COOPERATIVE NON-ORTHOGONAL MULTIPLE ACCESS IN 5G SYSTEMS WITH SWIPT

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ABSTRACT

In this paper, the application of simultaneous wireless information and power transfer (SWIPT) to non-orthogonal multiple access (NOMA) is investigated. A new cooperative SWIPT NOMA protocol is proposed in which near NOMA users which are close to the source act as energy harvesting relays to help far NOMA users. By assuming that all users are spatially randomly located in the network, new analytical expressions for outage probability are derived both for the near and far users, in order to characterize the performance of the proposed protocol. The diversity of both the near and far users is analyzed to demonstrate that the use of SWIPT will not jeopardize the diversity order compared to the conventional NOMA. Numerical results are also provided to verify the accuracy of the developed analytical results.

Index Terms— Non-orthogonal multiple access, simultaneously wireless information and power transfer, stochastic geometry

1. INTRODUCTION

Non-orthogonal multiple access (NOMA), as an effective means to improve spectral efficiency, has recently received attention for its promising application in fifth generation (5G) networks [1]. The key idea of NOMA is to achieve multiple access by using the power domain, which is fundamentally different from conventional orthogonal multiple access (MA) technologies (e.g. time/frequency/code division MA). In [2], the authors investigated the performance of a downlink NOMA scheme with randomly deployed users. An uplink transmission NOMA scheme was proposed in [3], and its performance was evaluated systematically. In [4], the impact of user pairing was characterized by analyzing the sum rates in two NOMA systems, namely, fixed power allocation NOMA and cognitive radio inspired NOMA. In [5], a new cooperative NOMA scheme was proposed and analyzed in terms of outage probability and diversity order.

In addition to improving spectral efficiency which is the motivation of NOMA, another key objective in future 5G networks is to maximize energy efficiency. Simultaneous wireless information and power transfer (SWIPT), which was initially proposed in [6], has rekindled the interest of researchers to explore more energy efficient networks. In [6], it is assumed that both the information and energy could be extracted from radio frequency signals at the same time, which does not hold in practice. Motivated by this issue, two practical receiver architectures, namely a time switching (TS) receiver and a power splitting (PS) receiver, were proposed in a multi-input and multi-output (MIMO) system in [7]. Since the point-to-point communication system with SWIPT has already been well studied, the recent research on SWIPT has focused mainly on two common cooperative relaying systems: amplify-and-forward (AF) and decode-and-forward (DF). On the one hand, for the AF relay system, a TS-based relaying protocol and a PS-based relaying protocol were proposed in [8]. On the other hand, for the DF relay system, the application of SWIPT to DF cooperative networks with spatially random relays was investigated in [9] by applying stochastic geometry in a scenario with one source-destination pair as well as in a scenario with multiple sources.

The aforementioned two communication concepts, NOMA and SWIPT, can be combined naturally, which is the focus of this paper. Specifically near users which are close to the source in NOMA systems are used as relays to help the far NOMA users with poorer channel conditions. In order to improve the reliability of these far NOMA users without draining the near users' batteries, we consider the application of SWIPT to NOMA, where SWIPT is performed at the near NOMA users. Users are spatially randomly deployed in two groups via a homogeneous Poisson point process (PPP); the near users are in one group which is close to the base station (BS) and the far users are deployed in the other group which is close to the edge of the cellular network. In this paper, we derive analytical expressions of outage probability for both the near and far users achieved by the proposed protocol. We also derive the diversity gain for the far users and conclude that the proposed cooperative SWIPT NOMA protocol will not decrease the diversity gain compared with a conventional cooperative network. The decreasing rate of outage probability for the proposed protocol is $\frac{\ln SNR}{SNR^2}$ while a rate of $\frac{1}{SNR^2}$ is achieved in a conventional cooperative network.

