Cooperative Non-Orthogonal Multiple Access with Simultaneous Wireless Information and Power Transfer

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Outline

From NOMA to Cooperative NOMA

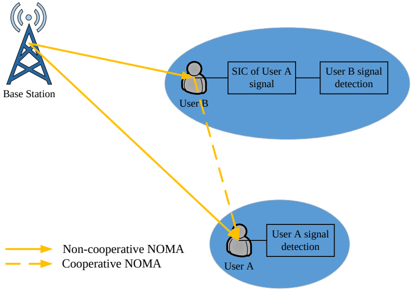
NOMA can squeeze a user with better channel conditions into a channel that is occupied by a user with worse channel conditions. For example, consider a downlink scenario in which there are two groups of users:

- **Near users:** close to the base station (BS) and have better channel conditions.
- **Far users:** close to the edge of the cell controlled by the BS and therefore have worse channel conditions.

While the spectral efficiency of NOMA is superior compared to orthogonal MA, the fact that the near users co-exist with the far users causes performance degradation to the far users. *This motivates us to consider the cooperative NOMA.*

What is Cooperative NOMA?

- **Cooperative NOMA**: the users that are close to the BS are used as relays to help the far users with poor channel conditions.



- **Advantages**: SIC is used and hence the information of the far users is known by these near users. Then it is natural to consider the use of the near users as DF relays.

SWIPT—Background

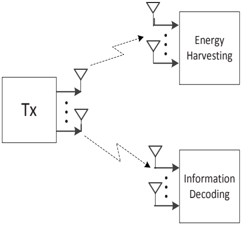
Wireless energy Transfer (WET)

- Key Idea: Energy is transmitted from a power source to a destination over the wireless medium.
- Motivation: 1) Ambient radio frequency signals are everywhere; 2) WET could be the only means to increase lifetime of energy constrained networks
- Tesla had already provided a successful demonstration to light electric lamps wirelessly in 1891, but been forgotten for long time due to the low energy efficiency.

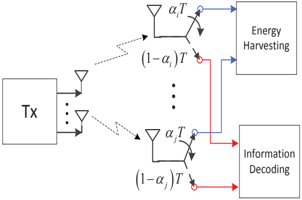
What has been changed now?

- More low power devices.
- Advanced smart antenna techniques for better energy efficiency.

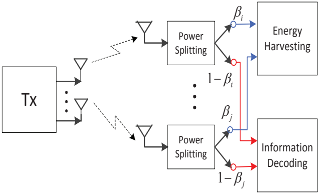
SWIPT—Basic receiver achitectures



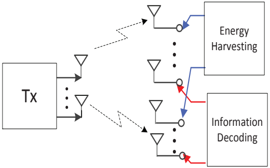
(a) Separated Receiver



(b) Time Switching Receiver



(c) Power Splitting Receiver

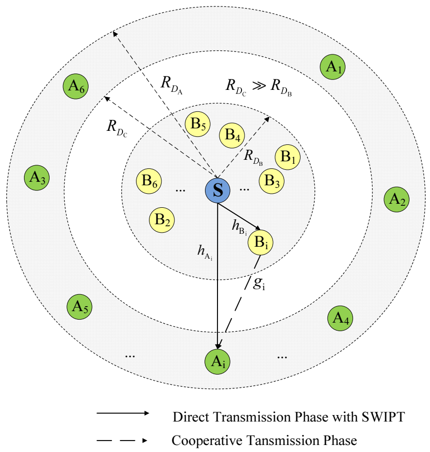


(d) Antenna Switching Receiver

Motivation

- To improve the reliability of the 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.
- Therefore, the aforementioned two communication concepts, cooperative NOMA and SWIPT, can be naturally linked together.
- To propose a new both spectral efficient and energy efficient wireless multiple access protocol, namely, the cooperative SWIPT NOMA protocol, is the main motivation of this paper.

