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Performance analysis of partial NOMA-based layered D2D communications

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Abstract

Conventionally, non-orthogonal multiple access (NOMA) has traditionally been implemented separately from orthogonal multiple access (OMA), aiming to improve the capacity of multi-user systems. However, a recent study has ventured beyond this conventional approach by integrating OMA and NOMA proportionally within the same system. In spite of these advancements, the consideration towards optimizing multi-user systems remains incomplete especially when user service requirements vary significantly. Therefore, this paper explores a novel layered device-to-device (D2D) partial NOMA (P-NOMA) scheme, which introduces a hybrid power-domain access method into multi-user systems. The analysis primarily focuses on evaluating both the system performance and the impact of various parameters on it. In contrast to conventional fully overlapped NOMA signals, P-NOMA signals are partially overlapped with an overlap rate that can be determined based on quality-of-service (QoS) requirements. Simulation results demonstrate that judicious utilization of P-NOMA can effectively enhance overall system performance, particularly in terms of sum rate (SR) metrics, while also flexibly accommodating diverse QoS requirements for multiple users.

Keywords: Partial non-orthogonal multiple access (P-NOMA), Device-to-device (D2D), Sum rate (SR), Outage performance

1 Introduction

The power-domain non-orthogonal multiple access (NOMA) has gained significant attention since the inception of discussions on 5G networks [1–4]. In contrast to orthogonal multiple access (OMA), NOMA facilitates spectrum sharing among multiple users and enhances accessibility through power-domain resource differentiation.

The cooperative transmission method has subsequently been employed in conventional NOMA systems [5–9] to exploit spatial diversity, with varying assumptions on channel state information (CSI) and channel models [10–12]. These approaches enable reduced system redundancy and improved fairness to be achieved. In the upcoming 6G-driven Internet of Things (IoTs) systems, a new ambient backscatter aided NOMA technology is proposed [13] to meet the requirements of lower power demand and higher transmission reliability, where not only physical layer authentication [14] but also finite SNR diversity multiplexing trade-off [15] is analyzed. Furthermore, several research works [16–18] have investigated an efficient device-to-device (D2D)-aided

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relaying approach for enhancing spectrum efficiency. By using D2D collaborative approach, nearby strong signal user equipment could act as a relay during transmission instead of relying on a specific relay node. Specifically for multi-user D2D communications, a two-layer transmission scheme has been proposed [19], along with a corresponding two-stage power allocation (PA) method based on the quality-of-service (QoS) difference between users. As a result of these advancements, both spectral efficiency and energy efficiency of the D2D system have been enhanced.

However, previous research primarily focused on fully overlapping scenarios. To address the limitation, a novel multi-user access technology known as partial non-orthogonal multiple access (P-NOMA) has been proposed [20] to further enhance spectral efficiency by introducing partial bandwidth overlapping. Hence, it raises a new question of how its integration in a D2D-assisted multi-user scenario would impact system performance.

Based on the factors mentioned above, we propose a novel P-NOMA strategy that incorporates layered D2D transmission in a multi-user system with diverse requirements. In contrast to conventional decoding and forwarding NOMA schemes [21–23], our approach aims to optimize wireless resource utilization by transmitting partially overlapping NOMA signals at specific phases. However, the reduction of outage probability primarily relies on the grouping operation within the multi-user system. To enhance the SR performance of all groups and minimize system-wide outage probability, we incorporate D2D auxiliary manners. The key contributions can be summarized as follows:

- The novel P-NOMA technique is proposed in a multi-user system to effectively utilize D2D auxiliary transmission at the BS edge, catering to a wider range of users' services. To meet the QoS requirements of user groups and intra-group channel conditions, we divide either signal overlapped rate or power allocation into two stages. Unlike conventional schemes, we investigate a concise partial protocol during the initial stage of two-stage communication to strike a better balance between interference and achievable rates in the multi-group system.
- To expand communication coverage and serve more users, strong users at the edge of the BS within each group decode P-NOMA signals from the BS and reconstruct new NOMA signals based on intra-group channel qualities before forwarding them within their respective groups. This approach leverages D2D assistance in the communication system by utilizing strong users as relay nodes. It not only expands spatial signal transmission but also improves resource efficiency.
- We evaluate the performance of our proposed scheme in terms of achievable rates and outage probability by considering independent Rayleigh fading channels. The closed-form expressions are derived for accurate evaluation. Numerical results validate the accuracy and superiority of our proposed P-NOMA scheme.

The remaining sections of this paper are structured as follows: Sect. 2 introduces the research problem and the proposed model, while Sect. 3 analyzes the performance in terms of achievable SR and outage probability. System simulation conditions and results are provided in Sect. 4, with a conclusion provided in Sect. 5.

