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SWIPT-Enabled Cooperative NOMA With *m*th Best Relay Selection

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ABSTRACT Non-orthogonal multiple access (NOMA) was recently regarded as a potential technique for next generation wireless networks. Recent works on relay selection for cooperative NOMA systems have mainly addressed the best relay selection to forward its received signals to terminal nodes. Nonetheless, in practical scenarios, the best relay may be unavailable due to non-ideal conditions such as scheduling and overload constraints or possibly due to channel feedback delay. Therefore, there is compelling need to consider a more practical solution, in which the best available relay is selected. In this article, we examine the error rate performance for simultaneous wireless information and power transfer (SWIPT)-enabled NOMA, while considering the selection of the *m*th best available relay. In particular, we present an exact pairwise error probability (PEP) expression to obtain a bit error rate (BER) upper bound. The asymptotic PEP is investigated to evaluate the achievable diversity order for NOMA users. Finally, simulation results are provided to verify the accuracy of the derived PEP expressions and to give more insights into the system performance.

INDEX TERMS Diversity order, NOMA, pairwise error probability, relay selection, SWIPT.

I. INTRODUCTION

NON-ORTHOGONAL multiple access (NOMA) technology will play a key role in the future cellular networks. Power-domain NOMA can be realized by allowing multiple users to utilize the wireless physical resources simultaneously, achieving enhanced spectral efficiency over conventional orthogonal multiple access (OMA) techniques [1]–[3]. In particular, superposition coding (SC) is exploited to multiplex users' signals in the power domain by assigning different power coefficients to different users. In each user terminal, multiuser detection based on successive interference cancellation (SIC) is utilized for efficient signal recovery [4]. Particularly, SIC at each user is performed in a decoding order associated with the gradually decreasing channel strength. Recently, cooperative NOMA has been considered as an efficient paradigm that offers reduced energy consumption, enhanced throughout, and extended coverage, compare to conventional OMA systems [5], [6]. In [5], a closed-form outage probability expression is derived for NOMA systems with employing amplify and forward (AF) relay. Multiple relay selection methods were investigated in [6], in order to minimize the outage probability in cooperative NOMA systems.

On the other hand, radio frequency (RF) energy harvesting (EH) scheme was proposed to provide perpetual energy replenishment for cooperative NOMA networks. RF energy

TABLE 1. Table of symbols.

Symbol	Notation
α_k	Power allocation coefficient of user k
$\hat{\Delta}_i$	SIC error of user i
G_f	Relay amplification factor
h_{rk}	Channel gain between the relay and user k
h_{sm}	Channel gain between the BS and relay m
K	Number of users
λ	Channel variance
M	Number of relays
n_c	RF-to-baseband conversion noise
n_{sm}	Additive white Gaussian noise at relay m
P_B	Total power of BS
P_r	Harvested power at the rth relay
ρ	Power splitting factor
s	Transmitted NOMA signal
σ_n^2	Noise variance
x_k	Transmitted signal of user k
y_r^m	Received signal of relay m

harvesting can be realized by allowing wireless devices, equipped with dedicated EH circuits, to harvest energy from either ambient RF signals or dedicated RF sources. It can be categorized into two main strategies, namely, wireless-powered communications (WPC) [7], [8] and simultaneous wireless information and power transfer (SWIPT) [9]–[11]. Recently, it has been illustrated that the latter can produce noticeable gains in the aspects of energy and spectral efficiencies. The authors in [12] derived closed-form outage probability and ergodic rate expressions for time switching (TS) and power splitting (PS) SWIPT AF relaying system, without considering a direct link. The authors in [13] extended the work in [12] by considering that direct links between the BS and the users exist.

The performance of NOMA systems was addressed in the literature, from different perspectives. For example, in [14], the authors presented a comprehensive framework to investigate the outage probability performance of NOMA systems, under generalized fading channels. In [15], the authors studied a cooperative NOMA network with two users and decode-and-forward (DF) relaying mode, where the *N*th optimal relay was selected. Subsequently the closed-form outage probability was derived. The *N*th best relay selection for a conventional cooperative system was investigated in terms of secrecy capacity and outage probability [16]. The authors in [17] investigated the error probability of point-to-point NOMA over Nakagami-*m* distributed wireless channels, where the authors derived the pairwise error probability (PEP) expressions for NOMA users. In [18], a PEP expression was derived for SWIPT-enabled NOMA relay systems, in which single relay is exploited to assist with data transmission between the base station (BS) and NOMA users. In [19], a PEP expression was derived for multiple relay NOMA network, without relay selection taken into account. The secrecy outage performance is analyzed for three relay selection schemes in [20].

In this article, we extend our conference paper [21] to more general scenarios involving multiple users with relay selection. We investigate the PEP and BER union bound performance in SWIPT-enabled NOMA networks by selecting the *m*th best available relay. A closed-form PEP expression is obtained by applying order statistics at both source-relay and relay-user links. In addition, an asymptotic closed-form PEP is analyzed to quantify the diversity gain for each user. It is worth highlighting that, unlike [15] where the analysis is limited to two users, we consider in this work the general case of K users. The main contributions of this article are listed as follows:

1) The PEP performance of multiple users is analyzed in a SWIPT-enabled cooperative NOMA system with relay selection over Rayleigh fading channels. In specific, a closed-form PEP expression is derived based on partial relay selection scheme.
2) In order to quantify the performance limit of the considered system, asymptotic diversity order is derived and further validated via numerical simulations.
3) Simulation results are presented to corroborate the derived expressions and present useful insights into the system performance.

The remaining part of this article is comprised of the following parts. The system and channel models are introduced in Section II. Section III presents an exact analytical PEP at each user. We provide the asymptotic PEP analysis to quantify the diversity order in Section IV. Simulation results are given in Section V. Section VI concludes this article.

To facilitate understanding the related symbols frequently used in this article, a table to interpret them is summarized in Table 1.

