Novel Receiver Design for the Cooperative Relaying System With Non-Orthogonal Multiple Access

Min Xu, Fei Ji, Miaowen Wen, and Wei Duan

***Abstract*— In this letter, a novel detection scheme for the cooperative relaying system using non-orthogonal multiple access (CRS-NOMA) is proposed. For CRS-NOMA, the source simultaneously transmits two symbols by employing the superposition code, and the relay decodes and forwards the symbol with lower allocated power by employing the successive interference cancellation (SIC). In the proposed scheme, the destination jointly decodes two symbols from both the directed signal and the forwarded signal by employing the maximum-ratio combination and another SIC. The ergodic sum rate and the outage performance of the system are investigated. A suboptimal allocation strategy is also designed. Both analysis and simulations reveal the advantages of the proposed scheme.**

***Index Terms*— Cooperative relaying system (CRS), non-orthogonal multiple access (NOMA), sum rate, power allocation.**

I. Introduction

So far, capacities of different relaying systems have been investigated [1], [2]. The cooperative relaying system (CRS) is shown to efficiently improve the network performance, but it may limit the spectral efficiency owing to duplicate transmission. Recently, the idea of non-orthogonal multiple access (NOMA) [3], which is considered as a promising candidate for the fifth generation (5G) wireless communication, has been extended to cooperative communication scenarios. In [4], a cooperative NOMA transmission scheme is proposed to fully exploit the prior information, which achieves the maximum diversity gain for all users. More recently, the CRS with NOMA (CRS-NOMA) is proposed in [5], where the NOMA is used in CRS for spatially multiplexed transmission to enhance the spectral efficiency.

In this letter, we propose a novel detection scheme for the CRS-NOMA. Different from the one in [5], our proposal allows the destination to jointly decode both symbols transmitted by the source by involving the maximum ratio combination (MRC) and the successive interference cancellation (SIC). The ergodic sum rate (SR) achieved by the proposed system is analyzed and its closed-form expression at high signal-to-noise (SNR) is derived. The outage performance is also studied and a practical power allocation strategy that maximizes the ergodic SR is designed. Simulation results show that our proposal significantly outperforms the one in [5], especially when the link from the source to the relay is better than that from the relay to the destination.

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II. System Model and Working Flow

Consider a cooperative communication scenario which consists of a source S, a relay R, and a destination D. The channels S-D, S-R, and R-D are respectively denoted by h_{SD}, h_{SR}, and h_{RD}, which are assumed to be independent complex Gaussian random variables with variances β_{SD}, β_{SR}, and β_{RD}, respectively. It is assumed that both the amplitude and the phase of channels S-D and R-D are available at the destination, while those of the S-R channel are available at the relay.

There are two phases involved in each transmission. At the first phase, the source broadcasts symbols s_1 and s_2 simultaneously to the relay and the destination. By adopting the superposition code, the transmitted signal is in the form of $\sqrt{a_1 P_t}s_1 + \sqrt{a_2 P_t}s_2$, where a_1 and a_2 with $a_1 + a_2 = 1$ denote the power allocation factors and P_t stands for the total transmit power. We assume that the S-D channel is relatively worse, and s_1 is allocated with more transmit power, i.e., $a_1 > a_2$. The received signals at the relay and the destination are thus given by

$$y_{SR} = h_{SR}\left(\sqrt{a_1 P_t}s_1 + \sqrt{a_2 P_t}s_2\right) + n_{SR}, \tag{1}$$

$$y_{SD} = h_{SD}\left(\sqrt{a_1 P_t}s_1 + \sqrt{a_2 P_t}s_2\right) + n_{SD}, \tag{2}$$

where n_δ, for $\delta \in \{SD, SR, RD\}$, is the additive white Gaussian noise experienced at the sink of the link δ, which has zero mean and variance σ_0^2.