2 Methods/experimental

Consider a multi-user D2D aiding network, where P-NOMA strategy is employed for layered transmission from the BS to "relay nodes", while NOMA is utilized for serving intra-group users. Without loss of generality, the network consists of two groups with distinct QoS requirements, and all nodes operate in single-antenna half-duplex mode. During the first stage, the BS serves m ($m = 2$) groups via channels denoted by h_{SD_m}. Subsequently, the strong users acting as "relay nodes" will decode and forward signals in the next stage, via channels denoted by $h_{D_m U_n}$. For the sake of distinction, i and j represent the number of users in group 1 and group 2, respectively. Additionally, P_t and P_r denote the transmitted powers of the BS and relay nodes. Furthermore, it is assumed that the independent and identically Rayleigh fading is experienced in system with variances λ_{SD_m} and $\lambda_{D_m U_n}$, respectively.

2.1 P-NOMA scheme

The P-NOMA protocol was initially investigated in [20], and the utilization of partially overlapping subcarrier signals was explored to enhance the achievable sum rate and provide greater system flexibility. Additionally, by controlling the extent of the overlap ratio, interference caused by fully bandwidth overlapped signals from other users can be reduced, achieving a balance between overlap ratio and interference. However, for simplicity and suitability in two independent regional groups, the transmitted partial overlap signals including OMA and NOMA regions can be further simplified as shown in Fig. 1 (similar to reference [24]). Consequently, for a system with two different QoS regional groups, partial overlapped group signals are transmitted from the source BS. Herein, A represents a combination of fully OMA and partially NOMA overlapped signals, while B denotes only partially overlapped NOMA signal. In other words, the former is allocated more subcarrier signals than the latter based on their respective QoS requirements differences. Specifically speaking, A and B represent the signals of each group with an overlap ratios of $\zeta + \eta = 1$ as well as the power allocation coefficients of $a_1 + a_2 = 1$.

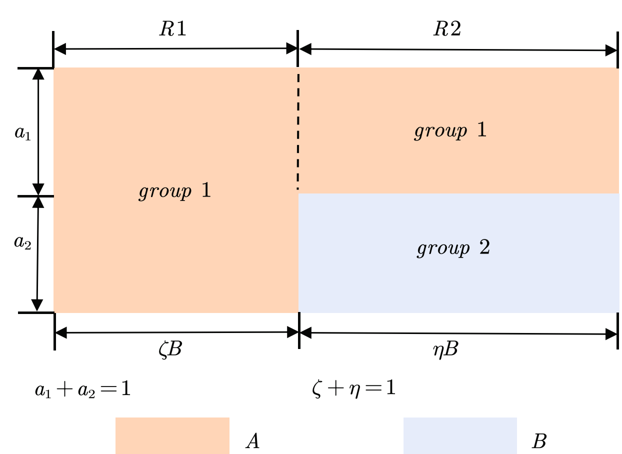

Fig. 1 Partial NOMA scheme for two-group system

Based on the signal structure of the above protocol, the received SINRs at "relay nodes" for group signals A and B can be expressed as

$$\mathrm{SINR}_{D_m}(A)[f] = \begin{cases} \left|h_{SD_m}\right|^2 \rho & \text{for} \quad f \in R_1 \\ \frac{\left|h_{SD_m}\right|^2 a_1 \rho}{\left|h_{SD_m}\right|^2 a_2 \rho + 1} & \text{for} \quad f \in R_2 \end{cases} \tag{1}$$

and

$$\mathrm{SINR}_{D_m}(B)[f] = \left|h_{SD_m}\right|^2 a_2 \rho \qquad for \quad f \in R_2 \tag{2}$$

where f represents the subcarrier in the frequency domain, ρ signifies the transmit SNR, R_1 and R_2 denote the non-overlapping and overlapping regions, respectively, while ζ and η are mainly used in subsequent calculations.

2.2 P-NOMA-based layered D2D scheme

Inspired by the advantages of P-NOMA, a concise partial overlapped protocol is considered in a multi-user two-layer D2D communication system, i.e., P-NOMA is used in the direct transmission layer while traditional NOMA in the relay forwarding phase. Without loss of generality and readability, multi-user in this paper is gathered together based on their prejudged QoS requirements and into two groups. For more details, users in group 1 demand for more QoS, and hence the target data rate or threshold is going to be high, while users in group 2 have low QoS requirements and lower target data rate or threshold. Consequently, two distinct groups are formed based on the diverse QoS requirements of regional users. The node exhibiting superior reception performance within each group assumes the role of a "relay node" to facilitate signal transmission within the groups, as illustrated in Fig. 2.