II. SYSTEM AND CHANNEL MODELS

A. SYSTEM MODEL

We consider a relay-assisted downlink NOMA network, which is equipped with a base station (BS), M relays, and K users, as depicted in Fig. 1. Data transmission from BS to K users is assisted by single relay with half-duplex mode, where the BS selects a favorable relay to forward the superimposed symbol to K users. The relay selection depends not only on the availability of relays, but also on the quality of the BS-to-R_m link, $m = 1, \ldots, M$. Here R_m indicates the mth relay. In particular, according to the channel quality of BS-to-R_m, the mth best relay is chosen from multiple candidate relays.

The BS forms a superimposed message and then transmits it to the NOMA users through the assistance of the selected mth SWIPT enabled relay. In specific, the selected relay consists of two circuits of EH receiver and information receiver, and utilizes the PS-based SWIPT scheme to forward the signals [12]. We would like to note that in our work, we consider harvest-then-transmit protocol, in which relays are not equipped by any energy resources nor batteries. In particular, we assume that the harvested energy exceeds the minimum energy required for a single transmission [11].

At the BS, the transmitted NOMA signal is formed by,

$$s = \sum_{k=1}^{K} \sqrt{\alpha_k P_B} x_k, \qquad (1)$$

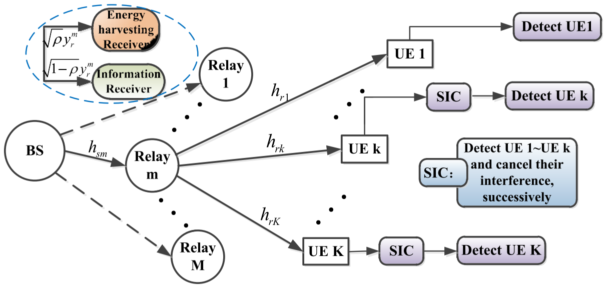


FIGURE 1. The considered NOMA system with relay selection.

where x_k indicates the transmitted signal from user k, P_B denotes the total power transmitted by BS. The power allocation coefficient for user k is denoted by α_k, and $\sum_{k=1}^{K}\alpha_k = 1$.

Data transmission is carried out over two phases. The BS broadcasts the signal to the relays in the first phase and then makes single relay selection. Moreover, recalling that some relays may be unavailable due to their engagement in other transmissions, the available best relay among BS-R_m links is selected to amplify and forward the message to the users. At the moment, the selected relay receives the signal, which is

$$y_r^m = h_{sm}s + n_{sm}, \tag{2}$$

where $h_{sm} \sim \mathcal{CN}(0, \lambda_r)$ represents the channel coefficient from the BS to the selected mth relay. Here $\mathcal{CN}(0, \lambda_r)$ denotes a complex Gaussian distribution with zero mean and variance λ_r. $n_{sm} \sim \mathcal{CN}(0, \sigma_n^2)$ indicates the additive white Gaussian noise (AWGN) at the mth relay.

Upon performing PS at the relay, the received signals from the energy harvesting device and the information receiver can be expressed as

$$y_r^{m,E} = \sqrt{\rho}(h_{sm}s + n_{sm}), \tag{3}$$

$$y_r^{m,I} = \sqrt{1-\rho}(h_{sm}s + n_{sm}) + n_c, \tag{4}$$

where $\rho \in (0, 1)$ is the PS factor. The term $n_c \sim \mathcal{CN}(0, \sigma_{n_c}^2)$ represents RF-to-baseband conversion noise [13]. Assuming average energy harvesting, the harvested power can be calculated as $P_r = \eta\rho\lambda_r P_B$, and the value of power conversion efficiency η is between 0 and 1.

In the second phase, the mth ordered relay is chosen to forward a scaled information signal to K users through AF. Hence, for user k, its received signal is

$$\begin{aligned} y_d^k &= G_f h_{rk} y_r^{m,I} + n_k \\ &= G_f' h_{sm} h_{rk} s + G_f' h_{rk} n_{sm} + G_f h_{rk} n_c + n_k, \end{aligned} \tag{5}$$

where G_f indicates the fixed-gain amplification factor [22], which is given by

$$G_f = \sqrt{\frac{P_r}{(1-\rho)\lambda P_B + (2-\rho)\sigma_n^2}}, \tag{6}$$

and $G_f' = G_f\sqrt{1-\rho}$. Note that G_f' represents the average amplification factor of the relay. In particular, it comprises the normalization factor and the transmission power dedicated to forward the information stream to the users. In addition, $h_{rk} \sim \mathcal{CN}(0, \lambda_k)$ represents the channel gain from relay m to user k link. Note that h_{sm} and h_{rk}, $\forall k$, are independent and identically distributed flat Rayleigh fading channels, and $\lambda_k = \lambda_r = \lambda$ is supposed. Moreover, $n_k \sim \mathcal{CN}(0, \sigma_{n_k}^2)$ is the AWGN at the kth user. Considering practical scenario, in this article we assume that $\sigma_{n_k}^2 = \sigma_{n_c}^2 = \sigma_n^2$.

B. ORDER CHANNEL STATISTICS FOR THE ORDERED USERS

In conventional NOMA systems, the users whose channel gains are significantly different can be combined to perform NOMA. Accordingly, the selected users should be ordered in terms of the channel strength at the BS. Power coefficients are assigned based on the users' channel gains. In particular, users with weak channel gains are allocated higher power coefficients, while users with stronger channels are assigned lower ones [3]. Here we assume that $\alpha_1 > \alpha_2 > \cdots > \alpha_K$. It is worth noting that, such power allocation scheme is utilized in order to enable all users to achieve a particular quality of service (QoS), i.e., a specific data rate threshold.

According to order statistics theory [23], with an ascending order, the probability density function (PDF) of the ordered $|h_{rk}|$ [17] for user k is given by

$$f_k(z_k) = A_k f(z_k)[F(z_k)]^{k-1}[1-F(z_k)]^{K-k}, \tag{7}$$

where $z_k = |h_{rk}|$, $k = 1, \ldots, K$, and $A_k = K!/((k-1)!(K-k)!)$. Moreover, $f(z_k)$ represents the original PDF while $F(z_k)$ denotes cumulative distribution function (CDF) concerning z_k.

