Outage Performance of the Downlink NOMA Relay Networks with RF Energy Harvesting and Buffer Aided Relay

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Abstract. In this paper, we investigate performance of a decode-and-forward Non-Orthogonal Multiple Access (NOMA) relay system using Simultaneous Information and Power Transfer (SWIPT). In the considered system a source node transmits data in the downlink simultaneously to two destination nodes via an energy-harvesting relay node. In order to cope with fading channels the relay is assumed to have an infinite capacity buffer to store data if the transmission link is in outage. We analyze outage performance of the system and obtain the closed-form expressions for the system outage probability for two cases, i.e. the relay is equipped and not equipped with the buffer. Numerical results are provided to demonstrate the merit of using the buffer-aided relay.

Keywords: NOMA · Energy harvesting
Successive interference cancellation · Power allocation
Buffer aided relay

1 Introduction

Recently, Non-Orthogonal-Multiple-Access (NOMA) technique has been realized as a promising multiuser communication technique for the fifth-generation (5G) mobile network due to its superior spectral efficiency [1]. The key idea of NOMA is to utilize power domain to differentiate users based on their power levels [2]. Recent researches have shown that NOMA can be applied not only to point-to-point but also relay networks [3,4]. The work [5] considered a conventional cooperative NOMA system with buffer-aided relaying and adaptive transmission which can operate in different modes for individual time slots. The authors of [4] proposed a dual-hop cooperative relaying scheme using NOMA, where the two terminal nodes communicate with each other simultaneously via a relay over the same frequency band. In this scheme, the received symbols with different power levels from two source nodes are encoded into a superposition symbol based on

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the NOMA principle and then forwarded back to the destination nodes. All users are assumed to be allocated with an equal power level.

On the other hand, harvesting energy from the ambient radio frequency (RF) environment has become a promising solution for energy-constrained electronic devices which are normally supported by a limited power source such as battery [6]. In many cases, especially ad-hoc wireless sensor networks or body area networks, charging battery is too expensive or even impossible. Meanwhile, natural energy sources such as solar, wind and radio wave can be effectively exploited for energy harvesting (EH). Among these sources, RF energy harvesting [7] has more advantages such as reliability and green energy. Recently, RF energy harvesting has also been considered for the NOMA relay networks [8,9] to prolong their lifetime. In [8] a simultaneous wireless information and power transfer (SWIPT) scheme was proposed for NOMA networks in which a base station serves both the relay and far users. The work [10] considered a NOMA system in which users near the source can act as the EH relays to assist far users in forwarding data to the destination.

In this paper, we apply SWIPT to NOMA relay systems which are supported by RF energy harvesting. In our proposed system, the relay is assumed to be able to harvest RF energy from the source to support its operation. Moreover, it is provided with a buffer for data processing and uses a cooperative decode-and-forward scheme to transmit superposition symbols from the source to end users in the context of a downlink NOMA relay system. We then derive the closed-form expression for the system outage probability and propose an optimal power allocation scheme to optimize performance of end users.

The main contributions of the paper can be summarized as follows:

- First, in order to support the sustainable operation of relay, we propose to use a time-switching SWIPT scheme in a downlink NOMA relay system.
- Using the Markov chain model to describe the operation of the buffer-aided relay we can derive the closed-form expression for the system outage probability and compare it with the case without using the buffer.
- Performance of the system in terms of outage probability over the Rayleigh fading channel is analyzed and verified using computer simulations.

The remainder of the paper is organized as follows. Section 2 presents the system model of the considered system. Outage performance of the system is analyzed in Sect. 3. Numerical results are shown in Sect. 4 and finally conclusions are drawn in Sect. 5.

2 System Model

2.1 System Configuration

The system model of a downlink NOMA relay network considered in this paper is shown in Fig. 1. In this model, a source node (basestation) S wishes to send its messages to two end users (destination nodes) D_1 and D_2 simultaneously via a

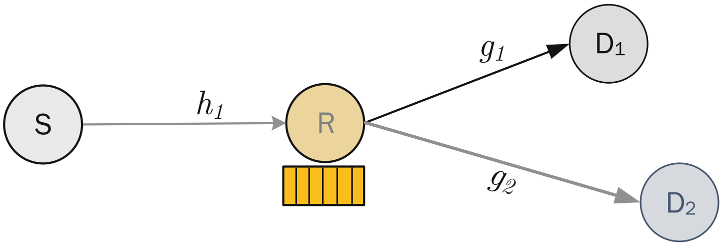

Fig. 1. Wirelessly powered NOMA downlink relaying network.

decode-and-forward (DF) relay node R. It is assumed that all three nodes S, D_1, and D_2 are powered by mains electricity while the relay is self-powered by the energy harvested from the RF transmitted signal of the source. In addition, the relay is assumed to have an unlimited-size buffer to store the received messages. We assume that the direct link between the source and the two destination nodes is not available and that the communication between them is always via the relay node. The channels between two arbitrary nodes are subject to block and flat Rayleigh fading. The assumption of block fading means that the channel coefficients are constant during each data block transmission interval τ but vary from one to another. All nodes are equipped with a single antenna and operate in a half-duplex mode.

