Exploiting user grouping and energy harvesting in downlink cellular system

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ABSTRACT

A mobile communication system combining energy harvesting with a cooperative non-orthogonal multiple access (NOMA) system is presented in this research. In the proposed scheme, the relay is assumed to have a limited power source, and it will harvest radio energy from the base station (BS) to serve the near and far users. In this scenario, we consider two possible situations during information transmission in the NOMA application system: perfect successive interference cancellation (SIC) and imperfect successive interference cancellation. The system performance is assessed primarily based on closed-form outage probability expressions. Numerical simulations are conducted to examine the outage probability of the proposed scheme and to verify the derived formulas. The study results have proved that the system performance is still good under the imperfect SIC condition, and several optimal parameters to improve the system performance have been found. Moreover, our research results have shown the superior performance of the proposed model compared with current orthogonal multiple access (OMA) networks.

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1. INTRODUCTION

Considered a promising wireless access solution for the fifth generation (5G) era, NOMA has great attentions [1]–[10]. According to the non-orthogonal multiple access (NOMA) principle, the transmission request is not orthogonal at the transmitter and the user’s signal is stacked in the power domain. As a result, greater spectrum efficiency is possible. More advances compared with traditional orthogonal multiple access (OMA), NOMA-aided transmitter can send signals to multiple terminals over the same resource block, and effective improvement can be obtained in term of sum rate. At the receiver, NOMA systems use successive interference cancellation (SIC) to decode the users’ signal. In term of decoding order, other users are considered noise by systems, which prioritize decoding the user with the best channel state.

NOMA was reviewed in reference [11]–[13], and the authors compared typical multiple access approaches to NOMA. Specifically, NOMA is recommended to apply to 5G communication system. NOMA can improve spectrum efficiency due to non-orthogonal transmission and SIC (SE). The normal energy supply is limited for the users in NOMA-aided systems, for example it is difficult to replace the battery in some places and/or limits the system performance improvement. To overcome this difficulty, energy harvesting (EH) architecture is studied to harvest the energy from the surrounding environments. To provide flexible, sustainable and
stable energy supply, radio frequency (RF) energy harvesting [14] allow users to harvest the energy from the radio-frequency signals. For example, simultaneous wireless information and power transfer (SWIPT) has been widely explored in emerging systems [15]–[20]. Reference [18] proposed an optimal wireless power method to improve the outage probability by utilizing the harvested RF energy. The RF energy harvesting strategy used in [19] benefits cognitive radio sensor networks.

The authors in [21] studied the resource optimization problem of NOMA heterogeneous small cell networks with SWIPT. Reference [22] took a two-user model for the downlink network and used an EH based incremental relaying cooperative NOMA (IR-EH-NOMA) technique. They developed analytical formulas for the IR-EH-NOMA network’s system throughput. In the delay-limited transmission mode, they evaluated the performance of a standard cooperative relaying NOMA network with EH (CR-EH-NOMA), two real situations are examined such as maximal ratio combining (MRC) and imperfect successive interference cancellation.

In addition, the main contribution and novelty of this paper are as follows: 1) we propose a novel relaying communication model that is based on the NOMA protocol and incorporates EH. Especially, the imperfect SIC problem in NOMA is also considered. 2) the closed-forms of outage probability as function of transmit signal-to-noise ratio (SNR) are calculated. Based on the proposed model, we have found some optimal parameters to enhance the system performance. Next, the outage performance is provided in Monte Carlo simulations to validate our analysis. Our research results have shown that the proposed model can improve the performance of the current OMA networks, as well as it demonstrates the feasibility of NOMA applying in the future networks.

2. SYSTEM MODEL

We consider the relaying system containing the BS with \( m \) (where \( m = 1, \ldots, M \)) antennas intends to serve the near (\( U_1 \)) and far user (\( U_2 \)) in the context of NOMA, shown as Figure 1. The BS communicates directly with \( U_1 \) and indirectly with \( U_2 \) through relay (\( R \)) which is able to harvest energy from the BS. In the first phase of communication, the BS will choose the best antenna to broadcasts the superposition signal \( x(t) = \sqrt{b_1}x_1 + \sqrt{b_2}x_2 \) to \( U_1 \) and \( R \), where \( x_i, i = (1, 2) \) denotes the information symbol to \( U_i \), and \( b_i \) denotes the power allocation factor, provided that \( b_1 + b_2 = 1 \) and \( b_1 < b_2 \). After receiving the signal from BS, \( R \) will perform decoding and forwarding the signal \( x_2 \) to \( U_2 \) in next phase with the help of SIC technology.

