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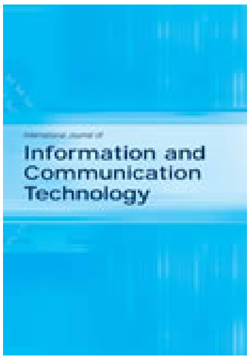

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Cooperative partner selection for coordinated direct and relayed transmission with NOMA and energy pricing

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Abstract: This paper considers a non-orthogonal multiple access (NOMA) and coordinated direct and relayed transmission (CDRT) based wireless network with one near user, one far user, and multiple idle users (potential relays). We propose a joint cooperative partner (relay) selection and power allocation scheme based on energy pricing. We derive the optimal power allocation between the base station (BS) and the active relay in the two-time slots and select the optimal cooperative relay according to minimum cost criteria. Simulation results show that the proposed scheme can extend the network lifetime by more than 50 % compared to other methods in some cases.

Keywords: NOMA; relay selection; power allocation; energy pricing.

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1 Introduction

Non-orthogonal multiple access (NOMA) is a promising technique to enhance multiuser channel capacity in wireless networks (Saito et al., 2013; Dai et al., 2015; Zhou et al., 2018). In NOMA systems, multiple wireless terminal shares the same time-frequency resources and transmit data to the receiver simultaneously. Compared with conventional orthogonal multiple access (OMA) techniques, such as frequency-division multiple access (FDMA) and time-division multiple access (FDMA), NOMA can improve user fairness, promote massive connectivity and increase reliability.

Recently, the NOMA technique has been applied to various wireless networks, such as cooperative communication systems (Ding et al., 2015), wireless relaying networks (Men et al., 2017), unmanned aerial vehicle (UAV) communication networks (Du et al., 2023; Huang et al., 2022), and satellite communication networks (Tegos et al., 2022; Chu et al., 2021). For instance, in Ding et al. (2015), the authors considered a two-user downlink cooperative NOMA system, in which the user with a better channel acts as a relay to help the weak user. It was shown that such a downlink cooperative NOMA scheme can improve the outage and sum-rate performance as compared with conventional OMA and non-cooperative NOMA schemes. Du et al. (2023), the authors proposed a NOMA-based dual-UAV data acquisition algorithm to maximise the minimum data collection rate of UAVs from IoT devices. Their results showed that the proposed scheme can effectively enhance the throughput compared to the benchmark strategies. NOMA has also been efficiently used in land mobile satellite communications to increase link availability, coverage, and reliability (Tegos et al., 2022).

Kim and Lee (2015), the authors proposed a spectral-efficient coordinated direct and relayed transmission (CDRT) scheme for a two-user downlink system. In this CDRT system, the base station (BS) communicates with one direct link user (near user) and one indirect link user (far user). A dedicated relay node was employed to assist the communication between the BS and the indirect link user. In their scheme, the BS sends superposition signals to the near user and the relay in the first phase. In the second phase, the relay forwards the decoded and re-encoded signal to the far user while the BS sends an additional signal to the near user, and the interference caused by the relay can be cancelled at the near user by exploiting the feature of NOMA. Such NOMA-based CDRT system has attracted a lot of research attention in recent years, and was further extended to various networks, including full-duplex relay networks (Zhong and Zhang, 2016), simultaneous wireless information and power transfer (SWIPT)-assisted NOMA networks (Guo et al., 2018), multi-relay networks (Xu et al., 2018), buffer-aided NOMA networks (Choi and Kim, 2018), and user cooperative NOMA systems (Kader and Shin, 2018; Yang et al., 2019).

However, in most of these existing works, the relay nodes are fixed infrastructure, which can lead to increased network construction costs. Instead of dedicated relay nodes, the authors in Yang et al. (2021) proposed a user-assisted CDRT system, where two near users were opportunistically selected from multiple users to serve the far user. A near-user scheduling strategy was also proposed to minimise the outage probabilities. In their work, it was assumed that the cooperative users were selfless and these users forward the far user’s data without considering its own power budget. While in real scenarios, wireless terminals’ energy is a valuable resource and these collaborating users are often selfish. Furthermore, for energy-limited wireless networks such as wireless sensor networks, maximising the network lifetime is more important than optimising the outage or rate performance.

