Analysis of cooperative non-orthogonal multiple access networks with energy harvesting

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Abstract. In this paper, we investigate the performance of cooperative non-orthogonal access (NOMA) network with energy harvesting, where, source node and relay node serving as energy-constrained nodes harvest energy from the power beacon PBS. Source sends the superposed message towards the nearly-located user and relay via NOMA principle. The relay superposes and forwards the decoded signal and its own signal to the far-located user and the destination according to NOMA protocol. To measure the performance of the system quantitatively, we derive the exact closed form expressions for the outage probabilities of the near user, far user, and destination respectively over Rayleigh fading channels. Simulation results show that the reasonable power distribution coefficient and the increasing of transmission power of the power beacon improve the performance of cooperative NOMA network.

Keywords: Cooperative transmission, NOMA, Energy harvesting, Outage performance.

1 Introduction

The demand of high data rate, mass connection, low latency and high spectrum efficiency for the fifth generation communication technology (5G) attaches plenty of attention in wireless transmission network [1–3]. Non-orthogonal multiple access (NOMA) has been recognized as a prominent and promising 5G technology to improve spectrum efficiency and expand connectivity due to multiplexing in new power domain [4, 5]. The former four mobile communication systems use the traditional orthogonal multiple access (OMA) technology [6, 7], which depends on orthogonality of wireless resource and restricts the improvement of the utilization of limited spectrum resources. To mitigate the restriction of OMA schemes in improving the utilization rate of spectrum resources, NOMA allows multiple users to share the same radio resource by transmitting signals of users in a power domain superposition manner which is not studied previously and receivers decode the mixed signal from transmitter by successive interference cancellation (SIC).

As a potent candidate technology to improve system performance in wireless transmission system, NOMA has received great attention in advanced communication network [8–10]. In the study of [8], a single-input-single-output (SISO) NOMA system is

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considered, the authors confirm that NOMA can improve the secrecy sum rate performance. The authors investigate a multiple-input single-output (MISO) NOMA network and analyse its performance by deriving the exact outage probability and the asymptotic outage probability in [9]. A NOMA-aided multiple- input-multiple-output (MIMO) system is proposed in [10], the authors compare the outage performance of system between in NOMA transmission and traditional OMA, which shows that NOMA protocol has advantage over OMA.

Cooperative relay transmission can improve reliability, network coverage, and achievable rate of mobile communication networks by sharing antennas between different transmission nodes to form virtual MIMO [11–16]. Therefore, integrating cooperative relaying into NOMA has been recognized as an effective way to improve system performance [17–21]. In [17], the authors consider a two-user cooperative NOMA network, in which the base station sends the mixed signal with NOMA principle towards the near user and the far user, particularly, the near user act as a relay to decode and forward remote user's signal to the far user. A multi-users cooperative NOMA network is investigated

in [18], where the base station broadcasts the superimposed signals of multiple users and each user decodes them in sequence via SIC. It is shown that NOMA can improve the performance of cooperative network by deriving the outage probability. In cooperative NOMA network, the relay is utilized to assist the transmission from the base station to users, where decode-and-forward (DF) is considered in [19] and amplify-and-forward (AF) is undertaking in [20], respectively. There are three different diversity combining strategies, namely, selection combining (SC), maximum ratio combining (MRC), equal gain combining (EGC) and maximum ratio combining (MRC), for the destination node

to combine the signals from the relay transmission and direct transmission for the cooperative NOMA network. In [21], the authors compare the symbol error rate performance of three schemes and affirm that the better performance is achieved under MRC.

Although cooperative CR-NOMA brings significant benefits for wireless transmission networks, however such a system causes high energy consumption burden. Due to the properties of providing stable and continuous energy guarantee, a prominent and promising technique termed as energy harvesting has attracted increasing attention from industry and academia. In [22], a two-user cooperative NOMA network with energy harvesting is proposed, in which the nearly-located NOMA user act as an energy harvesting relay to forward the signal of far-located NOMA user. In the study of [22], the authors consider a multiple NOMA users cooperative transmission network with energy harvesting. A multi-relay energy harvesting enabled cooperative NOMA network is proposed in [23], the authors derive the exact analytical and asymptotic expressions for the outage probability.