At the second phase, the relay forwards the decoded symbol s_2 with full transmit power P_t to the destination, and thus the received signal at the destination is given by

$$y_{RD} = h_{RD}\sqrt{P_t}s_2 + n_{RD}. \tag{3}$$

A. Recent Scheme Revisited

In [5], the relay and the destination decode s_1 from (1) and (2) at the first phase, respectively, by treating s_2 as interference, where the signal-to-interference-plus-noise ratios (SINRs) for s_1 experienced at both nodes are, respectively, given by

$$\gamma_1^R = \frac{|h_{SR}|^2 a_1 P_t}{|h_{SR}|^2 a_2 P_t + \sigma_0^2}, \tag{4}$$

$$\gamma_1^D = \frac{|h_{SD}|^2 a_1 P_t}{|h_{SD}|^2 a_2 P_t + \sigma_0^2}. \tag{5}$$

Then, by employing SIC, the relay decodes s_2 under the background noise only, leading to the SNR for s_2:

$$\gamma_2^R = \frac{|h_{SR}|^2 a_2 P_t}{\sigma_0^2}. \tag{6}$$

At the second phase, the destination decodes s_2 from (3), under the SNR of $\gamma_2^D = \frac{|h_{RD}|^2 P_t}{\sigma_0^2}$.

To ensure the decoding correctness, the achievable rates of s_1 and s_2 should be

$$R_1^{rec} = \frac{1}{2}\log_2\left(1+\gamma_1^{rec}\right), \gamma_1^{rec} = \min\left(\gamma_1^R, \gamma_1^D\right), \tag{7}$$

$$R_2^{rec} = \frac{1}{2}\log_2\left(1+\gamma_2^{rec}\right), \gamma_2^{rec} = \min\left(\gamma_2^R, \gamma_2^D\right). \tag{8}$$

B. Proposed Receiver Design

In CRS-NOMA, the *S-D* channel is usually tough, for which we need a relay to cooperate. Therefore, it is not wise to decode any symbol at the destination at the first phase. Instead, in the proposed scheme, we conserve the received signal y_{SD} at the first phase, and use it jointly with the received signal y_{RD} at the second phase for decoding purposes. In particular, the symbol s_1 with more allocated power is decoded first at the relay, and the symbol s_2 follows after SIC. To further exploit the space diversity and improve the achievable rate of s_2, the MRC is adopted by combining y_{SD} and y_{RD} with weights $\frac{h_{SD}^* a_2 P_t}{|h_{SD}|^2 a_1 P_t + \sigma^2}$ and $\frac{h_{RD}^* P_t}{\sigma^2}$, respectively. Then, using the SIC, we achieve a remarkable gain for the rate of s_1.

Define the transmit SNR as $\rho \triangleq \frac{P_t}{\sigma_0^2}$ and $\lambda_\delta \triangleq |h_\delta|^2$. The achievable rate of s_1 is given by $R_1 = \frac{1}{2}\log_2(1+\gamma_1)$, where

$$\gamma_1 = \min\left(\tfrac{\lambda_{SR} a_1 \rho}{\lambda_{SR} a_2 \rho + 1}, \lambda_{SD} a_1 \rho\right), \tag{9}$$

and that of s_2 is $R_2 = \frac{1}{2}\log_2(1+\gamma_2)$, where

$$\gamma_2 = \min\left(\lambda_{SR} a_2 \rho, \tfrac{\lambda_{SD} a_2 \rho}{\lambda_{SD} a_1 \rho + 1} + \lambda_{RD}\rho\right). \tag{10}$$

The superiority of our proposal over the one in [5] can be readily expected by comparing (7)-(10).

III. Performance Analysis

From (9), the complementary cumulative distribution function (CCDF) of γ_1 can be readily formulated as

$$\overline{F}_{\gamma_1}(x) = \Pr\left\{\lambda_{SD} a_1 \rho > x, \frac{\lambda_{SR} a_1 \rho}{\lambda_{SR} a_2 \rho + 1} > x\right\}. \tag{11}$$

Noting that the CCDF of λ_δ is $\overline{F}_{\lambda_\delta}(x) = e^{-\frac{x}{\beta_\delta}}$, when $x < a_1/a_2$, (11) is equivalent to

$$\begin{aligned}\overline{F}_{\gamma_1}(x) &= \overline{F}_{\lambda_{SD}}\left(\frac{x}{a_1\rho}\right)\overline{F}_{\lambda_{SR}}\left(\frac{x}{a_1\rho - x a_2 \rho}\right)\\ &= e^{-\frac{x}{a_1\rho\beta_{SD}} - \frac{x}{a_1\rho - x a_2\rho}\frac{1}{\beta_{SR}}}.\end{aligned} \tag{12}$$

