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Do, N. T., Benevides da Cost, D., Duong, T. Q., & An, B. (2016). A BNBF User Selection Scheme for NOMA-Based Cooperative Relaying Systems with SWIPT. *IEEE Communications Letters*.
<https://doi.org/10.1109/LCOMM.2016.2631606>

Published in:
IEEE Communications Letters

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
[Link to publication record in Queen's University Belfast Research Portal](#)

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A BNBF User Selection Scheme for NOMA-Based Cooperative Relaying Systems with SWIPT

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Abstract—In this letter, we investigate the outage performance of cooperative relaying transmissions in two-user non-orthogonal multiple access (NOMA) systems, wherein simultaneous wireless information and power transfer (SWIPT) is employed at the near users to power their relaying operations. To this end, a best-near best-far (BNBF) user selection scheme is proposed. Considering three relaying protocols, i.e., decode-and-forward (DF), amplify-and-forward (AF), and hybrid DF/AF protocols, tight closed-form approximate expressions for the outage probability (OP) are derived to evaluate the system performance. Numerical results reveal that, for any relaying protocols used, the diversity order achieved by the BNBF scheme is $M + 1$, where M is the number of far users, and does not depend on the number of near users.

Index Terms—Non-orthogonal multiple access (NOMA); outage performance; simultaneous wireless information and power transfer (SWIPT); user selection.

I. INTRODUCTION

Non-orthogonal multiple access (NOMA) has been considered as an emerging technology for the next generation of cellular networks (i.e., 5G) to improve spectral efficiency by superposing multiple users in power domain [1].

Considering a downlink scenario of a two-user NOMA network that consists of multiple near and far users, it is widely known that in a two-user NOMA system, far users have poorer channel conditions compared to that of near users. As reported in [2], [3], *opportunistic scheduling*, i.e., the source communicates with only one best destination with the assistance of only one best relay, has been recognized as an attractive scheduling method to improve system performance of such multiuser cooperative network since the time-varying nature of wireless channels is exploited. Owing to this fact, in this paper we adopt the concept of opportunistic scheduling to the two-user NOMA system, where the near users play the role of relays. To this end, a best-near best-far user selection

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The work of N. T. Do and B. An was supported by the Leading Human Resource Training Program of Regional Neo industry through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and future Planning (Grant No. 2016H1D5A1910577). The work of D. B. da Costa was supported by the CNPq under Grant 304301/2014-0. The work of T. Q. Duong was supported in part by the U.K. Royal Academy of Engineering Research Fellowship under Grant RF1415\14\22.

scheme is proposed. Additionally, three relaying protocols, i.e., decode-and-forward (DF), amplify-and-forward (AF), and hybrid DF/AF protocols, are considered.

However, an interesting question that arises is how to perform the cooperative relaying operation without draining the near users' batteries. Fortunately, simultaneous wireless information and power transfer (SWIPT) technique has arisen as a promising and sustainable solution for cooperative relaying in NOMA system, which was reported in several works, such as [1], [4], [5]. This is the motivation to investigate the outage performance of the cooperative two-user NOMA system with SWIPT being employed at the near users.

In our analysis, tight closed-form approximate expressions for the outage probability (OP) of the selected near and far users are obtained. Defining N and M as the numbers of near and far users, respectively, our results reveal that the diversity order achieved by the BNBF scheme for the selected near user is N ; while that for the selected far user is $M + 1$.

II. SYSTEM MODEL

Consider a cooperative network composed of one source, S , a cluster of M far users, $F = \{F_j, j = 1, \dots, M\}$, and a cluster of N near users, $N = \{N_i, i = 1, \dots, N\}$. We assume that all nodes are equipped with single antenna and operate in half-duplex mode. All wireless links are assumed to undergo independent and identically distributed (i.i.d.) Rayleigh block flat fading. Let h_{XY} and $|h_{XY}|^2$ denote the channel coefficient and the corresponding channel gain, respectively, of $X \rightarrow Y$ channel; let w_Y denote the additive white Gaussian noise (AWGN) at node Y , where $X \in \{S\} \cup N$, $Y \in N \cup F$. Without loss of generality, we assume that all terminals have the same AWGN mean power N_0 . We also assume that the source perfectly knows the channel state information (CSI) of all near and far users, as in [4].