Considering the maximization of system achievable rate, the P-NOMA protocol is implemented from the BS to D_1 and D_2. In other words, a partial overlapping strategy is employed in the first level of the two-layer system. Different from the previous research, in the first slot, the BS transmits a composite signal including OMA part and NOMA part, with $\sqrt{P_t}A$ in R_1 and $\sqrt{a_1 P_t}A$ in R_2 for group 1 as well as $\sqrt{a_2 P_t}B$ in R_2 only for group 2, where A or B is the signal of the corresponding group m ($m \in \{1, 2\}$),

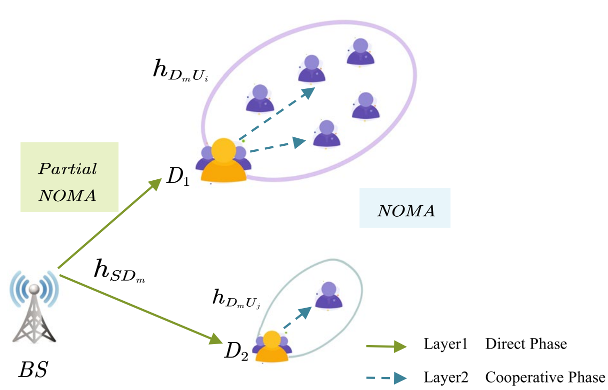

Fig. 2 The proposed P-NOMA-based layered D2D scheme

a_1 and a_2 are power allocation coefficients, respectively. Here, the difference is that the bandwidth is divided into two parts: one is for OMA, and the other is for NOMA. Overall, in unit bandwidth $(\zeta + \eta)B$ in Fig. 1, it is a partial NOMA structure, where ζB portion corresponds to OMA and ηB portion to NOMA. It is assumed that the power allocation coefficients of the first stage depend on the regional target data rates, and there is $a_1 \geq a_2$ since the users' QoS requirements in group 1 are greater than the requirements in group 2. Following the proposed decoding principle, the relay node D_1 will decode signal A for group 1 by OMA and partially by NOMA, i.e., OMA in R_1 and NOMA in R_2 frequency domain. To obtain signal B for group 2, SIC technology is also acquired at D_2. Obviously, in this manner, the received SINRs $\gamma_{SD_m}^{A}$ and $\gamma_{SD_m}^{B}$ at relay m node can be referenced by the above expressions (1) and (2) as

$$\gamma_{SD_1}^{A}[f] = \begin{cases} \left|h_{SD_1}\right|^2 \rho & for \quad f \in R_1 \\ \frac{\left|h_{SD_1}\right|^2 a_1 \rho}{\left|h_{SD_1}\right|^2 a_2 \rho + 1} & for \quad f \in R_2 \end{cases}. \tag{3}$$

and

$$\gamma_{SD_2}^{B}[f] = \left|h_{SD_2}\right|^2 a_2 \rho \qquad for \quad f \in R_2 \tag{4}$$

where the normalized additive white Gaussian noise (AWGN) $n_{D_m} \sim \mathcal{CN}(0, \sigma^2)$ is used during the first P-NOMA transmission with $\rho = \frac{P_t}{\sigma^2}$. According to the discussed power allocation criterion, parameters a_1 and a_2 can be deduced from the predicted data rates of groups.

Given the intra-group transmission nature, the second level of transmission pertains to conventional NOMA and is contingent upon the link qualities between relay node m and the inner-group users. To enhance the capacity of signal relaying and communication networks, a D2D strategy is employed at the relay layer in Fig. 2. Specifically, the most optimal receiving user is selected to partially decode signals from the BS and subsequently forwards the reconstructed NOMA signal S_{D_m} to other users within the inner group through device-to-device mode. Furthermore, in order to enhance system performance and minimize energy consumption among groups, a regional target transmission strategy is implemented. This involves decoding signal A and B within their respective groups before forwarding them to the corresponding users. Additionally, as previously mentioned, the users within each group are arranged based on their channel qualities. For the purpose of facilitating analysis, the assumption is made that there is $\left|h_{D_m U_1}\right|^2 \leq \cdots \leq \left|h_{D_m U_n}\right|^2$. Without loss of generality, the use of NOMA means $b_1 \geq b_2 \cdots b_{i-1} \geq b_i$ with $\sum_{n=1}^{i} b_n = 1$ for relay node D_1 in group 1 and $c_1 \geq c_2 \cdots c_{j-1} \geq c_j$ with $\sum_{n=1}^{j} c_n = 1$ for relay node D_2 in group 2, where b_n and c_n denote the second-level power allocation coefficients. In other words, the parameters b_n and c_n only need to satisfy the sorting relationship of the channel qualities during each group. Consequently, the transmitted signals at nodes D_1 and D_2 can be written as $S_{D_1} = \sqrt{b_1 P_{r_1}} x_1 + \sqrt{b_2 P_{r_1}} x_2 + \cdots + \sqrt{b_{i-1} P_{r_1}} x_{i-1} + \sqrt{b_i P_{r_1}} x_i$ and $S_{D_2} = \sqrt{c_1 P_{r_2}} z_1 + \sqrt{c_2 P_{r_2}} z_2 + \cdots + \sqrt{c_{j-1} P_{r_2}} z_{j-1} + \sqrt{c_j P_{r_2}} z_j$, where $P_{r_m} = a_m P_t$ denotes the transmitted power of relay. Finally, the received signal can be, respectively, described as $y_{D_1U_i} = h_{D_1U_i}S_{D_1} + n_{D_1U_i}$ and $y_{D_2U_j} = h_{D_2U_j}S_{D_2} + n_{D_2U_j}$, where $n_{D_mU_n}$ denotes the additive white Gaussian noise with zero mean and variance σ^2.