In the case of buffer-aided relay, it is assumed that the relay has perfect channel state information (CSI) of the links S $\rightarrow$ R and $D_1, D_2 \rightarrow$ R at the start of each time slot by using some pilot-assisted channel method. Based on assumption, the relay node R can decide to operate in the transmit or receive mode [11]. The complex channel coefficient of the link S $\rightarrow$ R is denoted by $h_1 \sim \mathcal{CN}(0, \Omega_0)$ while that of the link R $\rightarrow$ D_i is $g_i \sim \mathcal{CN}(0, \Omega_i)$ where $i = \{1, 2\}$, $\Omega_1 = \mathbb{E}\{|g_1|^2\}, \Omega_2 = \mathbb{E}\{|g_2|^2\}$. The additive white Gaussian noise (AWGN) at R, D_1 and D_2 is respectively denoted by $w_\Lambda \sim \mathcal{CN}(0, N_0)$, where $\Lambda \in \{R, D_1, D_2\}$ and N_0 is the single-sided AWGN power spectral density. Without loss of generality, we assume that the channel gains g_i are sorted in the descending order as follows: $|g_1|^2 > |g_2|^2$.

2.2 Data Buffer at Relay

Since the relay operates in the half-duplex mode, the received messages from the source node S need to be stored in the buffer and process before forwarding to the destination nodes D. Using RF energy harvesting, the relay node can be powered by the harvested energy directly or via a storage device such as battery or high volume capacitor [12]. The system operates in the time-switching mode, in which each operation period τ is divided into two portions depending on the fraction coefficient $\alpha, 0 \leq \alpha \leq 1$; the first portion $\alpha\tau$ is used for energy harvesting while the remaining $\tau(1 - \alpha)$ is for transmission and reception. During each time slot, the relay and the source node is selected to transmit data based on the buffer state and the available links that can guarantee the successful transmission or reception of one packet.

If S is selected, it will generate a transmission frame of size $2r_0\tau$ bits intended to the two destination nodes D_1 and D_2 and send it to the relay node, where r_0 is the target transmission rate of the system. Each frame contains two parts, the first one contains data symbols to be sent to D_1 and the second to D_2. The relay buffer has $L \geq 2$ storage units, each can store $2r_0\tau(1-\alpha)$ bits. The relay node decodes the received frame and stores into the storage device. Each storage device is split into two parts of the same length. The first part is used to store the information symbol intended to D_1. The second one is used for D_2.

2.3 Signal Model

During each time slot, if the source node is selected to transmit, it combines two symbols x_1 and x_2 to form a transmission packet, $x_\mathrm{S} = x_1 + x_2$ where $\mathbb{E}\{|x_1|^2\} = P_1$ and $\mathbb{E}\{|x_2|^2\} = P_2$. Based on the NOMA principle [13], in order for the relay node to decode the information symbols x_1 and x_2, the source node sets different power levels to x_1 and x_2. Assume that $P_1 \neq P_2$ and denote the total transmit power at the source by $P_\mathrm{S} = P_1 + P_2$. Then, the received signal at the relay is given by

$$y_\mathrm{R} = h_1 \sum_{k=1}^{2} \sqrt{P}_k x_k + w_\mathrm{R}. \tag{1}$$

The instantaneous SNR of the source-to-relay link is given by

$$\gamma_\mathrm{R} = \frac{P_\mathrm{S}|h_1|^2}{N_0}. \tag{2}$$

Recall that τ is the block duration of an entire communication period in which the information is transmitted from S to $\mathrm{D_i}$. For each period τ, the first duration, $\alpha\tau$, is used for energy harvesting at R, while the remaining duration, $(1-\alpha)\tau$, is used for transmitting and receiving the information. Therefore, the amount of harvested energy at the relay in one time slot is given by [14,15].

$$E_h = \alpha\tau\eta P_\mathrm{S}|h_1|^2, \tag{3}$$

where η denotes the energy conversion efficiency coefficient whose values range from 0 to 1, depending on the harvesting electric circuitry. From (3), the transmission power of the relay is given by

$$P_\mathrm{R} = \frac{E_h}{(1-\alpha)\tau/2} = \frac{2\alpha\eta P_\mathrm{S}|h_1|^2}{(1-\alpha)}. \tag{4}$$

In a specific time slot, if selected the relay R transmits a superposition modulated symbol $x_\mathrm{R} = \sqrt{a_1 P_\mathrm{R}} x_1 + \sqrt{(1-a_1)P_\mathrm{R}} x_2$ stored in the buffer, where x_1 and x_2 denote information symbols intended for D_1 and D_2, respectively; a_1 is the power allocation coefficient for D_1 and $(1-a_1)$ represents the power allocation coefficient for D_2. At the end of each time slot, the received signal at the destinations is given by

$$y_{D_i} = \sqrt{P_R} g_i(\sqrt{a_1}x_1 + \sqrt{1-a_1}x_2) + w_{D_i}. \tag{5}$$

When $|g_1|^2 > |g_2|^2$, based on the NOMA principle, the relay node allocates more power for D_2 in order to balance the fairness of the system performance. Due to the broadcast nature of the wireless environment, the instantaneous signal-to-interference-and noise ratio (SINR) of the $R \to D_2$ link given by