A. The Best-Near Best-Far (BNBF) User Selection Scheme

The proposed user selection process is conducted before data transmission through the signaling and channel state information estimation/calculation system. Specifically, a near user $N_s \in N$ and a far user $F_s \in F$ that have the best respective channel conditions will be selected in each transmission slot. Mathematically, the BNBF selection criterion can be described as $N_s = \arg \max_{i=1, \dots, N} |h_{SN_i}|^2$, $F_s = \arg \max_{j=1, \dots, M} |h_{SF_j}|^2$.

B. The NOMA-based Cooperative Transmission with SWIPT

In this paper, a two-user NOMA scheme is employed in a cooperative relaying downlink transmission, which consists of two phases, each phase has the same duration of T [4].

1) *The first phase (direct transmission)*: Following the principle of NOMA, messages x_{N_s} and x_{F_s} that will be transmitted to N_s and F_s , respectively, are superimposed as $\sqrt{\theta_{N_s}}x_{N_s} + \sqrt{\theta_{F_s}}x_{F_s}$ and then broadcasted by the source, where θ_{N_s} and θ_{F_s} are the power allocation coefficients. We assume that $|h_{SN_i}|^2 > |h_{SF_j}|^2$, and set $0 < \theta_{N_s} < \theta_{F_s}$ and $\theta_{N_s} + \theta_{F_s} = 1$. Thus, the received signal at F_s from S can be given by $y_{SF_s} = (\sqrt{\theta_{N_s}}P_S x_{N_s} + \sqrt{\theta_{F_s}}P_S x_{F_s})h_{SF_s} + w_{F_s}$, where P_S denotes the transmit power of the source.

At the far user, the received signal-to-interference-plus-noise ratio (SINR) at F_s to detect x_{F_s} transmitted from S can be written as

$$\gamma_{SF_s} = \theta_{F_s} \bar{\gamma} |h_{SF_s}|^2 / (\theta_{N_s} \bar{\gamma} |h_{SF_s}|^2 + 1), \quad (1)$$

where $\bar{\gamma} \triangleq \frac{P_S}{N_0}$ denotes the transmit signal-to-noise ratio (SNR).

At the near user, considering a static power-splitting receiver at N_s to harvest energy from received observations, herein, we further assume that the power splitting receiver only utilizes the signal power, but not the antenna noise power, as done in [6], the energy harvested by N_s can be expressed as $E_{N_s} = \rho \eta P_S |h_{SN_s}|^2 T$, where $0 < \rho < 1$ denoting the power-splitting ratio and $0 < \eta < 1$ denotes the energy conversion efficiency. Thus, the received signal at N_s transmitted by S using NOMA can be given by $y_{SN_s} = \sqrt{(1-\rho)}(\sqrt{\theta_{N_s}}P_S x_{N_s} + \sqrt{\theta_{F_s}}P_S x_{F_s})h_{SN_s} + w_{N_s}$. Note that we only consider the power-splitting receiver architecture in order to alleviate the complexity of cooperative relaying time frame structure. However, the analysis framework presented in this paper can be applied for the time-switching receiver architecture.

Adopting a successive interference cancellation (SIC) receiver [4], N_s first decodes x_{F_s} and then subtracts this component from the received signal to detect its own message, x_{N_s} . Thus, the received SINR at N_s to detect x_{F_s} can be written as

$$\gamma_{SN_s}^{x_{F_s}} = (1-\rho)\theta_{F_s}\bar{\gamma}|h_{SN_s}|^2 / [(1-\rho)\theta_{N_s}\bar{\gamma}|h_{SN_s}|^2 + 1], \quad (2)$$

and the received SNR at N_s to detect x_{N_s} is given by

$$\gamma_{SN_s}^{x_{N_s}} = (1-\rho)\theta_{N_s}\bar{\gamma}|h_{SN_s}|^2. \quad (3)$$

2) *The second phase (relaying transmission)*: Assuming that all the harvested energy is used, the transmit power of N_s can thus be given by $P_{N_s} = E_{N_s}/T = \rho \eta P_S |h_{SN_s}|^2$.

