Coordinated Direct and Relayed Transmission based on NOMA and Backscattering

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Abstract

We propose a spectral-efficient coordinated direct and relayed transmission (CDRT) scheme for a relay-assisted downlink system with two users. The proposed scheme is based on backscatter communication (BC) and non-orthogonal multiple access (NOMA) technique. With the proposed BC-NOMA-CDRT scheme, both users can receive one packet within one time slot. In contrast, in existing NOMA-CDRT schemes, the far user is only able to receive one packet in two time slots due to the half-duplex operation of the relay. We investigate the outage of the BC-NOMA-CDRT scheme, and derive the outage probability expressions in closed-form based on Gamma distribution approximation and Gaussian approximation. Numerical results show that the analytical results are accurate and the BC-NOMA-CDRT scheme outperforms the conventional NOMA-CDRT significantly.

Keywords: Backscatter communication, coordinated direct and relayed transmission, NOMA

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1. Introduction

Non-orthogonal multipleaccess (NOMA) is a promising multiple access technique to improve the spectral efficiency of cellular networks [1]-[3]. There are two different types of NOMA systems, i.e., power-domain NOMA and code-domain NOMA. In a power-domain NOMA system, multiple users share the same radio resources by using superposition coding and successive interference cancellation (SIC) techniques.

Recently, NOMA is combined with cooperative communication to improve the transmission reliability of wireless cooperative communication systems[4]-[7]. The main idea of cooperative NOMA is that the user with better link quality was selected as a relay to help the weak user. Cooperative NOMA for downlink transmission was first proposed in [4], where the strong user forwards decoded signals to the weak user to improve the outage and sum-rate performance. Later, cooperative NOMA was extended to uplink [5] and full-duplex systems [6]. Experiment results in [7] and [8] showed that cooperative NOMA can achieve a 30% throughput gain as compared with conventional non-cooperative NOMA systems.

In all these aforementioned works [4]-[7], it was assumed that directlink exists for each user. In some cases, it is possible that the user with a far distance can not communicate with the BS directly due to deep fading or blocking, i.e., the directlink doesn't exits. For such system, a dedicated relay can be employed to help the far user (indirect link user). Such NOMA-based coordinated direct and relayed transmission (CDRT) systems have attracted a lot of research attention in recent years [9][10]. In NOMA-CDRT, the BS sends power-domain superposition coded signals to the near user and the relay in the first phase. The BS sends an additional signal to the near user while the relay forwards signal to the far user in the second phase [9].

Afterwards, NOMA-CDRT was further extended to more sophisticated scenarios, e.g., full-duplex relay networks [10], simultaneous wireless information and power transfer (SWIPT)-assisted NOMA networks [11], multi-relay networks [12], buffer-aided NOMA networks [13], and user cooperative NOMA systems [14][15]. These studies revealed that the performance of NOMA-CDRT highly depends on the directlink between the BS and the near user. This is beacause the near user can only receive signals from the BS. Once the near user's channel experiences a deep fading, the near user may fail to decode its own signal and the far user's signal, which will be used as side information for interference cancellation in the second phase. As a result, the communication from the BS to the near user in the second phase will fail as well.

Recently, backscatter communications (BC) has been proposed to improve energy efficiency for low-power wireless communications [16][17]. In [18] and [19], the authors utilized the backscatter technique to enhance the reliability of wireless transmissions. In these approaches, idle nodes in wireless networks backscatter the received signal to the receiver node to improve the reception. It was shown that additional diversity gain can be achieved and the throughput can be improved with efficient energy beamforming and signal backscattering [18][19].

To enhance the performance of NOMA-CDRT systems,we incorporate the backscatter communication technique into NOMA-CDRT systems in this work. The proposed scheme, which is referred to as BC-NOMA-CDRT, is able to enhance the signal reception at both the far user and near user. In BC-NOMA-CDRT, the relays directly backscatter the received signals from the BS toimprove the reception at the two users. As a result, a new signalpath, i.e, from the BS to the near user via the relay, is constructed. Also, the far user is able to receive signal immediately via relay backscattering.

The main contributions of the paper are summarized as follows.