Since $\gamma_1 \le \frac{\lambda_{SR} a_1 \rho}{\lambda_{SR} a_2 \rho + 1} < a_1/a_2$, for $x \ge a_1/a_2$ we have $\overline{F}_{\gamma_1}(x) = 0$. Taking the derivative of (12), the probability distribution function (PDF) of γ_1 can be thus obtained as

$$\begin{aligned}f_{\gamma_1}(x) = &\left[\frac{1}{a_1\rho\beta_{SD}} + \frac{a_1}{(a_1 - x a_2)^2}\frac{1}{\rho\beta_{SR}}\right]\\ &\times e^{-\frac{x}{a_1\rho\beta_{SD}} - \frac{x}{a_1\rho - x a_2\rho}\frac{1}{\beta_{SR}}}, \quad 0 < x < a_1/a_2.\end{aligned} \tag{13}$$

Similarly, the CCDF of γ_2 can be derived from (10) as (14), as shown at the bottom of this page.

A. Outage Probability

Assume that the user's target rate is R_T. Therefore, the outage occurs when $\frac{1}{2}\log_2(1+\gamma_1) < R_T$ or $\frac{1}{2}\log_2(1+\gamma_2) < R_T$, resulting in an outage probability:

$$P_{out} = 1 - \Pr\left\{\gamma_1 > 2^{2R_T} - 1, \gamma_2 > 2^{2R_T} - 1\right\}. \tag{15}$$

Since γ_1 and γ_2 are correlated, the derivation of the outage probability from (15) is involved. In Section IV, we will resort to Monte Carlo simulations to examine the outage performance.

B. Ergodic Sum Rate

From (13), the ergodic achievable rate of s_1 can be readily calculated as

$$R_1 = \int_0^{\frac{a_1}{a_2}} \frac{1}{2}\log_2(1+x)\, f_{\gamma_1}(x)dx. \tag{16}$$

Similarly, the ergodic achievable rate of s_2 can be calculated as

$$\begin{aligned}R_2 &= \int_0^\infty \frac{1}{2}\log_2(1+x)\, f_{\gamma_2}(x)\,dx\\ &= \frac{1}{2\ln 2}\int_0^\infty \frac{1 - F_{\gamma_2}(x)}{1+x}dx.\end{aligned} \tag{17}$$

Consider the high transmit SNR case, in which $\frac{\lambda_{SR} a_1 \rho}{\lambda_{SR} a_2 \rho + 1} \sim \frac{a_1}{a_2}$. After some mathematical manipulations with

$$\begin{aligned}\overline{F}_{\gamma_2}(x) &= \Pr\{\lambda_{SR} a_2 \rho > x, \frac{\lambda_{SD} a_2 \rho}{\lambda_{SD} a_1 \rho + 1} + \lambda_{RD}\rho > x\}\\ &= \Pr\{\lambda_{SR} a_2 \rho > x\} \cdot \begin{cases}\Pr(\frac{\lambda_{SD} a_2 \rho}{\lambda_{SD} a_1 \rho + 1} > x) + \Pr(\frac{\lambda_{SD} a_2 \rho}{\lambda_{SD} a_1 \rho + 1} < x)\Pr(\lambda_{RD}\rho > x - \frac{\lambda_{SD} a_2 \rho}{\lambda_{SD} a_1 \rho + 1}), x < \frac{a_2}{a_1}\\ \Pr(\lambda_{RD}\rho > x - \frac{\lambda_{SD} a_2 \rho}{\lambda_{SD} a_1 \rho + 1}), x > \frac{a_2}{a_1}\end{cases}\\ &= e^{-\frac{x}{a_2\rho\beta_{SR}}} \cdot \begin{cases} e^{-\frac{x}{a_2\rho - x a_1\rho}\frac{1}{\beta_{SD}}} + (1 - e^{-\frac{x}{a_2\rho - x a_1\rho}\frac{1}{\beta_{SD}}}) e^{-\frac{x}{\rho\beta_{RD}}} \int_0^\infty e^{\frac{u a_2}{u a_1 \rho + 1}\frac{1}{\beta_{RD}}} \frac{1}{\beta_{SD}} e^{-\frac{u}{\beta_{SD}}} du, x < \frac{a_2}{a_1}\\ e^{-\frac{x}{\rho\beta_{RD}}} \int_0^\infty e^{\frac{u a_2}{u a_1 \rho + 1}\frac{1}{\beta_{RD}}} \frac{1}{\beta_{SD}} e^{-\frac{u}{\beta_{SD}}} du, x > \frac{a_2}{a_1}\end{cases}\end{aligned} \tag{14}$$