Assuming that DF protocol is adopted at N_s , the received signal at F_s from N_s can be expressed as $y_{N_s F_s}^{DF} = P_{N_s} h_{N_s F_s} x_{F_s} + w_{F_s}$. Consequently, the received SNR at F_s to detect x_{F_s} transmitted by N_s can be written as

$$\gamma_{N_s F_s}^{DF} = \rho \eta \bar{\gamma} |h_{SN_s}|^2 |h_{N_s F_s}|^2. \quad (4)$$

Assuming variable-gain AF protocol is adopted at N_s with an amplification factor $G^2 = \frac{P_{N_s}}{P_S |h_{SN_s}|^2 + N_0} = \frac{\rho \eta \bar{\gamma} |h_{SN_s}|^2}{\bar{\gamma} |h_{SN_s}|^2 + 1}$, the

received SINR at F_s to detect x_{F_s} transmitted from N_s using AF protocol can be given by

$$\gamma_{N_s F_s}^{AF} = \frac{\rho(1-\rho)\eta\bar{\gamma}^2\theta_{F_s}|h_{SN_s}|^4|h_{N_s F_s}|^2}{[\rho(1-\rho)\eta\bar{\gamma}^2\theta_{N_s}|h_{SN_s}|^4|h_{N_s F_s}|^2 + \rho\eta\bar{\gamma}|h_{SN_s}|^2|h_{N_s F_s}|^2 + \bar{\gamma}|h_{SN_s}|^2 + 1]}. \quad (5)$$

It is noteworthy that AF protocol can be employed even if N_s fails to decode x_{F_s} .

Assuming hybrid protocol is adopted at N_s , if N_s successfully decodes x_{F_s} , then DF protocol will be used to forward x_{F_s} to F_s , otherwise, AF protocol will be used.

Finally, F_s combines two signals, i.e., the direct signal from S and the relaying signal from N_s using selection combining (SC) technique.

III. PERFORMANCE ANALYSIS

Considering i.i.d. Rayleigh channels, $|h_{SN_i}|^2$, $|h_{SF_j}|^2$, and $|h_{N_i F_j}|^2$, where $i = 1, \dots, N$, $j = 1, \dots, M$, follow exponential distributions with parameters $\lambda_{SN} = d_{SN}^\epsilon$, $\lambda_{SF} = d_{SF}^\epsilon$, $\lambda_{NF} = d_{NF}^\epsilon$, respectively, where d and ϵ denote the Euclidean distance and path-loss exponent, respectively.

Let $X \triangleq |h_{SN_s}|^2$, $Y \triangleq |h_{SF_s}|^2$, and $V \in \{X, Y\}$. The cumulative distribution function (CDF), $F_V(z)$, and the probability density function (PDF), $f_V(v)$, are written as $F_V(v) = \sum_{k=0}^K \binom{K}{k} (-1)^k e^{-k\lambda_V v}$, and $f_V(v) = \sum_{k=1}^K \binom{K}{k} (-1)^{k+1} k\lambda_V e^{-k\lambda_V v}$, respectively, where $K \in \{M, N\}$, $\lambda_V \in \{\lambda_{SF}, \lambda_{SN}\}$. Regarding the CDF and PDF of V , these are the order statistics for the maximum of the i.i.d. channel gains. However it is implied that the destinations can be located in a relatively small area, and so do the relays.

Let R_1 and R_2 (bits/s/Hz) denote target data rates of N_s and F_s , respectively. Consequently, $\gamma_i = 2^{2R_i} - 1$, $i = 1, 2$ are the SNR thresholds for correctly decoding x_{N_s} and x_{F_s} , respectively. And let $\gamma_{e2e, F_s}^{DF} = \max\{\gamma_{SF_s}, \gamma_{N_s F_s}^{DF}\}$ and $\gamma_{e2e, F_s}^{AF} = \max\{\gamma_{SF_s}, \gamma_{N_s F_s}^{AF}\}$ denote the end-to-end SNR of the selected far user F_s in the case of using DF and AF protocols, respectively.