In the NOMA protocol, whether the data transmission is successful or not depends mainly on SIC technology. In the following part, we will analyze two possible cases: perfect SIC and imperfect SIC.

\[ y_{SU_1} = \sqrt{P_1} f_{1,m} \left( \sqrt{b_1} x_1 + \sqrt{b_2} x_2 \right) + n_{U_1}, \]  

where \( f_{1,m} \sim CN \left( 0, \eta_1 \right) \) is the channel coefficient between the BS-\( U_1 \), \( n_{U_1} \) denotes the additive white Gaussian noise (AWGN) at \( D_i \), with \( n_{U_1} \sim CN \left( 0, N_0 \right) \), \( P_1 \) is the power of the BS.

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Regarding the link BS-U₁, the received signal-to-interference-plus-noise ratio (SINR) at U₁ to detect U₂’s message and its own message, i.e. x₁, are provided by:

\[
\gamma_{SU_1} = \frac{P_1 b_1 |f_{1,m}|^2}{P_2 b_1 |f_{1,m}|^2 + N_0}, \quad \gamma_{SU_1} = \frac{P_1 b_1 |f_{1,m}|^2}{N_0}.
\] (2)

The R harvests energy from the BS in the first phase and uses this energy to relay the signal to U₁ and U₂ in the next phase. Therefore, by employing power splitting protocol (PS) [20], [21], the signal received at R in the first period is represented as:

\[
y_{SR} = (1 - \theta) \sqrt{P_1} f_{2,m} \left( \sqrt{b_1} x_1 + \sqrt{b_2} x_2 \right) + n_R,
\] (3)

where \( f_{2,m} \sim CN \left(0, \eta_2\right) \) is the channel coefficient between the BS–R, \( n_R \) represents the AWGN at R with \( n_R \sim CN \left(0, N_0\right) \), \( \theta \) is the power separation factor.

Also in the first stage, the signal-to-interference-noise ratio (SINR) at R for message detection of U₂ and for its message detection, i.e. x₁, is calculated by:

\[
\gamma_{SR} = \frac{(1 - \theta) P_1 b_2 |f_{2,m}|^2}{(1 - \theta) P_1 b_1 |f_{2,m}|^2 + N_0}, \quad \gamma_{SR} = \frac{(1 - \theta) P_1 b_1 |f_{2,m}|^2}{N_0}.
\] (4)

In the second stage of communication, the signal received at U₁, i = (1, 2) is being as:

\[
y_{RU_1} = \sqrt{P_2} f_\lambda \left( \sqrt{b_1} x_1 + \sqrt{b_2} x_2 \right) + n_{U_1},
\] (5)

where \( \lambda = \{3, 4\} \), \( P_2 \) is the power of the R, \( f_3 \sim CN \left(0, \eta_3\right) \) and \( f_4 \sim CN \left(0, \eta_4\right) \) are the channel factor of the links R-U₁ and R-U₂. Similarly, the SINR at U₂ to detect its own message, i.e x₂, is provided by:

\[
\gamma_{RU_2} = \frac{P_2 b_2 |f_{4}|^2}{P_2 b_1 |f_{4}|^2 + N_0}.
\] (6)

The SINR at U₁ to detect U₂’s message and to detect its own message, i.e. x₁, in this stage are calculated by:

\[
\gamma_{RU_1} = \frac{P_2 b_2 |f_{4}|^2}{P_2 b_1 |f_{4}|^2 + N_0}, \quad \gamma_{RU_1} = \frac{P_2 b_2 |f_{4}|^2}{N_0}.
\] (7)

We assume that U₁ regarding two associated links and hence, the decision rule for selecting one of the links at U₁ in the case of the full selection combining (SC) [22]. Therefore, the instantaneous SINR at user U₁ is written as:

\[
\Gamma_{U_1} = \max \left\{ \min \left( \gamma_{RU_1}, \gamma_{SU_1} \right), \min \left( \gamma_{SU_1}, \gamma_{RU_1}, \gamma_{RU_1} \right) \right\}.
\] (8)

Moreover, the energy obtained at relay R is provided by \( P_2 = \beta \beta P_1 |f_{2,m}|^2 \) [19], where \( \beta \) is energy conversion efficiency.