$$\hat{R}_2 = \int_0^{\infty} \frac{\log_2(1+x)}{2}\left(\frac{1}{a_2\rho\beta_{SR}}+\frac{1}{\rho\beta_{RD}}\right)e^{-\frac{x}{a_2\rho\beta_{SR}}-\frac{x}{\rho\beta_{RD}}+\frac{a_2}{a_1\rho\beta_{RD}}}dx = \frac{-e^{\frac{1}{a_1\rho\beta_{RD}}+\frac{1}{a_2\rho\beta_{SR}}}}{2\ln 2}Ei\left(-\frac{1}{a_2\rho\beta_{SR}}-\frac{1}{\rho\beta_{RD}}\right). \tag{19}$$

$$\frac{\partial\hat{R}_{sum}}{\partial a_2} = \frac{1}{a_1^2\rho\beta_{SD}}\frac{e^{\frac{1}{a_1\rho\beta_{SD}}}}{2\ln 2}\left[Ei\left(-\frac{1}{a_1a_2\rho\beta_{SD}}\right)-Ei\left(-\frac{1}{a_1\rho\beta_{SD}}\right)\right]+\frac{e^{\frac{1}{a_1\rho\beta_{SD}}}}{2\ln 2}\left(\frac{2a_2-1}{a_1a_2}e^{-\frac{1}{a_1a_2\rho\beta_{SD}}}-\frac{1}{a_1}e^{-\frac{1}{a_1\rho\beta_{SD}}}\right)$$
$$-\left(\frac{1}{a_1^2\rho\beta_{RD}}-\frac{1}{a_2^2\rho\beta_{SR}}\right)\frac{e^{\frac{1}{a_1\rho\beta_{RD}}+\frac{1}{a_2\rho\beta_{SR}}}}{2\ln 2}Ei\left(\frac{-1}{a_2\rho\beta_{SR}}-\frac{1}{\rho\beta_{RD}}\right)+\frac{e^{\frac{1}{a_1\rho\beta_{RD}}+\frac{1}{a_2\rho\beta_{SR}}-\frac{1}{a_2\rho\beta_{SR}}-\frac{1}{\rho\beta_{RD}}}}{2\ln 2}\frac{\beta_{RD}}{a_2\beta_{RD}+a_2^2\beta_{SR}}. \tag{21}$$

the help of software Mathematica, the ergodic achievable rate of s_1 can be solved as

$$\begin{aligned}\hat{R}_1 &= \int_0^{\frac{a_1}{a_2}} \frac{1}{2}\log_2(1+x)\frac{1}{a_1\rho\beta_{SD}}e^{-\frac{x}{a_1\rho\beta_{SD}}}dx \\ &\quad + \int_{\frac{a_1}{a_2}}^{\infty}\frac{1}{2}\log_2\left(1+\frac{a_1}{a_2}\right)\frac{1}{a_1\rho\beta_{SD}}e^{-\frac{x}{a_1\rho\beta_{SD}}}dx \\ &= \frac{e^{\frac{1}{a_1\rho\beta_{SD}}}}{2\ln 2}\left[Ei\left(\frac{-1}{a_1a_2\rho\beta_{SD}}\right)-Ei\left(\frac{-1}{a_1\rho\beta_{SD}}\right)\right],\end{aligned} \tag{18}$$