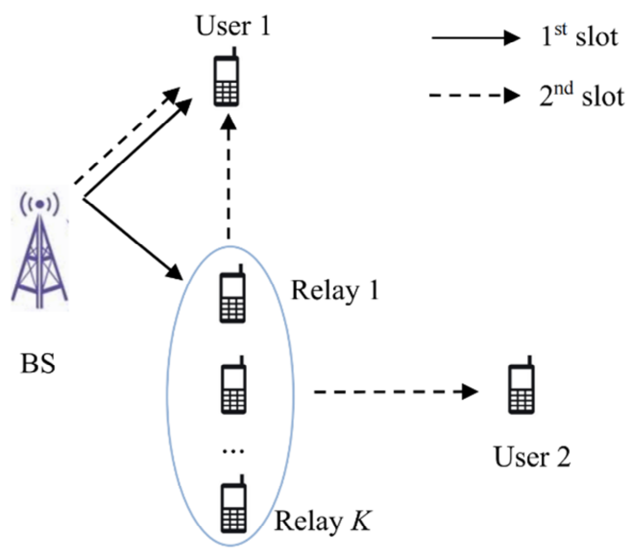
In this work, we consider a downlink NOMA CDRT system with one near user, one far user, and multiple idle users. These idle users can be selected to act as a relay node to help the far user. Different from the previous work in Yang et al. (2021), we aim to maximise the network lifetime by using the energy pricing mechanism. Note that energy pricing mechanisms can effectively balance the energy consumption among different idle users, prevent certain users from being overused or underused, and ultimately enhance the overall energy efficiency and fairness of the system. We investigate the joint relay selection and power allocation problem by considering the battery level of the users. Numerical results are presented to show the performance of the proposed energy pricing-based NOMA CDRT scheme with existing schemes.

2 System model

Figure 1 shows a downlink transmission system with a BS, two users U_1 and U_2, and K idle users (potential relays) $R_1, \ldots, R_K$. Note that user U_2 is far from the BS and no direct link exists between the BS and user U_2, while user U_1 is close to the BS and can communicate with the BS. Hence, one of the K idle users is selected as a relay to assist the communication between the BS and the far user U_2.

We assume the time-division duplex (TDD) mode is adopted and that two time slots are needed to complete the data transmission. In the first time slot, the BS sends NOMA signals to the near user and the relays. In the second time slot, one of the relays is selected to forward signals to the far user, while the BS sends a new signal to the near user. In this work, we assume all the terminals are equipped with a single antenna, and all the channels are assumed to be unchanged and reciprocal during the two time slots.

Figure 1 A NOMA CDRT wireless network with k potential relays (see online version for colours)



2.1 The first slot

In the first time slot, the downlink transmission signal at the BS is given by

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

where $s_{B,1}$ and $s_{B,2}$ are the downlink signal for the near user U_1 and far user U_2, respectively, α_1 and α_2 are power allocation factors with $\alpha_1 < \alpha_2$ and $\alpha_1 + \alpha_2 = 1$. P_B is the transmit power budget of the BS in the first time slot.

Let h_{B,U_1} be the channel coefficient from the BS to user U_1. The received signal at the near user U_1 in the first slot is given by

$$y_{U_1} = h_{B,U_1} x_{B,1} + n_{U_1}, \tag{2}$$

where $n_{U_1} \sim CN\left(0, \sigma^2\right)$ is the additive white Gaussian noise (AWGN).

User U_1 detects $s_{B,2}$ first by treating $s_{B,1}$ as a noise. Then, $s_{B,2}$ is removed from the received signal to detect $s_{B,1}$. The achievable downlink data rates from the BS to user U_1 are given by respectively.

$$R_{1,B\to U_1} = \frac{1}{2}\log_2\left(\frac{1+\alpha_1 P_B \mid h_{B,U_1} \mid^2}{\sigma^2}\right) \tag{3}$$

and

$$R_{2,B\to U_1} = \frac{1}{2}\log_2\left(\frac{1+\alpha_2 P_B \mid h_{B,U_1} \mid^2}{\alpha_1 P_B \mid h_{B,U_1} \mid^2 + \sigma^2}\right) \tag{4}$$