The chosen antenna can be selected to strengthen the BS-U₁, BS-R link as \( m^* = \arg \max_{m=1, \ldots, M} \left(|f_{1,m}^*|\right)^2 \) [23]. Base on [24], the selected channel has CDF, and PDF of \(|f_{1,m}^*|^2\), respectively as:

\[
F_{|f_{1,m}^*|^2}(x) = 1 - \sum_{m=1}^{M} C_m^M (-1)^{m-1} \exp \left(-\frac{m^2}{\eta}\right), \quad f_{|f_{1,m}^*|^2}(x)
\] = \sum_{m=1}^{M} C_m^M (-1)^{m-1} \frac{1}{\eta^m} \exp \left(-\frac{m^2}{\eta}\right).
\] (9)

2.2. Scheme 2: imperfect successive interference cancellation

In this section, because the imperfections of SIC in real networks are entirely possible, we examine and evaluate the system’s performance assuming imperfect SIC at the relay and U₁. Regarding to the imperfect
SIC, the received SINR at BS-$U_1$ to detect its own message $x_1$, the received SINR at BS-$R$ to detect its own message $x_1$ and the received SINR at $R-U_1$ to detect its own message $x_1$ are given by:

\[
\gamma_{SU_1}^{(x_1,x_1)} = \frac{P_0 b_1 |f_1|^2}{P_1 b_2 |f_1|^2 + N_0}, \quad \gamma_{SR}^{(x_1,x_1)} = \frac{(1-\theta) P_0 b_1 |f_2|^2}{(1-\theta) P_1 b_2 |f_2|^2 + N_0}, \quad \gamma_{RU_1}^{(x_1,x_1)} = \frac{P_0 b_1 |f_3|^2}{P_1 b_2 |f_3|^2 + N_0},
\]

where $f_k \sim CN (0, \chi_k b_k), (k = 1, m; 2, m; 3), \chi_i (0 \leq \chi_i \leq 1)$ denote the level of residual interference at BS-$U_1$, BS-$R$, R-$U_1$ because of SIC imperfection. As a particular case, $\chi_i = 0$ and $\chi_i = 1$ represent perfect SIC and no SIC, respectively.

3. OUTAGE PROBABILITY

3.1. Scheme 1: perfect successive interference cancellation

3.1.1. Outage probability of $U_1$

Based on (5), the outage probability (OP) for $U_1$ can be obtained as [23], [24]:

\[
\Phi_1 = \Pr\left\{\min_{\Theta_1} \left(\frac{\gamma_{SU_1}^{(x_1,x_1)}}{\gamma_{SU_1}^{(x_1,x_1)}}, \frac{\gamma_{SR}^{(x_1,x_1)}}{\gamma_{SU_1}^{(x_1,x_1)}}\right) < \psi_1\right\}
= \Pr\left\{\min_{\Theta_2} \left(\frac{\gamma_{SU_1}^{(x_1,x_1)}}{\gamma_{SU_1}^{(x_1,x_1)}}, \frac{\gamma_{RU_1}^{(x_1,x_1)}}{\gamma_{SU_1}^{(x_1,x_1)}}\right) < \psi_1\right\},
\]

where $\psi_1 = 2^{2R_1} - 1$, $i = (1, 2)$, $R_i$ is target rates of $U_i$.