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2. NETWORK MODEL

We consider a network with one source S (the base station (BS)) and two groups of randomly deployed users $\{\mathrm{A_i}\}$ and $\{\mathrm{B_i}\}$. We assume the group $\{\mathrm{B_i}\}$ is close to the BS and the other group $\{\mathrm{A_i}\}$ is close to the edge of cellular network. We assume that the BS is located at the origin of a disc, denoted by $\mathcal{D}$. The group of the near users $\{\mathrm{B_i}\}$ has radius R_{D_B} and the group of the far users $\{\mathrm{A_i}\}$ has radius between R_{D_C} and R_{D_A}. Both the near and far users are modeled using a homogeneous PPP Φ_κ ($\kappa \in \{\mathrm{A}, \mathrm{B}\}$) with density λ_{Φ_κ} and uniformly distributed within the disc. All channels are assumed to be frequency flat quasi-static Rayleigh fading channels. In our network, we consider that the users in $\{\mathrm{B_i}\}$ are used as energy harvesting relays, i.e., they can harvest energy from the BS and forward the information to $\{\mathrm{A_i}\}$ by using the harvested energy. Two phases are used in our cooperative NOMA system, which is described in detail in the following.

2.1. Direct transmission phase with SWIPT

During this phase, the BS sends two messages (i.e. $p_{i1}x_{i1} + p_{i2}x_{i2}$) to two selected users $\mathrm{A_i}$ and $\mathrm{B_i}$ based on the NOMA principle, where p_{i1} and p_{i2} are the power allocation coefficient and x_{i1} and x_{i2} are the messages for $\mathrm{A_i}$ and $\mathrm{B_i}$, respectively. The observation at $\mathrm{A_i}$ is given by

$$y_{\mathrm{A_i},1} = \sqrt{P_\mathrm{S}} \sum_{k\in\{1,2\}} p_{ik}x_{ik}\frac{h_{\mathrm{A_i}}}{\sqrt{1+d_{\mathrm{A_i}}^{\alpha}}} + n_{\mathrm{A_i},1}, \quad (1)$$

where P_S is the transmit power at the BS, $h_{\mathrm{A_i}}$ is the small-scale Rayleigh fading gain from the BS to $\mathrm{A_i}$ with $h_{\mathrm{A_i}} \sim \mathcal{CN}(0,1)$, $n_{\mathrm{A_i},1}$ is additive Gaussian white noise (AWGN) at $\mathrm{A_i}$ with variance $\sigma^2_{\mathrm{A_i}}$, $d_{\mathrm{A_i}}$ is the distance between the BS and $\mathrm{A_i}$, and α is the path loss exponent. We use the bounded path loss model to ensure that the path loss is always larger than one for any distance [9].

Without loss of generality, we assume that $|p_{i1}|^2 > |p_{i2}|^2$ with $|p_{i1}|^2 + |p_{i2}|^2 = 1$. We carry out successive interference cancellation (SIC) at $\mathrm{B_i}$ at the end of the direct transmission phase. The received signal to the interference and noise ratio (SINR) for $\mathrm{A_i}$ to detect the message x_{i1} is given by

$$\gamma^{x_{i1}}_{\mathrm{S,A_i}} = \frac{\rho|h_{\mathrm{A_i}}|^2|p_{i1}|^2}{\rho|p_{i2}|^2|h_{\mathrm{A_i}}|^2 + 1 + d^\alpha_{\mathrm{A_i}}}, \quad (2)$$

where $\rho = \frac{P_\mathrm{S}}{\sigma^2}$ is the transmit signal to noise radio (SNR) (assuming $\sigma^2_{\mathrm{A_i}} = \sigma^2_{\mathrm{B_i}} = \sigma^2$ and the same in the sequel).

