathcal{P}_{12}^{\rm NC} + \mathcal{P}_{21}^{\rm NC} + (1 + (1 - P_{\rm out})^2)(\mathcal{P}_{\rm 1b}^{\rm NC} + \mathcal{P}_{2b}^{\rm NC}),$$
(6)

where P_{out} is the target outage probability, and to meet the target outage probability, where \mathcal{P}_{12}^{NC} , \mathcal{P}_{21}^{NC} , \mathcal{P}_{1b}^{NC} and \mathcal{P}_{2b}^{NC} are the desired transmission power from U1 to U2, U2 to U1, U1 to the BS and U2 to the BS, respectively, which are given by (9) and (13).

Proof: Due to the limited error correction capability in practical communication systems, both the short-range and cellular communications cannot achieve the Shannon capacity. Therefore, let $\Delta_s > 1$ and $\Delta_c > 1$ denote the performance gaps for the short-range communication and the cellular communication from their respective capacity limits, respectively. Using (3) and considering the performance gap Δ_s away from Shannon capacity, we obtain the maximum achievable rate from U1 to U2 of the short-range communication of the NNCC scheme as

$$C_{12}^{\rm NC} = B_{\rm s} \log_2(1 + \frac{\gamma_{12}^{\rm NC}}{\Delta_{\rm s}})$$

= $B_{\rm s} \log_2\left(1 + \frac{\mathcal{P}_{12}^{\rm NC} G_{\rm U1} G_{\rm U2} |h_{12}|^2}{\Delta_{\rm s} N_0 B_{\rm s}} \left(\frac{\lambda_{\rm s}}{4\pi r}\right)^2\right).$ (7)

In a Rayleigh fading channel, all random variables $|h_{12}|^2$, $|h_{21}|^2$, $|h_{1b}|^2$ and $|h_{2b}|^2$ follow independent exponential distributions with means σ_{12}^2 , σ_{21}^2 , σ_{1b}^2 and σ_{2b}^2 , respectively. As we know, an outage event occurs when the channel capacity falls below the required data rate. Using (4) and considering the performance gap Δ_s away from Shannon capacity, we can obtain the outage probability of the short-range transmission from U1 to U2 as

$$P_{\text{out12}}^{\text{NC}} = \Pr\left(C_{12}^{\text{NC}} < R\right)$$

= $1 - \exp\left(-\frac{16\pi^2 \Delta_{\text{s}} N_0 B_{\text{s}} r^2 \left(2\frac{R}{B_{\text{s}}} - 1\right)}{\mathcal{P}_{12}^{\text{NC}} \sigma_{12}^2 G_{\text{U1}} G_{\text{U2}} \lambda_{\text{s}}^2}\right).$ (8)

Assuming $P_{\text{out12}}^{\text{NC}} = P_{\text{out}}$, we can obtain the desired power consumption of MSs for short-range communication $\mathcal{P}_{\text{ij}}^{\text{NC}}$ from (8) as

$$\mathcal{P}_{ij}^{NC} = -\frac{16\pi^2 \Delta_s N_0 B_s \left(2^{\frac{R}{B_s}} - 1\right)}{\sigma_{ij}^2 G_{U1} G_{U2} \lambda_s^2 \ln\left(1 - P_{out}\right)} r^2.$$
(9)

Given $\sigma_{21}^2 = \sigma_{12}^2$, we can obtain $\mathcal{P}_{12}^{\text{NC}} = \mathcal{P}_{21}^{\text{NC}} = \zeta r^2$, where $\zeta = -\frac{16\pi^2 \Delta_{\text{s}} N_0 B_{\text{s}} \left(2^{\frac{R}{B_{\text{s}}}} - 1\right)}{\sigma_{\text{ij}}^2 G_{\text{U1}} G_{\text{U2}} \lambda_{\text{s}}^2 \ln(1 - P_{\text{out}})}.$

As discussed before, case $\delta = 0$ implies that both U1 and U2 succeed in decoding each other's signals through short range communications, and $\delta = 1$ means that either U1 or U2 (or both) fails to decode in the short-range transmissions. We can describe $\delta = 0$ and $\delta = 1$ as follows.