At the k^{th} relay, the received signal can be expressed as

$$y_{R,k} = h_{BR_k} x_{B,1} + n_{R,k} \tag{5}$$

where h_{BR_k} is the channel coefficient from the BS to relay R_k, and $n_{R,k} \sim CN(0, \sigma^2)$ is the AWGN. Note that relay R_k only needs to detect $s_{B,2}$, by treating $s_{B,1}$ as a noise. The achievable data rate for the far user U_2 from the BS to relay R_k is given by

$$R_{2,B\to R_k} = \frac{1}{2}\log_2\left(1+\frac{\alpha_2 P_B \mid h_{BR_k} \mid^2}{\alpha_1 P_B \mid h_{BR_k} \mid^2 + \sigma^2}\right) \tag{6}$$

2.2 The second slot

In the second time slot, assuming relay R_k is selected, the transmit signal at R_k is

$$x_{R_k} = \sqrt{P_{R_k}}\; s_{B,2} \tag{7}$$

where P_{R_k} is the transmit power of R_k.

The received signal at the far user can be expressed as

$$y_{U,2} = g_{R_k,U_2}\sqrt{P_{R_k}}\, s_{B,2} + n_{U,2} \tag{8}$$

where g_{R_k,U_2} denotes the channel from relay r_k to user U_2, and $n_{U,2} \sim CN(0, \sigma^2)$ is the AWGN. The achievable data rate for the link from the relay R_k to the far user is

$$R_{2,R_k\to U_2} = \frac{1}{2} log_2\left(1+\frac{P_{R_k} \mid g_{R_k,U_2} \mid^2}{\sigma^2}\right) \tag{9}$$

Meanwhile, the BS sends a new signal $s_{B,1}'$ to the near user with an average power of P_B'. The received signal at user U_1 can be expressed as

$$y'_{U_1} = h_{B,U_1}\sqrt{P'_B}s'_{B,1} + g_{R_k,U_1}\sqrt{P_{R_k}}s_{B,2} + n'_{U_1} \tag{10}$$

where g_{R_k,U_1} denotes the channel from relay R_k to the near user U_1, and $n'_{U_1} \sim CN\left(0, \sigma^2\right)$ is the AWGN. Note that the second term on the right-hand side of equation (10) denotes the interference from the active relay. However, this interference can be cancelled by the near user as $s_{B,2}$ is decoded by the near user in the first time slot. Hence, the achievable data rate for the near user in the second slot is given by

$$R'_{1,B\to U_1} = \frac{1}{2}\log_2\left(1 + \frac{P'_B \mid h_{B,U_1} \mid^2}{\sigma^2}\right) \tag{11}$$

3 Joint power allocation and relay section

In this section, we investigate the joint power allocation and relay selection problem for the considered NOMA-CDRT network.

3.1 Problem formulation

In this work, the network lifetime is defined as the network operation time until the first terminal exhausts its energy (Zhou et al., 2008). In order to make balanced use of each terminal's energy, we propose a joint power allocation and cooperative partner (relay) selection scheme based on energy pricing.

Let T_0 denote the length of the time slot. Then the total consumed energy of the BS in two time slots is

$$E_B = \left(P_B + P'_B\right)T_0 \tag{12}$$

while that of the active relay R_k is

$$E_{R_k} = P_{R_k}T_0 \tag{13}$$

Let β_B and β_{R_k} denote the energy price of the BS and the relay R_k, respectively. The cost function of the network when R_k is selected as the cooperative relay can be expressed as

$$C_k\left(P_B, P'_B, P_{R_k}, \alpha_1, \alpha_2\right) = \beta_B E_B + \beta_{R_k} E_{R_k} \tag{14}$$

and the optimal relay selection criteria can be written as

$$R_{opt} = \underset{R_k}{argmin}\, C_k\left(P_B, P'_B, P_{R_k}, \alpha_1, \alpha_2\right) \tag{15}$$

3.2 Energy pricing

Since the BS has a constant energy supply, its energy price β_B can be a fixed value. For the relays, from a supply and demand perspective, the wireless terminals that have less residual energy should charge a higher price, and vice versa. Inspired by the work in (Zhu et al., 2017; Guo et al., 2016), we can use the following pricing policy for the relays:

$$\beta_{R_k} = R_{k,max}\left(1-\left(\frac{Q_{R_k}}{Q_{R_k,0}}\right)^m\right) \tag{16}$$

where $\beta_{R_{k,max}}$ is the maximum price, Q_{R_k} is the residual energy, $Q_{R_{k,0}}$ is the initial energy of R_k, and m is an integer.