To the best of our knowledge, the performance of the EH-based cooperative NOMA network with DF relay over Rayleigh fading channel has not been analyzed yet. This paper aims to fill this gap. In this paper, the understudy cooperative NOMA transmission network are expected to cooperatively transmit messages to the far user, near user, and destination node. we assume that source and relay are energy limited devices; thus, they have to harvest energy from the power beacon PBS. Considering that source cannot directly transmit signal to far user, it is necessary to forward signal assisted by the relay, which superposes and forwards the decoded signal and its own signal to the far user and the destination according to NOMA protocol. With the energy harvested from the power beacon, exact

closed form expressions for the outage probabilities of each user are derived for cooperative NOMA network with energy harvesting. Our results show that the outage performance is significantly improved with the reasonable power distribution coefficient and the increasing of transmission power of the power beacon.

The remainder of the paper is organized as follows: Section 2 shows the channel and signal model. In Section 3, we derive the outage probabilities of the near user, far user, and the destination over Rayleigh fading channels. Simulation results and discussions are given in Section 4. Finally, Section 5 provides conclusion of this paper.

2 System and channel model

We consider an energy harvesting wireless cooperative transmission network, which consists of a power beacon PBS, a source S, a single relay R, a destination D and two users {U_N, U_F}. The source S intends to communicate with the near user U_N through the direct link and with the far user U_F via the help of a DF relay R. To make full use of wireless resource, relay node R tries to send messages towards destination D simultaneously. We assume both the source S and relay R harvest energy from the power beacon PBS through the radio frequency signals since the energy of source S and relay R are limited. All nodes in the system are equipped with single omni-directional antenna. We denote the Rayleigh fading coefficient of the channel between i and j by h_{ij} , $i=\{PBS,S,R\}$, $j=\{S,R,U_N,U_F,D\}$, which is circularly symmetric complex Gaussian random variable having mean zero and variance N_0 . Meanwhile, the channel gain between i and j is expressed as g_{ij} , $g_{ij}=\left|h_{ij}\right|^2$, which follow exponential distributions with mean σ_{ij}^2 .

The time slot structure of the communication procedure is divided into energy harvest phase and data transmission phase. It is assumed that the length of the total communication procedure is T , where $\lambda T\left(1\le\lambda\le1\right)$ is used for energy harvest and the rest $\left(1-\lambda\right)T$ is used for data transmission.

In the energy harvesting phase, the source S and the relay R transmit with the energy harvested from radio frequency signals radiated by a power beacon PBS. The harvested energy for the secondary s and relay r_n can be expressed as [24].

$$E_S=\eta\cdot P_B g_{BS}\cdot\lambda T \tag{1}$$

$$E_R=\eta\cdot P_B g_{BR}\cdot\lambda T \tag{2}$$

where η denotes the energy harvesting efficiency, P_B is the transmission power of the power beacon PBS. The power obtained in the energy harvesting phase for the transmission of the source S and the relay R in the following data transmission phase are given by

$$P_S=\frac{E_S}{\left(1-\lambda\right)T/2}=\frac{\eta\cdot P_B g_{BS}\cdot\lambda T}{\left(1-\lambda\right)T/2}=\varepsilon g_{BS} \tag{3}$$

$$P_R=\frac{E_R}{\left(1-\lambda\right)T/2}=\frac{\eta\cdot P_B g_{BR}\cdot\lambda T}{\left(1-\lambda\right)T/2}=\varepsilon g_{BR} \tag{4}$$

where $\frac{\eta\lambda P_B}{\left(1-\lambda\right)/2}$.

Without loss of generality, half-duplex mode with time division multiple access is used. Hence, the data transmission phase is divided into two time slots. Based on the different scenario, we present three cooperation NOMA transmission schemes with energy harvesting mainly depends on the transmission way of far user UF, and formulate the signal model for these schemes in Rayleigh fading environment subsequently.