Network Model



- An illustration of a downlink SWIPT NOMA system with a base station S (blue circle). The spatial distributions of the near users (yellow circles) and the far users (green circles) follow homogeneous PPPs.

Network Model

- The locations of the near and far users are modeled as homogeneous PPPs Φ_κ $(\kappa \in \{\mathrm{A}, \mathrm{B}\})$ with densities λ_{Φ_κ}.
- The near users are uniformly distributed within the disc and the far users are uniformly distributed within the ring.
- the users in $\{\mathrm{B_i}\}$ are energy harvesting relays that harvest energy from the BS and forward the information to $\{\mathrm{A_i}\}$ using the harvested energy as their transmit powers.
- The DF strategy is applied at $\{\mathrm{B_i}\}$ and the cooperative NOMA system consists of two phases.
- It is assumed that the two phases have the same transmission periods.

Phase 1: Direct Transmission

During the first phase, the BS sends two messages $p_{i1}x_{i1} + p_{i2}x_{i2}$ to two selected users $\mathrm{A_i}$ and $\mathrm{B_i}$ based on NOMA, where p_{i1} and p_{i2} are the power allocation coefficients and x_{i1} and x_{i2} are the messages of $\mathrm{A_i}$ and $\mathrm{B_i}$, respectively. The observation at $\mathrm{A_i}$ is given by

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

Without loss of generality, we assume that $|p_{i1}|^2 > |p_{i2}|^2$ with $|p_{i1}|^2 + |p_{i2}|^2 = 1$. The received signal to interference and noise ratio (SINR) at $\mathrm{A_i}$ to detect x_{i1} is given by

$$\gamma_{\mathrm{S,A_i}}^{x_{i1}} = \frac{\rho|h_{\mathrm{A_i}}|^2|p_{i1}|^2}{\rho|p_{i2}|^2|h_{\mathrm{A_i}}|^2 + 1 + d_{\mathrm{A_i}}^{\alpha}}, \quad (2)$$

where $\rho = \frac{P_{\mathrm{S}}}{\sigma^2}$ is the transmit signal to noise radio (SNR).

Phase 1: Direct Transmission

We consider that the near users have rechargeable storage ability and power splitting is applied to perform SWIPT. Thus, the observation at $\mathrm{B_i}$ is given by

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

where β_i is the power splitting coefficient.
The received SINR at $\mathrm{B_i}$ to detect x_{i1} of $\mathrm{A_i}$ is given by

$$\gamma_{\mathrm{S,B_i}}^{x_{i1}} = \frac{\rho |h_{\mathrm{B_i}}|^2 |p_{i1}|^2 (1-\beta_i)}{\rho |h_{\mathrm{B_i}}|^2 |p_{i2}|^2 (1-\beta_i) + 1 + d_{\mathrm{B_i}}^{\alpha}}. \tag{4}$$

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

$$\gamma_{\mathrm{S,B_i}}^{x_{i2}} = \frac{\rho |h_{\mathrm{B_i}}|^2 |p_{i2}|^2 (1-\beta_i)}{1 + d_{\mathrm{B_i}}^{\alpha}}. \tag{5}$$

Phase 1: Direct Transmission

Based on (4), the data rate supported by the channel from the BS to $\mathrm{B_i}$ for decoding x_{i1} is given by

$$R_{x_{i1}} = \frac{1}{2}\log\left(1 + \frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2(1-\beta_i)}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2(1-\beta_i) + 1 + d_{\mathrm{B_i}}^{\alpha}}\right). \quad (6)$$

In order to ensure that $\mathrm{B_i}$ can successfully decode the information of $\mathrm{A_i}$, we have a rate, i.e., $R_1 = R_{x_{i1}}$. Therefore, the power splitting coefficient is set as follows:

$$\beta_i = \max\left\{0, 1 - \frac{\tau_1\left(1 + d_{\mathrm{B_i}}^{\alpha}\right)}{\rho\left(|p_{i1}|^2 - \tau_1|p_{i2}|^2\right)|h_{\mathrm{B_i}}|^2}\right\}, \quad (7)$$

where $\tau_1 = 2^{2R_1} - 1$. Here $\beta_i = 0$ means that all the energy is used for information decoding and no energy remains for energy harvesting.