3.3 Optimal power allocation

Let R_1^* and R_2^* denote the target data rate of the near user and the far user, respectively. We aim to minimise the energy cost function while the target data rates are guaranteed. When R_k is selected as the relay, the optimal power allocation problem can be formulated as

$$\begin{aligned} &\min_{P_B,\, P'_B,\, P_{R_k},\, \alpha_1,\, \alpha_2} \; C_k\left(P_B, P'_B, P_{R_k}, \alpha_1, \alpha_2\right) \\ s.t. \;\; &\alpha_1 + \alpha_2 = 1 \\ &R_{1,B\to U_1} + R'_{1,B\to U_1} \geq R_1^* \\ &min\left(R_{2,B\to U_1}, R_{2,B\to R_k}, R_{2,R_k\to U_2}\right) \geq R_2^* \end{aligned} \tag{17}$$

The first constraint in (17) denotes the power allocation for NOMA signalling at the BS. The second constraint denotes that the total data rate for the near user in the two-time slots should be satisfied, while the third constraint is the data rate requirement for the far user.

To solve the above optimisation problem, we define $P_{B,1} = \alpha_1 P_B$ and $P_{B,2} = \alpha_2 P_B$. Furthermore, let $C_u^* = 2^{2R_u^*} - 1$, u = 1, 2, G $G_{B,U_1} = | h_{B,U_1} |^2 / \sigma^2$, $G_{B,R_k} = | h_{B,R_k} |^2 / \sigma^2$ and $G_{R_k,U_2} = | h_{R_k,U_2} |^2 / \sigma^2$. Problem (17) can be written as

$$\begin{aligned} &\min_{P_{B,1},\, P_{B,2},\, P'_B,\, P_{R_k}} \; \beta_B E_B + \beta_{R_k} E_{R_k} \\ s.t. \;\; &\left(1 + G_{B,U_1} P_{B,1}\right)\left(1 + G_{B,U_1} P'_B\right) \geq C_1^* + 1 \\ &G_{B,U_1} P_{B,2} - C_2^* G_{B,U_1} P_{B,1} \geq C_2^* \\ &G_{B,R_k} P_{B,2} - C_2^* G_{B,R_k} P_{B,1} \geq C_2^* \\ &G_{R_k,U_2} P_{R_k} \geq C_2^*) \end{aligned} \tag{18}$$

The above problem is a simple optimisation problem and can be efficiently solved. The optimal solution of (18) is given by

$$
\begin{aligned}
P_{B,1}^{opt} &= \begin{cases} \dfrac{1}{G_{B,U_1}} & \left(\sqrt{\dfrac{C_1^*+1}{C_2^*+1}}-1\right) C_1^* > C_2^* \\ 0 & C_1^* \le C_2^* \end{cases} \\
P_{B,2}^{opt} &= C_2^*\left(P_{B,1}^* + \frac{1}{min\left(G_{B,U_1}, G_{B,R_k}\right)}\right) \\
P_B'^{opt} &= \frac{1}{G_{B,U_1}}\left(\frac{1+C_1^*}{1+G_{B,U_1}P_{B,1}{}^*}-1\right) \\
P_{R_k}^{opt} &= \frac{C_2^*}{G_{R_k,U_2}}
\end{aligned}
\tag{19}
$$

Finally, the optimal power allocation factors α_1^{opt} and α_2^{opt} can be determined as

$$
\begin{aligned}
\alpha_1^{opt} &= P_{B,1}^{opt} / P_B^{opt} \\
\alpha_2^{opt} &= P_{B,2}^{opt} / P_B^{opt}
\end{aligned}
\tag{20}
$$

where $P_B^{opt} = P_{B,1}^{opt} + P_{B,2}^{opt}$.