where $Ei(\cdot)$ denotes the exponential integral function. Similarly, we can obtain the ergodic achievable rate of s_2 at high SNR as (19), as shown at the top of this page. Finally, combining (18) with (19), we can express the ergodic SR of our proposal as

$$\begin{aligned}\hat{R}_{sum} &= \frac{e^{\frac{1}{a_1\rho\beta_{SD}}}}{2\ln 2}\left[Ei\left(-\frac{1}{a_1a_2\rho\beta_{SD}}\right)-Ei\left(-\frac{1}{a_1\rho\beta_{SD}}\right)\right] \\ &\quad -\frac{e^{\frac{1}{a_1\rho\beta_{RD}}+\frac{1}{a_2\rho\beta_{SR}}}}{2\ln 2}Ei\left(-\frac{1}{a_2\rho\beta_{SR}}-\frac{1}{\rho\beta_{RD}}\right).\end{aligned} \tag{20}$$

C. Power Allocation

Let us focus on the power allocation issue at high transmit SNR. The derivative of the ergodic SR in (20) with respect to the power allocation factor a_2 can be obtained as (21), as shown at the top of this page.

Denote Ec as the Euler constant. By applying the approximations $Ei(-x) \sim Ec + \ln x$ and $e^x \sim 1 + x$ for $x \ll 1$, and $a_2\beta_{SR} + \beta_{RD} \sim \beta_{RD}$ for a small a_2, to (21), we have

$$\frac{\partial\hat{R}_{sum}}{\partial a_2} \sim \frac{1}{2\ln 2}\left[\frac{1-a_2^2\rho\beta_{SD}}{a_2^2\rho\beta_{SD}}-\frac{Ec-\ln(a_2\rho\beta_{SD})}{a_2^2\rho\beta_{SR}}-\frac{\beta_{SR}}{\beta_{RD}}\right], \tag{22}$$

and

$$\frac{\partial^2\hat{R}_{sum}}{\partial a_2^2} \sim -\frac{1}{a_2^3\rho\beta_{SD}\ln 2}+\frac{Ec-\ln(a_2\rho\beta_{SD})+1}{a_2^3\rho\beta_{SR}\ln 2}. \tag{23}$$

From (23), it is easy to see that as long as $a_2 > \frac{1}{\rho\beta_{SD}}e^{Ec+1-\beta_{SR}/\beta_{SD}}$, it follows that $\frac{\partial^2\hat{R}_{sum}}{\partial a_2^2} < 0$. Note that the above condition can be always satisfied as $\frac{1}{\rho\beta_{SD}}e^{Ec+1-\beta_{SR}/\beta_{SD}}$ approaches zero for $\rho \gg 1$. Since $\frac{\partial\hat{R}_{sum}}{\partial a_2}$ is a decreasing function, there exists the maximum $\hat{R}_{sum}$ associated with $\frac{\partial\hat{R}_{sum}}{\partial a_2} = 0$. Letting $\frac{\partial\hat{R}_{sum}}{\partial a_2} = 0$, the optimal power allocation factor a_2^* can be obtained from

$$\begin{aligned}a_2^{*2} &= \frac{\beta_{RD}\ln a_2^*}{(\beta_{RD}+\beta_{SR})\rho\beta_{SR}}-\frac{\beta_{RD}Ec}{(\beta_{RD}+\beta_{SR})\rho\beta_{SR}} \\ &\quad +\frac{\beta_{RD}}{\beta_{RD}+\beta_{SR}}\left(\frac{1}{\beta_{SR}\rho}+\frac{\ln(\beta_{SD}\rho)}{\beta_{RD}\rho}\right).\end{aligned} \tag{24}$$

After introducing $\varsigma = \ln a_2^*$, (24) can be rewritten as

$$\begin{aligned}e^{2\varsigma} &= \frac{\beta_{RD}}{(\beta_{RD}+\beta_{SR})\rho\beta_{SR}}\varsigma-\frac{\beta_{RD}}{(\beta_{RD}+\beta_{SR})\rho\beta_{SR}}Ec \\ &\quad +\frac{\beta_{RD}}{\beta_{RD}+\beta_{SR}}\left(\frac{1}{\beta_{SR}\rho}+\frac{\ln(\beta_{SD}\rho)}{\beta_{RD}\rho}\right).\end{aligned} \tag{25}$$

Finally, we can obtain

$$\varsigma = -\frac{1}{2}W(w)+Ec+\kappa, \tag{26}$$

where $W(w)$ is the Lambert function,

$$w = -\frac{2(\beta_{RD}+\beta_{SR})\beta_{SR}\rho}{\beta_{RD}}e^{2Ec+2\kappa}, \tag{27}$$

and $\kappa = -\frac{\beta_{SR}}{\beta_{RD}} - \ln(\beta_{SD}\rho)$.