For $\mathrm{B_i}$, the power splitting architecture [7] is applied to perform SWIPT. The energy harvested at $\mathrm{B_i}$ is used as two parts. One part is used for information decoding by directing the observation flow to the detection circuit and the remaining part is used for energy harvesting, where the harvested energy is to power the relay $\mathrm{B_i}$ for helping $\mathrm{A_i}$. Thus,

$$y_{\mathrm{B_i},1} = \sqrt{P_\mathrm{S}} \sum_{k\in\{1,2\}} p_{ik}x_{ik}\frac{\sqrt{1-\beta_i}h_{\mathrm{B_i}}}{\sqrt{1+d_{\mathrm{B_i}}^{\alpha}}} + n_{\mathrm{B_i},1}, \quad (3)$$

where β_i is the power splitting coefficient which will be explained in (6), $h_{\mathrm{B_i}}$ is the small-scale Rayleigh fading gain from the BS to $\mathrm{B_i}$ with $h_{\mathrm{B_i}} \sim \mathcal{CN}(0,1)$, $n_{\mathrm{B_i}}$ is AWGN at $n_{\mathrm{B_i},1}$ with variance $\sigma^2_{\mathrm{B_i}}$, and $d_{\mathrm{B_i}}$ is the distance between the BS and $\mathrm{B_i}$.

Applying the NOMA principle, $\mathrm{B_i}$ first decodes the message of $\mathrm{A_i}$, then subtracts this component from the received signal to get its own information. Therefore, the received S-INR for $\mathrm{B_i}$ to detect x_{i1} of $\mathrm{A_i}$ is given by

$$\gamma^{x_{i1}}_{\mathrm{S,B_i}} = \frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2\left(1-\beta_i\right)}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2\left(1-\beta_i\right) + 1 + d^\alpha_{\mathrm{B_i}}}. \quad (4)$$

The received SNR for $\mathrm{B_i}$ to detect x_{i2} of $\mathrm{B_i}$ is given by

$$\gamma^{x_{i2}}_{\mathrm{S,B_i}} = \frac{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2\left(1-\beta_i\right)}{1 + d^\alpha_{\mathrm{B_i}}}. \quad (5)$$

In this case, the data rate supported by the channel from the BS to $\mathrm{B_i}$ for decoding x_{i1} is given by $R_{x_{i1}} = \frac{1}{2}\log\left(1 + \frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2(1-\beta_i)}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2+1+d^\alpha_{\mathrm{B_i}}}\right)$. To make sure $\mathrm{B_i}$ can decode x_{i1} successfully at a given targeted rate, i.e., $R_1 = R_{x_{i1}}$, the power splitting coefficient β_i is set as follows:

$$\beta_i = \max\left\{0, 1 - \frac{\tau_1\left(1+d^\alpha_{\mathrm{B_i}}\right)}{\rho|h_{\mathrm{B_i}}|^2\left(|p_{i1}|^2 - \tau_1|p_{i2}|^2\right)}\right\}, \quad (6)$$

where $\tau_1 = 2^{2R_1} - 1$ and $\tau_2 = 2^{2R_2} - 1$.

Here $\beta_i = 0$ indicates that all the energy is used for information decoding and there is no energy left for energy harvesting. We assume that $\beta_i > 0$ in the following of this paper. The transmit power at $\mathrm{B_i}$ which is determined by the harvested energy can be expressed as follows:

$$P_{\mathrm{B_i}} = \frac{\eta P_\mathrm{S}\beta_i|h_{\mathrm{B_i}}|^2}{1+d^\alpha_{\mathrm{B_i}}}, \quad (7)$$

where η is the energy harvesting coefficient.

2.2. Cooperative transmission phase

During this phase, $\mathrm{B_i}$ forwards x_{i1} to $\mathrm{A_i}$ with the harvested energy. In this case, user $\mathrm{A_i}$ observes the following:

$$y_{\mathrm{A_i},2} = \frac{\sqrt{P_{\mathrm{B_i}}}x_{i1}g_\mathrm{i}}{\sqrt{1+d^\alpha_{\mathrm{C_i}}}} + n_{\mathrm{A_i},2}, \quad (8)$$

where g_i is the Rayleigh fading channel gain from $\mathrm{B_i}$ to $\mathrm{A_i}$, $n_{\mathrm{A_i},2}$ is AWGN at $\mathrm{A_i}$ with variance $\sigma^2_{\mathrm{A_i}}$, and $d_{\mathrm{C_i}} =$