Phase 1: Direct Transmission

Based on (3), the energy harvested at $\mathrm{B_i}$ is given by

$$E_{\mathrm{B_i}} = \frac{T\eta P_{\mathrm{S}}\beta_i |h_{\mathrm{B_i}}|^2}{2\left(1 + d_{\mathrm{B_i}}^{\alpha}\right)}, \tag{8}$$

where T is the time period for the entire transmission including the direct transmission phase and the cooperative transmission phase, and η is the energy harvesting coefficient. We assume that the two phases have the same transmission period, and therefore, the transmit power at $\mathrm{B_i}$ can be expressed as follows:

$$P_t = \frac{\eta P_{\mathrm{S}}\beta_i |h_{\mathrm{B_i}}|^2}{1 + d_{\mathrm{B_i}}^{\alpha}}. \tag{9}$$

Phase 2: Cooperative Transmission

During this phase, $\mathrm{B_i}$ forwards x_{i1} to $\mathrm{A_i}$ by using the harvested energy during the direct transmission phase. In this case, $\mathrm{A_i}$ observes

$$y_{\mathrm{A_i},2} = \frac{\sqrt{P_t} x_{i1} g_{\mathrm{i}}}{\sqrt{1 + d_{\mathrm{C_i}}^{\alpha}}} + n_{\mathrm{A_i},2}, \tag{10}$$

Based on (9) and (10), the received SNR for $\mathrm{A_i}$ to detect x_{i1} forwarded from $\mathrm{B_i}$ is given by

$$\gamma_{\mathrm{A_i},\mathrm{B_i}}^{x_{i1}} = \frac{P_t |g_i|^2}{\left(1 + d_{\mathrm{C_i}}^{\alpha}\right) \sigma^2} = \frac{\eta \rho \beta_i |h_{\mathrm{B_i}}|^2 |g_i|^2}{\left(1 + d_{\mathrm{C_i}}^{\alpha}\right)\left(1 + d_{\mathrm{B_i}}^{\alpha}\right)}. \tag{11}$$

Phase 2: Cooperative Transmission

At the end of this phase, $\mathrm{A_i}$ combines the signals from the BS and $\mathrm{B_i}$ using maximal-ratio combining (MRC). Combining the SNR of the direct transmission phase (2) and the SINR of the cooperative transmission phase (11), we obtain the received SINR at $\mathrm{A_i}$ as follows:

$$\gamma_{\mathrm{A_i},\mathrm{MRC}}^{x_{i1}} = \frac{\rho |h_{\mathrm{A_i}}|^2 |p_{i1}|^2}{\rho |h_{\mathrm{A_i}}|^2 |p_{i2}|^2 + 1 + d_{\mathrm{A_i}}^{\alpha}} + \frac{\eta \rho \beta_i |h_{\mathrm{B_i}}|^2 |g_i|^2}{\left(1 + d_{\mathrm{B_i}}^{\alpha}\right)\left(1 + d_{\mathrm{C_i}}^{\alpha}\right)}. \quad (12)$$

Non-Orthogonal Multiple Access with User Selection

A natural question arises: which near NOMA user should help which far NOMA user?
To investigate the performance of one pair of selected NOMA users, three opportunistic user selection schemes are proposed, based on locations of users to perform NOMA as follows:

- random near user and random far user (RNRF) selection, where both the near and far users are randomly selected from the two groups.
- nearest near user and nearest far user (NNNF) selection, where a near user and a far user closest to the BS are selected from the two groups.
- nearest near user and farthest far user (NNFF) selection, where a near user which is closest to the BS is selected and a far user which is farthest from the BS is selected.