Considering the reception and decoding of signals, both SINR and SNR are employed due to slight variations in the last user compared to the preceding ones. For instance, in group 1, user 1 to user $i-1$ employs SINR for decoding, while the last user i employs SNR for decoding. Consequently, there will be corresponding expressions of SINRs for $x_k\,(1 \le k \le i-1)$ and an expression of SNR for x_i, as depicted below

$$\gamma^{1k}_{D_1,U_{1k}} = \frac{\left|h_{D_1U_k}\right|^2 b_k \xi_1}{\left|h_{D_1U_k}\right|^2 \sum_{e=k+1}^{i} b_e \xi_1 + 1} \tag{5}$$

and

$$\gamma^{1i}_{D_1,U_{1i}} = \left|h_{D_1U_i}\right|^2 b_i \xi_1 \tag{6}$$

where $\xi_1 = \frac{P_{r_1}}{\sigma^2} = a_1\rho$ denotes the transmit SNR in group 1. Accordingly, the expressions for SINRs and SNR in group 2 can be shown as

$$\gamma^{2l}_{D_2,U_{2l}} = \frac{\left|h_{D_2U_l}\right|^2 c_l \xi_2}{\left|h_{D_2U_l}\right|^2 \sum_{f=l+1}^{j} b_f \xi_2 + 1} \tag{7}$$

and

$$\gamma^{2j}_{D_2,U_{2j}} = \left|h_{D_2U_j}\right|^2 c_j \xi_2 \tag{8}$$

where ξ_2 denotes the transmit SNR in group 2 with the value of $a_2\rho$.

3 Performance analysis

In this section, we will analyze the performance of our proposed P-NOMA-based layered D2D scheme for independent Rayleigh fading channels in terms of the ergodic SR and the outage probability.

3.1 Ergodic SR analysis

Assume that the achievable rates for signals can always be uniformly described as $R^k_{SD_m}$; based on Shannon's theorems, $R^{D_m}_{\text{sum}} = \sum_{k=1}^{n} R^k_{SD_m}$ is the SR performance of each group with the general form $R^k_{SD_m} = \frac{B}{2}\log_2(1 + \min\{\gamma^{\text{M}}_{\text{SD}_\text{m}}, \gamma^{\text{mk}}_{\text{D}_\text{m}\text{U}_\text{mk}}\})$ where M is the received message A/B for group $m(1/2)$ as revealed in the aforementioned model. Therefore, $R_{\text{sum}} = \sum_{m=1}^{2} R^{D_m}_{\text{sum}}$ is evidently the SR of the proposed system network.

For the sake of facilitating subsequent analysis, denoting $\left|h_{SD_m}\right|^2 = \lambda_{SD_m}$ and $\left|h_{D_mU_n}\right|^2 = \lambda_{D_mU_n} = \lambda_{D_{mn}}$, from (3) and (4), the expression related to rate of each group during the first phase can be specifically written as $R^A_{SD_1} = \frac{\zeta B}{2}\log_2(1 + \lambda_{SD_1}\rho) + \frac{\eta B}{2}\log_2(1 + \frac{\lambda_{SD_1}a_1\rho}{\lambda_{SD_1}a_2\rho + 1})$ and $R^B_{SD_2} = \frac{\eta B}{2}\log_2(1 + \lambda_{SD_2}a_2\rho)$. In addition, considering the second relaying phase, combined with (5) and (6), the rate expression for the preceding k-th user in group 1 could be described as

$$\begin{aligned}\mathcal{Q}_1 =&\min\left\{\gamma^{\mathrm{A}}_{\mathrm{SD_1}}[\mathrm{f}],\gamma^{\mathrm{1k}}_{\mathrm{D_1U_{1k}}}\right\}\\ =&\min\left\{\chi_1,\chi_2\right\}.\end{aligned} \tag{9}$$

where $\chi_1 = \zeta\lambda_{SD_1}\rho + \eta\frac{\lambda_{SD_1}a_1\rho}{\lambda_{SD_1}a_2\rho+1}$ and $\chi_2 = \frac{\lambda_{D_{1k}}b_k a_1\rho}{\lambda_{D_{1k}}\tau a_1\rho+1}$ with $\tau = \sum_{e=k+1}^{i} b_e$. Moreover, for the last user i in group 1, the rate expression could be described as