$\sqrt{d_{\mathrm{A_i}}^2 + d_{\mathrm{B_i}}^2 - 2d_{\mathrm{A_i}} d_{\mathrm{B_i}} \cos(\theta_i)}$ is the distance between $\mathrm{B_i}$ and $\mathrm{A_i}$ with θ_i denoting the angle $\angle \mathrm{A_i S B_i}$.

At the end of this phase, $\mathrm{A_i}$ combines the signals from the BS and $\mathrm{B_i}$ during the direct phase and the cooperative phase by applying maximal-ratio combining (MRC). The overall received SINR at $\mathrm{A_i}$ can be expressed as follows:

$$\gamma_{\mathrm{A_i,MRC}}^{x_{i1}} = \frac{\rho |h_{\mathrm{A_i}}|^2 |p_{i1}|^2}{\rho |h_{\mathrm{A_i}}|^2 |p_{i2}|^2 + 1 + d_{\mathrm{A_i}}^\alpha} + \frac{\eta \rho \beta_i |h_{\mathrm{B_i}}|^2 |g_i|^2}{\left(1 + d_{\mathrm{B_i}}^\alpha\right)\left(1 + d_{\mathrm{C_i}}^\alpha\right)}. \tag{9}$$

3. PERFORMANCE ANALYSIS OF NON-ORTHOGONAL MULTIPLE ACCESS

In this section, the performance of the proposed protocol is analyzed. In this protocol, the BS selects both the near and far NOMA users randomly. This selection scheme provides fair opportunity to each user to access the BS via the NOMA protocol.

3.1. Outage probability of the near users

In the NOMA protocol, an outage of $\mathrm{B_i}$ can occur in two situations. The first is when $\mathrm{B_i}$ cannot detect x_{i1}. The second is when $\mathrm{B_i}$ can detect x_{i1} but cannot detect x_{i2}. To guarantee that the NOMA protocol can be implemented, the condition $|p_{i1}|^2 - |p_{i2}|^2 \tau_1 > 0$ should be satisfied [2]. Based on (4), the outage probability of $\mathrm{B_i}$ can be expressed as follows:

$$\begin{aligned} P_{\mathrm{B_i}} = &\Pr\left(\frac{\rho |h_{\mathrm{B_i}}|^2 |p_{i1}|^2}{\rho |h_{\mathrm{B_i}}|^2 |p_{i2}|^2 + 1 + d_{\mathrm{B_i}}^\alpha} < \tau_1\right) \\ &+ \Pr\left(\frac{\rho |h_{\mathrm{B_i}}|^2 |p_{i1}|^2}{\rho |h_{\mathrm{B_i}}|^2 |p_{i2}|^2 + 1 + d_{\mathrm{B_i}}^\alpha} > \tau_1, \gamma_{\mathrm{S,B_i}}^{x_{i2}} < \tau_2\right). \end{aligned} \tag{10}$$

Substituting (5) into (10), defining $X_i = \frac{|h_{\mathrm{A_i}}|^2}{1+d_{\mathrm{A_i}}^\alpha}$ and $Y_i = \frac{|h_{\mathrm{B_i}}|^2}{1+d_{\mathrm{B_i}}^\alpha}$, the outage probability of the near users is given by

$$P_{\mathrm{B_i}} = \Pr\left(Y_i < \varepsilon_{\mathrm{A}_i}\right) + \Pr\left(Y_i > \varepsilon_{\mathrm{A}_i}, \varepsilon_{\mathrm{A}_i} < \varepsilon_{\mathrm{B}_i}\right), \tag{11}$$

where $\varepsilon_{\mathrm{A}_i} = \frac{\tau_1}{\rho\left(|p_{i1}|^2 - \tau_1 |p_{i2}|^2\right)}$ and $\varepsilon_{\mathrm{B}_i} = \frac{\tau_2}{\rho |p_{i2}|^2}$.