The data transmission phase consists of two equal phases. In the first time slot of data transmission, the source S broadcasts the mixed signal $x_S = \sqrt{\alpha_1} x_N + \sqrt{\alpha_2} x_F$ via NOMA scheme, where x_N denotes the signals which is intended to send to the near user U_N, and x_F denotes the signals which is intended to send to the far user U_F. Especially, the near user is assumed to be closer to the source S compared to the far user U_F. Hence, we allocate mmore power to the far user U_F, namely, $\alpha_1 < \alpha_2$. Therefore, the instantaneous SINR and SNR at the near user U_N for decoding signals x_F and x_N can be expressed, respectively, as

$$\gamma_{SN}^{x_F} = \frac{\alpha_2 P_S |h_{SN}|^2}{\alpha_1 P_S |h_{SN}|^2 + N_0} = \frac{\alpha_2 \varepsilon g_{BS} g_{SN}}{\alpha_1 \varepsilon g_{BS} g_{SN} + N_0} \tag{5}$$

$$\gamma_{SN}^{x_N} = \frac{\alpha_1 P_S |h_{SN}|^2}{P_U |h_{UN}|^2 + N_0} = \frac{\alpha_1 \varepsilon g_{BS} g_{SN}}{N_0} \tag{6}$$

The instantaneous SINR at the relay R for decoding signals x_F is written as

$$\gamma_{SR}^{x_F} = \frac{\alpha_2 P_S |h_{SR}|^2}{\alpha_1 P_S |h_{SR}|^2 + N_0} = \frac{\alpha_2 \varepsilon g_{BS} g_{SR}}{\alpha_1 \varepsilon g_{BS} g_{SR} + N_0} \tag{7}$$

In the second time slot of data transmission, the relay R tries to decode the signals of far user x_F. If the relay R can successfully decode the signal of far user x_F, the relay combines the signals of far user x_F and the signal of destination x_D by NOMA scheme as the superimposed signals $x_R = \sqrt{\beta_1} x_F + \sqrt{\beta_2} x_D$, where $\beta_1 < \beta_2$ since the destination D is farther to the relay R compared to the far user U_F. In this case, the instantaneous SINR and SNR at the far user U_F for decoding signals x_D and x_F can be shown as

$$\gamma_{RF}^{x_D} = \frac{\beta_2 P_R |h_{RF}|^2}{\beta_1 P_R |h_{RF}|^2 + N_0} = \frac{\beta_2 \varepsilon g_{BR} g_{RF}}{\beta_1 \varepsilon g_{BR} g_{RF} + N_0} \tag{8}$$

$$\gamma_{RF}^{x_F} = \frac{\beta_1 P_R |h_{RF}|^2}{N_0} = \frac{\beta_1 \varepsilon g_{BR} g_{RF}}{N_0} \tag{9}$$

The instantaneous SINR at the destination D for decoding signals x_D is expressed as

$$\gamma_{RD}^{x_D} = \frac{\beta_2 P_R |h_{RD}|^2}{\beta_1 P_R |h_{RD}|^2 + N_0} = \frac{\beta_2 \varepsilon g_{BR} g_{RD}}{\beta_1 \varepsilon g_{BR} g_{RD} + N_0} \tag{10}$$

Otherwise, if the relay R cannot successfully decode the signal of far user x_F, the relay only transmit the signals of the destination x_D by the harvested energy in the second time slot of data transmission. In this case, the instantaneous SNR at the destination D can be shown as

$$\gamma_{RD}^{OMA,x_D} = \frac{P_R \left|h_{RD}\right|^2}{N_0} = \frac{P_R g_{RD}}{N_0} \tag{11}$$

3 Performance analysis

In this section, we derive the exact outage probability expressions of cooperative NOMA networks with energy harvesting for the near user, far user, and the destination in Rayleigh fading channels.

3.1 Outage probability of the near user U_N

According to the definition of outage event, the outage probability of the near user U_N can be expressed as

$$\begin{aligned} P_{out}^{N} &= \Pr\left(\gamma_{SN}^{x_F} < \gamma_F \cup \gamma_{SN}^{x_F} > \gamma_F, \gamma_{SN}^{x_N} < \gamma_N\right) \\ &= 1 - \Pr\left(\gamma_{SN}^{x_F} > \gamma_F, \gamma_{SN}^{x_N} > \gamma_N\right) \end{aligned} \tag{12}$$

which means that the near user can communicate normally only when the near user U_N can successfully decode both the signals x_F and x_N . In (24), $\Pr\left(\gamma_{SN}^{x_F} > \gamma_F, \gamma_{SN}^{x_N} > \gamma_N\right)$ can be calculated as

$$\Pr\left(\gamma_{SN}^{x_F} > \gamma_F, \gamma_{SN}^{x_N} > \gamma_N\right) = \begin{cases} 0 & \frac{\alpha_2}{\alpha_1} < \gamma_F \\ \sqrt{\frac{4\Delta_1 N_0}{\varepsilon \Omega_{SN} \Omega_{BS}}} K_1\left(\sqrt{\frac{4\Delta_1 N_0}{\varepsilon \Omega_{SN} \Omega_{BS}}}\right) & \frac{\alpha_2}{\alpha_1} > \gamma_F \end{cases} \tag{13}$$

where K_v is the modified Bessel function of the second kind and v denotes the order. Thus, the outage probability for the near user U_N can be obtained.