Based on (11), $\Theta_1$ can be written as:

\[
\Theta_1 = 1 - \Pr\left(\left|f_{1,m}\right|^2 \geq \Omega\right) = 1 - \sum_{m=1}^{M} C_m^M (-1)^{m-1} \exp\left(-\frac{m\Omega}{\eta_1}\right), \tag{12}
\]

where $\Omega = \max\left(\frac{N_0 b_1}{P_1 b_1}, \frac{N_0 \psi_1}{P_1 b_1}\right)$.

Based on (11), $\Theta_2$ can be expressed as:

\[
\Theta_2 = 1 - \Pr\left(\gamma_{SU_1}^{(x_1,x_1)} \geq \psi_1\right) \Pr\left(\min_{\Theta_2} \left(\frac{\gamma_{SU_1}^{(x_1,x_1)}}{\gamma_{SU_1}^{(x_1,x_1)}}, \frac{\gamma_{RU_1}^{(x_1,x_1)}}{\gamma_{SU_1}^{(x_1,x_1)}}\right) \geq \psi_1\right)
= 1 - \Pr\left(\left|f_{2,m}\right|^2 \geq \frac{N_0 \psi_1}{(1-\theta) P_1 b_1}\right) \Pr\left(\left|f_{3}\right|^2 \geq \frac{\Omega}{\gamma_{RU_1}^{(x_1,x_1)}}\right)
= \sum_{m=1}^{M} \sum_{r=1}^{M} C_m^M C_r^M (-1)^{r+m-2} \exp\left(-\frac{m N_0 \psi_1}{(1-\theta) P_1 b_1}\right) \int_{0}^{\frac{\psi_1}{\gamma_{RU_1}^{(x_1,x_1)}}} \int_{0}^{\frac{\Omega}{\psi_1}} \exp\left(-\frac{4\Omega}{\theta_2 \psi_1}\right) dx \tag{13}
\]

where the last expression is derived from the fact that $\int_{0}^{\infty} e^{-\frac{\pi r^2}{\theta_2 \psi_1}} dy = \sqrt{\frac{\pi}{\theta_2 \psi_1}} K_1\left(\sqrt{\frac{\pi}{\theta_2 \psi_1}}\right)$,

Finally, from (12) and (13) into (11) the exact OP of $U_1$ can be written as:

\[
\Phi_1 = \left[1 - \sum_{m=1}^{M} C_m^M (-1)^{m-1} \exp\left(-\frac{m\Omega}{\eta_1}\right)\right] \left[1 - \sum_{m=1}^{M} \sum_{r=1}^{M} C_m^M C_r^M (-1)^{r+m-2}\right]
\times \exp\left(-\frac{m N_0 b_1}{(1-\theta) P_1 b_1}\right) \sqrt{\frac{4\Omega}{\theta_2 \psi_1}} K_1\left(\sqrt{\frac{4\Omega}{\theta_2 \psi_1}}\right). \tag{14}
\]

3.1.2. Outage probability of $U_2$

In this case, an outage event at $U_2$ will occur if $U_2$ and $R$ are unable to correctly detect $x_2$, according to the NOMA principle. As a result, the OP of $U_2$ can be written as:

\[
\Phi_2 = 1 - \Pr\left\{\gamma_{SU_1}^{(x_2,x_2)} \geq \psi_2\right\} \Pr\left\{\gamma_{RU_2}^{(x_2,x_2)} \geq \psi_2\right\}, \tag{15}
\]

Similar as (14) after several steps, the exact OP of $U_2$ can be written as:

\[
\Phi_2 = \left[1 - \sum_{m=1}^{M} C_m^M (-1)^{m-1} \exp\left(-\frac{m\Omega}{\eta_1}\right)\right] \left[1 - \sum_{m=1}^{M} \sum_{r=1}^{M} C_m^M C_r^M (-1)^{r+m-2}\right]
\times \sqrt{\frac{4\Omega b_2 N_0}{(1-\theta) b_2 - \psi_2 (1-\theta) b_1 P_1 b_2}} K_1\left(\sqrt{\frac{4\Omega b_2 N_0}{(1-\theta) b_2 - \psi_2 (1-\theta) b_1 P_1 b_2}}\right). \tag{16}
\]
3.2. Sheme 2: imperfect successive interference cancellation