If $\varepsilon_{\mathrm{A}_i} < \varepsilon_{\mathrm{B}_i}$, we notice that the outage probability of the near users is always one. For the case $\varepsilon_{\mathrm{A}_i} \geq \varepsilon_{\mathrm{B}_i}$, the cumulative distribution function (CDF) of the channel gain for $\mathrm{B_i}$ is given by

$$F_{Y_i}(\varepsilon) = \frac{2}{R_{D_\mathrm{B}}^2} \int_0^{R_{D_\mathrm{B}}} \left(1 - e^{-(1+r^\alpha)\varepsilon}\right) r dr. \tag{12}$$

We note that it is very challenging to obtain an insightful closed-form expression for the CDF. Thus, we use Gaussian-Chebyshev quadrature to obtain the outage probability for the near users as follows:

$$P_{\mathrm{B_i}} \approx \frac{1}{2} \sum_{n=1}^{N} \omega_N \sqrt{1 - {\phi_n}^2} \left(1 - e^{-c_n \varepsilon_{\mathrm{A}_i}}\right) (\phi_n + 1), \tag{13}$$

where $c_n = 1 + \left(\frac{R_{D_\mathrm{B}}}{2}(\phi_n + 1)\right)^\alpha$, $\omega_N = \frac{\pi}{N}$, and $\phi_n = \cos\left(\frac{2n-1}{2N}\pi\right)$.

3.2. Diversity analysis for the near users

We carry out high SNR approximations to (13) using $1 - e^{-x} \approx x$ and obtain

$$P_{\mathrm{B_i}} \approx \frac{1}{2} \sum_{n=1}^{N} \omega_N \sqrt{1 - {\phi_n}^2} c_n \varepsilon_{\mathrm{A}_i} (\phi_n + 1). \tag{14}$$

The diversity gain is defined as follows:

$$d_\mathrm{B} = - \lim_{\rho \to \infty} \frac{\log P_{\mathrm{B_i}}(\rho)}{\log \rho}. \tag{15}$$

Substituting (14) into (15), we obtain the diversity gain for the near users is one, which means that using NOMA with energy harvesting will not decrease the diversity gain.

3.3. Outage probability of the far users

In the proposed protocol, an outage of $\mathrm{A_i}$ can occur in two situations. The first is when $\mathrm{B_i}$ can detect x_{i1} but the overall received SINR at $\mathrm{A_i}$ cannot support the targeted rate. The second is when neither $\mathrm{A_i}$ nor $\mathrm{B_i}$ can detect x_{i1}. Based on this, the outage probability can be expressed as follows:

$$\begin{aligned} P_{\mathrm{A_i}} = &\underbrace{\Pr\left(\gamma_{\mathrm{A_i,MRC}}^{x_{i1}} < \tau_1, \frac{\rho |h_{\mathrm{B_i}}|^2 |p_{i1}|^2}{\rho |h_{\mathrm{B_i}}|^2 |p_{i2}|^2 + 1 + d_{\mathrm{B_i}}^\alpha} > \tau_1\right)}_{\Theta_1} \\ &+ \underbrace{\Pr\left(\gamma_{\mathrm{S,A_i}}^{x_{i1}} < \tau_1, \frac{\rho |h_{\mathrm{B_i}}|^2 |p_{i1}|^2}{\rho |h_{\mathrm{B_i}}|^2 |p_{i2}|^2 + 1 + d_{\mathrm{B_i}}^\alpha} < \tau_1\right)}_{\Theta_2}, \end{aligned} \tag{16}$$

where Θ_1 and Θ_2 are calculated below.