 $\delta = 0$:

$$B_{\rm s} \log_2 \left(1 + \frac{\gamma_{12}^{\rm NC}}{\Delta_{\rm s}} \right) \ge R \text{ and } B_{\rm s} \log_2 \left(1 + \frac{\gamma_{21}^{\rm NC}}{\Delta_{\rm s}} \right) \ge R.$$

$$\delta = 1:$$
(10)

$$B_{\rm s} \log_2 \left(1 + \frac{\gamma_{12}^{\rm NC}}{\Delta_{\rm s}} \right) < R \, {\rm or} \, B_{\rm s} \log_2 \left(1 + \frac{\gamma_{21}^{\rm NC}}{\Delta_{\rm s}} \right) < R.$$
(11)

Denote the target outage probability for short-range communication between U1 and U2 by P_{out} , given $P_{\text{out}12}^{\text{NC}} = P_{\text{out}21}^{\text{NC}} = P_{\text{out}}$, we have

 $\Pr(\delta = 0) = (1 - P_{out})^2$,

and

$$\Pr(\delta = 1) = 1 - (1 - P_{\text{out}})^2.$$

Moreover, denote the target outage probability for cellular communication from U1, U2 to the BS by $P_{\text{out}}^{\text{NC}}$, and given $P_{\text{out1b}}^{\text{NC}} = P_{\text{out2b}}^{\text{NC}} = P_{\text{out}}^{\text{NC}}$, we have $\Pr(C_{1b} < R) =$ $\Pr(C_{2b} < R)$, then we obtain the outage probability of the NNCC scheme by from (10) and (11) as

$$P_{\text{out}} = (1 - P_{\text{out}})^2 * (P_{\text{out}}^{\text{NC}})^2 + (1 - (1 - P_{\text{out}})^2) * (1 - (1 - P_{\text{out}})^2).$$

Then, we obtain

$$P_{\text{out}}^{\text{NC}} = \frac{\sqrt{\left(1-\epsilon\right)^2 + P_{\text{out}}\left(2\epsilon - 1\right) - \left(1-\epsilon\right)}}{2\epsilon - 1},\qquad(12)$$

where $\epsilon = (1 - P_{\text{out}})^2$.

We can obtain the power consumption of Ui for cellular communication from (12) as

$$\mathcal{P}_{\rm ib}^{\rm NC} = -\frac{16\pi^2 \triangle_{\rm c} N_0 B_{\rm c} \left(2^{\frac{R}{B_{\rm c}}} - 1\right)}{\sigma_{\rm ib}^2 G_{\rm Ui} G_{\rm BS} \lambda_{\rm c}^2 \ln \left(1 - P_{\rm out}^{\rm NC}\right)} r_i^2.$$
(13)

Given
$$\sigma_{1b}^2 = \sigma_{2b}^2$$
, we can obtain $\mathcal{P}_{1b}^{NC} = \eta r_1^2$ and $\mathcal{P}_{2b}^{NC} = \eta r_2^2$, where $\eta = -\frac{16\pi^2 \Delta_c N_0 B_c \left(2^{\frac{R}{B_c}} - 1\right)}{\sigma_{ib}^2 G_{U2} G_{BS} \lambda_c^2 \ln(1 - P_{out}^{NC})}$.