- A new NOMA and BC-based CDRT scheme BC-NOMA-CDRT is proposed,in which both the far user and the near user can receive one packet from the transmitter in one time slot. In contrast, in all these existing NOMA-CDRT schemes [9][10][13]–[15], the far user is only able to receive one packet in two time slots due to the half-duplex relaying.
- We study the outage performance of BC-NOMA-CDRT and derive closed-form expressions. Specifically, we analyze the outage performance of the near user based on Gamma distribution approximation. While forthe far user, the closed-form outage expression is derived based on Gaussian distribution approximation.
- Simulation results demonstrate that the analyzed results are accurate in most cases, and it is also shown that the proposed BC-NOMA-CDRT scheme outperforms existing NOMA-CDRT schemes.

2. System Model

Consider a downlink NOMA-CDRT system with two users U_1 and U_2 as shown in **Fig. 1**, where the far user U_2 can not communicate with the BS as no direct link exists between the BS and U_2. K relays, R_1,...,R_K, are deployed to assist the downlink transmission. Note that these relays can be fixed relay stations or idle users in the system. For such a downlink NOMA-CDRT system, two slots are required for each round of transmission in these existing half-duplex NOMA-CDRT schemes [9][11][12]. In contrast, both the directlink user U_1 and the indirect link user U_2 are able to receive one data packet within one time slot in the proposed scheme.

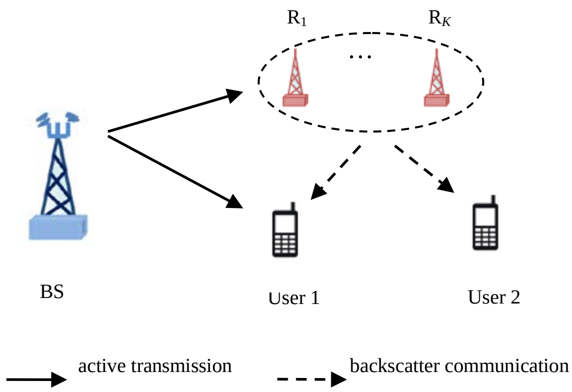

Fig. 1. The BC-NOMA-CDRT scheme.

2.1 Signal Transmission

The transmit signal of the BS is

$$x_{B,1} = \sqrt{\alpha_1 P_B} s_{B,1} + \sqrt{\alpha_2 P_B} s_{B,2}, \tag{1}$$

where $s_{B,m}$ is intended for user $U_m, m = 1,2$, α_1 and α_2 are power allocation factors with $\alpha_1 < \alpha_2$ and $\alpha_1 + \alpha_2 = 1$. P_B is the BS's transmit power.

At each relay node, by adjusting it's load impedance, the relay backscatters the signals to user U_1 and U_2 immediately. let η_k denote the backscatter coefficient at relay $R_k, k = 1, \ldots, K$. Then, user U_1's received signal is

$$\begin{aligned} y_{U,1} &= h_{BU_1} x_{B,1} + \sum_{k=1}^{K} \eta_k h_{BR_k} h_{R_k U_1} x_{B,1} + n_{U,1} \\ &= h_1 (\sqrt{\alpha_1 P_B} s_{B,1} + \sqrt{\alpha_2 P_B} s_{B,2}) + n_{U,1}, \end{aligned} \tag{2}$$

where $h_{R_k U_1}$ denotes the channel between relay R_k and U_1,$n_{U,1} \sim CN(0, \sigma^2)$ is the additive white Gaussian noise (AWGN), and h_1 is defined as

$$h_1 = h_{BU_1} + \sum_{k=1}^{K} \eta_k h_{BR_k} h_{R_k U_1}. \tag{3}$$

In case of perfect channel state information (CSI), each relay adjusts its backscattering coefficient η_k to make sure that the backscattered signal is aligned with the directlink signal. In other words, we choose $\eta_k = e^{j\theta_k}$, where $\theta_k = \angle h_{BU_1} - \angle h_{BR_k} h_{R_k U_1}$, such that $|h_1| = |h_{BU_1} + \sum_{k=1}^{K} \eta_k h_{BR_k} h_{R_k U_1}| = |h_{BU_1}| + \sum_{k=1}^{K} |h_{BR_k}||h_{R_k U_1}|$.