A. Outage Probability (OP) of The Selected Far User F_s

1) *DF Protocol*: The OP of F_s can be expressed as

$$P_{out, F_s}^{DF} = \Pr(\gamma_{SN_s}^{x_{F_s}} < \gamma_2, \gamma_{SF_s} < \gamma_2) + \Pr(\gamma_{SN_s}^{x_{F_s}} \geq \gamma_2, \gamma_{e2e, F_s}^{DF} < \gamma_2). \quad (6)$$

Let $\theta_s \triangleq \theta_{F_s}/\theta_{N_s}$. The first term of the right-hand side of (6) can be obtained as

$$\Phi_1 = \Pr(\gamma_{SN_s}^{x_{F_s}} < \gamma_2) \Pr(\gamma_{SF_s} < \gamma_2) = \Phi_{1A} \Phi_{1B}, \quad (7)$$

where

$$\Phi_{1A} = \Pr\left(\frac{a_1 X}{a_2 X + 1} < \gamma_2\right) = \sum_{k=0}^N \binom{N}{k} (-1)^k e^{-\frac{k\lambda_{SN}\gamma_2}{a_1 - a_2\gamma_2}}, \quad (8)$$

if $\gamma_2 < a_1/a_2 = \theta_s$, otherwise, $\Phi_1 = 1$, where $a_1 \triangleq (1-\rho)\theta_{F_s}\bar{\gamma}$, $a_2 \triangleq (1-\rho)\theta_{N_s}\bar{\gamma}$; and

$$\Phi_{1B} = \Pr\left(\frac{b_1 Y}{b_2 Y + 1} < \gamma_2\right) = \sum_{k=0}^M \binom{M}{k} (-1)^k e^{-\frac{k\lambda_{SF}\gamma_2}{b_1 - b_2\gamma_2}}. \quad (9)$$

if $\gamma_2 < b_1/b_2 = \theta_s$, otherwise, $\Phi_{2A} = 1$, where $b_1 \triangleq \theta_{F_s} \bar{\gamma}$, $b_2 \triangleq \theta_{N_s} \bar{\gamma}$.

The second term of the right-hand side of (6) can be re-expressed as

$$\Phi_2 = \Pr(\gamma_{SF_s} < \gamma_2) \Pr(\gamma_{SN_s}^{x_{F_s}} \geq \gamma_2, \gamma_{N_s F_s}^{DF} < \gamma_2) = \Phi_{1B} \Phi_{2A}, \quad (10)$$

where

$$\Phi_{2A} = \Pr\left(\frac{a_1 X}{a_2 X + 1} \geq \gamma_2, cXZ < \gamma_2\right), \quad (11)$$

where $c \triangleq \rho \eta \bar{\gamma}$, and $Z \triangleq |h_{N_s F_s}|^2$. Considering i.i.d. channels, we have $\Pr(N_s = N_i) = 1/N$ and $\Pr(F_s = F_j) = 1/M$. Thus, $F|_{h_{N_s F_s}|^2}(z) = \sum_{m=1}^M \sum_{n=1}^N \frac{1}{MN} F|_{h_{N_i F_j}|^2}(z)$. Consequently, $F_Z(z) = 1 - e^{-\lambda_{NF} z}$. It can be observed that $\Phi_{2A} = 0$ if $\gamma_2 \geq \theta_s$. For the case $\gamma_2 < \theta_s$, conditioning on $X = x$, Φ_{2A} can be rewritten as

$$\begin{aligned} \Phi_{2A} &= \int_0^\infty \Pr\left(\frac{a_1 x}{a_2 x + 1} \geq \gamma_2, cxZ < \gamma_2\right) f_X(x) dx, \\ &= \int_\mu^\infty F_Z\left(\frac{\gamma_2}{cx}\right) f_X(x) dx = \Phi_{2A_1} - \Phi_{2A_2}, \end{aligned} \quad (12)$$