Using the approximation [6, eq. (3)]:

$$W(w) \approx \ln(-w)-\frac{2}{\alpha}\left[1-\left(1+\alpha\left(-\frac{1+\ln(-w)}{2}\right)^{\frac{1}{2}}\right)^{-1}\right], \tag{28}$$

where $\alpha = 0.3205$. we can obtain the approximations of ς and the corresponding power allocation factor, which is referred to as the suboptimal power allocation scheme in this letter.

IV. Numerical Results

In this section, we examine the performance of our proposal in terms of the ergodic SR by setting $\beta_{SD} = 1$. Comparisons are made with the recently proposed CRS-NOMA in [5].

First, we studied the ergodic SR performance versus the transmit SNR and the power allocation factor a_2, respectively, obtaining results shown in Figs. 1 and 2. To see how the location of the relay affects the performance, we considered the following three different system setups: $\beta_{SR} = \beta_{RD} = 10$ (Case 1); $\beta_{SR} = 10$, $\beta_{RD} = 2$ (Case 2); $\beta_{SR} = 2$, $\beta_{RD} = 10$ (Case 3). From Fig. 1, we see that the analytic result that is obtained as (20) is valid and the ergodic SR of our proposal outperforms that of the recent one for a large

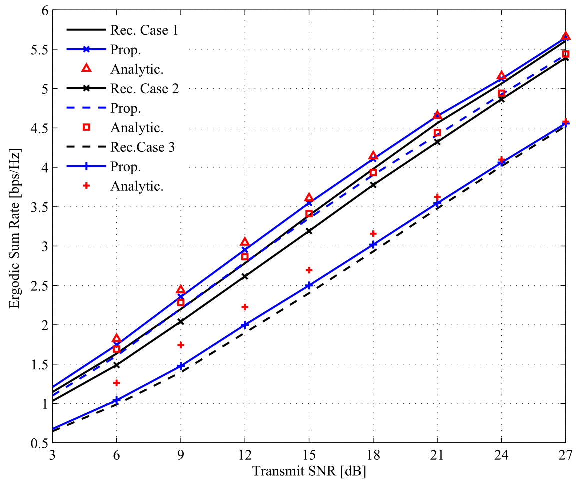

Fig. 1. Comparison of ergodic SRs of the proposal and the one in [5] versus the transmit SNR with $a_1 = 0.9$, $a_2 = 0.1$, and $\beta_{SD} = 1$.

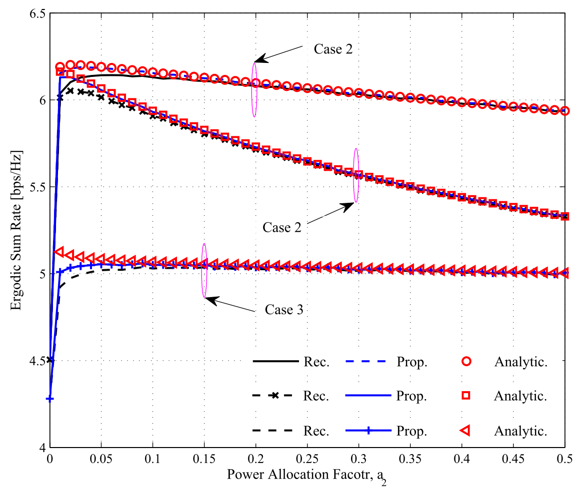

Fig. 2. Comparison of the ergodic SRs of the proposal and the recent CRS-NOMA versus the power allocation factor a_2 with $\rho = 20$dB.