The optimal solution in (19) suggests that if the target rates for the two users satisfy $C_1{}^* \le C_2{}^*$, no power should be allocated to the near user in the first slot, i.e., the BS sends the data of the far user to the relays only, and the relay forward it to the far user in the second time slot. In this case, no successive interference cancellation (SIC) detection is required at the near user or the relays. On the other hand, if $C_1{}^* \ge C_2{}^*$, the BS should send superimposed signals to the near user and the relays in the first slot, i.e., the downlink NOMA is constructed at the BS, and SIC detection is required at the near user or the relays.

3.4 The overall algorithm

With the above optimal power allocation, the optimised cost function of the network when R_k is selected as the cooperative partner is $C_k^{opt}\left(P_B^{opt}, P_B'^{opt}, P_{R_k}^{opt}, \alpha_1^{opt}, \alpha_2^{opt}\right)$, and the optimal relay can be determined as

$$
R_{opt} = \underset{R_k}{argmin}\, C_k^{opt}\left(P_B^{opt}, P_B'^{opt}, P_{R_k}^{opt}, \alpha_1^{opt}, \alpha_2^{opt}\right) \tag{21}
$$

The joint relay selection and power allocation algorithm is given in the following.

Algorithm 1 Joint relay selection and power allocation

Initialise: Energy price β_B and β_{R_k}, $k = 1, 2, \ldots, K$, the initial energy Q_B and $Q_{R_k}, k = 1, 2, \ldots, K,$ and the target data rates R_1^* and R_2^*.

For: $k = 1: K$

Update the energy price of the relay R_k in (16)

Solve the optimisation problem (17) to find the optimal power allocation $P_B^{opt}, P_B'^{opt}, P_{R_k}^{opt}, \alpha_1^{opt}, \alpha_2^{opt}$;

Calculate the cost value $C_k\left(P_B^{opt}, P_B'^{opt}, P_{R_k}^{opt}, \alpha_1^{opt}, \alpha_2^{opt}\right)$ in (14).

End for

Output: $k_{opt} = \arg\min_k C_k\left(P_B^{opt}, P_B'^{opt}, P_{R_k}^{opt}, \alpha_1^{opt}, \alpha_2^{opt}\right)$ as the optimal relay, and $P_B^{opt}, P_B'^{opt}, P_{R_k}^{opt}, \alpha_1^{opt}, \alpha_2^{opt}$ are the corresponding optimal power allocation solution.

The proposed method integrates the system performance and the residual energy of each idle user, and is able to reach a compromise between system performance and network lifetime. Most of the existing methods are designed to minimise the total system energy consumption or maximise the system performance without considering the network lifetime.

4 Numerical results

In the simulations, the channel coefficient between node i and node j is modelled as $h_{i,j} = 0.001 d_{i,j}^{-3} x_{i,j}$, where the $d_{i,j}$ is the distance between the transmitter i and the receiver j, and $x_{i,j}$ is the small-scale Rayleigh fading coefficient. We consider a network that relay R_1 is close to the far user while the other relays are close to the BS. Specifically, we set $d_{B,U_1} = 50\ m,\ d_{B,R_1} = 80\ m,\ d_{R_1,U_2} = 20\ m,\ d_{B,R_k} = 20\ m,\ d_{R_k,U_2} = 80\ m,$ $k = 2, 3, \ldots, K$. We assume there are $K = 5$ idle users (potential relays) unless otherwise specified. The energy price is $\beta_B = 1$ and $\beta_{R_k,max} = 10^6, \forall k,$ since the energy in the relay's battery is much more expensive than the BS with a stable energy supply. The initial battery energy is $Q_{R_k,0} = 1\ J, \forall k,$ and the noise power is $\sigma^2 = -90$ dBm. All the numerical results are obtained by averaging over 1,000 channel realisations. The optimal power allocation for the proposed scheme is calculated based on equations (19) and (20), and the optimal relay is selected based on the algorithm presented in Section 3.4.