$$\begin{aligned}\mathcal{G}_1 =&\min\left\{\gamma^{\mathrm{A}}_{\mathrm{SD_1}}[\mathrm{f}],\gamma^{\mathrm{1i}}_{\mathrm{D_1U_{1i}}}\right\}\\ =&\min\left\{\chi_1,\chi_3\right\}\end{aligned} \tag{10}$$

where χ_1 is given as shown earlier and $\chi_3 = \lambda_{D_{1i}}b_i a_1\rho$. Hence, from equations (9) and (10), using the complementary cumulative distribution function (CCDF), the probability density function (PDF) and some complex calculations, the rates of all users' in group 1 could be deduced.

Considering the statistical distribution, the CCDF of $\mathcal{Q}_1$ can be formulated as $\overline{F}_{\mathcal{Q}_1}(q_1) = \Pr\left\{\chi_1{>}q_1,\chi_2{>}q_1\right\}$. Suppose that the CCDF of λ_δ is $\overline{F}_{\lambda_\delta}(q) = e^{-\frac{q}{\beta_\delta}}$ for $\delta\in\{SD_m,D_{mn}\}$; hence, $\overline{F}_{\mathcal{Q}_1}(q_1) = e^{-\phi q_1}$ always holds under certain conditions. According to [10], the rate for preceding user k in group 1 could be solved as

$$\begin{aligned}C^k_{SD_1} =&\int_0^\infty \frac{1}{2}\log_2(1{+}q_1)f_{\mathcal{Q}_1}(q_1)dq_1\\ =&\frac{1}{2\ln 2}\int_0^\infty \frac{1-F_{\mathcal{Q}_1}(q_1)}{1+q_1}dq_1\\ =&-\frac{1}{2\ln 2}\left(e^{\mu}\mathrm{Ei}(-\mu) - \mathrm{e}^{\nu}\mathrm{Ei}(-\nu)\right),\end{aligned} \tag{11}$$

where $\mu = \frac{1}{\rho\beta_{SD_1}}{+}\frac{1}{a_1\rho\beta_{D_{1k}}}$, $\nu = \frac{1}{a_2\rho\beta_{SD_1}}{+}\frac{1}{\tau a_1\rho\beta_{D_{1k}}}$. For g_1, considering the case of high SNR, where $\frac{\lambda_{SD_1}a_1\rho}{\lambda_{SD_1}a_2\rho+1}{\sim}\frac{a_1}{a_2}$, after some mathematical manipulations, the rate for the last user, i.e., $C^i_{SD_1}$, could be expressed as

$$\begin{aligned}C^i_{SD_1} =&\frac{1}{2\ln 2}\int_0^\infty \frac{1-F_{\mathcal{G}_1}(g_1)}{1+g_1}dg_1\\ =&\frac{-1}{2\ln 2}e^{\alpha}\left(\mathrm{Ei}(-\kappa)\right),\end{aligned} \tag{12}$$

where $\alpha = \frac{1}{a_2\zeta\rho\beta_{SD_1}} + \frac{1}{b_i a_1\rho\beta_{D_{1i}}}$ and $\kappa = \frac{1}{b_i a_1\rho\beta_{D_{1i}}} + \frac{1}{\zeta\rho\beta_{SD_1}}$. Combining (11) and (12), the closed-form expression of all users' SR in group 1 could be written as $C^{D_1}_{\mathrm{sum}} = \sum_{k=1}^{i-1} C^k_{SD_1}{+}C^i_{SD_1}$. Similarly, considering users in group 2, the corresponding $\mathcal{Q}_2$ and $\mathcal{G}_2$ could be expressed as

$$\begin{aligned}\mathcal{Q}_2 =&\min\left\{\gamma_{\mathrm{SD_2}}^{\mathrm{B}}[\mathrm{f}], \gamma_{\mathrm{D_2U_{2l}}}^{\mathrm{2l}}\right\}\\ =&\min\left\{\chi_4, \chi_5\right\}\end{aligned} \tag{13}$$

with $\chi_4 = \eta\lambda_{SD_2}a_2\rho$, $\chi_5 = \frac{\lambda_{D_{2l}}c_l a_2\rho}{\lambda_{D_{2l}}\tau' a_2\rho+1}$ and $\tau' = \sum_{f=l+1}^{j} c_f$, whereas

$$\begin{aligned}\mathcal{G}_2 =&\min\left\{\gamma_{\mathrm{SD_2}}^{\mathrm{B}}[\mathrm{f}], \gamma_{\mathrm{D_2U_{2j}}}^{\mathrm{2j}}\right\}\\ =&\min\left\{\chi_4, \chi_6\right\}\end{aligned} \tag{14}$$