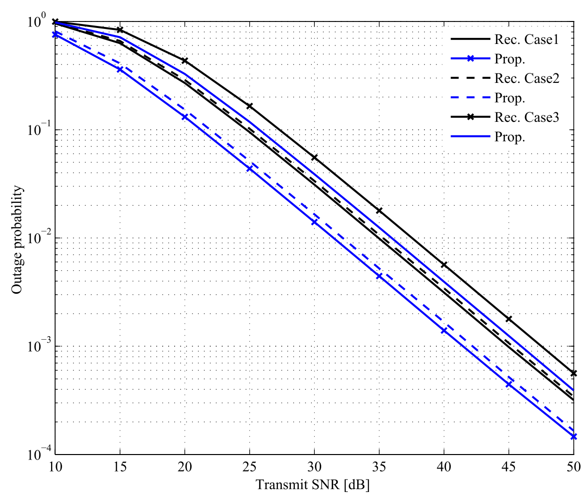

Fig. 3. The outage probability of the proposal, the recent CRS-NOMA versus the transmit SNR with $a_1 = 0.9$, $a_2 = 0.1$ and $\beta_{SD} = 1$, $R_T = 1$ bps. For Case 1, $\beta_{SR} = 10, \beta_{RD} = 10$, for Case 2, $\beta_{SR} = 10, \beta_{RD} = 2$, for Case 3, $\beta_{SR} = 2, \beta_{RD} = 10$.

transmit SNR range. Besides, from Fig. 2 we see that our proposal shows a remarkable gain over the recent one at peaks.

Then, we turned to compare the outage performance of two schemes in Fig. 3. Results reveal that our proposal has

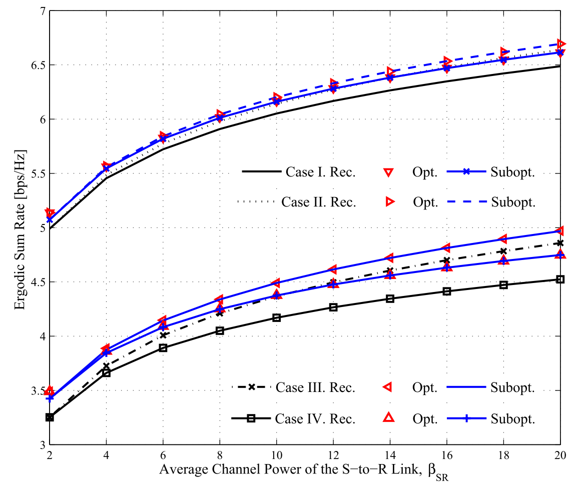

Fig. 4. The ergodic SR of the proposal and the recent CRS-NOMA with the optimal and the suboptimal power allocation scheme when $\beta_{SD} = 1$ and $\beta_{RD} = \beta_{SR}, \rho = 30$dB (Case I), $\beta_{RD} = 2, \rho = 30$dB (Case II), $\beta_{RD} = \beta_{SR}, \rho = 20$dB (Case III), $\beta_{RD} = 2, \rho = 20$dB (Case IV).

an obvious advantage over the recent one, especially when $\beta_{SR} \geq \beta_{RD}$. Finally, we investigated the ergodic SR performance versus the average channel power of *S-R* link with the optimal and the suboptimal power allocation schemes. We made two different assumptions: 1) $\beta_{SR} = \beta_{RD}$ and 2) $\beta_{RD} = 2$, and obtained results in Fig. 4, where the exhaustive search is used to obtain the optimal power allocation factor a_2 and the suboptimal one is obtained from (26)-(28). From the figure, it is clear that the suboptimal solution is close to the optimal one especially for a larger β_{SR}, which supports the practical utility of our design.

V. Conclusions and Future Work

In this letter, we have proposed a novel receiver design for the CRS with NOMA. Compared with the recent CRS-NOMA scheme, our proposal achieves a remarkable gain in terms of the ergodic SR and significant decline on outage probability. A suboptimal and practical power allocation strategy has been also provided, which exhibits almost the same performance as the optimal one. To explore the capacity further, possible schemes like allowing the source to transmit at the second phase or using incremental redundancy techniques will be involved in our future work.

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