2.2 Signal Detection

User U_1 decodes $s_{B,1}$ after decoding $s_{B,2}$ with the SIC technique. The detection SINR for $s_{B,2}$ and $s_{B,1}$ are given by

$$\gamma_{1,2} = \frac{\alpha_2 P_B |h_1|^2}{\alpha_1 P_B |h_1|^2 + \sigma^2}, \tag{4}$$

and

$$\gamma_1 = \frac{\alpha_1 P_B |h_1|^2}{\sigma^2}, \tag{5}$$

respectively.

U_2 receives signals backscattered by the relays, which is given by

$$y_{U,2} = \sum_{k=1}^{K} \eta_k h_{BR_k} g_{R_k U_2} (\sqrt{\alpha_1 P_B} s_{B,1} + \sqrt{\alpha_2 P_B} s_{B,2}) + n_{U,2}, \tag{6}$$

where $g_{R_k U_2}$ denotes the channel between relay R_k and the far user U_2. From (6), by treating $s_{B,1}$ as interference, user U_2 is able to detect $s_{B,2}$ from $y_{U,2}$. The corresponding detecting SINR is given by

$$\gamma_2 = \frac{\alpha_2 P_B |h_2|^2}{\alpha_1 P_B |h_2|^2 + \sigma^2}, \tag{7}$$

where

$$h_2 = \sum_{k=1}^{K} \eta_k h_{BR_k} g_{R_k U_2}. \tag{8}$$

3. Performance Analysis

In this section, we first derive the approximate outage probabilities for the two users using Gamma distribution approximation and Gaussian approximation. Then, closed-form expressions are derived for both users in the high SNR region.

3.1 The Near User

3.1.1 Gamma Distribution Approximation

Let us define $\xi_k = |h_{BR_k} h_{R_k U_1}|$ and $\xi = \sum_{k=1}^{K} |h_{BR_k}||h_{R_k U_1}| = \sum_{k=1}^{K} \xi_k$. Then, the equivalent channel h_1 in (3) for user U_1 can be expressed as

$$h_1 = h_{BU_1} + \xi. \tag{9}$$

Note that the PDF of $\xi_k = |h_{BR_k} h_{R_k U_1}|$ is given by [20]

$$f_{\xi_k}(x) = \frac{4x}{G_{BR_k} G_{R_k U_1}} Y_0\left(\frac{2x}{\sqrt{G_{BR_k} G_{R_k U_1}}}\right), \tag{10}$$

where $Y_n(x)$ is the modified Bessel function of the second kind with order n. $G_{BR_k} = E\left(|h_{BR_k}|^2\right)$, and $G_{R_k U_1} = E\left(|h_{R_k U_1}|^2\right)$. The mean and the variance of ξ_k are given by [23, eq.(6.561.16)],

$$\begin{aligned} \mu_{\xi_k} &= \mathbb{E}(\xi_k) = \int_0^\infty x f_{\xi_k}(x) dx \\ &= \frac{\pi}{4}\sqrt{G_{BR_k} G_{R_k U_1}}, \end{aligned} \tag{11}$$

and

$$\begin{aligned} \sigma_{\xi_k}^2 &= \mathbb{E}\left(|\xi_k - \mu_{\xi_k}|^2\right) \\ &= \int_0^\infty (x - \mu_{\xi_k})^2 f_{\xi_k}(x) dx \\ &= \left(1 - \frac{\pi^2}{16}\right) G_{BR_k} G_{R_k U_1}, \end{aligned} \tag{12}$$

respectively.