Considering the PDF and CDF of a Rayleigh random variable [24] as well as utilizing binomial expansion, (7) is further given by

$$f_k(z_k) = A_k \sum_{\ell=0}^{k-1} \binom{k-1}{\ell} (-1)^{\ell} \frac{2z_k}{\lambda} e^{\frac{-K' z_k^2}{\lambda}}, \tag{8}$$

where $K' = K - k + \ell + 1$.

C. THE BEST AVAILABLE RELAY SELECTION

Due to low implementation complexity, the partial relay selection (PRS) scheme is adopted [25], in which relays are selected according to the partial channel quality on either the BS-to-R_m (*s*-*m*) links or the R_m-to-users (*m*-*k*) links. More specifically, our selection criterion is only based on the channel energies from BS to the M relays regardless of the other channels. Therefore, the selected mth relay should satisfy the following criterion

$$m^{th} \max_{m=1,\ldots,M} |h_{sm}|^2 \tag{9}$$

where $m^{th}\max\{\cdot\}$ means selecting the mth maximum.

Without loss of generality, we assume that relays are ordered based on the channel gains between the BS and the M relays. Specifically, we assume the the first relay is the one which has the weakest link with the BS, while the Mth relay is the one with the strongest, i.e., $|h_{s1}| < |h_{s2}| < \cdots < |h_{sM}|$. According to (9), the relay selected to froward the message to the users should have the strongest channel gain with the BS. However, in practical wireless scenarios, the best relay may not be available for several reasons, e.g., engaged in another transmission, load balancing, scheduling, or feedback delay. Hence, it is essential to analyze the error performance when the mth available ordered relay is selected to forward the signal.

As for the selected relay, the ordered PDF of its channel gain $|h_{sm}|$ can be given by

$$f_m(z_r) = A_m \sum_{i=0}^{m-1} \binom{m-1}{i} (-1)^i \frac{2z_r}{\lambda} e^{\frac{-M' z_r^2}{\lambda}}, \tag{10}$$

where $z_r = |h_{sm}|$, $m = 1, \ldots, M$, $M' = M - m + i + 1$ and $A_m = M!/((m-1)!(M-m)!)$.

III. PAIRWISE ERROR PROBABILITY ANALYSIS

PEP is regarded as an error rate performance metric. In this section, we mainly provide a generalized PEP expression of each NOMA user for the considered system.

A. PEP ANALYSIS OF THE *K*TH USER

According to NOMA, users should perform SIC [1] to reduce the interference resulted from multi-user transmission. Therefore, the kth user first detects the lower order users' signals, i.e., $x_1, \ldots, x_{k-1}$ before attempting to detect its own signal. Note that the kth user treats the higher order users' signal as noise.

For the kth user, through SIC process, the output can be represented as

$$\begin{aligned} y_d^k = &\left(\sqrt{\alpha_k P_B} x_k + \sum_{i=1}^{k-1} \sqrt{\alpha_i P_B} \hat{\Delta}_i + \sum_{j=k+1}^{K} \sqrt{\alpha_j P_B} x_j \right) \\ &\times G'_f h_{sm} h_{rk} + G'_f h_{rk} n_{sm} + G_f h_{rk} n_c + n_k, \end{aligned} \tag{11}$$

where $\hat{\Delta}_i = x_i - \hat{x}_i$ denotes the interference cancellation error, and $\hat{x}_i$ is the detected symbol of the ith user. It is worthwhile to note that SIC decoding process may be unsuccessful, yielding inter-user interference. This may happen if the chosen power allocation scheme is inefficient, or the targeted data rate at the kth user to detect the ith message ($i = 1, \ldots, K$, $i \neq k$) is not supported by the kth receiver.

After some mathematical manipulations similar to [17, Eqs. 7 and 8], the conditional PEP of user k is able to be expressed as

$$\Pr\left(x_k \to \check{x}_k | h_{rk}, h_{sm}\right) = Q\left(\frac{|h_{rk}||h_{sm}|\zeta_k}{\varphi_k}\right), \tag{12}$$

where $\check{x}_k$ denotes the erroneously detected symbol corresponding to x_k. In (12), $Q(\cdot)$ represents Q-function from the standard normal distribution, where the ζ_k and φ_k are given by

$$\begin{aligned} \zeta_k = &G'_f \sqrt{\alpha_k P_B} \left|\check{\Delta}_k\right|^2 + 2G'_f \\ &\times \Re\left\{ \check{\Delta}_k \left[\sum_{i=1}^{k-1} \sqrt{\alpha_i P_B} \hat{\Delta}_i^* + \sum_{j=k+1}^{K} \sqrt{\alpha_j P_B} x_j^* \right] \right\}, \end{aligned} \tag{13}$$

and

$$\varphi_k = \sqrt{2}\sigma_n \left|\check{\Delta}_k\right| \sqrt{1 + G_r^2 |h_{rk}|^2}, \tag{14}$$

where $G_r^2 = {G'_f}^2 + G_f^2$ and $(\cdot)^*$ denotes the conjugate operation. It is worth highlighting that ζ_K for user K can be expressed as

$$\zeta_K = G'_r \left\{ \sqrt{\alpha_K P_B} \left|\check{\Delta}_K\right|^2 + 2\Re\left[\check{\Delta}_k S_{\hat{\Delta}}\right] \right\}, \tag{15}$$

where $S_{\hat{\Delta}} = \sum_{i=1}^{K-1} \sqrt{\alpha_i P_B} \hat{\Delta}_i^*$.