Figure 2 shows the network lifetime of the proposed scheme under various target data rates for the far user, while Figure 3 shows the average consumed power of the relays per frame. The target data rate for the near user is fixed to be $R_1^* = 5$ bps/Hz. We compare the proposed scheme with the following schemes:

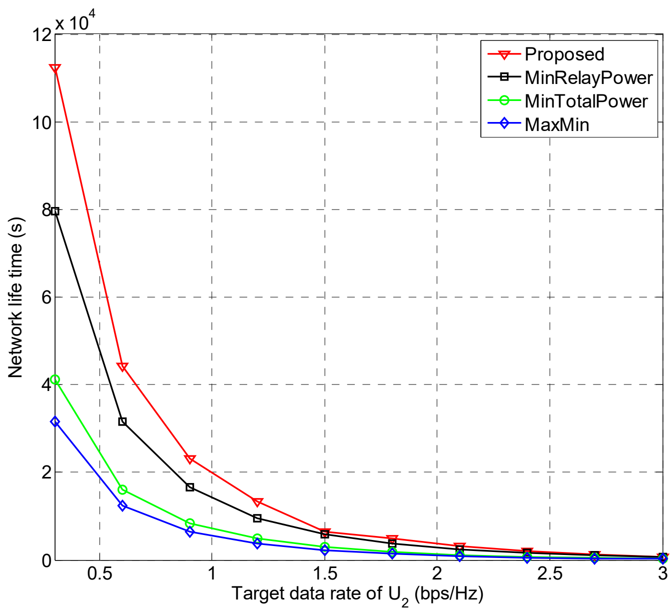
1 Minimising the total transmit power of the BS and the selected relay (labelled as 'MinTotalPower')

2 Minimising the transmit power of the selected relay (labelled as 'MinRelayPower')

3 Maximising the minimal gain of the relay channels (labelled as 'MaxMin').

From Figure 2, we see that when the target data rate of user U_2 is low, the proposed scheme outperforms its counterpart significantly. For instance, a gain of more than 40% is observed when $R_2^* = 0.3$ bps/Hz. As R_2^* increases, the gain reduces. From Figure 3, we see that the average consumed power of the proposed scheme is lower than the 'MinTotalPower' and 'MaxMin' schemes. For instance, more than 70% power of the relays can be saved as compared with the MaxMin scheme for a target data rate of 1.8 bps/Hz. Even though the average consumed power per frame of the proposed scheme is a little higher than that of the 'MinRelayPower' scheme, the proposed scheme allows for a more balanced and efficient use of the valuable energy of the different relays, and therefore a longer network lifetime can be obtained as shown in Figure 2.

Figure 2 Network lifetime versus target data rates of the far user U_2 (see online version for colours)



In Figure 4, we plot the network lifetime of the considered network with different relay energy budgets. The target data rates for the near user and the far user are fixed to be $R_1^* = 5$ bps/Hz, and $R_2^* = 1$ bps/Hz, respectively. Other simulation parameters are the same as those in Figure 2. It can be seen that the network lifetime of all these schemes increases with the relay's energy. The proposed scheme outperforms the other three schemes for all relay energy budgets, and the performance gain enlarges as the relay's energy increases. For instance, the network lifetime of the proposed method is nearly 2 times higher than that of the 'MinTotalPower' and 'Maxmin' schemes when the energy budget of each relay is 2 J, and a 50% performance gain is observed as compared with the 'MinRelayPower' scheme. Figure 5 shows the number of transmitted data frames for each relay when the energy budget of each relay is 2 J. For all these schemes, relay R_1

transmits the most frames as compared with the other relays, which means that R_1 was selected as the best relay most time. This is because relay R_1 is close to the far user and the required transmit power can be greatly reduced as the channel between R_1 and the far user is better than those between other relays and the far user most time. These results show that the proposed scheme can balance the channel condition and residual energy to prolong the network lifetime.