Unfortunately, the exact PDF of $\xi = \sum_{k=1}^{K} \xi_k$ is analytically intractable. However, ξ can be approximately distributed as Gamma distribution. The PDF of ξ can be approximated by [22]

$$f_\xi(y) = \frac{\beta^\alpha}{\Gamma(\alpha)} y^{\alpha-1} e^{-\beta y}, \tag{13}$$

where

$$\alpha = \frac{\mu_\xi^2}{\sigma_\xi^2}, \tag{14}$$

and

$$\beta = \frac{\mu_\xi}{\sigma_\xi^2}. \tag{15}$$

Here, μ_ξ and σ_ξ^2 denote the mean and variance of ξ. As $\xi_k, k = 1, \ldots, K$, are independently distributed, the mean and the variance of $\xi = \sum_{k=1}^{K} \xi_k$ are given by

$$\begin{aligned} \mu_\xi &= \sum_{k=1}^{K} \mu_{\xi_k} \\ &= \sum_{k=1}^{K} \frac{\pi}{4}\sqrt{G_{BR_k} G_{R_k U_1}}, \end{aligned} \tag{16}$$

and

$$\begin{aligned} \sigma_\xi^2 &= \sum_{k=1}^{K} \sigma_{\xi_k}^2 \\ &= \sum_{k=1}^{K} \left(1 - \frac{\pi^2}{16}\right) G_{BR_k} G_{R_k U_1}, \end{aligned} \tag{17}$$

respectively.

3.1.2 The Outage Probability of U_1

Based on the Gamma approximation in (13), we are now able to derive the outage probability of U_1. Note that $|h_1| = |h_{BU_1}| + \xi$ for perfect backscattering, and $|h_{BU_1}|$ and ξ are independent. Hence, the PDF of $|h_1|$ is the convolution of $f_{|h_{BU_1}|}(x)$ and $f_\xi(y)$:

$$f_{|h_1|}(x) = \int_{-\infty}^{+\infty} f_{|h_{BU_1}|}(x-y) f_\xi(y) dy. \tag{18}$$

Let $\gamma_{th,1}$ be the threshold SINR for the near user. Then, the outage probability of U_1 can be calculated by

$$\begin{aligned} P_{out,1} &= \Pr(\gamma_1 < \gamma_{th,1}) \\ &= \Pr\left(|h_1| < \sqrt{\gamma_{th,1}/\alpha_1 \rho_B}\right) \\ &= \int_0^{c_1} f_{|h_1|}(x) dx \end{aligned} \tag{19}$$

where $c_1 = \sqrt{\gamma_{th,1}/\alpha_1 \rho_B}$ and $\rho_B = \frac{P_B}{\sigma^2}$, and $f_{|h_1|}(x)$ is given in (18).

3.1.3The Closed-form Asymptotic Outage Probability of U_1

From (18) and (19), $P_{out,1}$ for user U_1 can be calculated as

$$P_{out,1} = \int_0^{c_1} \int_0^{c_1 - y} f_{|h_{BU_1}|}(x) dx f_\xi(y) dy \tag{20}$$

where $f_{|h_{BU_1}|}(x) = \frac{2x}{G_{BU_1}} e^{-\frac{x^2}{G_{BU_1}}}$ is the PDF of $|h_{BU_1}|$. Substituting $f_{|h_{BU_1}|}(x)$ into (20), we have

$$P_{out,1} = \int_0^{c_1} \int_0^{c_1 - y} \frac{2x}{G_{BU_1}} e^{-\frac{x^2}{G_{BU_1}}} dx f_\xi(y) dy$$

$$\begin{aligned}
&= \int_0^{c_1} \left(1 - e^{-\frac{(c_1-y)^2}{G_{BU_1}}}\right) f_\xi(y)dy \\
&\simeq \int_0^{c_1} \frac{(c_1-y)^2}{G_{BU_1}} f_\xi(y)dy \\
&= \frac{\beta^\alpha}{\Gamma(\alpha)G_{BU_1}} \int_0^{c_1} (c_1-y)^2 y^{\alpha-1} e^{-\beta y} dy \\
&= \frac{1}{\beta^2\Gamma(\alpha)G_{BU_1}} [\beta^2 c_1^2 \gamma(\alpha,\beta c_1) \\
&-2\beta c_1 \gamma(\alpha+1,\beta c_1) + \gamma(\alpha+2,\beta c_1)],
\end{aligned} \tag{21}$$

where we have used the approximation that $1 - e^{-\frac{(c_1-y)^2}{G_{BU_1}}} \simeq \frac{(c_1-y)^2}{G_{BU_1}}$ in the high SNR region in the third step. $\gamma(s,x) = \int_0^x t^{s-1}e^{-t}dt$ is the incomplete gamma function.