Proposition 1: The exact analytical PEP for user k is formulated as

$$\begin{aligned} \Pr\left(x_k \to \check{x}_k\right) = &\frac{1}{2} - \frac{A_k A_m}{2} \sum_{\ell=0}^{k-1} \binom{k-1}{\ell} (-1)^\ell \\ &\times \sum_{i=0}^{m-1} \binom{m-1}{i} (-1)^i \frac{a_k}{K' M' u_k} \\ &\times e^{a_k} (K_1(a_k) - K_0(a_k)), \end{aligned} \tag{16}$$

where $a_k = K'(1 - 1/u_k^2)/(2\lambda G_r^2)$, and $u_k = \sqrt{1 + 4M'\sigma_n^2 |\check{\Delta}_k|^2 G_r^2/(\lambda \zeta_k^2)}$. Besides, $K_n(\cdot)$ denotes the modified Bessel function of the second kind with the nth order.

Proof: The analytical PEP for user k is given by

$$\Pr\left(x_k \to \check{x}_k\right) = \int_0^\infty f_k(z_k) \underbrace{\int_0^\infty f_m(z_r) Q\left(\frac{z_k \zeta_k z_r}{\varphi_k}\right) dz_r}_{\mathrm{I}_k} dz_k, \tag{17}$$

where $z_k = |h_{rk}|$ and $z_r = |h_{sm}|$. Starting by integrating with respect to z_r in (17), I_k is further derived as (18), given at the bottom of the page, in which the inclusive integral refers to [26, Eq. 4.3.4].

Subsequently, substituting φ_k in (14) into (18) yields

$$\begin{aligned} I_k = &\frac{1}{2} - \frac{A_m}{2} \\ &\times \sum_{i=0}^{m-1} \binom{m-1}{i} (-1)^i \frac{z_k}{M' u_k \sqrt{z_k^2 + \left(1 - \frac{1}{u_k^2}\right) \frac{1}{G_r^2}}}. \end{aligned} \tag{19}$$

$$\mathrm{I}_k = \frac{1}{2} - \frac{A_m}{2} \int_0^\infty \sum_{i=0}^{m-1} \binom{m-1}{i} (-1)^i \times \frac{2z_r}{\lambda} e^{\frac{-M' z_r^2}{\lambda}} \operatorname{erf}\left(\frac{z_k \zeta_k z_r}{\sqrt{2}\varphi_k}\right) dz_r = \frac{1}{2} - \frac{A_m}{2} \sum_{i=0}^{m-1} \binom{m-1}{i} (-1)^i \frac{z_k}{M' \sqrt{z_k^2 + \frac{2M'\varphi_k^2}{\lambda \zeta_k^2}}} \tag{18}$$

Plugging (19) into (17), the exact PEP of the kth user is given by (20), given at the bottom of the page. Let $t_k = z_k^2$, then I_t in (20) can be written as

$$\mathrm{I}_t = \int_0^{\infty} \frac{1}{\lambda} e^{\frac{-K' t_k}{\lambda}} \frac{\sqrt{t_k}}{M' u_k \sqrt{t_k + \left(1 - \frac{1}{u_k^2}\right)\frac{1}{G_r^2}}} dt_k. \tag{21}$$

Utilizing the following factorization

$$\frac{\sqrt{t_k}}{\sqrt{t_k + a}} = \frac{t_k + \frac{a}{2}}{\sqrt{t_k(t_k + a)}} - \frac{\frac{a}{2}}{\sqrt{t_k(t_k + a)}}, \tag{22}$$

and using [28, Eqs. 3.366.2 and 3.364.3], the integral of I_t can be calculated as

$$\mathrm{I}_t = \frac{a_k}{K' M' u_k} e^{a_k} (K_1(a_k) - K_0(a_k)), \tag{23}$$

where $a_k = K'(1 - 1/u_k^2)/(2\lambda G_r^2)$.

Therefore, using (20) and (23), the analytical PEP expression regarding user k is formulated as (16). ■

Proposition 1 is a generalized PEP expression in terms of different NOMA users. For the specific case with only single relay scenario, the PEP expression in (16) can rewritten as

$$\Pr\left(x_k \to \check{x}_k\right) = \frac{1}{2} - \frac{A_k}{2} \sum_{\ell=0}^{k-1} \binom{k-1}{\ell} \times (-1)^{\ell} \frac{a_k}{b_k} e^{a_k} (K_1(a_k) - K_0(a_k)), \tag{24}$$

where the coefficients $b_k = K' u_k$, $a_k = \frac{K'}{2\lambda G_r^2}(1 - \frac{1}{u_k^2})$, and $u_k = \sqrt{1 + 4\sigma_n^2 |\check{\Delta}_k|^2 G_r^2 / (\lambda \zeta_k^2)}$.

Remarks 1: Considering average channel gain, (14) can be simplified as the following

$$\varphi_k' = \sqrt{2}\sigma_n \left|\check{\Delta}_k\right| \sqrt{1 + G_r^2 \lambda}. \tag{25}$$

It further yields

$$\Pr\left(x_k \to \check{x}_k\right) = \frac{1}{2} - \frac{A_k A_m}{2} \sum_{\ell=0}^{k-1} \binom{k-1}{\ell} (-1)^{\ell} \times \sum_{i=0}^{m-1} \binom{m-1}{i} (-1)^{i} \frac{\tilde{a}_k}{\tilde{b}_k} \times e^{\tilde{a}_k} (K_1(\tilde{a}_k) - K_0(\tilde{a}_k)), \tag{26}$$

where $\tilde{b}_k = K' M'$, $\tilde{a}_k = K' M'^{\varphi_k'^2} / (\lambda^2 \zeta_k^2)$.

B. BER UNION BOUND

The BER union bound derivation is the motivation behind investigating the PEP, where an accurate BER upper bound is able to be deduced from averaging the PEP over all different constructive and destructive scenarios. On the basis of the aforementioned analytical PEP, the expression of BER union bound is provided with [17]

$$\mathrm{P_b} \le \frac{1}{n} \sum_{x_k} \Pr(x_k) \Pr\left(x_k \to \check{x}_k | x_j, \hat{\Delta}_i\right), \forall i, j \ne k, \tag{27}$$

where $\Pr(x_k)$ is the probability of transmitted signals x_k. Besides, $\Pr(x_k \to \check{x}_k | x_j, \hat{\Delta}_i)$ represents the derived PEP expressions conditioned on x_j and $\hat{\Delta}_i$.