with $\chi_6 = \lambda_{D_{2j}}c_j a_2\rho$. In this case, there is a simpler χ_4. Hence, the closed-form expression of rates would be more convenient than the former. It can be seen from (13) and (14) that the rates of user l and user j in group 2 can also be deduced by using the analysis method similar to that in group 1. Specifically, the closed-form expressions could be indicated as

$$C_{SD_2}^{l} = \frac{1}{2\ln 2}e^{\eta'}\left(\mathrm{Ei}\left(-\psi'\right) - \mathrm{Ei}\left(-\eta'\right)\right), \tag{15}$$

where $\eta' = \frac{1}{\eta a_2\rho\beta_{SD_2}}$ and $\psi' = \frac{1}{\eta a_2\tau'\rho\beta_{SD_2}}$, as well as

$$C_{SD_2}^{j} = -\frac{1}{2\ln 2}e^{\mu'}\mathrm{Ei}\left(-\mu'\right) \tag{16}$$

where $\mu' = \frac{1}{\eta a_2\rho\beta_{SD_2}} + \frac{1}{a_2\rho c_j\beta_{D_{2j}}}$. Then, the closed-form SR expression for users in group 2 is $C_{\mathrm{sum}}^{D_2} = \sum_{l=1}^{j-1} C_{SD_2}^{l} + C_{SD_2}^{j}$. Finally, the closed-form expression of the total SR for P-NOMA layered D2D system could be clearly indicated as $C_{\mathrm{sum}} = C_{SD_1}^{\mathrm{sum}} + C_{SD_2}^{\mathrm{sum}}$. Up to this point, the first performance analysis in terms of SR is complete.

3.2 Outage probability analysis

To further investigate performance, the outage probability will continue to be analyzed. Given the users' QoS requirements, each user has a predetermined target data. Once the link capacity fails to meet the demand, system communication will be interrupted. Following the above, the outage probability of the proposed P-NOMA layered D2D system will be analyzed. In group 1, assume that the target rate of user k is R_{1k}, and the predefined target data rate threshold is $R_{\mathcal{T}_{1k}}$; hence, the outage probability expressed by OP_1 could be described as

$$\begin{aligned} OP_1 =&1\text{–}\Pr\Big\{R_{11}>2^{2R_{\mathcal{T}_{11}}}-1\cdots R_{1k}>2^{2R_{\mathcal{T}_{1k}}}-1\\ =&\cdots R_{1i}>2^{2R_{\mathcal{T}_{1i}}}-1\Big\}\\ =&1\text{–}\Pr\Big\{\Big(R_{11}>2^{2R_{\mathcal{T}_{11}}}-1\Big)\cap\cdots\cap\Big(R_{1i}>2^{2R_{\mathcal{T}_{1i}}}-1\Big)\Big\}\\ =&1\text{–}\prod_{k=1}^{i}\underbrace{\Pr\Big(R_{1k}>2^{2R_{\mathcal{T}_{1k}}}-1\Big)}_{\mathcal{M}_{1k}}. \end{aligned} \tag{17}$$

For simplicity, it is assumed that $\omega_{1k}=2^{2R_{\mathcal{T}_{1k}}}\text{–}1$ in analysis. Based on the SR analysis above, the $\mathcal{M}_{1k}$ could be expressed as

$$\begin{aligned} \mathcal{M}_{1k} =&\Pr\Big\{\min\Big\{\gamma^{\mathrm{A}}_{\mathrm{SD_1}},\gamma^{\mathrm{1k}}_{\mathrm{D_1,U_{1k}}}\Big\}>\omega_{\mathrm{1k}}\Big\}\\ =&\Pr\big\{\gamma^{A}_{SD_1}>\omega_{1k}\big\}\Pr\big\{\gamma^{1k}_{D_1,U_{1k}}>\omega_{1k}\big\}, \end{aligned} \tag{18}$$

i.e., $\mathcal{M}_{1k}\approx e^{-\frac{\omega_{1k}}{(a_1\rho-a_2\rho\omega_{1k})\beta_{SD_1}}-\frac{\omega_{1k}}{(b_ka_1\rho-\tau a_1\rho\omega_{1k})\beta_{D_{1k}}}}$ for the high transmit SNR case according to the above analysis. However, for the last case, i.e., $k=i$, there is an approximate expression described as $\mathcal{M}_{1i}\approx e^{-\frac{\omega_{1i}}{(a_1\rho-a_2\rho\omega_{1i})\beta_{SD_1}}-\frac{\omega_{1i}}{(b_ia_1\rho)\beta_{D_{1i}}}}$. By substituting $\mathcal{M}_{1k}$ and $\mathcal{M}_{1i}$ back into (17), the outage probability for group 1 could be approximated by Eq. (19) as shown below.