Using the recurrence relation that $\gamma(s+1,x) = s\gamma(s,x) - x^s e^{-x}$, we have

$$\gamma(\alpha+1,\beta c_1) = \alpha\gamma(\alpha,\beta c_1) - (\beta c_1)^\alpha e^{-\beta c_1}, \tag{22}$$

and

$$\begin{aligned}
\gamma(\alpha+2,\beta c_1) \quad &= \alpha(\alpha+1)\gamma(\alpha,\beta c_1) \\
&-[(\beta c_1)^{\alpha+1} + (\alpha+1)(\beta c_1)^\alpha]e^{-\beta c_1}.
\end{aligned} \tag{23}$$

Substituting (22) and (23) into (21), $P_{out,1}$ for U_1 can be expressed as

$$P_{out,1} = \frac{(\beta c_1-\alpha)^2+\alpha}{\beta^2\Gamma(\alpha)G_{BU_1}} \gamma(\alpha,\beta c_1) + \theta_1, \tag{24}$$

where $\theta_1 = \frac{(\beta c_1-\alpha-1)(\beta c_1)^\alpha e^{-\beta c_1}}{\beta^2\Gamma(\alpha)G_{BU_1}}$.

3.2 The Far User

3.2.1The Outage Probability of U_2

For the far user, h_2 in (8) is a sum of K complex-valued random variables. For large K, based on the central limit theorem, the variable h_2 can be approximated as a zero mean Gaussian random variable with a variance of $\sigma_2^2 = \sum_{k=1}^K G_{BR_k}G_{R_kU_2}$.

Let $\gamma_{th,2}$ denotes the target SINR for user U_2. Then, the outage probability of user U_2 is given by

$$\begin{aligned}
P_{out,2} \quad &= \Pr(\min(\gamma_{1,2},\gamma_2) < \gamma_{th,2}) \\
&= 1 - \Pr(\min(\gamma_{1,2},\gamma_2) \geq \gamma_{th,2}) \\
&= 1 - \Pr(|h_1|^2 \geq c_2^2) \times \Pr(|h_2|^2 \geq c_2^2) \\
&= 1 - e^{-c_2^2/\sigma_2^2} \int_{\sqrt{c_2}}^{+\infty} f_{|h_1|}(x)dx,
\end{aligned} \tag{25}$$

where $c_2 = \sqrt{\gamma_{th,2}/(\alpha_2 - \alpha_1\gamma_{th,2})\rho_B}$, and $f_{|h_1|}(x)$ is given in (18).

3.2.2 The Closed-form Asymptotic Outage Probability of U_2

To obtain a closed-form expression, we use the same approach as that for the near user U_1. Note that the term $\Pr(|h_1|^2 \geq c_2)$ in (25) can be approximated as

$$\begin{aligned}\Pr(|h_1|^2 \geq c_2) &= 1 - \Pr(|h_1|^2 < c_2^2)\\ &= 1 - \Pr(|h_{BU_1}| + \xi < c_2)\\ &= 1 - \int_0^{c_2} \int_0^{c_2 - y} f_{|h_{BU_1}|}(x) dx f_\xi(y) dy\\ &\simeq 1 - \frac{(\beta c_2 - \alpha)^2 + \alpha}{\beta^2 \Gamma(\alpha) G_{BU_1}} \gamma(\alpha, \beta c_2) - \theta_2,\end{aligned} \tag{26}$$

where $\theta_2 = \frac{(\beta c_2 - \alpha - 1)(\beta c_2)^\alpha e^{-\beta c_2}}{\beta^2 \Gamma(\alpha) G_{BU_1}}$.

With (26), the outage probability for U_2 can be approximated by

$$P_{out,2} \simeq 1 - e^{-c_2^2/\sigma_2^2}\left[1 - \frac{(\beta c_2 - \alpha)^2 + \alpha}{\beta^2 \Gamma(\alpha) G_{BU_1}} \gamma(\alpha, \beta c_2) - \theta_2\right]. \tag{27}$$

4. Simulation Results

During simulation, we compare the proposed BC-NOMA-CDRT scheme with the conventional 2-slot NOMA-CDRT scheme [9] and 3-slot TDMA-based orthogonal relaying scheme to show the performance gain. The channels are independently Rayleigh distributed. For both NOMA-CDRT and TDMA-based schemes, the transmit power of each relay is 10 dB less than that of the BS. The target rates and other parameters are given in Table 1, and the corresponding target SINRs are $\gamma_{th,k} = 2^{R_k} - 1, k = 1,2$.