RNRF Selection Scheme—Outline

This selection scheme provides a fair opportunity for each user to access the source with the NOMA protocol.
Advantage: it does not require the knowledge of instantaneous channel state information (CSI).

1. Outage Probability of the Near Users of RNRF
2. Outage Probability of the Far Users of RNRF
3. Diversity Analysis of RNRF
4. System Throughput in Delay-Sensitive Transmission Mode of RNRF

Outage Probability of the Near Users of RNRF

An outage of $\mathrm{B_i}$ can occur for two reasons.

1. $\mathrm{B_i}$ cannot detect x_{i1}.
2. $\mathrm{B_i}$ can detect x_{i1} but cannot detect x_{i2}.

Based on this, the outage probability of $\mathrm{B_i}$ can be expressed as follows:

$$P_{\mathrm{B_i}} = \Pr\left(\frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2 + 1 + d_{\mathrm{B_i}}^{\alpha}} < \tau_1\right) + \Pr\left(\frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2 + 1 + d_{\mathrm{B_i}}^{\alpha}} > \tau_1, \gamma_{\mathrm{S,B_i}}^{x_{i2}} < \tau_2\right). \qquad (13)$$

Outage Probability of the Near Users of RNRF

Theorem 3.1

Conditioned on the PPPs, the outage probability of the near users $\mathrm{B_i}$ *can be approximated as follows:*

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

Proof.

We first derive the CDF of Y_i *as*

$$F_{Y_i}\left(\varepsilon\right) = \frac{2}{R_{D_{\mathrm{B}}}^2} \int_0^{R_{D_{\mathrm{B}}}} \left(1 - e^{-\left(1 + r^{\alpha}\right)\varepsilon}\right) r dr, \tag{15}$$

With the aid of Gaussian-Chebyshev quadrature, we find the approximation of (15)*. Applying* $\varepsilon_{\mathrm{A}_i} \to \varepsilon$, (14) *is obtained.* □

Outage Probability of the Far Users of RNRF

Outage experienced by $\mathrm{A_i}$ can occur in two situations.

1. $\mathrm{B_i}$ can detect x_{i1} but the overall received SNR at $\mathrm{A_i}$ cannot support the targeted rate.
2. Neither $\mathrm{A_i}$ nor $\mathrm{B_i}$ can detect x_{i1}.

Based on this, the outage probability can be expressed as follows:

$$P_{\mathrm{A_i}} = \Pr\left(\gamma^{x_{i1}}_{\mathrm{A_i,MRC}} < \tau_1,\, \gamma^{x_{i1}}_{\mathrm{S,B_i}}\Big|_{\beta_i=0} > \tau_1\right) + \Pr\left(\gamma^{x_{i1}}_{\mathrm{S,A_i}} < \tau_1,\, \gamma^{x_{i1}}_{\mathrm{S,B_i}}\Big|_{\beta_i=0} < \tau_1\right). \tag{16}$$

Outage Probability of the Far Users of RNRF

Theorem 3.2

Conditioned on the PPPs, and assuming $R_{D_{\mathrm{C}}} \gg R_{D_{\mathrm{B}}}$, the outage probability of $\mathrm{A_i}$ can be approximated as follows:

$$
\begin{aligned}
P_{\mathrm{A_i}} \approx \zeta_1 \sum_{n=1}^{N} (\phi_n + 1) \sqrt{1 - {\phi_n}^2} c_n \sum_{k=1}^{K} \sqrt{1 - \psi_k^2} s_k (1 + s_k^{\alpha})^2 \\
\times \sum_{m=1}^{M} \sqrt{1 - \varphi_m^2} e^{-\left(1+s_k^{\alpha}\right) t_m} \chi_{t_m} \left(\ln \frac{\chi_{t_m} \left(1 + s_k^{\alpha}\right)}{\eta \rho} c_n + 2c_0 \right) \\
+ a_1 \sum_{n=1}^{N} \sqrt{1 - {\phi_n}^2} c_n \left(\phi_n + 1\right) \sum_{k=1}^{K} \sqrt{1 - {\psi_k}^2} (1 + s_k^{\alpha}) s_k,
\end{aligned}
\tag{17}
$$

Proof.