$$\gamma_{D_2}^{x_2} = \frac{(1-a_1)P_R|g_2|^2}{a_1 P_R|g_2|^2 + N_0}, \tag{6}$$

where the information symbol x_1 is treated as the interference at D_2. D_1 needs to decode its own information symbol x_1. Using the ideal SIC estimation [16], D_1 can remove the estimated information symbol x_2 from the received signal. From (5), the instantaneous SNR and SINR of the $R \to D_1$ link is given by

$$\gamma_{D_1}^{x_2 \to x_1} = \frac{(1-a_1)P_R|g_1|^2}{a_1 P_R|g_1|^2 + N_0}. \tag{7}$$

$$\gamma_{D_1}^{x_1} = \frac{a_1 P_R|g_1|^2}{N_0}. \tag{8}$$

3 Outage Probability Analysis for Buffer-Aided Relay Systems

In this section, we analyze the outage performance of the downlink SWIPT NOMA relay system for two cases, namely, the end-to-end outage probability and the individual outage probability for each destination node.

3.1 Overall Outage Probability

The overall outage probability (OOP) of the system is defined as the probability that neither the $S \to R$ link nor the $R \to D_i$ links is available for transmission so that the target predefined transmission rate is achieved. In wireless communication links, outage occurs when the output SNR, γ_{e2e}, falls below a certain threshold, $\gamma_{th} = 2^{\frac{2r_0}{1-\alpha}} - 1$. Using theoretical analysis we have derived the exact and approximated closed-form expressions for the OOP of the downlink SWIPT-NOMA relay system. The proof of the Theorem is omitted here due to page limit.

Theorem 1. *The overall outage probability of the downlink SWIPT-NOMA relay system when the relay knows both g_1 and g_2 is given by:*

$$\mathrm{OOP} = 1 - \frac{1}{\Omega_1}\sum_{k=0}^{\infty}\frac{(-1)^k}{k!}\left(\frac{\Psi_{\min}}{\Omega_2}\right)^k\left[\frac{(-1)^k}{(k-1)!}\left(\frac{1}{\Omega_1}\right)^{k-1}\mathrm{Ei}\left(-\frac{\gamma_{th}}{\Omega_1 P_S}\right) + \Delta_1\right], \tag{9}$$

where $\mathrm{Ei}(x)$ *denotes the exponential integral function [17],* $\phi = \frac{2\alpha\eta}{1-\alpha}$, $a_1 < \frac{1}{1+\gamma_{\mathrm{th}}}$, $\Psi_{\min} = \min\left\{\frac{\gamma_{\mathrm{th}}}{a_1\phi P_{\mathrm{S}}}, \frac{\gamma_{\mathrm{th}}}{\phi P_{\mathrm{S}}(1-a_1(1+\gamma_{\mathrm{th}}))}\right\}$, $\varDelta_1 = \frac{\exp\left(-\frac{\gamma_{\mathrm{th}}}{\varOmega_1 P_{\mathrm{S}}}\right)}{\left(\frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}\right)^{k-1}} \sum_{j=0}^{k-2} \frac{(-1)^j \left(\frac{\gamma_{\mathrm{th}}}{\varOmega_1 P_{\mathrm{S}}}\right)^j}{\prod_{\ell=0}^{j}(k-1-\ell)}$.
In the high SNR regime, the approximated OOP *is given by*

$$\mathrm{OOP} \approx 2 - \exp\left(-\frac{\gamma_{\mathrm{th}}}{\Omega_1 P_{\mathrm{S}}}\right) - \sqrt{\frac{4\Psi_{\min}}{\Omega_1\Omega_2}}\mathcal{K}_1\left(\sqrt{\frac{4\Psi_{\min}}{\Omega_1\Omega_2}}\right), \tag{10}$$

where $\mathcal{K}_1(\cdot)$ *is the first-order modified Bessel function of the second kind.*

3.2 Outage Probability at Destination Nodes

In this section, we derive the closed-form expression for the outage probability at the destination nodes. When a destination node suffers from outage, the other can detect its own information symbols. The system may switch to using an orthogonal multiple access scheme such as the code division multiple access (CDMA). After a straighforward mathematical analysis, we have found the closed-form expression for the outage probability of the destination nodes given in Theorem 2. Due to page limit, the proof of the theorem is omitted here.

Theorem 2. *The outage probability at* D_1 *and* D_2 *are given respectively in* (11) *and* (12), $a_1 \leq \frac{1}{1+\xi_i}$, $i \in \{1, 2\}$.