Remarks 2: As observed from (16), the PEP of each user is relevant to the parameters x_j and $\hat{\Delta}_i$. Therefore, the BER union bound is computed according to the average of the PEPs involving possible error events, which gives a tight BER union bound.

IV. ASYMPTOTIC DIVERSITY ORDER ANALYSIS

A. ASYMPTOTIC PEP

In view of the need of quantifying the asymptotic diversity order about the users within considered setup, we begin with the analysis of asymptotic PEP. Exploiting Chernoff bound [27], the asymptotic PEP of user k conditioned on the two-link channels is represented by

$$\Pr\left(x_k \to \check{x}_k | h_{rk}, h_{sm}\right) \le \exp\left(-\frac{|h_{rk}|^2 |h_{sm}|^2 \zeta_k^2}{2\varphi_k^2}\right). \tag{28}$$

As is noticed from Fig. 3 in the Section V, the slope of the PEP is identical for the exact and approximated scenarios, which are given by (16) and (26), respectively. This implies that the approximation given in (25) has negligible effect on the achievable diversity gain. Therefore, to facilitate the analysis, we consider φ_k' in (25) to evaluate the asymptotic PEP. Consequently, the asymptotic PEP can be written as

$$\Pr\left(x_k \to \check{x}_k | \gamma\right) \le \exp\left(-\frac{|h_{rk}|^2 |h_{sm}|^2 \zeta_k^2}{4\sigma_n^2 \left|\check{\Delta}_k\right|^2 \left(1 + G_r^2 \lambda\right)}\right) = \exp(-c\gamma), \tag{29}$$

where the instantaneous SNR is denoted as $\gamma = |h_{rk}|^2 |h_{sm}|^2 / \sigma_n^2 = \bar{\gamma} \Omega_{sr} \Omega_{rd}$, and $\Omega_{sr} = |h_{sr}^m|^2$, $\Omega_{rd} =$

$$\begin{aligned}\Pr\left(x_k \to \check{x}_k\right) &= \frac{1}{2} - \frac{A_m}{2} \sum_{i=0}^{m-1} \binom{m-1}{i} (-1)^{i} \times \int_0^{\infty} f_k(z_k) \frac{z_k}{M' u_k \sqrt{z_k^2 + \left(1 - \frac{1}{u_k^2}\right)\frac{1}{G_r^2}}} dz_k \\ &= \frac{1}{2} - \frac{A_k A_m}{2} \sum_{\ell=0}^{k-1} \binom{k-1}{\ell} \sum_{i=0}^{m-1} \binom{m-1}{i} (-1)^{\ell + i} \times \underbrace{\int_0^{\infty} \frac{2 z_k}{\lambda} e^{\frac{-K' z_k^2}{\lambda}} \frac{z_k}{M' u_k \sqrt{z_k^2 + \left(1 - \frac{1}{u_k^2}\right)\frac{1}{G_r^2}}} dz_k}_{\mathrm{I}_t}\end{aligned} \tag{20}$$

$|h_{rk}|^2$. The average SNR $\bar{\gamma} = 1/\sigma_n^2$. Moreover, $c = \zeta_k^2/(4|\check{\Delta}_k|^2(1+G_r^2\lambda))$.

The unconditional asymptotic PEP can be evaluated as

$$\Pr\left(x_k \to \check{x}_k\right) \le \int_0^{\infty} f(\gamma)\exp(-c\gamma)d\gamma. \tag{30}$$

Subsequently, we attempt to obtain the PDF $f(\gamma)$. Since Ω_{sr} and Ω_{rd} follow the exponential distribution, the ordered CDF with respect to γ can be acquired by

$$\mathrm{F}(\gamma) = \int_0^{\infty} \mathrm{F}(\gamma \mid \Omega_{rd}) f_k(\Omega_{rd}) d\Omega_{rd}, \tag{31}$$

where $f_k(\Omega_{rd})$ is the ordered PDF of Ω_{rd}, namely

$$\begin{aligned} f_k(\Omega_{rd}) &= A_k f(\Omega_{rd})[\mathrm{F}(\Omega_{rd})]^{k-1}[1-\mathrm{F}(\Omega_{rd})]^{K-k} \\ &= A_k \sum_{\ell=0}^{k-1}\binom{k-1}{\ell}(-1)^{\ell}\exp\left(-K'\Omega_{rd}\right). \end{aligned} \tag{32}$$

Given Ω_{rd}, the conditional CDF with respect to γ is given by

$$\begin{aligned} \mathrm{F}(\gamma \mid \Omega_{rd}) &= \mathrm{F}(\Omega_{sr})\big|_{\Omega_{sr}=\frac{\gamma}{\bar{\gamma}\Omega_{rd}}} \\ &= \int_0^{\frac{\gamma}{\bar{\gamma}\Omega_{rd}}} f_m(\Omega_{sr}) d\Omega_{sr}, \end{aligned} \tag{33}$$

where the ordered PDF of Ω_{sr} is

$$f_m(\Omega_{sr}) = A_m \sum_{i=0}^{m-1}\binom{m-1}{i}(-1)^{i}\exp\left(-M'\Omega_{sr}\right). \tag{34}$$

It follows from (33) that

$$\begin{aligned} \mathrm{F}(\gamma \mid \Omega_{rd}) = {} & A_m \sum_{i=0}^{m-1}\binom{m-1}{i}\frac{(-1)^{i}}{M'} \\ & \times \left(1-\exp\left(-\frac{\gamma M'}{\bar{\gamma}\Omega_{rd}}\right)\right). \end{aligned} \tag{35}$$