See Appendix A.

Diversity Analysis of RNRF—Near Users

The diversity gain is defined as follows:

$$d = -\lim_{\rho \to \infty} \frac{\log P(\rho)}{\log \rho}. \tag{18}$$

Near users: When $\varepsilon \to 0$, a high SNR approximation with $1 - e^{-x} \approx x$ is given by

$$F_{Y_i}(\varepsilon) \approx \frac{1}{2} \sum_{n=1}^{N} \omega_N \sqrt{1 - {\phi_n}^2} c_n \varepsilon_{\mathrm{A}_i} (\phi_n + 1). \tag{19}$$

Substituting (19) into (18), we obtain that the diversity gain for the near users is one, which means that using NOMA with energy harvesting will not decrease the diversity gain.

Diversity Analysis of RNRF—Far Users

Far users: For the far users, substituting (17) into (18), we obtain

$$
\begin{aligned}
d &= -\lim_{\rho\to\infty} \frac{\log\left(-\frac{1}{\rho^2}\log\frac{1}{\rho}\right)}{\log\rho} \\
&= -\lim_{\rho\to\infty} \frac{\log\log\rho - \log\rho^2}{\log\rho} = 2.
\end{aligned} \tag{20}
$$

Remarks:

- This result indicates that using NOMA with an energy harvesting relay will not affect the diversity gain.
- At high SNRs, the dominant factor for the outage probability is $\frac{1}{\rho^2}\ln\rho$.
- The outage probability of using NOMA with SWIPT decays at a rate of $\frac{\ln SNR}{SNR^2}$. However, for a conventional cooperative system without energy harvesting, a faster decreasing rate of $\frac{1}{SNR^2}$ can be achieved.

System Throughput in Delay-Sensitive Transmission Mode of RNRF

In this mode, the transmitter sends information at a fixed rate and the throughput is determined by evaluating the outage probability. As a result, the system throughput of RNRF in the delay-sensitive transmission mode is given by

$$R_{\tau_{\mathrm{RNRF}}} = \left(1 - P_{\mathrm{A_i}}\right) R_1 + \left(1 - P_{\mathrm{B_i}}\right) R_2, \tag{21}$$

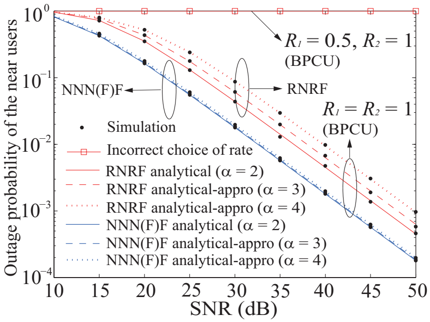
where $P_{\mathrm{A_i}}$ and $P_{\mathrm{B_i}}$ are obtained from (17) and (14), respectively.

NNNF Selection Scheme and NNFF Selection Scheme

- **Advantage of NNNF**: it can minimize the outage probability of both the near and far users.
- **Advantage of NNFF**: NOMA can offer a larger performance gain over conventional MA when user channel conditions are more distinct.

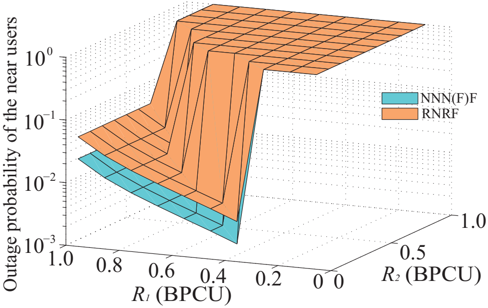
Follow the similar procedure with RNRF, we can obtain the outage probability, diversity gain, and the throughput of NNNF and NNFF.