$$\mathrm{OP}_{\mathrm{D}_1} = 1 - \frac{1}{\varOmega_1}\sum_{t=0}^{\infty}\frac{(-1)^t}{t!}\left(\frac{\mathcal{Q}_{\max}}{\varOmega_2}\right)^t\left[\frac{(-1)^t}{(t-1)!}\left(\frac{1}{\varOmega_1}\right)^{t-1}\mathrm{Ei}\left(-\frac{\xi_1}{\varOmega_1 P_{\mathrm{S}}}\right) + \varDelta_2\right], \tag{11}$$

$$\mathrm{OP}_{\mathrm{D}_2} = 1 - \frac{1}{\varOmega_1}\sum_{m=0}^{\infty}\frac{(-1)^m}{m!}\left(\frac{b}{\varOmega_2}\right)^m\left[\frac{(-1)^m}{(m-1)!}\left(\frac{1}{\varOmega_1}\right)^{m-1}\mathrm{Ei}\left(-\frac{\xi_2}{\varOmega_1 P_{\mathrm{S}}}\right) + \varDelta_3\right], \tag{12}$$

where $\mathcal{Q}_{\max} = \max\left\{\frac{\xi_1}{a_1\phi P_{\mathrm{S}}}, \frac{\xi_1}{\phi P_{\mathrm{S}}(1-a_1(1+\xi_1))}\right\}$, $b = \frac{\xi_2}{\phi P_{\mathrm{S}}(1-a_1(1+\xi_2))}$, $\xi_1 = 2^{\frac{2r_1}{1-\alpha}} - 1$, $\xi_2 = 2^{\frac{2r_2}{1-\alpha}} - 1$, r_1 *and* r_2 *are the target transmission rates at* D_1 *and* D_2, $\varDelta_2 = \frac{\exp\left(-\frac{\xi_1}{\varOmega_1 P_S}\right)}{\left(\frac{\xi_1}{P_S}\right)^{t-1}}\sum_{k=0}^{t-2}\frac{(-1)^k\left(\frac{1}{\varOmega_1}\right)^k\left(\frac{\xi_1}{P_S}\right)^k}{\prod_{\ell=0}^{k}(t-1-\ell)}$,

$\varDelta_3 = \frac{\exp\left(-\frac{\xi_2}{\varOmega_1 P_S}\right)}{\left(\frac{\xi_2}{P_S}\right)^{m-1}}\sum_{q=0}^{m-2}\frac{(-1)^q\left(\frac{1}{\varOmega_1}\right)^q\left(\frac{\xi_2}{\mathrm{P}}^S\right)^q}{\prod_{v=0}^{q}(m-1-v)}$.

4 Outage Probability with Buffer Aided Relay

In this section, we investigate the outage performance of the downlink SWIPT-NOMA relay system with a buffer-aided relay. For convenience of analysis, we assume that the source node always has data to transmit. We also assume that each packet contains one transmit symbol. During each time slot, either the source or the relay node is selected to transmit a packet. In order for this selection to be possible, the information on the outage states of the links S $\rightarrow$ R and R $\rightarrow$ D is required. The system can use one bit for the feedback information from the destination to the relay node. This feedback helps the relay node R to know whether the link R $\rightarrow$ D is in outage. One more bit, fed back from the relay to the source node, is used to control the state of the source node, i.e. in the transmit or silent mode. The source node transmits data packets to the relay which decodes the packets and stores them in the buffer. The relay node then forwards the packets to the destination node. If the source node is selected to transmit but the link S $\rightarrow$ R is in outage, the source remains silent. Similarly, if the relay node is selected to transmit but the link R $\rightarrow$ D is in outage, the relay also stays silent. Since the outage could be avoided the system performance will be improved significantly. Unlike the case without a buffer-aided relay, the outage event in this case is defined as the probability that the relay does not receive and transmit data, i.e. the relay remains silent. To describe the state transition of the buffer-aided relay operation, we denote the outage events of S $\rightarrow$ R link and R $\rightarrow$ D link by $\mathcal{O}_{\mathrm{SR}}$ and $\mathcal{O}_{\mathrm{RD}}$, respectively. The probabilities that these links are not in outage are given respectively by $1 - \mathcal{O}_{\mathrm{SR}} = \bar{\mathcal{O}}_{\mathrm{SR}}$ and $1 - \mathcal{O}_{\mathrm{RD}} = \bar{\mathcal{O}}_{\mathrm{RD}}$. Table 1 shows different states of the relay nodes and associated outage probabilities.

Table 1. The relay decision scheme

Case	SR	RD	l	Relay	$\mathcal{OP}$
A	0	0		Silent	$\mathcal{O}_{\mathrm{SR}}\mathcal{O}_{\mathrm{RD}}$
B	0		$l = 0$	Silent	$\mathcal{O}_{\mathrm{SR}}$
C		0	$l = L$	Silent	$\mathcal{O}_{\mathrm{RD}}$
D	1	0	$l < L$	Receive	$\bar{\mathcal{O}}_{\mathrm{SR}}\mathcal{O}_{\mathrm{RD}}$
E	0	1	$l > 0$	Transmit	$\mathcal{O}_{\mathrm{SR}}\bar{\mathcal{O}}_{\mathrm{RD}}$
F	1	1	$l \geqslant 2$	Transmit	$\bar{\mathcal{O}}_{\mathrm{SR}}\bar{\mathcal{O}}_{\mathrm{RD}}$
G	1	1	$l \leqslant 1$	Receive	$\bar{\mathcal{O}}_{\mathrm{SR}}\bar{\mathcal{O}}_{\mathrm{RD}}$

In Table 1, "SR" denotes the link from the source to the relay node, "RD" refers to the link from the relay to the destination node; 'l' and 'L' respectively represent the packets stored in the buffer and the buffer size at the relay node. 'Relay' denotes the state decision of the relay node (silent, receive or transmit), '$\mathcal{OP}$' is the system outage probability. The outage and non-outage links are indicated by '0' and '1', respectively.