Table 1. Experimental Parameters

Parameters	Values
Direct channel gains	$G_{BU_1} = G_{BR_k} = 1, \forall k$
Backscattered channel gains	$G_{R_k U_1} = G_{R_k U_2} = 0.1, \forall k$
Power allocation factors	$\alpha_1 = 0.1$ and $\alpha_2 = 0.9$
Target rates	$R_1 = 2$ bps/Hz and $R_2 = 0.5$ bps/Hz

In **Fig. 2**, we plot the outage probabilities of the BC-NOMA-CDRT scheme, where four relays are deployed in the system. We also plot the analyzed outage probabilities in (19) and (25), as well as the closed-form asymptotic outage probabilities in (21) and (27) in the figure. For user 1, we can see that the analyzed outage probability in (19) is accurate in the whole SNR region, and the derived asymptotic result in (21) is also accurate when the SNR is higher than 15 dB. For user U_2, the outage performance analysis is not so accurate as that of user U_1. This is due to the fact that both (25) and (27) are based on Gaussian approximation, which requires a large number of relays according to the central limit theorem.

Fig. 3 compares the outage probabilities of BC-NOMA-CDRT with the conventional NOMA-CDRT scheme and TDMA-based scheme. As shown in the figure, the BC-NOMA-CDRT scheme achieves a much lower outage probability for both U_1 and U_2 .

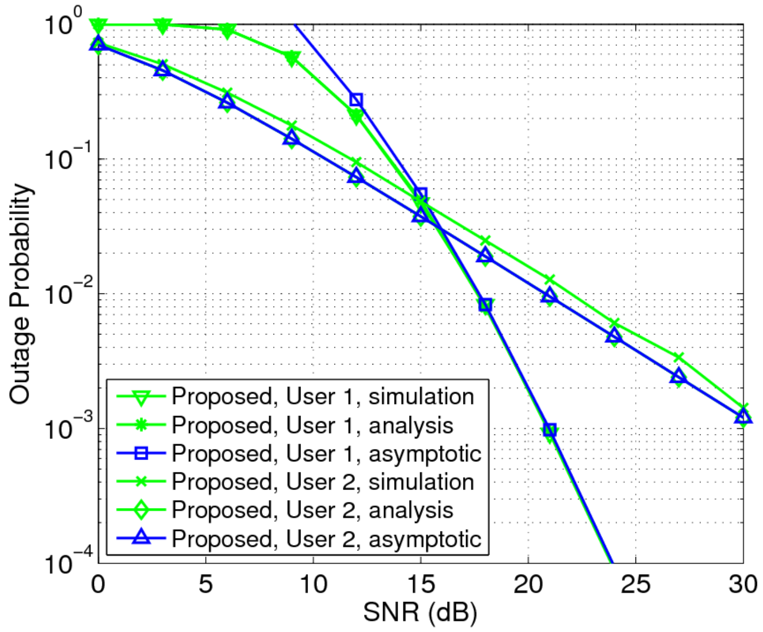

Fig. 2. Outage performance of the BC-NOMA-CDRT scheme.