3.2 Outage probability of the far user U_F

In the absence of the direct link for the far user U_F, the far user U_F only obtain messages from the relay R when the relay can successfully decode the signals of the far user x_F. As such, the outage probability of the far user U_F can be described as

$$\begin{aligned} P_{out}^{F} &= \Pr\left(\gamma_{SR}^{x_F} > \gamma_F, \gamma_{RF}^{x_D} > \gamma_D, \gamma_{RF}^{x_F} < \gamma_F\right) \\ &+ \Pr\left(\gamma_{SR}^{x_F} < \gamma_F\right) + \Pr\left(\gamma_{SR}^{x_F} > \gamma_F, \gamma_{RF}^{x_D} < \gamma_D\right) \end{aligned} \tag{14}$$

Note that the first term and the second term in (27) can be simplified as

$$\begin{aligned}&\Pr\left(\gamma_{SR}^{x_F}>\gamma_F,\gamma_{RF}^{x_D}>\gamma_D,\gamma_{RF}^{x_F}<\gamma_F\right)+\Pr\left(\gamma_{SR}^{x_F}>\gamma_F,\gamma_{RF}^{x_D}<\gamma_D\right)\\&=\Pr\left(\gamma_{SR}^{x_F}>\gamma_F\right)-\Pr\left(\gamma_{SR}^{x_F}>\gamma_F\right)\Pr\left(\gamma_{SR}^{x_F}>\gamma_F,\gamma_{RF}^{x_D}>\gamma_D\right)\end{aligned}\tag{15}$$

Based on (27) and (28), the outage probability of the far user UF can be rewritten as

$$P_{out}^{F}=1-\Pr\left(\gamma_{SR}^{x_F}>\gamma_F\right)\Pr\left(\gamma_{SR}^{x_F}>\gamma_F,\gamma_{RF}^{x_D}>\gamma_D\right)\tag{16}$$

where

$$\Pr\left(\frac{\alpha_2\varepsilon g_{BS}g_{SR}}{\alpha_1\varepsilon g_{BS}g_{SR}+N_0}>\gamma_F\right)=\begin{cases}0 & \dfrac{\alpha_2}{\alpha_1}<\gamma_F\\ \sqrt{\dfrac{4\gamma_F N_0}{(\alpha_2-\gamma_F\alpha_1)\varepsilon\Omega_{SR}\Omega_{BS}}}K_1\left(\sqrt{\dfrac{4\gamma_F N_0}{(\alpha_2-\gamma_F\alpha_1)\varepsilon\Omega_{SR}\Omega_{BS}}}\right) & \dfrac{\alpha_2}{\alpha_1}>\gamma_F\end{cases}\tag{17}$$

and, by a similar way as calculating $\Pr\left(\gamma_{SN}^{x_F}>\gamma_F,\gamma_{SN}^{x_N}>\gamma_N\right)$,we get $\Pr\left(\gamma_{RF}^{x_D}>\gamma_D,\gamma_{RF}^{x_F}>\gamma_F\right)$ as

$$\Pr\left(\gamma_{RF}^{x_D}>\gamma_D,\gamma_{RF}^{x_F}>\gamma_F\right)=\begin{cases}0 & \dfrac{\beta_2}{\beta_1}<\gamma_D\\ \sqrt{\dfrac{4\gamma_F N_0}{(\alpha_2-\gamma_F\alpha_1)\varepsilon\Omega_{BR}\Omega_{RF}}}K_1\left(\sqrt{\dfrac{4\gamma_F N_0}{(\alpha_2-\gamma_F\alpha_1)\varepsilon\Omega_{BR}\Omega_{RF}}}\right) & \dfrac{\beta_2}{\beta_1}>\gamma_D\end{cases}\tag{18}$$