Substituting (9) into (16), we express Θ_1 as (17) on the top of next page, where $pw_{\mathrm{B_i}}(\omega_{\mathrm{B_i}}) = \frac{1}{\pi R_{D_\mathrm{B}}^2}$, $pw_{\mathrm{A_i}}(\omega_{\mathrm{A_i}}) = 1/\pi\left(R_{D_\mathrm{A}}^2 - R_{D_\mathrm{C}}^2\right)$, $f_{X_i}(x) = \left(1 + d_{\mathrm{A_i}}^\alpha\right) e^{-\left(1 + d_{\mathrm{A_i}}^\alpha\right)x}$, and $f_{Y_i}(y) = \left(1 + d_{\mathrm{B_i}}^\alpha\right) e^{-\left(1 + d_{\mathrm{B_i}}^\alpha\right)y}$.

Based on (17), applying [10, Eq. (3.324)], we obtain

$$\Xi = e^{-\left(1 + d_{\mathrm{B_i}}^\alpha\right)\varepsilon_{\mathrm{A}_i}} \left(1 - 2\sqrt{\chi \Lambda} K_1\left(2\sqrt{\chi \Lambda}\right)\right), \tag{18}$$

where $\Lambda = \frac{\left(1 + d_{\mathrm{B_i}}^\alpha\right)\left(1 + d_{\mathrm{C_i}}^\alpha\right)}{\eta \rho}$ and $\chi = \tau_1 - \frac{\rho x |p_{i1}|^2}{\rho x |p_{i2}|^2 + 1}$.

$$\Theta_1 = \int_{D_{\mathrm{B_i}}} \int_{D_{\mathrm{A_i}}} \int_0^{\varepsilon_{\mathrm{A}_i}} \underbrace{\int_{\varepsilon_{\mathrm{A}_i}}^{\infty} \left(1 - e^{-\left(1+d_{\mathrm{C_i}}^{\alpha}\right) \frac{\tau_1 - \frac{\rho x |p_{i1}|^2}{\rho x |p_{i2}|^2+1}}{\eta\rho\left(y-\varepsilon_{\mathrm{A}_i}\right)}} \right)}_{\Xi} f_{Y_i}(y)\, dy f_{X_i}(x)\, dx p w_{\mathrm{A_i}}(\omega_{\mathrm{A_i}})\, d\omega_{\mathrm{A_i}} p w_{\mathrm{B_i}}(\omega_{\mathrm{B_i}})\, d\omega_{\mathrm{B_i}}, \quad (17)$$

We use the series representation of Bessel functions to obtain a large-SNR approximation as $xK_1(x) \approx 1 + \frac{x^2}{2}\left(\ln\frac{x}{2} + c_0\right)$ with $c_0 = -\frac{\varphi(1)}{2} - \frac{\varphi(2)}{2}$, and $\varphi(\cdot)$ denotes the psi function. Then we rewrite (17) as follows:

$$\Theta_1 \approx -\int_0^{\varepsilon_{\mathrm{A_i}}} \chi \int\limits_{D_{\mathrm{A_i}}} \Lambda e^{-\left(1+d_{\mathrm{A_i}}^{\alpha}\right)x} \times \underbrace{\int\limits_{D_{\mathrm{B_i}}} \left(1+d_{\mathrm{B_i}}^{\alpha}\right)\left(\ln\chi\Lambda + 2c_0\right) p w_{\mathrm{B_i}}(\omega_{\mathrm{B_i}})\, d\omega_{\mathrm{B_i}}}_{\Phi} \times p w_{\mathrm{A_i}}(\omega_{\mathrm{A_i}})\, d\omega_{\mathrm{A_i}} dx. \quad (19)$$

Since $R_{D_{\mathrm{C}}} \gg R_{D_{\mathrm{B}}}$, we can approximate the distance as $d_{\mathrm{A_i}} \approx d_{\mathrm{C_i}}$. Then we use Gaussian-Chebyshev quadrature to find an approximation of Φ as follows:

$$\Phi \approx \frac{\omega_N}{2} \sum_{n=1}^{N} \left(\sqrt{1-{\phi_n}^2} c_n \left(\ln m_0 c_n + 2c_0\right)\left(\phi_n + 1\right) \right). \quad (20)$$