$$\begin{aligned} OP_1 =&1-\prod_{k=1}^{i}\underbrace{\Pr\Big(R_{1k}>2^{2R_{\mathcal{T}_{1k}}}-1\Big)}_{\mathcal{M}_{1k}}\\ \approx&1-e^{-\Sigma_{k=1}^{i-1}\left(\frac{\omega_{1k}}{(a_1\rho-a_2\rho\omega_{1k})\beta_{SD_1}}+\frac{\omega_{1k}}{(b_ka_1\rho-\tau a_1\rho\omega_{1k})\beta_{D_{1k}}}\right)-\frac{\omega_{1i}}{(a_1\rho-a_2\rho\omega_{1i})\beta_{SD_1}}-\frac{\omega_{1i}}{(b_ia_1\rho)\beta_{D_{1i}}}} \end{aligned} \tag{19}$$

For the users in group 2, the outage probability OP_2 can also be obtained by using a similar analysis method with the target rate described as R_{2l} and the predefined threshold as $R_{\mathcal{T}_{2l}}$. The specific expression is shown in Eq. (20). Up to now, two performance indexes have been analyzed.

$$\begin{aligned} OP_2 =&1-\prod_{l=1}^{j}\underbrace{\Pr\Big(R_{2l}>2^{2R_{\mathcal{T}_{2l}}}-1\Big)}_{\mathcal{M}_{2l}}\\ =&1-e^{-\Sigma_{l=1}^{j-1}\left(\frac{\omega_{2l}}{(\eta a_2\rho)\beta_{SD_2}}+\frac{\omega_{2l}}{(c_la_2\rho-\tau' a_2\rho\omega_{2l})\beta_{D_{2l}}}\right)-\frac{\omega_{2j}}{(\eta a_2\rho)\beta_{SD_2}}-\frac{\omega_{2j}}{(c_ja_2\rho)\beta_{D_{2j}}}} \end{aligned} \tag{20}$$

4 Numerical results

In this section, the performance simulations of the proposed P-NOMA-based layered D2D scheme are evaluated and compared with several previous schemes. For the convenience of simulation, the scenario of two users ($i=2$) in group 1 and one user ($j=1$) in group 2 is considered. Furthermore, assume that all numerical results are averaged over 50,000 channel realizations. In addition, the power distribution follows the characteristics and structure of system model, namely layered, mixed and D2D NOMA.

In Fig. 3, for ergodic SRs, the analytical results match the simulated results well. Especially after 15dB, the SR of the proposed scheme is significantly improved compared

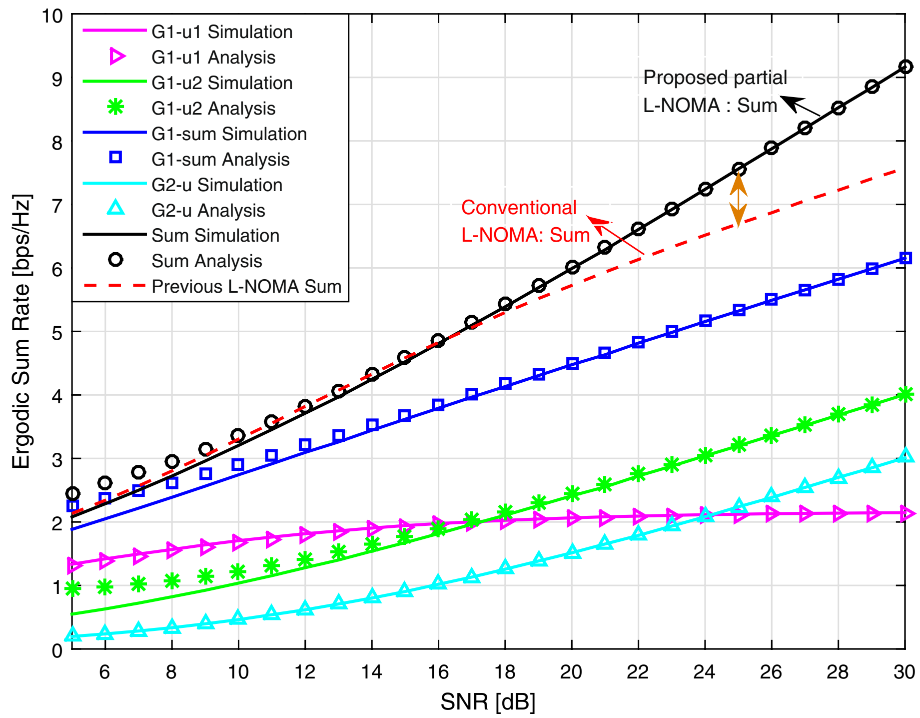

Fig. 3 The ergodic SRs achieved by the proposed partial L-NOMA and conventional L-NOMA schemes with respect to transmit SNR