Therefore, we can obtain

$$\begin{aligned} \mathrm{F}(\gamma) = {} & A_m A_k \sum_{i=0}^{m-1}\binom{m-1}{i}\frac{(-1)^{i}}{M'}\sum_{\ell=0}^{k-1}\binom{k-1}{\ell}(-1)^{\ell} \\ & \times \underbrace{\int_0^{\infty}\exp\left(-K'\Omega_{rd}\right)\left(1-\exp\left(-\frac{\gamma M'}{\bar{\gamma}\Omega_{rd}}\right)\right)d\Omega_{rd}}_{I_\gamma}. \end{aligned} \tag{36}$$

Hence, using [28, Eq. 3.471.9] yields

$$I_\gamma = \frac{1}{K'} - 2\sqrt{\frac{\gamma M'}{\bar{\gamma}K'}}K_1\left(2\sqrt{\frac{\gamma M'K'}{\bar{\gamma}}}\right). \tag{37}$$

After that, we derive $\mathrm{F}(\gamma)$ to get the PDF as the following

$$\begin{aligned} f(\gamma) = {} & A_m A_k \sum_{i=0}^{m-1}\binom{m-1}{i}(-1)^{i}\sum_{\ell=0}^{k-1}\binom{k-1}{\ell}(-1)^{\ell} \\ & \times \frac{2}{\bar{\gamma}}K_0\left(2\sqrt{\frac{\gamma M'K'}{\bar{\gamma}}}\right). \end{aligned} \tag{38}$$

Therefore, (30) can be evaluated to

$$\begin{aligned} \Pr\left(x_k \to \check{x}_k\right) \le {} & A_m A_k \sum_{i=0}^{m-1}\binom{m-1}{i}\sum_{\ell=0}^{k-1}\binom{k-1}{\ell}(-1)^{i+\ell} \\ & \times \frac{2}{\bar{\gamma}}\int_0^{\infty} K_0\left(2\sqrt{\frac{\gamma M'K'}{\bar{\gamma}}}\right)\exp(-c\gamma)d\gamma. \end{aligned} \tag{39}$$

Using [28, Eq. 6.614.4], the integral in (39) can be expressed as

$$\begin{aligned} \Pr\left(x_k \to \check{x}_k\right) \le {} & A_m A_k \sum_{i=0}^{m-1}\binom{m-1}{i}\sum_{\ell=0}^{k-1}\binom{k-1}{\ell}(-1)^{i+\ell} \\ & \times \frac{1}{\sqrt{c\bar{\gamma}M'K'}}\exp\left(\frac{M'K'}{2c\bar{\gamma}}\right)W_{-\frac{1}{2},0}\left(\frac{M'K'}{c\bar{\gamma}}\right), \end{aligned} \tag{40}$$

where $W_{a,b}(\cdot)$ indicates the Whittaker function.

B. ASYMPTOTIC DIVERSITY ORDER

With the aid of the slope of the PEP within high SNR regimes, we can evaluate the achievable diversity order as

$$\mathrm{d} = \lim_{\bar{\gamma}\to\infty} -\frac{\log\Pr\left(x_k \to \check{x}_k\right)}{\log\bar{\gamma}}. \tag{41}$$

It should be pointed out that deriving a closed-form expression for the diversity order is mathematically intractable, due to the high complexity of (40). However, motivated by the fact that the diversity order is limited to the minimum diversity orders of the two links, *s*-*m* and *m*-*k*, and given that we employed order statistics, we deduce that the achievable diversity can be evaluated as

$$d = \min(m, k). \tag{42}$$

This illustrates that the performance bottleneck is determined by the minimal diversity order between the *s*-*m* and *m*-*k* links.

V. NUMERICAL RESULTS

In this section, some numerical and Monte Carlo simulation results are provided to assess the performance for the considered NOMA SWIPT-enabled system with partial relay selection, and the effectiveness of the analytical expressions is corroborated. In specific we consider a NOMA system includes single BS, two or three relays, i.e., $M = 2$ or 3, and $K = 3$. The binary phase shift keying modulation is adopted by the transmitted symbols. All the channel coefficients are assumed flat Rayleigh fading channels with normalized energy, $\lambda = 1$. The channels of all users are generated randomly and ordered based on their gains. In addition, each channel is generated independently and identically distributed. Other parameters are set up as follows: the transmitted power $P_B = 1$ at the BS, the energy conversion efficiency $\eta = 0.8$ [29], and the adopted power allocation coefficient vector is $\alpha = [0.68, 0.24, 0.08]$ for K users, and imperfect SIC is considered. Monte Carlo simulation is used