Substituting (20) into (19) and applying Gaussian-Chebyshev quadrature two times, we can obtain

$$\Theta_1 \approx \zeta_1 \sum_{n=1}^{N} (\phi_n+1)\sqrt{1-{\phi_n}^2} c_n \sum_{k=1}^{K} \sqrt{1-\psi_k^2} s_k (1+s_k^{\alpha})^2 \sum_{m=1}^{M} \sqrt{1-\varphi_m^2} e^{-(1+s_k^{\alpha})t_m} \chi_{t_m} \left(\ln \frac{\chi_{t_m}(1+s_k^{\alpha})}{\eta\rho} c_n + 2c_0 \right), \quad (21)$$

where $\zeta_1 = -\frac{\varepsilon_{\mathrm{A}_i} R_{D_{\mathrm{B_i}}} \omega_N \omega_K \omega_M}{8\left(R_{D_{\mathrm{A_i}}} + R_{D_{\mathrm{C_i}}}\right)\eta\rho}$, $s_k = \frac{R_{D_{\mathrm{A}}} - R_{D_{\mathrm{C}}}}{2}(\psi_k+1) + R_{D_{\mathrm{C}}}, \omega_K = \frac{\pi}{K}, \psi_k = \cos\left(\frac{2k-1}{2K}\pi\right)$, $t_m = \frac{\varepsilon_{\mathrm{A}_i}}{2}(\varphi_m+1)$, $\omega_M = \frac{\pi}{M}, \varphi_m = \cos\left(\frac{2m-1}{2M}\pi\right)$, and $\chi_{t_m} = \tau_1 - \frac{\rho t_m |p_{i1}|^2}{\rho t_m |p_{i2}|^2+1}$.

We express Θ_2 as follows:

$$\Theta_2 = \Pr\left(X_i < \varepsilon_{\mathrm{A}_i}\right)\Pr\left(Y_i < \varepsilon_{\mathrm{A}_i}\right). \quad (22)$$

Similar to the procedure used to obtain (12), with Gaussian-Chebyshev quadrature approximation, we obtain

$$\Theta_2 \approx a_1 \sum_{n=1}^{N} \sqrt{1-{\phi_n}^2} c_n (\phi_n+1) \sum_{k=1}^{K} \sqrt{1-{\psi_k}^2} \times (1+s_k^{\alpha}) s_k, \quad (23)$$

where $a_1 = \frac{\omega_K \omega_N \varepsilon_{\mathrm{A}_i}^2}{2\left(R_{D_{\mathrm{A}}} + R_{D_{\mathrm{C}}}\right)}$.

Combining (21) and (23), we can obtain the outage probability for the far users.

3.4. Diversity analysis for the far users

Based on the outage probability of the far users, we obtain

$$d_{\mathrm{A}} = -\lim_{\rho\to\infty} \frac{\log P_{\mathrm{A_i}}(\rho)}{\log\rho} = -\lim_{\rho\to\infty} \frac{\log\log\rho - \log\rho^2}{\log\rho} = 2. \quad (24)$$

Therefore, the diversity gain for the proposed protocol is two, which is the same as for a conventional cooperative network. This result indicates that using NOMA with SWIPT will not affect the diversity gain. We see that at high SNR, the dominant factor of the outage probability is $\frac{1}{\rho^2}\ln\rho$; therefore we conclude that using NOMA with SWIPT achieves a decreasing rate of $\frac{\ln SNR}{SNR^2}$ for the outage probability. However, for the conventional MA system without an energy harvesting relay, a faster decreasing rate of $\frac{1}{SNR^2}$ is achieved.