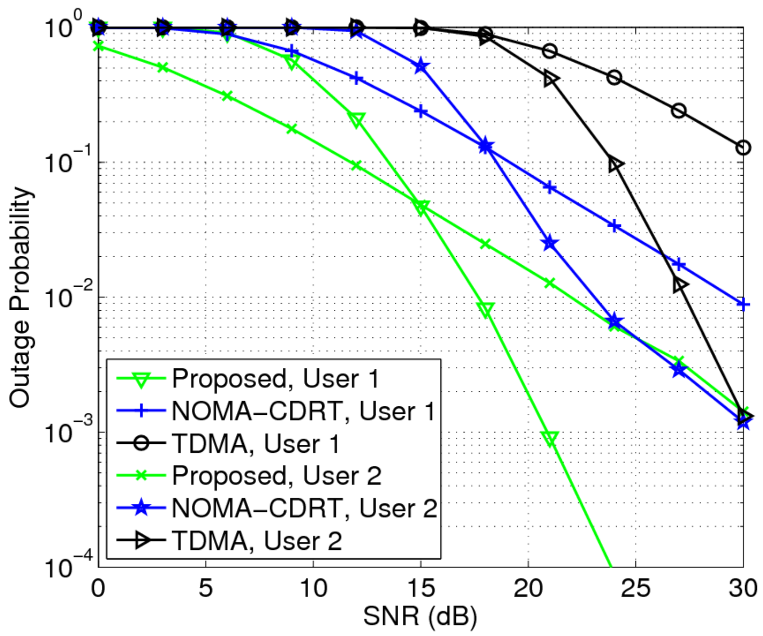

Fig. 3. Outage performance comparison.

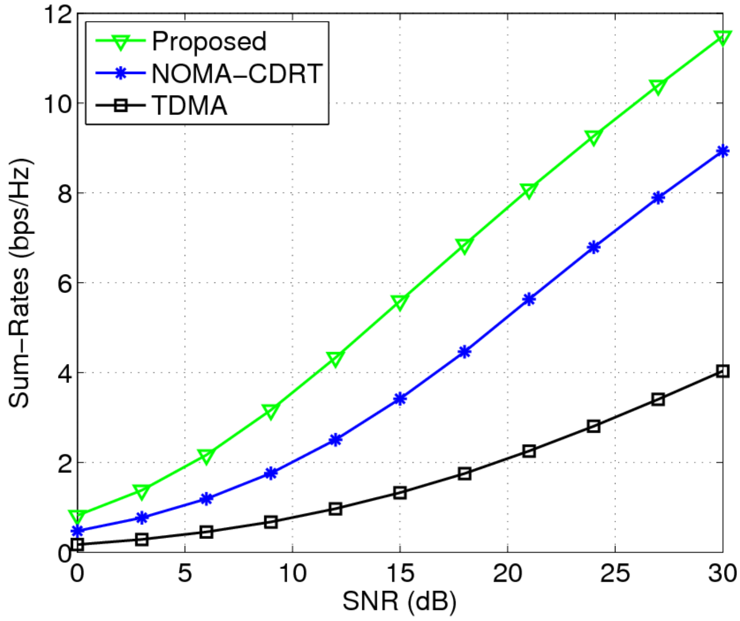

Fig. 4. Sum-rate performance comparison, *K*=4 relays.

Fig. 4 shows the achievable sum-rates, while **Fig. 5** shows the individual data rates of BC-NOMA-CDRT. There are *K*=4 relays in the system. From **Fig. 4**, we see that the proposed scheme outperforms the two counterparts significantly. For example, as compared with the NOMA-CDRT scheme, a sum-rate gain of 50% is obtained when SNR=20 dB as shown in **Fig. 4**.

The outage performance of BC-NOMA-CDRT with different number of relays is plotted in **Fig. 6**, where SNR=20 dB. The other system parameters are listed in **Table 1**. The analyzed exact outage probabilities and asymptotic outage probabilities derived in Section 3 are also shown in the figure. One can see that the analyzed result in (19) and the asymptotic outage probability in (21) for user U_1 are accurate regardless the number of the relays. While for user U_2, the accuracy improves as the number of relays increases. This is reasonable as the Gaussian approximation based on the central limit theorem becomes more accurate when then number of relays becomes large. Compared with the other two schemes, the outage probabilities of BC-NOMA-CDRT decrease rapidly as the number of relays increases. Note that for NOMA-CDRT and TDMA schemes, the outage probability of U_1 is fixed. This is due to the fact that the relay's signal is treated as interference and is completely removed at user U_1 in the NOMA-CDRT scheme. While for TDMA based scheme, the signal transmission/reception of near user U_1 is independent of the relays.