Figure 3 Average consumed energy per data frame (see online version for colours)

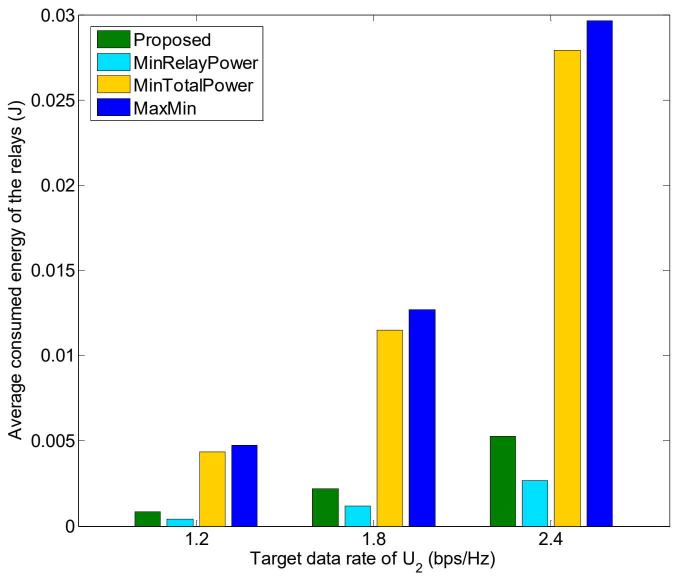


Figure 4 Network lifetime versus the relay's energy (see online version for colours)

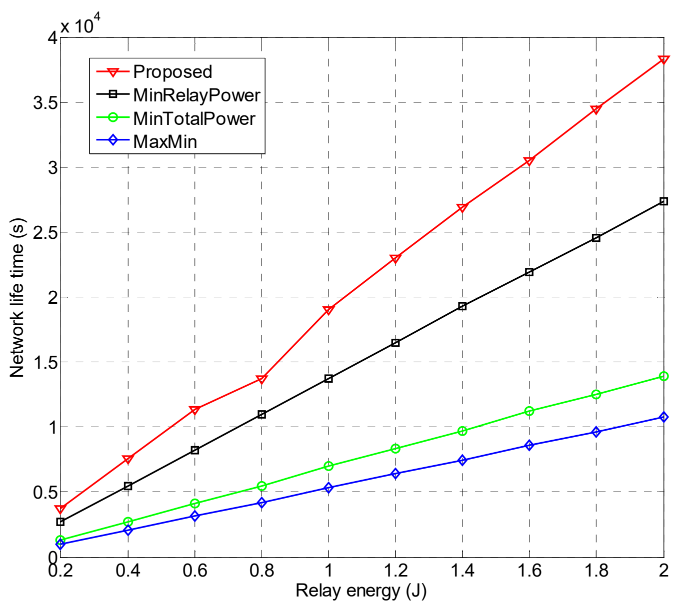


Figure 5 Number of transmitted frames per relay (see online version for colours)