4. NUMERICAL RESULTS

In this section, representative numerical results are presented to illustrate the performance evaluations in terms of the outage probability of near and far users of the cooperative SWIPT NOMA protocol. In the considered network, we set the energy conversion efficiency of SWIPT as $\eta = 0.7$ and the power allocation coefficients of NOMA as $|p_{i1}|^2 = 0.8$ and $|p_{i1}|^2 = 0.2$. We use the radius region with $R_{D_{\mathrm{A}}} = 10, R_{D_{\mathrm{B}}} = 2$, and $R_{D_{\mathrm{C}}} = 8$.

In Fig. 1, the curves, representing the analytical results, are obtained from (13). We use Monte Carlo simulation points marked as "•" to verify our derivation. The figure shows precise agreement between the simulation and analytical curves. One can observe that lower outage probability is achieved by increasing SNR. The figure also demonstrates that as α increases, higher outage occurs since the path loss becomes larger in this case.

In Fig. 2, the dashed curves, representing the analytical results, are obtained from combining (21) and (23). The simulation and the analytical approximation are very close, particularly in the high SNR region, which validates our analytical results. One can observe that higher outage occurs as α

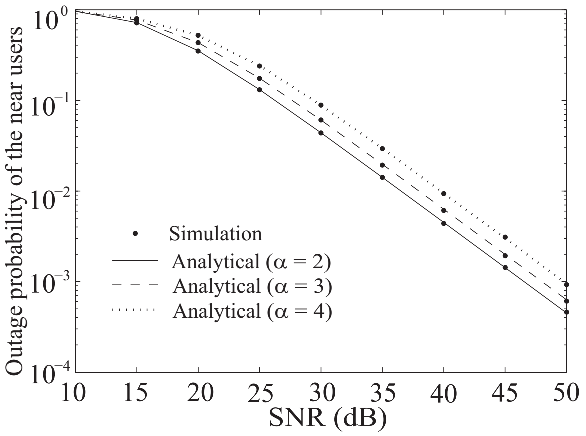

Fig. 1. Outage probability of the near users versus SNR with $R_1 = 1$ and $R_2 = 0.5$.

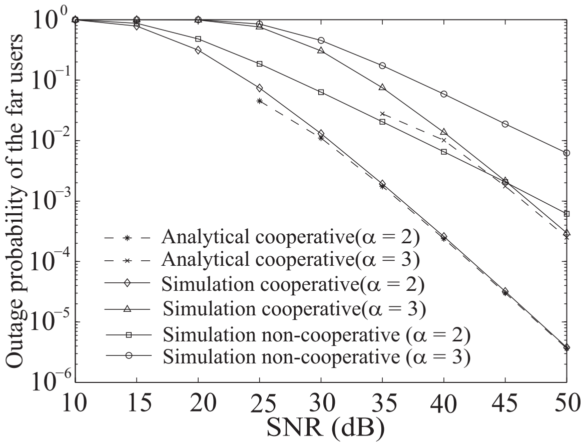

Fig. 2. Outage probability of the far users with $R_1 = 0.3$.

increases because of higher pass loss. The figure also demonstrates that by applying cooperative NOMA transmission, the outage probability of the far users has a larger slope than the non-cooperative case due to the higher diversity gain. In the diversity analysis part, we derive the diversity gain of cooperative case is two. The simulation validates the analytical results and indicates that NOMA with SWIPT will not affect the diversity gain.

5. CONCLUSIONS

In this paper, the application of simultaneously wireless information and power transfer (SWIPT) in non-orthogonal multiple access (NOMA) has been considered. In particular, a novel cooperative SWIPT NOMA protocol has been proposed. Stochastic geometry has been used to provide a complete framework to model the locations of users and evaluate the performance of the proposed protocol. New analytical results have been derived in terms of outage probability to determine the system performance. The diversity gain has also been characterized and proved to be the same as that of a conventional cooperative network. Numerical results have been presented to validate our analysis. We conclude that by carefully choosing the parameters of the network, acceptable system performance can be guaranteed based on the proposed cooperative SWIPT NOMA protocol in practical networks.

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