In our proposed system model, $U_1$ and $R$ are two devices that will apply SIC technology to decode $x_1$ signals. Therefore, imperfect SIC will not affect the outage performance at $U_2$. In other words, the outage performance at $U_2$ in both perfect and imperfect SIC scheme is the same. For that reason, in this part, we only calculate the OP at $U_1$ is being as:

$$\Phi_{ip,1} = \Pr \left( \frac{\gamma_{SU_1}}{\psi_1} < \psi_1 \right) \Pr \left( \min \left( \frac{\gamma_{SR}}{\psi_1}, \frac{\gamma_{RU_1}}{\psi_1} \right) < \psi_1 \right).$$

(17)

Base on (17), $\Lambda_1$ is given by:

$$\Lambda_1 = 1 - \Pr \left\{ \left| f_{1,m^*} \left| ^2 \geq \psi_1 \left( \frac{P_{1,R_2}}{P_{1,R_1}} \right)^2 + N_0 \right. \right\}$$

$$= 1 - \sum_{m=1}^{M} \sum_{r=1}^{M} C_m^M C_r^M (-1)^{r-m+2} \frac{r \chi \eta_3}{\psi_1 \eta_3} \exp \left( -\frac{m \psi_1 N_0}{P_{1,R_1} \eta_3} \right) \int_0^\infty \exp \left( -\frac{m \psi_1 b_2}{P_{1,R_1} \eta_3} + \frac{r \chi \eta_3}{\psi_1 \eta_3} \right) dx \right. \right.$$  

$$= 1 - \sum_{m=1}^{M} \sum_{r=1}^{M} C_m^M C_r^M (-1)^{r-m+2} \frac{r \chi \eta_3}{\psi_1 \eta_3} \exp \left( -\frac{m \psi_1 N_0}{P_{1,R_1} \eta_3} \right) \int_0^\infty \exp \left( -\frac{m \psi_1 b_2}{P_{1,R_1} \eta_3} + \frac{r \chi \eta_3}{\psi_1 \eta_3} \right) dx \right. \right.$$  

(18)

Then, $\Lambda_2$ can be written by $\Lambda_2 = 1 - \Pr \left( \frac{\gamma_{SR}}{\psi_1} \geq \psi_1 \right) \Pr \left( \frac{\gamma_{RU_1}}{\psi_1} \geq \psi_1 \right)$. Then, $\Lambda_{2a}$ is calculated is being as:

$$\Lambda_{2a} = \Pr \left\{ \left| f_{2,m^*} \left| ^2 \geq \psi_1 \left( \frac{1-\theta}{1-\beta} \right)^2 + N_0 \right. \right\}$$

$$= \sum_{m=1}^{M} \sum_{r=1}^{M} C_m^M C_r^M (-1)^{r-m+2} \frac{r \chi \eta_3}{\psi_1 \eta_3} \exp \left( -\frac{m \psi_1 N_0}{P_{1,R_1} \eta_3} \right) \int_0^\infty \exp \left( -\frac{m \psi_1 b_2}{P_{1,R_1} \eta_3} + \frac{r \chi \eta_3}{\psi_1 \eta_3} \right) dx \right. \right.$$  

$$= \sum_{m=1}^{M} \sum_{r=1}^{M} C_m^M C_r^M (-1)^{r-m+2} \frac{r \chi \eta_3}{\psi_1 \eta_3} \exp \left( -\frac{m \psi_1 N_0}{P_{1,R_1} \eta_3} \right) \int_0^\infty \exp \left( -\frac{m \psi_1 b_2}{P_{1,R_1} \eta_3} + \frac{r \chi \eta_3}{\psi_1 \eta_3} \right) dx \right. \right.$$  

(19)

We focus on the high SNR approximation of $\Lambda_{2b}$ which is given by:

$$\Lambda_{2b} \approx \Pr \left\{ \left| \tilde{f}_{2,1} \right| ^2 \geq \frac{\psi_1 b_2}{b_1} \right\} \approx \frac{1}{\chi \eta_3} \int_0^\infty \exp \left( -\frac{\psi_1 b_2}{b_1 \eta_3} + \frac{1}{\chi \eta_3} \right) dx \approx \frac{b_1}{\psi_1 \eta_3 b_1 + b_1}.$$