Notice that in case of $\delta = 0$, cooperation communication is employed and there are energy consumption at both time slot 2 and time slot 3, resulting in that a total power consumption of $2(\mathcal{P}_{1b}^{NC} + \mathcal{P}_{2b}^{NC})$ is consumed by U1 and U2 in transmitting to BS. In case of $\delta = 1$, U1 and U2 consume a total power consumption of $(\mathcal{P}_{1b}^{NC} + \mathcal{P}_{2b}^{NC})$ for transmitting to BS. Therefore, considering both the short-range communication and cellular transmissions, the total power consumption by the NNCC scheme is given by

$$\mathcal{P}^{\mathrm{NC}}$$

$$= \mathcal{P}_{12}^{\rm NC} + \mathcal{P}_{21}^{\rm NC} + (2Pr(\delta = 0) + Pr(\delta = 1)) (\mathcal{P}_{1b}^{\rm NC} + \mathcal{P}_{2b}^{\rm NC}) \\= \mathcal{P}_{12}^{\rm NC} + \mathcal{P}_{21}^{\rm NC} + (1 + (1 - P_{\rm out})^2) (\mathcal{P}_{1b}^{\rm NC} + \mathcal{P}_{2b}^{\rm NC}).$$

In order to compare our method and the traditional method, we give the same target interrupt probability definition about two schemes, and then we will derive the power consumption for the conventional scheme without user cooperation, in which both U1 and U2 succeed in transmitting their data to the BS separately. Similarly to the power consumption analysis of the NNCC scheme, assuming that $P_{\text{out1b}}^{\text{C}} = P_{\text{out2b}}^{\text{C}} = P_{\text{out}}^{\text{C}}$, the total power consumption of U1 and U2 under conventional non-cooperative communication can be obtained by

$$\mathcal{P}^{\mathrm{C}} = \sum_{i=1}^{2} \mathcal{P}^{\mathrm{C}}_{\mathrm{ib}},\tag{14}$$

where

and

$$\mathcal{P}_{\rm ib}^{\rm C} = -\frac{16\pi^2 \triangle_{\rm c} N_0 B_{\rm c} r_{\rm i}^2 \left(2^{\frac{R}{B_{\rm c}}} - 1\right)}{\sigma_{\rm ib}^2 G_{\rm Ui} G_{\rm BS} \lambda_{\rm c}^2 \ln\left(1 - P_{\rm out2}^{\rm C}\right)},\tag{15}$$

$$P_{\rm out}^{\rm C} = 1 - \sqrt{1 - P_{\rm out}}.$$
 (16)

As (12) and (16) show, the NNCC scheme can save more energy than the conventional scheme because it can work under larger target outage probability. Theorem 1 and (14) give the relations between the desired transmission powers and the target outage probabilities as well as other impact factors, e.g., path loss, fading, and thermal noise, under the NNCC scheme and the conventional non-cooperative scheme, respectively. Based on them, some further performance analysis, such as the energy efficiency analysis in Section III-B, can be presented.

B. Energy Efficiency Analysis based on PPP

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In order to get more performance analysis about the NNCC scheme, we put the NNCC scheme on a more general environment, we will consider MSs satisfy Poisson point process, which meet actual situation. The result is more practical and performance analysis is more accurate. Moreover, considering the stochastic spatial distribution of the MSs, we can derive the CDF and PDF of the desired transmission power which meet the target outage probability and rate requirement.

Theorem 2. When the spatial distribution of the MSs follows a homogeneous PPP with density ρ , the PDF of \mathcal{P}^{NC} is

$$f_{\mathcal{P}^{\rm NC}}\left(\mathcal{P}^{\rm NC}\right) = \begin{cases} \int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} \left(\frac{\rho R_2 e^{\left(-\pi\rho R_2^2\right)} + \rho R_1 e^{\left(-\pi\rho R_1^2\right)}}{2\Delta_R}\right) d\theta, & Q_1 \\ \int_{-\frac{\pi}{2}}^{\frac{3\pi}{2}} \frac{\rho R_2 e^{\left(-\pi\rho R_2^2\right)}}{2\Delta_R} d\theta, & Q_2, \end{cases}$$