where $\mu \triangleq \gamma_2/(a_1 - a_2 \gamma_2)$, and Φ_{2A_1} is obtained as $\Phi_{2A_1} = \sum_{k=1}^N \binom{N}{k} (-1)^{k+1} e^{-k \lambda_{SN} \mu}$, while Φ_{2A_2} can be expressed as

$$\Phi_{2A_2} = \sum_{k=1}^N \binom{N}{k} (-1)^{k+1} k \lambda_{SN} \int_\mu^\infty e^{-\frac{\lambda_{NF} \gamma_2}{cx} - k \lambda_{SN} x} dx. \quad (13)$$

Since the integral in (13) cannot be further simplified, we will make use of the following approximation $e^{-\alpha x} \approx 1 - \alpha x$ for small value of $|x|$. Afterwards, by plugging (13) into (12), Φ_{2A} can be derived as

$$\Phi_{2A} = \sum_{k=1}^N \binom{N}{k} (-1)^{k+1} \frac{k \lambda_{SN} \lambda_{NF} \gamma_2}{c} (-\text{Ei}(-k \lambda_{SN} \mu)), \quad (14)$$

where $\text{Ei}(\cdot)$ denotes the exponential integral function [7, Eq. (8.211.1)]. Finally, by substituting (9) and (14) into (10), and then combining with (7), P_{out, F_s}^{DF} is attained as

$$P_{\text{out}, F_s}^{DF} = \Phi_{1B|Eq. (9)} (\Phi_{1A|Eq. (8)} + \Phi_{2A|Eq. (14)}), \quad (15)$$

when $\gamma_2 < \theta_s$, otherwise, $P_{\text{out}, F_s}^{DF} = 1$.

2) *AF Protocol*: The OP of F_s can be expressed as

$$P_{\text{out}, F_s}^{AF} = \Pr(\gamma_{e^{2e}, F_s}^{AF} < \gamma_2), \quad (16)$$

which can be rewritten as

$$P_{\text{out}, F_s}^{AF} = \Pr(\gamma_{SF_s} < \gamma_2) \Pr(\gamma_{N_s F_s}^{AF} < \gamma_2) = \Phi_{1B} \Psi, \quad (17)$$

where

$$\Psi = \Pr\left(\frac{a_1 c X^2 Z}{a_2 c X^2 Z + c X Z + \bar{\gamma} X + 1} < \gamma_2\right). \quad (18)$$

Since it is hard to directly derive (18), we will resort on $\frac{\alpha}{\beta+1} \approx \frac{\alpha}{\beta}$ which holds when β is sufficient large. Then, Ψ can be approximated by

$$\begin{aligned} \Psi &\approx \Pr\left(\frac{a_1 c X Z}{a_2 c X Z + c Z + \bar{\gamma}} < \gamma_2\right) \\ &= \int_0^\infty \Pr([(a_1 - a_2 \gamma_2) x - \gamma_2] c Z < \bar{\gamma} \gamma_2) f_X(x) dx. \end{aligned} \quad (19)$$

As can be observed, $\Phi_{2A} = \Psi = 1$ if $\gamma_2 \geq \theta_s$. For the case $\gamma_2 < \theta_s$, conditioning on $X = x$, Ψ can be expressed as

$$\begin{aligned} \Psi &= \int_0^\mu f_X(x) + \int_\mu^\infty \Pr\left(Z < \frac{\bar{\gamma} \gamma_2}{[(a_1 - a_2 \gamma_2) x - \gamma_2] c}\right) f_X(x) \\ &= 1 - \sum_{k=1}^N \binom{N}{k} (-1)^{k+1} k \lambda_{SN} \\ &\quad \times \int_\mu^\infty e^{-\frac{\lambda_{NF} \bar{\gamma} \gamma_2}{[(a_1 - a_2 \gamma_2) x - \gamma_2] c} - k \lambda_{SN} x} dx, \end{aligned} \quad (20)$$