Numerical Results



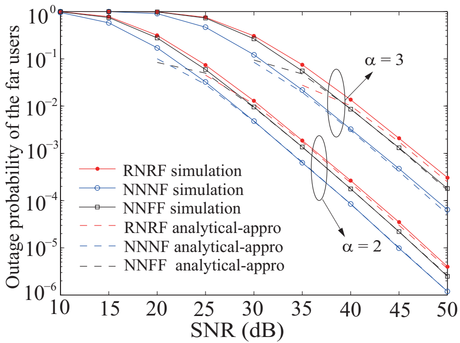
- Lower outage probability is achieved than with RNRF.
- All curves have the same slopes, which indicates the same diversity gains.
- Incorrect choice of rate make the outage probability of the near users be always one.

Numerical Results



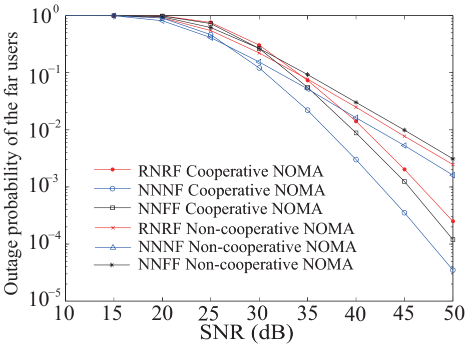
- The outage of the near users occurs more frequently as the rate of the far user, R_1, increases.
- For the choice of R_1, it should satisfy the condition $(|p_{i1}|^2 - |p_{i2}|^2\tau_1 > 0)$.
- For the choice of R_2, it should satisfy the condition that the split energy for detecting x_{i1} is also sufficient to detect x_{i2} $(\varepsilon_{\mathrm{A}_i} \geq \varepsilon_{\mathrm{B}_i})$.

Numerical Results



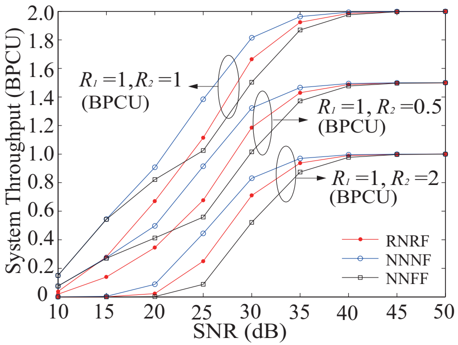
- NNNF achieves the lowest outage probability.
- NNFF achieves lower outage than RNRF, which indicates that the distance of the near users has more impact than that of the far users.
- All of the curves have the same slopes, which indicates that the diversity gains of the far users are the same.

Numerical Results



- Cooperative NOMA has a larger slope than that of non-cooperative NOMA.
- NNNF achieves the lowest outage probability.
- NNFF has higher outage probability than RNRF in non-cooperative NOMA, however, it achieves lower outage probability than RNRF in cooperative NOMA.

Numerical Results



- NNNF achieves the highest throughput since it has the lowest outage probability.
- The existence of the throughput ceilings in the high SNR region.
- Increasing R_2 from $R_2 = 0.5$ BPCU to $R_2 = 1$ BPCU can improve the throughput; however, for the case $R_2 = 2$ BPCU, the throughput is lowered.

Conclusions

- The application of SWIPT to NOMA has been considered. A novel cooperative SWIPT NOMA protocol with three different user selection criteria has been proposed.
- Stochastic geometric approach was used to provide a complete framework to model the locations of users and evaluate the performance of the proposed user selection schemes.
- Closed-form results have been derived in terms of outage probability and delay-sensitive throughput to determine the system performance.
- The diversity gain of the three user selection schemes has also been characterized and proved to be the same as that of a conventional cooperative network.
- We conclude that by carefully choosing the parameters of the network, (e.g., transmission rate or power splitting coefficient), acceptable system performance can be