and the CDF of $\mathcal{P}^{\rm NC}$ is

$$F_{\mathcal{P}^{\mathrm{NC}}}\left(\mathcal{P}^{\mathrm{NC}}\right) = \begin{cases} \int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} \frac{\mathrm{e}^{\left(-\pi\rho\mathrm{R}_{1}^{2}\right)} - \mathrm{e}^{\left(-\pi\rho\mathrm{R}_{2}^{2}\right)}}{2\pi} d\theta, & Q_{1} \\ \int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} \frac{1 - \mathrm{e}^{\left(-\pi\rho\mathrm{R}_{2}^{2}\right)}}{2\pi} d\theta + F_{\mathcal{P}^{\mathrm{NC}}}\left(2\varepsilon\eta\mathrm{r}_{1}^{2}\right), & Q_{2}, \end{cases}$$

where

$$\varepsilon = 1 + (1 - P_{\text{out}})^2, \qquad (17)$$

$$\Delta_R = \sqrt{(\varepsilon \eta r_1 \cos \theta)^2 - (2\zeta + \varepsilon \eta)(2\varepsilon \eta r_1^2 - \mathcal{P}^{\rm NC})}, \quad (18)$$

$$R_2 = \frac{-\varepsilon\eta r_1\cos\theta + \Delta_R}{2\zeta + \varepsilon\eta},\tag{19}$$

and

$$R_1 = \frac{-\varepsilon \eta r_1 \cos \theta - \Delta_R}{2\zeta + \varepsilon \eta}.$$
 (20)

 Q_1 stands for $2\varepsilon\eta r_1^2 - \frac{(\varepsilon\eta r_1\cos\theta)^2}{2\zeta+\varepsilon\eta} < \mathcal{P}^{\mathrm{NC}} \leqslant 2\varepsilon\eta r_1^2$ and Q_2 stands for $\mathcal{P}^{\mathrm{NC}} > 2\varepsilon\eta r_1^2$.

Proof: Due to independence of random variables r and θ , considering θ follows the uniform distribution between $-\frac{\pi}{2}$ and $\frac{3\pi}{2}$, r satisfies (1), the PDF of r and θ can be obtained as

$$f(r,\theta) = \rho r \exp\left(-\pi \rho r^2\right). \tag{21}$$

Substituting (6) into (2), we obtain

$$\mathcal{P}^{\rm NC} = (2\zeta + \varepsilon\eta) r^2 + 2\varepsilon\eta r_1 \cos\theta r + 2\varepsilon\eta r_1^2.$$
 (22)

So the the CDF of $\mathcal{P}^{\rm NC}$ is

$$F_{\mathcal{P}^{\mathrm{NC}}}\left(p^{\mathrm{NC}}\right) = \Pr\left(P^{\mathrm{NC}} \leqslant p^{\mathrm{NC}}\right)$$
$$= \Pr\left(\left(2\zeta + \varepsilon\eta\right)r^2 + 2\varepsilon\eta r_1\cos\theta r + 2\varepsilon\eta r_1^2 \leqslant p^{\mathrm{NC}}\right). \quad (23)$$

Based on (21) and (23), we can acquire the CDF and PDF of desired power for NNCC scheme as Theorem 2 expresses. ■

From Theorem 2, we will know the PDF and CDF of \mathcal{P}^{NC} and can easily obtain its expectation. It can help us to find the energy efficiency. Based on Theorem 2, it is easy to derive the relations between desired transmission power of the NNCC scheme and the target outage probability as well as other impact factors. Considering a successful transmission delivering both data of U1 and U2 by the total power consumption \mathcal{P}^{NC} , the energy efficiency of the NNCC scheme can be derived by

$$EE^{\rm NC} = \frac{2R}{E\left(\mathcal{P}^{\rm NC}\right)}.$$
(24)

In Section IV, some numerical results about the desired transmission power and the energy efficiency of the NNCC scheme are given.