To calculate $\mathcal{OP}$ of the system, based on Table 1 we create the Markov chain. We start at the initial state $l = 0$ (i.e. when the buffer is empty). If the link SR is in outage which means the source does not transmit, then the buffer will be empty. In other words, the buffer state moves from $l = 0$ to $l = 0$ with probability of $\mathcal{O}_{\rm SR}$ (Case B). When the link SR is not in outage, we consider two cases. The first case is when the link RD is in outage (Case D). Consequently, the relay receives the signal, making the buffer state move from $l = 0$ to $l = 1$ with probability $(1 - \mathcal{O}_{\rm SR})\mathcal{O}_{\rm RD}$. The second case is when the link RD is not in outage (Case G). The relay receives the signal, making the buffer state move from $l = 0$ to $l = 1$ with probability $(1 - \mathcal{O}_{\rm SR})(1 - \mathcal{O}_{\rm RD})$. Combining these two cases shows that the buffer state moves from $l = 0$ to $l = 1$ with probability $1 - \mathcal{O}_{\rm SR}$. Similarly, we can obtain the probability of moving to the next state. From here, we have the Markov chain showing the state transitions as depicted in Fig. 2. When the buffer is empty ($l = 0$), it stays in the empty state with probability of $\mathcal{O}_{\rm SR}$ (case B) and receives a packet with probability $1-\mathcal{O}_{\rm SR}$ (case D, G). When the buffer has one packet ($l = 1$), it stays in the current state with probability of $\mathcal{O}_{\rm SR}\mathcal{O}_{\rm RD}$ if the relay does not receive and transmit (case A). If the relay receives one packet, it moves to the new state ($l = 2$) with probability of $1 - \mathcal{O}_{\rm SR}$ (case D, G) and returns to the initial state ($l = 0$) with probability $\mathcal{O}_{\rm SR}(1 - \mathcal{O}_{\rm RD})$ (case E). When the buffer has l packets ($2 \leqslant l \leqslant L - 1$), it stays in this state with probability of $\mathcal{O}_{\rm SR}\mathcal{O}_{\rm RD}$ (case A), receives one packet with probability $(1 - \mathcal{O}_{\rm SR})\mathcal{O}_{\rm RD}$ (case D), and transmits one packet with probability $1 - \mathcal{O}_{\rm RD}$ (case E, F). If the buffer is full, which means that it has L packets, it remains in the same state with probability $\mathcal{O}_{\rm RD}$ (case C) and transmits one packet with probability $1 - \mathcal{O}_{\rm RD}$ (case E, F).

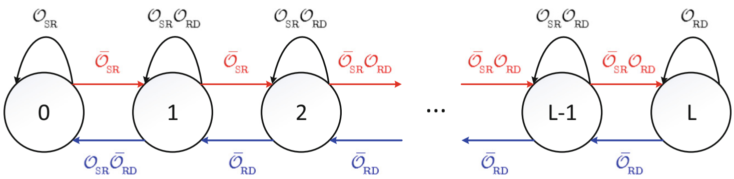

Fig. 2. The Markov chain diagram of buffer states at the relay node.

Using Table 1 and the given Markov chain, the system outage probability is calculated as

$$\mathcal{OP} = \mathcal{O}_{\rm SR}\Pr\{l = 0\} + \mathcal{O}_{\rm RD}\Pr\{l = L\} + \mathcal{O}_{\rm SR}\mathcal{O}_{\rm RD}(1 - \Pr\{l = 0\} - \Pr\{l = L\}), \quad (13)$$

where $\Pr\{l = 0\}$ and $\Pr\{l = L\}$ are the probabilities of the events that the buffer is empty and full, respectively. To derive $\mathcal{OP}$ of the system in (13), we define a state transition matrix $\mathbf{A}$ with size of $(L + 1) \times (L + 1)$ of the Markov chain, where $\mathbf{A}_{ij}$ denotes the element of the ith row and jth column of the matrix $\mathbf{A}$ which refers to the probability of moving from state i at time t to state j at time $t + 1$, i.e.,

$$\mathbf{A}_{ij} = \Pr\{l_{t+1} = j | l_t = i\}. \quad (14)$$

For the case of $L = 5$, matrix $\mathbf{A}$ is expressed as follows

$$\mathbf{A} = \begin{pmatrix} \mathcal{O}_{\mathrm{SR}} & \bar{\mathcal{O}}_{\mathrm{SR}} & 0 & 0 & 0 & 0 \\ \mathcal{O}_{\mathrm{SR}}\bar{\mathcal{O}}_{\mathrm{RD}} & \mathcal{O}_{\mathrm{SR}}\mathcal{O}_{\mathrm{RD}} & \bar{\mathcal{O}}_{\mathrm{SR}} & 0 & 0 & 0 \\ 0 & \bar{\mathcal{O}}_{\mathrm{RD}} & \mathcal{O}_{\mathrm{SR}}\mathcal{O}_{\mathrm{RD}} & \bar{\mathcal{O}}_{\mathrm{SR}}\mathcal{O}_{\mathrm{RD}} & 0 & 0 \\ 0 & 0 & \bar{\mathcal{O}}_{\mathrm{RD}} & \mathcal{O}_{\mathrm{SR}}\mathcal{O}_{\mathrm{RD}} & \bar{\mathcal{O}}_{\mathrm{SR}}\mathcal{O}_{\mathrm{RD}} & 0 \\ 0 & 0 & 0 & \bar{\mathcal{O}}_{\mathrm{RD}} & \mathcal{O}_{\mathrm{SR}}\mathcal{O}_{\mathrm{RD}} & \bar{\mathcal{O}}_{\mathrm{SR}}\mathcal{O}_{\mathrm{RD}} \\ 0 & 0 & 0 & 0 & \bar{\mathcal{O}}_{\mathrm{RD}} & \mathcal{O}_{\mathrm{RD}} \end{pmatrix}. \quad (15)$$