where $\mu = \gamma_2/(a_1 - a_2 \gamma_2)$. By using the following change of variables, i.e., $u = (a_1 - a_2 \gamma_2)x - \gamma_2$, and then applying the formula $\int_0^\infty e^{-\frac{\beta}{4x} - \gamma x} dx = \sqrt{\frac{\beta}{\gamma}} K_1(\sqrt{\beta \gamma})$ [7, Eq. (3.324.1)], Ψ can be derived as

$$\Psi = 1 - \sum_{k=1}^N \binom{N}{k} (-1)^{k+1} e^{-k \lambda_{SN} \mu} \sqrt{\chi} K_1(\sqrt{\chi}), \quad (21)$$

where $\chi = \frac{4k \lambda_{SN} \lambda_{NF} \bar{\gamma} \mu}{c}$, and $K_1(\cdot)$ denotes the first-order modified Bessel function of the second kind [7, Eq. (8.407.1)]. By plugging (9) and (21) into (17), P_{out, F_s}^{AF} is attained as

$$P_{\text{out}, F_s}^{AF} = \Phi_{1B|Eq. (9)} \Psi|_{Eq. (21)}, \quad (22)$$

when $\gamma_2 < \theta_s$, otherwise, $P_{\text{out}, F_s}^{AF} = 1$.

3) *Hybrid Protocol*: The OP of F_s can be expressed as

$$\begin{aligned} P_{\text{out}, F_s}^{\text{Hybrid}} &= \Pr(\gamma_{SN_s}^{x_{F_s}} < \gamma_2, \max\{\gamma_{SF_s}, \gamma_{N_s F_s}^{AF}\} < \gamma_2) \\ &\quad + \Pr(\gamma_{SN_s}^{x_{F_s}} \geq \gamma_2, \max\{\gamma_{SF_s}, \gamma_{N_s F_s}^{DF}\} < \gamma_2) \\ &= \Phi_{1B} \Theta + \Phi_2, \end{aligned} \quad (23)$$

where Φ_{1B} and Φ_2 are presented in (9) and (10), respectively, and Θ can be derived as

$$\begin{aligned} \Theta &= \Pr\left(\frac{a_1 X}{a_2 X + 1} < \gamma_2, \frac{a_1 c X^2 Z}{a_2 c X^2 Z + c X Z + \bar{\gamma} X + 1} < \gamma_2\right) \\ &= \Pr(a_1 X - a_2 \gamma_2 X - \gamma_2 < 0, \\ &\quad (a_1 X - a_2 \gamma_2 X - \gamma_2) c X Z < \gamma_2 \bar{\gamma} X + \gamma_2). \end{aligned} \quad (24)$$

Conditioning on $X = x$, from (24) we can see that $\Pr\left(Z > \frac{\gamma_2 \bar{\gamma} x + \gamma_2}{(a_1 x - a_2 \gamma_2 x - \gamma_2) c x}\right) = 1$ since $a_1 x - a_2 \gamma_2 x - \gamma_2 < 0$. Consequently, Θ can be attained as

$$\Theta = \int_0^\mu f_X(x) dx = \sum_{k=1}^N \binom{N}{k} (-1)^{k+1} \left[1 - e^{-\frac{k \lambda_{SN} \gamma_2}{a_1 - a_2 \gamma_2}}\right]. \quad (25)$$

Thus, the OP of F_s using hybrid protocol achieved as

$$P_{\text{out}, F_s}^{\text{Hybrid}} = \Phi_{1B|Eq. (9)} (\Phi_{2A|Eq. (14)} + \Theta|_{Eq. (25)}), \quad (26)$$

when $\gamma_2 < \theta_s$, otherwise, $P_{\text{out}, F_s}^{\text{Hybrid}} = 1$.