IV. NUMERICAL RESULTS

In this section, we present the analytical results of the proposed NNCC scheme and compare it to the existed schemes. We compare different schemes under the same definition of target outage probability. In our simulation, the frequency and bandwidth of the short-range communication are given as $f_{\rm s} = 2.4 \,{\rm GHz}$ and ${\rm B_s} = 2 \,{\rm MHz}$, respectively. In the cellular communication they are given as $f_{\rm c} = 2100 \,{\rm MHz}$ and ${\rm B_c} = 5 \,{\rm MHz}$, respectively. The antenna gains of U1 and U2 are set as $G_{\rm U1} = G_{\rm U2} = 0 \,{\rm dB}$ and the BS's antenna gain is set as $G_{\rm BS} = 5 \,{\rm dB}$. The performance gaps $\Delta_{\rm s}$ and $\Delta_{\rm c}$ of short-range and cellular communication are given by $\Delta_{\rm s} = 4 \,{\rm dB}$ and $\Delta_{\rm c} = 2 \,{\rm dB}$.



Fig. 3. Energy consumption by various transmission schemes with target outage probability $P_{\rm out}=10^{-3}$, effective rate R=100000 bits/s, and inter-user distance r=20 m.

Energy consumption is influenced by some parameters, such as distances between the MSs and the BS, distance between MSs, the density of MS and the target outage probability. In Fig. 3, we discuss the impact of distances between the MSs and the BS on energy consumption. We compare the desired transmission power of the NNCC scheme to the conventional non-cooperative scheme and the inter-network cooperative communication scheme by orthogonal matrix proposed in [11]. The result shows that the power consumption of the NNCC scheme is significantly lower than the non-operative scheme and slightly higher than the inter-network cooperative scheme. It demonstrates the effectiveness of the NNCC scheme, while considering the simplicity and feasibility of the NNCC scheme, which does not need the knowledge of the instantaneous status of the channel and can be easily applied in the scenario of the MSs with stochastic spatial distribution. Similarly to Fig. 3, we present the comparison of the energy efficiency among the schemes in Fig. 4.

In Fig. 5, we present the relations between the desired transmission power consumption and the density of the MSs under different distances between the MS U1 and the BS. It is shown that the power consumption decreases as the density of MSs increases, because the distance between the



Fig. 4. Energy efficiency by various transmission schemes with target outage probability $P_{\text{out}} = 10^{-3}$, effective rate R = 100000 bits/s, and inter-user distance r = 20 m.

cooperative MSs tends to be smaller when the density of the MSs increases, and thus less power consumption is required in step 1. Fig. 6 demonstrates that the energy consumptions of the NNCC scheme decreases as the target outage probability increases with various densities of the MSs.



Fig. 5. Relation between the desired the transmission power and the density of MSs, with target outage probability $P_{\text{out}} = 10^{-3}$, effective rate R = 10000000 bits/s, and U1-BS distance $r_1 = 2000 \text{ m}$.

V. CONCLUSIONS

In this paper, we propose a cooperative communication scheme, namely the NNCC scheme, in which a MS in HCN and its nearest neighbor MS exploit a short-range communication network to assist the cellular transmissions. The energy efficiency of the NNCC scheme is analyzed and derived in closed-form expressions, which provide insights into the relations between energy efficiency and many important factors, e.g., MS density, the distance between the MSs and the BS, the target outage probability and etc.. Numerical results show that the NNCC scheme is simple, yet efficient



Fig. 6. Desired transmission power with regard to the target outage probability with effective rate R = 1000000 bits/s, and U1-BS distance $r_1 = 150$ m.

compared to the existing schemes. Although this article studies collaboration between two MSs only, it's obvious that there are vast energy saving comparing with the traditional scheme, no matter from the aspects of the distance between BS and MSs or expectation. In this paper, we have only considered the scenario of a single BS and allow only two MSs cooperate with each other. In the future, we will extend the work to the multicell scenario with multi-MS cooperative communications.

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