Note that matrix $\mathbf{A}$ is asymmetric because the states are not symmetric and the number of links to other states is not the same, leading to different transition probabilities. The stationary distribution $\boldsymbol{\pi}$ of the Markov chain is expressed as

$$\boldsymbol{\pi} = (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1}\mathbf{b}, \quad (16)$$

where $\mathbf{I}$ is an identity matrix, $\mathbf{B}$ is an $(L+1) \times (L+1)$ matrix with all elements equal to 1, and $\mathbf{b} = [1\ 1\ ...\ 1]^T$.

Theorem 3. *With the buffer-aided relaying, the outage probability of the downlink SWIPT-NOMA relay system is given by*

$$\mathcal{OP} = \sum_{i=1}^{L+1} \boldsymbol{\pi}_i \mathbf{A}_{ii}. \quad (17)$$

To determine the state transit matrix $\mathbf{A}$, we need to derive $\mathcal{O}_{\mathrm{SR}}$ and $\mathcal{O}_{\mathrm{RD}}$. We assume that the minimum data transmission rate of the link from $\mathrm{S} \rightarrow \mathrm{R}$ is r_0, then the outage probability of the link $\mathrm{S} \rightarrow \mathrm{R}$ can be defined as follows

$$\mathcal{O}_{\mathrm{SR}} = \Pr\left(\frac{1-\alpha}{2}\log_2(1+\gamma_{\mathrm{R}}) < r_0\right) = 1 - \exp\left(-\frac{\gamma_{\mathrm{th}}}{\Omega_{\mathrm{SR}} P_{\mathrm{S}}}\right).$$

Based on the SIC principle, if D_1 is able to remove x_2 from its received signal, the outage probability of the link $\mathrm{R} \rightarrow \mathrm{D}_i$ is given by

$$\mathcal{O}_{\mathrm{RD}} = \Pr\left(\frac{1-\alpha}{2}\log_2\left(1+\max\left\{\gamma_{\mathrm{D}_1}^{x_1}, \gamma_{\mathrm{D}_2}^{x_2}\right\}\right) < r_0\right). \quad (18)$$

After some mathematical manipulations, we obtain

$$\mathcal{O}_{\mathrm{RD}} = 1 - \sqrt{\frac{4\mathcal{A}}{\Omega_{\mathrm{SR}}}}\mathcal{K}_1\left(\sqrt{\frac{4\mathcal{A}}{\Omega_{\mathrm{SR}}}}\right) - \sqrt{\frac{4\mathcal{B}}{\Omega_{\mathrm{SR}}}}\mathcal{K}_1\left(\sqrt{\frac{4\mathcal{B}}{\Omega_{\mathrm{SR}}}}\right) + \sqrt{\frac{4\mathcal{C}}{\Omega_{\mathrm{SR}}}}\mathcal{K}_1\left(\sqrt{\frac{4\mathcal{C}}{\Omega_{\mathrm{SR}}}}\right), \quad (19)$$

where $\mathcal{A} = \frac{\gamma_{\mathrm{th}}}{\Omega_{\mathrm{RD}_1} a_1 \phi P_{\mathrm{S}}}$ and $\mathcal{B} = \frac{\gamma_{\mathrm{th}}}{\Omega_{\mathrm{RD}_2} \phi P_{\mathrm{S}}(1-a_1(1+\gamma_{\mathrm{th}}))}$ with $\mathcal{C} = \mathcal{A} + \mathcal{B}$ and $\mathcal{K}_1(\cdot)$ is the first-order modified Bessel function of the second kind.

5 Numerical Results

In this section, numerical results are analyzed to illustrate the outage performance of the downlink SWIPT-NOMA relay system. For comparison, we also provide the performance of the SWIPT-OMA relay system with the same parameters. Configurations and parameters of the systems are explained as follows. D_1 is closer to R than D_2. The power allocation coefficient for D_1 is fixed at $a_1 = 0.3$ and that for D_2 is $1 - a_1$. The energy harvesting fraction is $\alpha = 0.3$ and the energy conversion efficiency is $\eta = 0.95$. The system data rate is $r_1 = 1$ and $r_2 = r_0 = 0.5$ [b/s/Hz].