3.3 Outage probability of destination D

When the relay R cannot successfully decode the signals of far user x_F and the destination D cannot successfully decode the its signals x_F transmitted by the OMA mode, or when the relay R can successfully decode the signals of far user x_F but the destination D cannot successfully decode the its signals x_F transmitted by the NOMA mode, the destination D is in outage. Mathematically, the outage probability for the destination D is given by

$$\begin{aligned}P_{out}^{D}&=\Pr\left(\gamma_{SR}^{x_F}<\gamma_F,\gamma_{RD}^{OMA,x_D}<\gamma_D\right)+\Pr\left(\gamma_{SR}^{x_F}>\gamma_F,\gamma_{RD}^{x_D}<\gamma_D\right)\\&=\Pr\left(\gamma_{SR}^{x_F}<\gamma_F\right)\Pr\left(\gamma_{RD}^{OMA,x_D}<\gamma_D\right)+\Pr\left(\gamma_{SR}^{x_F}>\gamma_F\right)\Pr\left(\gamma_{RD}^{x_D}<\gamma_D\right)\end{aligned}\tag{19}$$

where

$$\Pr\left(\gamma_{RD}^{OMA,x_D}<\gamma_D\right)=1-\sqrt{\frac{4\gamma_D N_0}{\varepsilon\Omega_{SR}\Omega_{BS}}}K_1\left(\sqrt{\frac{4\gamma_D N_0}{\varepsilon\Omega_{SR}\Omega_{BS}}}\right)\tag{20}$$

$$\Pr\left(\gamma_{SR}^{x_F}<\gamma_F\right)=1-\Pr\left(\gamma_{SR}^{x_F}>\gamma_F\right)\tag{21}$$

and

$$\Pr\left(\gamma_{RD}^{x_D} < \gamma_D\right) = \begin{cases} 1 & \dfrac{\beta_2}{\beta_1} < \gamma_D \\ \sqrt{\dfrac{4\gamma_D N_0}{\left(\beta_2 - \beta_1\gamma_D\right)\varepsilon\Omega_{RF}\Omega_{BR}}} K_1\left(\sqrt{\dfrac{4\gamma_D N_0}{\left(\beta_2 - \beta_1\gamma_D\right)\varepsilon\Omega_{RF}\Omega_{BR}}}\right) & \dfrac{\beta_2}{\beta_1} > \gamma_D \end{cases} \tag{22}$$

Finally, by some appropriate substitutions, the outage probability for the destination node D can be obtained.

4 Simulation results

In this section, the simulation results are used to corroborate derived analysis for the proposed cooperative NOMA network with energy harvesting. The systems parameters are set as follows: $\Omega_{SN} = \Omega_{SR} = 10dB, \Omega_{BS} = \Omega_{BR} = 8dB, \Omega_{RF} = 7dB, \gamma_N = \gamma_N = 1$.

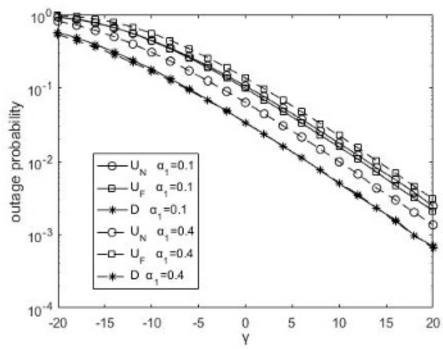

Fig. 1. outage probability against γ with $\lambda = 0.5, P_B = 5dB, \Omega_{RD} = \Omega_{SF} 5dB$.

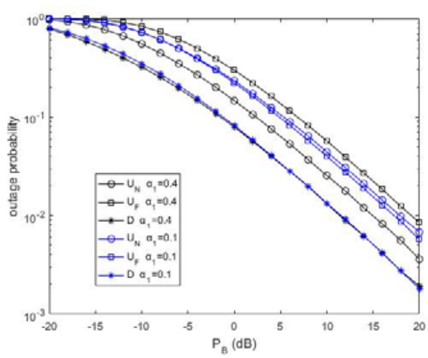

Fig. 2. Outage probability against γ with $\lambda = 0.5, \Omega_{RD} = \Omega_{SF} 5dB$.