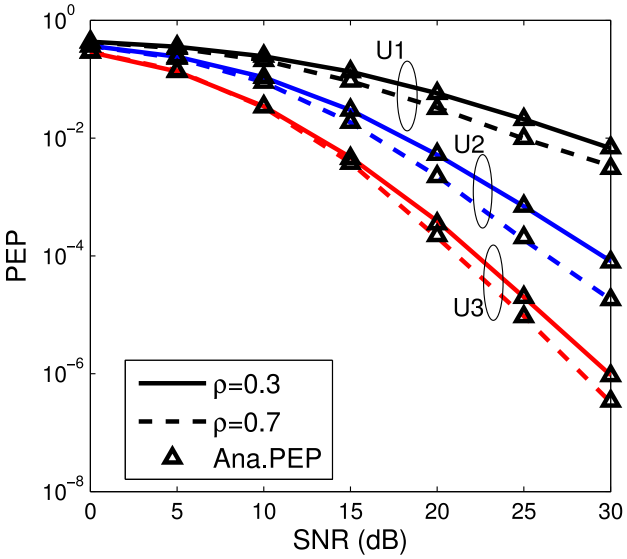


FIGURE 2. **Analytical PEP of each user with $\rho = 0.3, 0.7$, and $M = 3$.**

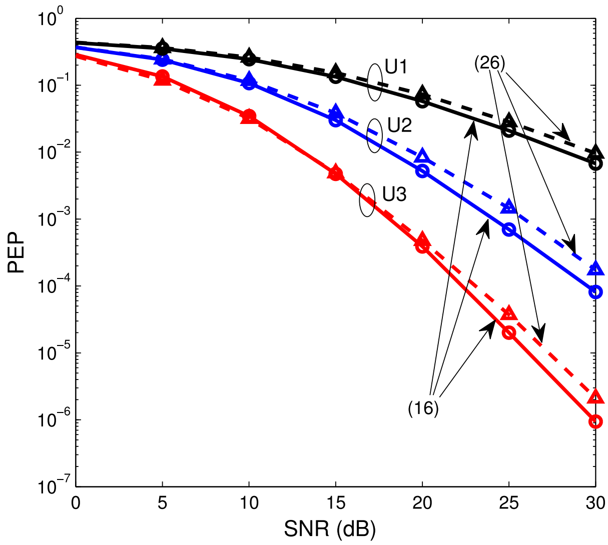
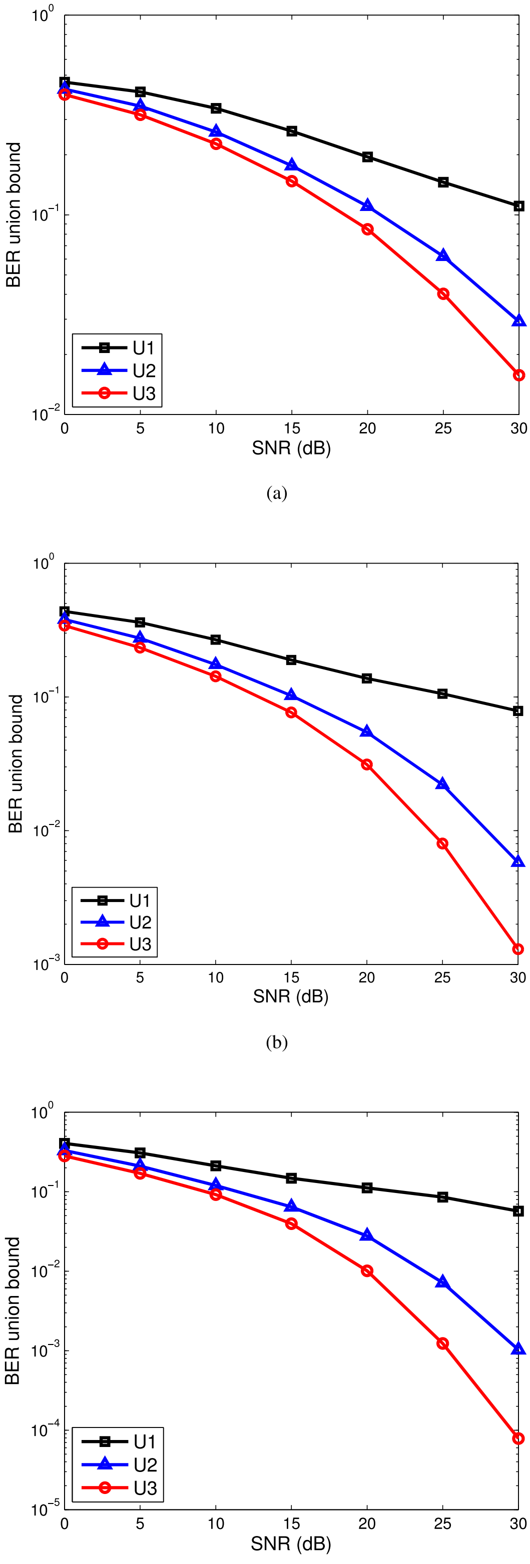


FIGURE 3. **PEP comparisons based on (16) and (26), $\rho = 0.3$, $M = 3$.**



(a)

(b)

(c)

FIGURE 4. **BER union bound vs. SNR for each user, $\rho = 0.7$, $M = 3$. (a) m = 1; (b) m = 2; (c) m = 3.**

to generate the simulated PEP results. Unless stated otherwise, the selected best relay is the one with the strongest channel gain, i.e., $m = 2$ or 3 for $M = 2$ or 3, respectively.

In Fig. 2, we plot the simulated and numerical PEP to confirm the correctness of the analytical PEP expression with (16). It can be observed that the derived and simulated PEPs perfectly overlap for all users with $\rho = 0.3$ and $\rho = 0.7$, over the entire SNR range, which corroborates (16). It should be specified that, in the legends of the following figures, Ui is referred to as the ith user ($i = 1, 2, 3$).

Fig. 3 verifies the accuracy of the adopted assumption in (25), where the exact (solid line) and the approximated (dashed line) PEP are presented. In the low SNR regime, error rate performance is dominated by the effect of the AWGN. On the other hand, at high SNR values, the system performance is determined based-on the effect of fading. Therefore, the effect of the approximation in (26) is more noticeable at higher SNR values, as depicted in Fig. 3. However, it can be observed that, for practical SNR values,

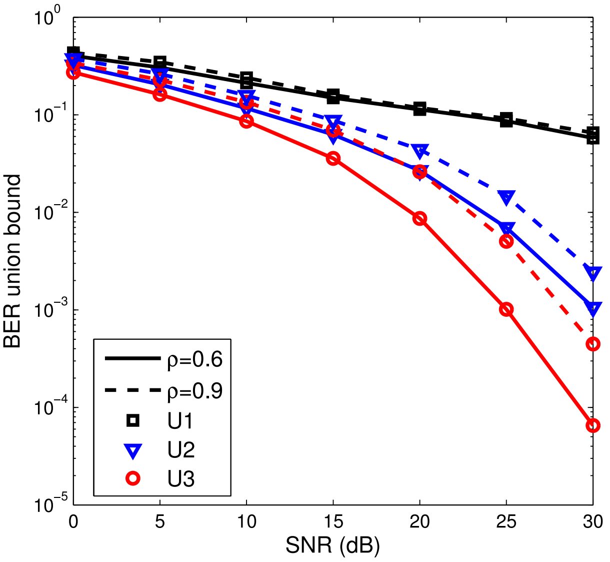


FIGURE 5. BER union bound vs. SNR for different ρ values, $M = 3$.