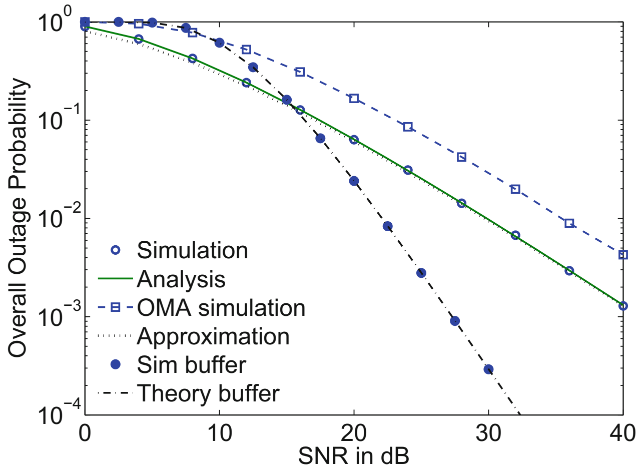

Fig. 3. Overall outage probability versus average SNRs for the case with buffer and without buffer-aided relay.

Figure 3 illustrates the overall outage probability versus the average transmit power of S in two cases, i.e., with and without buffer aided relay. As observed from the figure, the system with buffer-aided relay outperforms that without buffer-aided relay significantly. The outage curves clearly show that the system with a buffer-aided relay achieves diversity order 2 while that without a buffer-aided relay only diversity 1. Furthermore, the approximated results obtained using (10) match well with those using the exact calculation in (9), especially at the high SNR region. Therefore, the approximation in (10) can be used for convenient calculation of OOP. We can also see that the outage performance of the NOMA system is much better than that of the OMA system.

Figure 4 compares the overall outage probability of the system and the outage probability of D_1 and D_2, respectively. We can see that the outage performance of D_1 is better than D_2. This is because the distance from R to D_2 is longer than that from R to D_1 [18]. The overall outage probability is calculated from the probability of the event that both D_1 and D_2 cannot decode their symbols

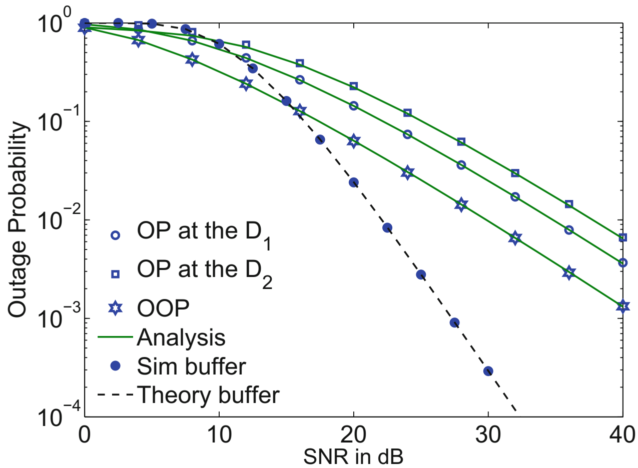

Fig. 4. Outage probability versus the SNR with optimal power allocation for the case with buffer and without buffer-aided relay.

successfully. It can be seen that the simulation and analytical results agree well with each other, which validates the correctness of the closed-form expression of (9), (11) and (12). From Fig. 4, we can observe that the joint outage of D_1 and D_2 are less than the individual outage of each D_1 and D_2. This is relevant since in practice the probability that both D_1 and D_2 in outage is always less than the probability that D_1 or D_2 is in outage.

We plot in Fig. 5 the average packet delay of the SWIPT-OMA relay system. The figure shows that in the high SNR region the average packet delay equal 4 packets. This delay is acceptable when considering the fairness of the outage performance. As a result, depending on the specific requirement of the system we can choose to the relay node with or without the buffer-aid. More specifically, when the system requires better performance, the buffer-aided relay node is used, otherwise, it can use a relay without buffer if the destination node needs to maintain low delay reception. Figure 6 depicts the effect of the power allocation on the outage probability. In order to get the results we derived the coefficient for D_2, the coefficient for D_1 is then given by $1-a_1$. As shown in the figure different data rates, r_2, exhibit different minimum values of the outage probability. We can see from the figure that when the transmission rate r_2 reduces, the power allocation coefficient for D_2 also decreases to get better system performance for the fairness of D_1 and D_2.

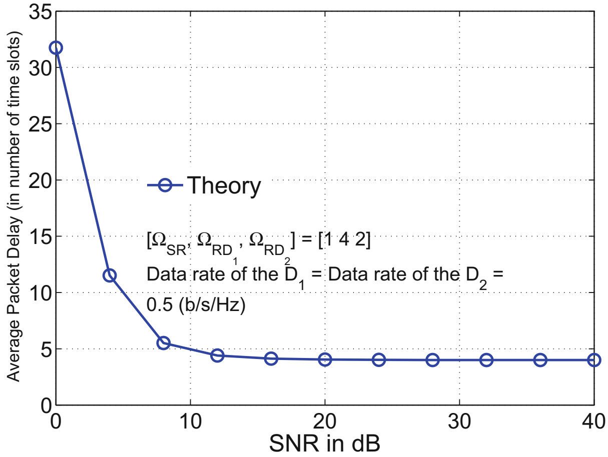

Fig. 5. The average packet delay versus SNR.