(20)

From (18)-(20) into (17), the exact OP of $U_1$ for imperfect SIC can be written as:

$$\Phi_{ip,1} = \left[ 1 - \sum_{m=1}^{M} \sum_{r=1}^{M} C_m^M C_r^M (-1)^{r-m+2} \frac{r \chi \eta_3}{\psi_1 \eta_3} \exp \left( -\frac{m \psi_1 N_0}{P_{1,R_1} \eta_3} \right) \int_0^\infty \exp \left( -\frac{m \psi_1 b_2}{P_{1,R_1} \eta_3} + \frac{r \chi \eta_3}{\psi_1 \eta_3} \right) dx \right. \right.$$  

$$\times \left[ 1 - \sum_{m=1}^{M} \sum_{r=1}^{M} C_m^M C_r^M (-1)^{r-m+2} \frac{r \chi \eta_3}{\psi_1 \eta_3} \exp \left( -\frac{m \psi_1 N_0}{P_{1,R_1} \eta_3} \right) \int_0^\infty \exp \left( -\frac{m \psi_1 b_2}{P_{1,R_1} \eta_3} + \frac{r \chi \eta_3}{\psi_1 \eta_3} \right) dx \right. \right.$$  

(21)

4. NUMERICAL RESULTS

In this part, simulation results are provided by using Monte Carlo simulation method to demonstrate the performance of the proposed cooperative NOMA systems. In particular, the following set of parameters are used: $b_1 = 0.25, R_1 = R_2 = 0.7$ (bps/Hz), $\theta = \beta = 0.6, \eta_1 = \eta_2 = \eta_3 = \eta_4 = 1, \chi = \chi_1 = \chi_2 = \chi_3 = 0.1, P_1/N_0 = 10$ (dB), $M = 2$. Some simulation parameters are given in the caption and the legend of the figures.

As the observation, Figure 2 and Figure 4 plot the OP for proposed NOMA scheme under two scenerios of perfect SIC and imperfect SIC. Observing the Figure 2 we may conclude that, despite the faulty SIC, the system performance still performs well. User $U_1$ has superior outage performance than user $U_2$ over the whole range of transmit SNR at source. More specifically, the system achieves better performance in perfect SIC case and the system performance will get better as the number of antennas increases. Besides, we also found from Figure 4 that the NOMA technique performed better than the conventional OMA technology. Furthermore, when increasing the power splitting coefficient of energy harvesting protocol ,i.e., $\theta$, the system performance
is also better. This proves that our proposed model can improve the performance of existing mobile communication networks.

The outage performance is illustrated in Figure 4 as the goal rates are varied. It can be shown that the greater the target rate, the higher the harvested power and the lower the outage performance. Furthermore, when $b_1$ increases from 0 to 0.35, the perfect SIC mode outperforms the imperfect mode in terms of outage performance. However, according to the principles of NOMA, increasing $b_1$ means that $b_2$ is reduced so the performance of $U_2$ also decreases. Therefore, in order for system performance to be guaranteed for all cases, we obtain the optimal power distribution coefficient at values around $b_1 = 0.2$. We can easily see from Figure 5 that the perfect SIC case always achieves better performance than the imperfect SIC case for different values of SINR and $R_1$. In addition, it can also be observed that the system performance is significantly enhanced at small target rates and high SINR.

5. CONCLUSION

In this work, we investigated the impact of energy harvesting on the system performance metric of the NOMA system. Simultaneously, the issue of NOMA’s imperfect SIC was investigated. We focus on outage probability for two users with fixed power allocation factors adopted to make differences among two user. When the relay is able harvest larger amount of harvested energy, the system performance can be improved

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significantly. Further, we have obtained optimal values of several important parameters that help to greatly improve the system performance. Finally, having more antennas at the source improves the system’s outage performance, and our findings suggest that the proposed model can increase the performance of current OMA networks while also demonstrating the potential of using NOMA in future networks.

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REFERENCES


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