B. Outage Probability (OP) of The Selected Near User N_s

The OP of the selected near user N_s can be expressed as

$$P_{\text{out}}^{N_s} = \Pr(\gamma_{SN_s}^{x_{F_s}} < \gamma_2) + \Pr(\gamma_{SN_s}^{x_{F_s}} \geq \gamma_2, \gamma_{SN_s}^{x_{N_s}} < \gamma_1). \quad (27)$$

which can be attained as

$$\begin{aligned} P_{\text{out}}^{N_s} &= \sum_{k=0}^N \binom{N}{k} (-1)^k e^{-k \lambda_{SN} \gamma_1 / a_2}, \text{ if } \gamma_1 > \mu a_2, \gamma_2 < \theta_s; \\ P_{\text{out}}^{N_s} &= \sum_{k=0}^N \binom{N}{k} (-1)^k e^{-k \lambda_{SN} \mu}, \text{ if } \gamma_1 \leq \mu a_2, \gamma_2 < \theta_s; \text{ and} \\ P_{\text{out}}^{N_s} &= 1, \text{ if } \gamma_2 \geq \theta_s, \forall \gamma_1. \end{aligned}$$

C. Diversity Analysis of The Selected Far Users F_s

Using [7, Eq. (1.111)] and the fact that $e^{-\alpha/y} \approx 1 - \alpha/y$ when $y \rightarrow \infty$, we have

$$\Phi_{1A}^{\text{asym}} = \Theta^{\text{asym}} = [\lambda_{SN}\gamma_2 / ((1-\rho)(\theta_{F_s} - \theta_{N_s}\gamma_2)\bar{\gamma})]^N, \quad (28)$$

$$\Phi_{1B}^{\text{asym}} = [\lambda_{SF}\gamma_2 / ((\theta_{F_s} - \theta_{N_s}\gamma_2)\bar{\gamma})]^M. \quad (29)$$

Also, relying on the fact that $\text{Ei}(-x) \approx C + \ln(x)$ when $x \rightarrow 0^+$ [7, Eq. (8.214.1)], where C denotes the Euler's constant [7, Eq. (8.367.1)], and the formula $\sum_{k=1}^N \binom{N}{k} (-1)^{k+1} k = 0$ [7, Eq. (0.154.2)], Φ_2 in (14) can be approximated by

$$\Phi_{2A}^{\text{asym}} = - \sum_{k=1}^N \binom{N}{k} (-1)^{k+1} \frac{ku_1}{\bar{\gamma}} \ln \left(\frac{ku_2}{\bar{\gamma}} \right), \quad (30)$$

where $u_1 = \frac{\lambda_{SN}\lambda_{NF}\gamma_2}{\rho\eta}$ and $u_2 = \frac{\lambda_{SN}\gamma_2}{(1-\rho)(\theta_{F_s} - \theta_{N_s}\gamma_2)}$.

On the other hand, using the formula $xK_1(x) \approx 1 + \frac{x^2}{2} \ln \frac{x}{2}$ [8, Eq. (25)] and $\sum_{k=1}^N \binom{N}{k} (-1)^{k+1} k = 0$, Θ_2 in (21) can be approximated by

$$\Psi^{\text{asym}} = - \sum_{k=1}^N \binom{N}{k} (-1)^{k+1} \frac{2ku_3}{\bar{\gamma}} \ln \left(\sqrt{\frac{ku_3}{\bar{\gamma}}} \right), \quad (31)$$

where $u_3 = \lambda_{SN}\lambda_{NF}\gamma_2 / [\rho\eta(1-\rho)(\theta_{F_s} - \theta_{N_s}\gamma_2)]$.

From (28), (29), (30), and (31), the asymptotic OPs of F_s using DF, AF, and hybrid DF/AF protocols can be obtained.

Since $\lim_{x \rightarrow \infty} \frac{\log[-\frac{\alpha}{x^{M+1}} \ln(\frac{\beta}{x^\kappa})]}{\log x} = -(M+1)$, where $\kappa = 1/2$ or 1, and $\sum_{k=1}^N \binom{N}{k} (-1)^{k+1} = 1$, it can be concluded that the diversity order achieved by the BBNBF scheme at F_s is $M+1$.