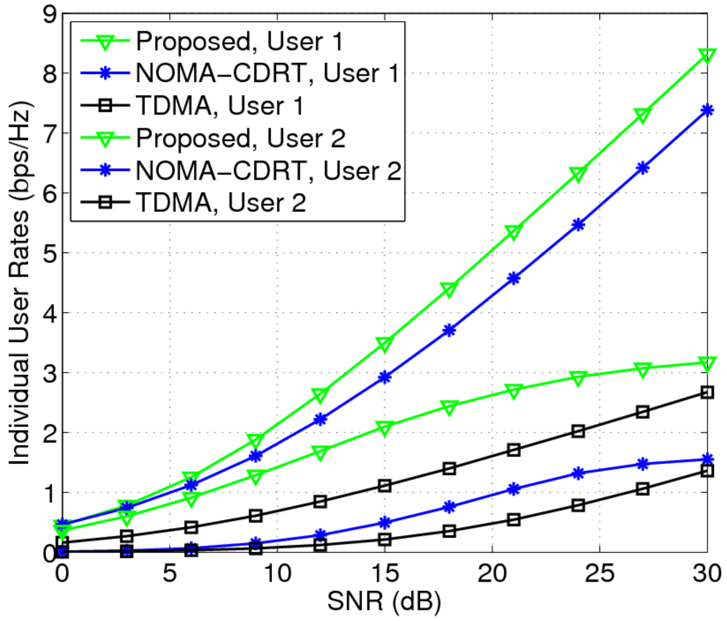

Fig. 5. Individual user rates of the proposed BC-NOMA-CDRT scheme.

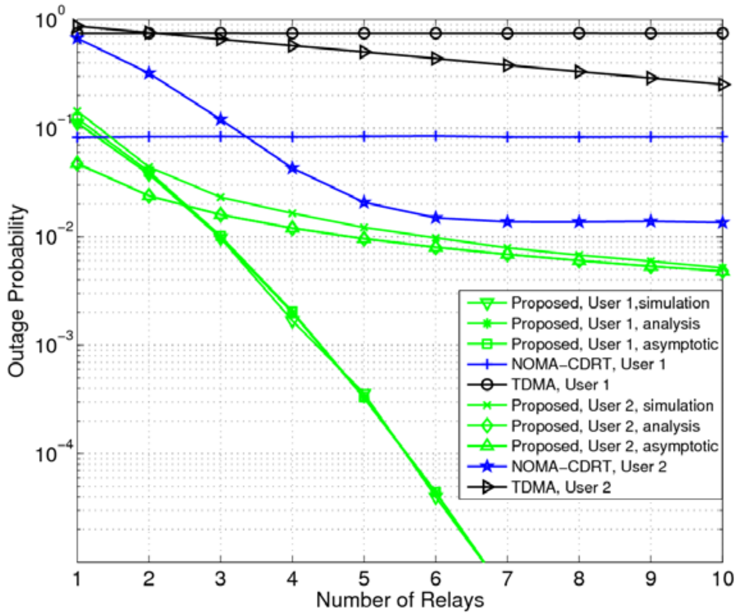

Fig. 6. Outage probability versus the number of relays, SNR = 20dB.

5. Conclusion

This paper proposed an efficient backscatter-based transmission approach BC-NOMA-CDRT for a CDRT system. Based on Gamma distribution approximation and Gaussian approximation, the achievable outage performance is analyzed and closed-form expressions for the approximate outage probabilities in the high SNR region were derived. Numerical results show thatthe analytical results are accurate under certain conditions. Specifically, for the near user, the analyzed outage probability is accurate when the SNR is above 15 dB. While the analyzed outage probability for the far user is accurate when there are more than 6 relays in the system. It is also shown that BC-NOMA-CDRT outperforms the conventional NOMA-CDRT scheme significantly, and more than 3 dB gain was observed in the simulations. The proposed approach can also be applied to NOMA-CDRT system with more than two users, as well as two-way NOMA-CDRT transmissions. The performance of BC-NOMA-CDRT under imperfect channel state information would also be an interesting research direction in the future.

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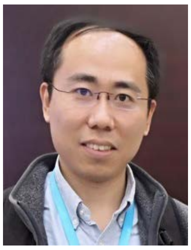

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