Figure 1 shows the outage performance of the near user, the far user and the destination node versus the system SNR $\gamma\left(\gamma = 1/N_0\right)$ for power distribution coefficient $\alpha_1 = 0.1$ and $\alpha_1 = 0.4$, where the outage probability decreases as the system SNR γ increases. As expected, the change of α_1 has little influence on the performance of the destination node. However, the outage performance of the far user is better than the near user when $\alpha_1 = 0.1$

while the outage performance of near user is better than far user when $\alpha_1 = 0.4$. This is the reason that the larger α_1 means more power allocated to the near user.

The relationship between the outage probability and the transmit power of power beacon P_B and power distribution coefficient for the far user, near user, and relay destination node is depicted in Figure 2. Obviously, with the increase of the transmit power of power beacon P_B , the outage probability of all cases decreases. Clearly, the performance for the far user is worst, which is also the reason that the incremental cooperative NOMA transmission should be designed.

We plot the outage probability of destination node against the system SNR γ for the proposed cooperative NOMA network with energy harvesting with the average channel gain between the relay and the destination node $\Omega_{RD} = 1dB, \Omega_{RD} = 5dB$ and $\Omega_{RD} = 10dB$ in Figure 3. Clearly, the outage performance of the destination node is decreased with the increase of Ω_{RD} since the higher Ω_{RD} means the better channel conditions between the relay and the destination.

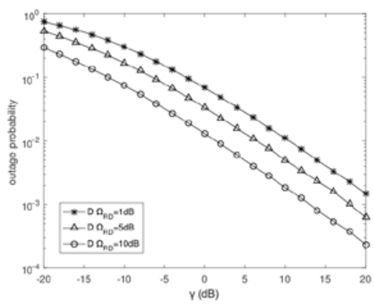

Fig. 3. Outage probability against γ **with** $\lambda = 0.5, P_B = 5dB, \Omega_{SF} 5dB, \alpha_1 = 0.4$.

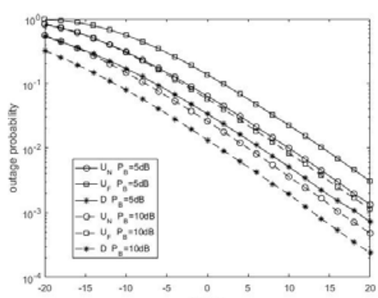

Fig. 4. Outage probability against γ **with** $\lambda = 0.5, \Omega_{RD} = \Omega_{SF} 5dB, \alpha_1 = 0.4$.

Figure 4 illustrates the exact outage probability of the proposed cooperative NOMA network against the system SNR γ for different transmission powers of the power beacon PBS $P_B = \{5dB, 10dB\}$. Expectedly, the larger SNR γ , the lower outage probability for all users. This is reasonable since the quality of received signals at the near user, the far user, and the destination improves as SNR increasing. Moreover, increasing the transmission power of the power beacon PBS P_B decreases the outage probability since the source node and the relay can obtain more energy from the power beacon. As can be observed, $P_B = 10dB$ provides superior performance than $P_B = 5dB$. Also, it can be seen that, for the understudy cooperative NOMA network, the performance of the destination node is optimal.

5 Conclusion

In this paper, an energy harvesting cooperative NOMA network is proposed, where source and relay harvest energy from the power beacon PBS due to energy is constrained. Source broadcasts signal towards the near user and relay, and then relay sends the superposed signal to the far user and the destination after decoding the signal successfully. To obtain further insights, the closed-form expressions of the outage probability of near user, far user and destination are derived respectively. Finally, we simulate the derived theoretical values and verify that the derivation is correct due to the consistency of simulated and theoretical values. It is show that the outage performance is significantly improved with the reasonable power distribution coefficient and the increasing of transmission power of the power beacon.

I would like to thank all the authors for their help and support during my research and writing for this thesis. They have talked with me several times during the whole thesis-writing process, discussing my research ideas and approaches and giving me advice on how to conduct the research and present it on paper. Thanks the National Natural Science Foundation of China, the Science and Technology Department of Gansu Province Project and the Foundation of A Hundred Youth Talents Training Program of Lanzhou Jiaotong University for their financial support. This work was supported by the National Natural Science Foundation of China under grant 61901201, 62001359, 61762058; the Science and Technology Department of Gansu Province Project under grant 20JR5RA387, 20JR10RA273; the Foundation of A Hundred Youth Talents Training Program of Lanzhou Jiaotong University.

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