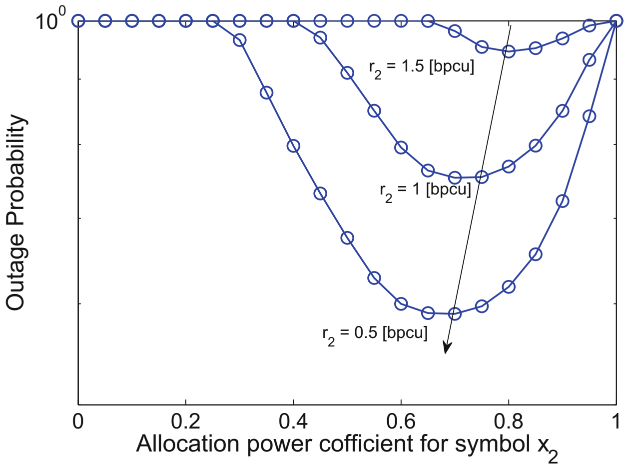

Fig. 6. Effect of power allocation on the outage probability for different data rates; $E_b/N_0 = 10\,\text{dB}$.

6 Conclusion

In this paper, we investigated performance of a downlink NOMA-SWIPT relay system under the assumption that the relay is equipped and not equipped with a buffer for storing data if transmission links are in outage. We derived closed-form expressions for the exact and approximated outage probability of the system. We showed that using a buffer at the relay can increase the outage performance of the system significantly while keeping the incurred delay at an acceptable level. The system then can choose whether to use the buffer at the relay depending on the application requirement. Due to the incurred delay the system is more suitable for delay non-sensitive applications.

References

1. Wang, Y., Ren, B., Sun, S., Kang, S., Yue, X.: Analysis of non-orthogonal multiple access for 5G. China Commun. **13**(Suppl. 2), 52–66 (2016)
2. Dai, L., Wang, B., Yuan, Y., Han, S., Chih-Lin, I., Wang, Z.: Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends. IEEE Commun. Mag. **53**(9), 74–81 (2015)
3. Yang, Z., Ding, Z., Fan, P., Al-Dhahir, N.: The impact of power allocation on cooperative non-orthogonal multiple access networks with SWIPT. IEEE Trans. Wirel. Commun. **16**(7), 4332–4343 (2017)
4. Kader, M.F., Shahab, M.B., Shin, S.-Y.: Exploiting non-orthogonal multiple access in cooperative relay sharing. IEEE Commun. Lett. **21**(5), 1159–1162 (2017)
5. Luo, S., Teh, K.C.: Adaptive transmission for cooperative NOMA system with buffer-aided relaying. IEEE Commun. Lett. **21**(4), 937–940 (2017)
6. Du, C., Chen, X., Lei, L.: Energy-efficient optimisation for secrecy wireless information and power transfer in massive MIMO relaying systems. IET Commun. **11**(1), 10–16 (2017)
7. Varshney, L.R.: Transporting information and energy simultaneously. In: 2008 IEEE International Symposium on Information Theory (ISIT), pp. 1612–1616, July 2008
8. Ashraf, M., Shahid, A., Jang, J.W., Lee, K.-G.: Energy harvesting non-orthogonal multiple access system with multi-antenna relay and base station. IEEE Access **5**, 17660–17670 (2017)
9. Han, W., Ge, J., Men, J.: Performance analysis for NOMA energy harvesting relaying networks with transmit antenna selection and maximal-ratio combining over Nakagami-m fading. IET Commun. **10**(18), 2687–2693 (2016)
10. Liu, Y., Ding, Z., Elkashlan, M., Poor, H.V.: Cooperative non-orthogonal multiple access with simultaneous wireless information and power transfer. IEEE J. Sel. Areas Commun. **34**(4), 938–953 (2016)
11. Luo, S., Yang, G., Teh, K.C.: Throughput of wireless-powered relaying systems with buffer-aided hybrid relay. IEEE Trans. Commun. **15**(7), 4790–4801 (2016)
12. Ju, H., Zhang, R.: Throughput maximization in wireless powered communication networks. IEEE Trans. Wirel. Commun. **13**(1), 418–428 (2014)
13. Benjebbour, A., Saito, K., Li, A., Kishiyama, Y., Nakamura, T.: Non-orthogonal multiple access (NOMA): concept and design. In: Signal Processing for 5G: Algorithms and Implementations, pp. 143–168, August 2016
14. Luo, S., Teh, K.C., Wang, W.: Wireless-powered cooperative communications with buffer-aided relay. In: Proceedings of 2016 International Conference on Communications (ICC), pp. 1–6. IEEE, May 2016
15. Michalopoulos, D.S., Suraweera, H.A., Schober, R.: Relay selection for simultaneous information transmission and wireless energy transfer: a tradeoff perspective. IEEE J. Sel. Areas Commun. **33**(8), 1578–1594 (2015)
16. Pedersen, K.I., Kolding, T.E., Seskar, I., Holtzman, J.M.: Practical implementation of successive interference cancellation in DS/CDMA systems. In: 5th IEEE International Conference on Universal Personal Communications, vol. 1, pp. 321–325. IEEE (1996)

17. Zwillinger, D.: Table of Integrals, Series, and Products. Elsevier, Amsterdam (2014)
18. Lu, X., Wang, P., Niyato, D., Kim, D.I., Han, Z.: Wireless networks with RF energy harvesting: a contemporary survey. IEEE Commun. Tutor. **17**(2), 757–789 (2015)