D. Diversity Analysis of The Selected Near Users N_s

Similar to (28), the asymptotic OP of N_s is obtained as: $P_{\text{asym}}^{N_s} = (\lambda_{SN}\gamma_1 / (1-\rho) / \theta_{N_s} / \bar{\gamma})^N$ if $\gamma_1 > \mu a_2$, $\gamma_2 < \theta_s$, $P_{\text{asym}}^{N_s} = (\lambda_{SN}\gamma_2 / (1-\rho) / (\theta_{F_s} - \theta_{N_s}\gamma_2) / \bar{\gamma})^N$ if $\gamma_1 \leq \mu a_2$, $\gamma_2 < \theta_s$, otherwise, $P_{\text{out,asym}}^{N_s} = 1$. Consequently, the diversity order achieved by the BBNBF selection scheme for N_s is N .

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this Section, we set $\theta_{N_s} = 1/5$, $\theta_{F_s} = 4/5$; and $\epsilon = 3$, $\eta = 0.7$, $\rho = 0.5$, the target data rates $R_1 = R_2 = 1$ (bits/s/Hz), the coordinates of source, near users, and far users are $(0, 0.5)$, $(0.2, 0.5)$, and $(1, 0.5)$, respectively.

As shown in Fig. 1, the hybrid DF/AF protocol and the DF protocol have similar performance and are better than that of the AF protocol. This can be explained that, in (24), $\Pr\left(\frac{a_1cx^2Z}{a_2cx^2Z+cxZ+\bar{\gamma}x+1} < \gamma_2\right) = 1$ when $\frac{a_1x}{a_2x+1} < \gamma_2$ means that when N_s fails to decode x_{F_s} , its amplifying and forwarding signal does not help to improve the reliability of F_s . As can be observed, based on the slopes of performance curves at high SNR regime, for any relaying protocols used, the diversity order achieved by the BBNBF scheme at the far user is the same and higher than that achieved at the near user.

In Fig. 2, we compare the performance of the BBNBF scheme with that of best-near worst-far (BNWF) scheme, worst-near best-far (WNBF) scheme, and random-near random-far

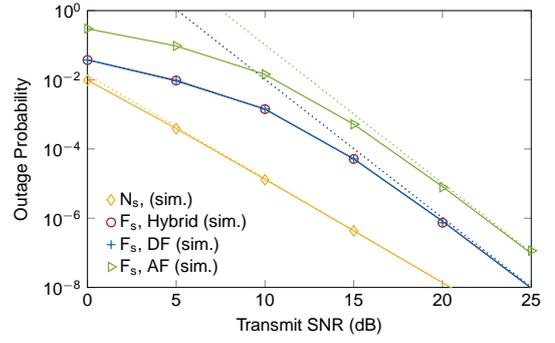


Fig. 1. Outage probability and asymptotic OP of N_s and F_s as a function of transmit SNR. Solid lines and dotted lines represent approximate results and asymptotic results, respectively.

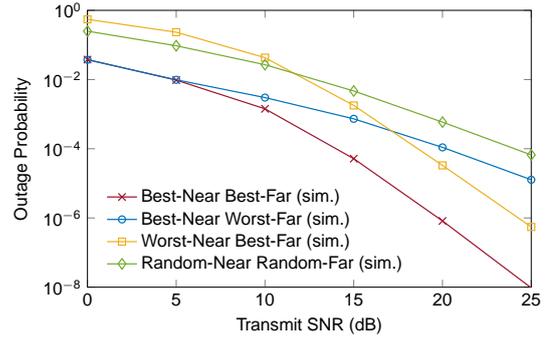


Fig. 2. Performance comparison between BBNBF, BNWF, WNBF, and RNRF schemes.

(RNRF) scheme using computer simulation. As can be seen, the outage performance of the BBNBF scheme is the best. Also note that the diversity order of BBNBF scheme is higher than that of BNWF and RNRF schemes and is similar to that of WNBF scheme. This is consistent with our analysis, i.e., the diversity order achieved by the BBNBF scheme is $M+1$, and does not depend on the number of near users N .

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