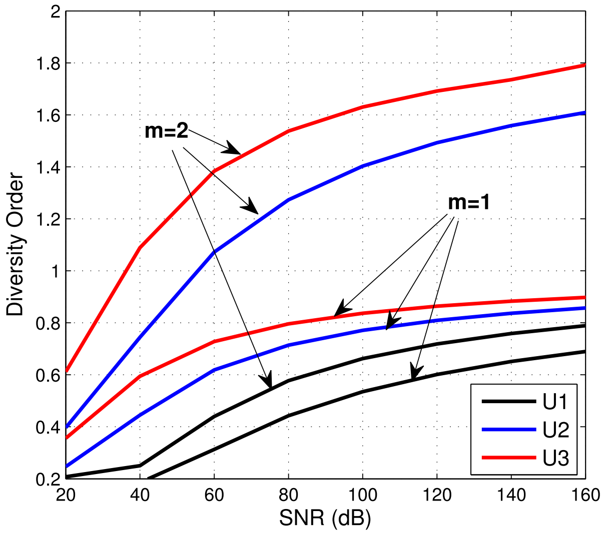


FIGURE 7. Diversity order for three users, $M = 2$.

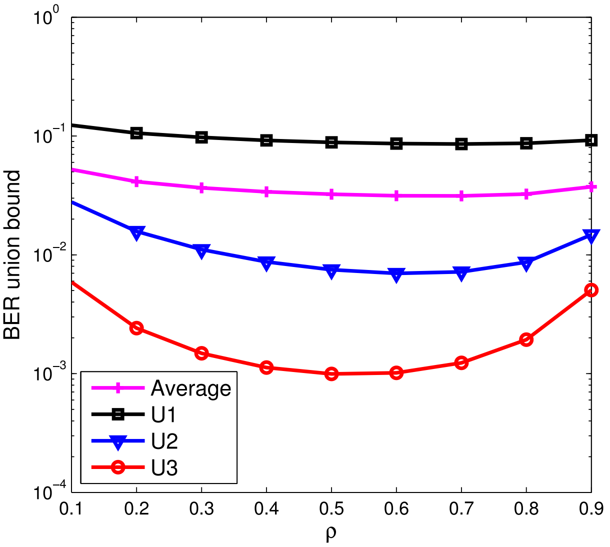


FIGURE 6. The average and individual union bounds of three users vs. PS factor ρ, $M = 3$, SNR = 25dB.

the approximation in (26) is accurate and can give useful insights into the error rate performance of the adopted system model. In specific, it can be noticed that the performance difference between (16) and (26) is negligible. Furthermore, the slope of the PEPs in Fig. 3 is equal for the two scenarios, which means that the approximation in (26) has no effect on the achievable diversity order.

PEP analyses with the corresponding BER union bound can be exploited to make an evaluation on the error rate performance of NOMA users. Fig. 4 simulates the union bound of BER versus SNR for each user with the mth relay, $m = 1, 2, 3$, and $\rho = 0.7$. Owing to the possible reasons, such as the occupied best relay, load balancing, scheduling, or channel feedback delay, the other suboptimal relays exert a significant effect especially on the second and third users as shown in Fig. 4. We can observe the fact that relay selection almost exerts no influence on the BER performance of the first user, which is due to the reason that the diversity order of user 1 is limited to one due to order statistics, which implies the first user hardly benefits from the more favorable relay selection. On the other hand, the users with better conditions can benefit more from the preferable relay, for example, at SNR= 25dB, the union bound of user 2 is 0.02 when $m = 1$ as depicted in Fig. 4(a). Meanwhile, the BER union bound decreases to 0.007 when $m = 2$, as illustrated in Fig. 4(b). The similar conclusion is applicable to the third user with different m values.

The union bounds of BER for all users are compared with different ρ in Fig. 5, which manifests that the error performance of U2 and U3, when $\rho = 0.6$, outperforms that of U2 and U3 when $\rho = 0.9$. Furthermore, the BER performance of the first user is less susceptible to ρ. Nevertheless, it can be noticed that the choice of ρ makes no impacts on the achievable diversity order of all users.

The average and individual union bounds of three users versus ρ are depicted in Fig. 6, at SNR = 25 dB. It is noticed from the figure that the optimum value for ρ lies on the range $0.5 \sim 0.6$ for the third user while $\rho = 0.6 \sim 0.7$ is the optimum range for the second user. Moreover, it can be observed that the effect of ρ on the average union bound is negligible, this is because the average union bound performance is dominated by the weakest user's performance, here the weakest user corresponds to the first user.

The diversity order for each user is evaluated in Fig. 7, based on (41) and (40), for M = 2 two relay setting. The annotation '$m = 2$' corresponds to the best relay while '$m = 1$' stands for the other suboptimal relay. Fig. 7 manifests that the maximum diversity orders of different users gradually approach one as SNR increases to infinity when $m = 1$. Meanwhile, for the nearest user 'U3', its maximum achievable diversity order would approach two with the selected relay $m = 2$. Consequently, we can draw a conclusion that the maximum achievable diversity order for user k is restricted as $\min(m, k)$.

VI. CONCLUSION

This article investigated the error performance in downlink NOMA system incorporating SWIPT enabled relays. To evaluate the BER upper bound of the considered system, we derived the exact analytical PEP expression of NOMA users with partial relay selection. Specifically, the selected mth relay utilizes its EH receiver to perform energy harvesting, while the information receiver takes advantage of the harvested energy to amplify and forward the received signal to the users. Moreover, we derived the asymptotic PEP expression to assess the approximate diversity order of each user with relay selection. The accuracy of the analytical PEP expressions was validated by Monte Carlo simulations. Additionally, it was shown from the numerical and simulation results that the maximum achievable diversity order of the kth user is dependent on the minimum between the mth selected relay and user k.

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