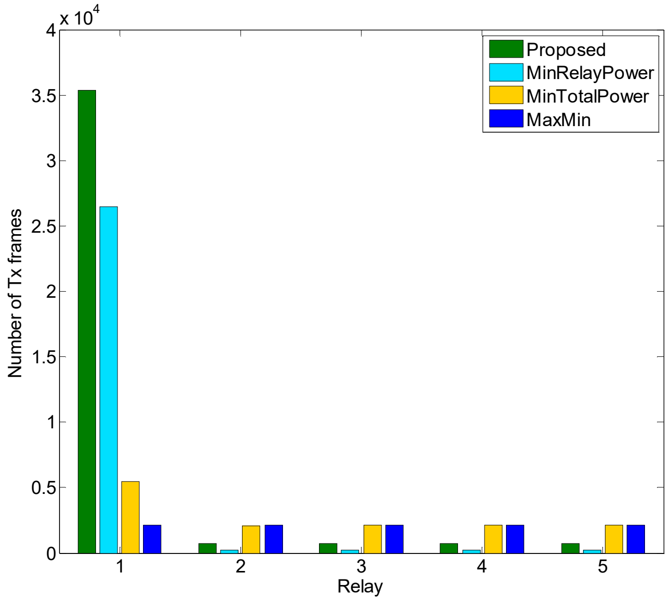
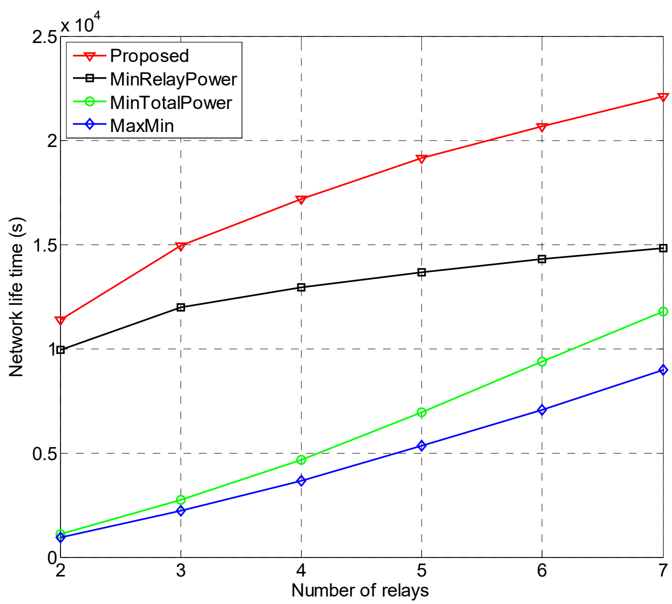
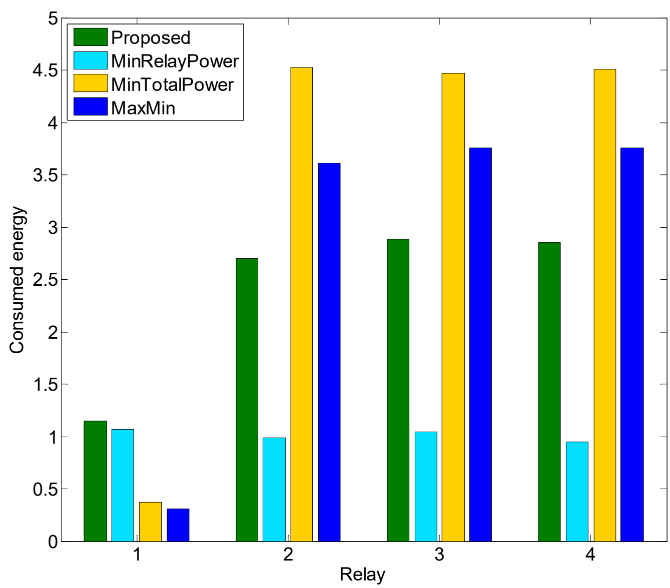


Figure 6 Network lifetime versus the number of relays (see online version for colours)



Finally, Figure 6 shows the network lifetime of the proposed scheme with a different number of relays. The target data rates for the near user and the far user are fixed to be $R_1^* = 5$ bps/Hz, and $R_2^* = 1$ bps/Hz, respectively. The energy budget of each relay is 1 J. It is clear that with more relays, the network lifetime of all these four schemes can be improved. Compared with the MinRelayPower scheme, a performance gain of 48% is obtained by the proposed scheme when there are 7 relays in the network. The is due to the fact that the MinRelayPower scheme aims to minimise the transmit power of the selected relay without considering the residual energy. Figure 7 plots the total consumed energy for each relay node in a NOMA CDRT network with $K = 4$ relays. For all these schemes, Relay R_1 consumes the least amount of energy compared to the other three relays, while the consumed energy of the other three relays is almost the same due to the reason that the channel conditions for these three relays are the same. Of all these four schemes, the consumed energy of the 'MinTotalPower' scheme is the highest, as it aims to minimise the total power of the BS and the relays without taking into account the preciousness of the relay energy.

Figure 7 Total consumed energy for each relay in a NOMA CDRT network with K = 4 relays (see online version for colours)



5 Conclusions

In this paper, we investigated the joint relay selection and power allocation problem in a user-assisted downlink NOMA CDRT system. We proposed a relay selection scheme based on energy pricing, in which relays with less residual energy charge a higher price. Simulation results show that the lifetime of the considered NOMA CDRT network can be significantly prolonged using the proposed scheme as compared with other existing schemes.

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Declarations

All authors declare that they have no conflicts of interest. All authors declare that no AI-assisted writing tools were used in the preparation of this manuscript.

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