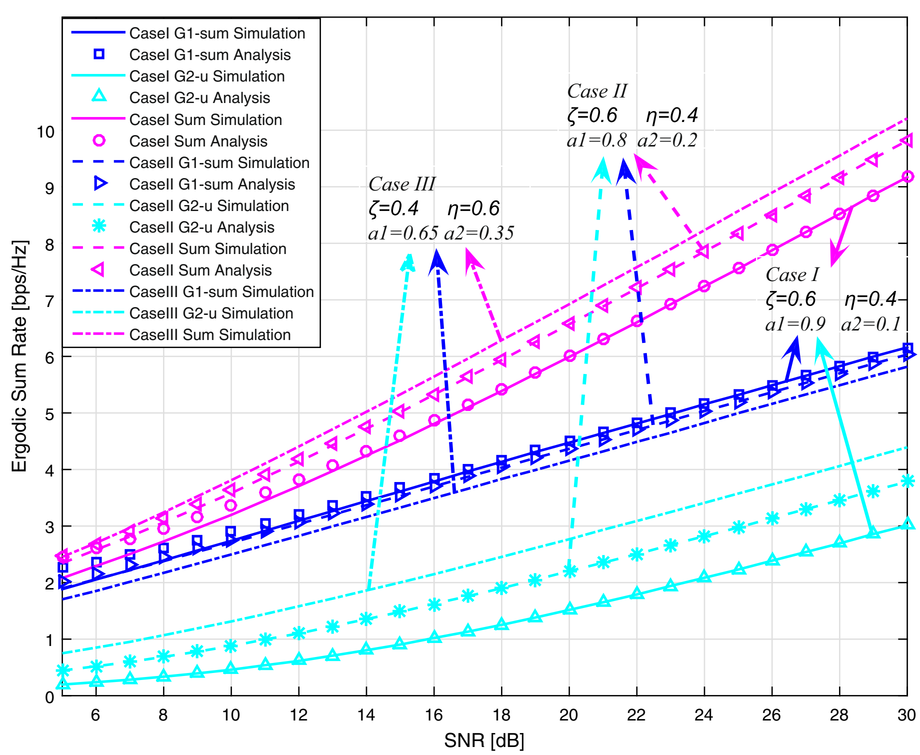

Fig. 4 The ergodic SRs achieved by the proposed partial L-NOMA scheme versus three cases of different PA factors and partial rates

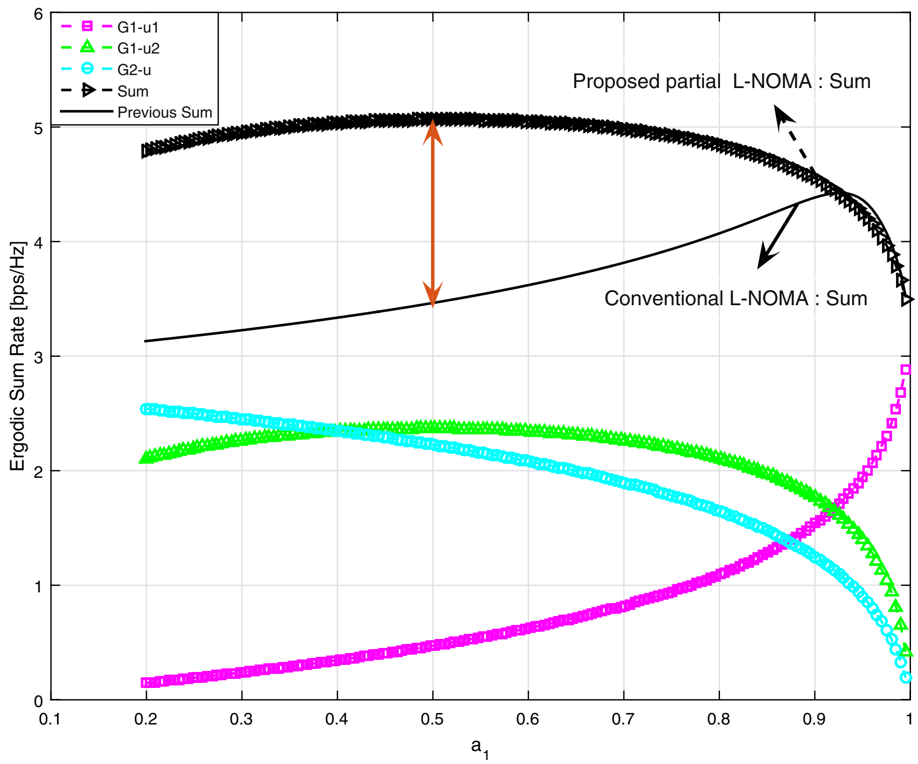

Fig. 5 The ergodic SRs achieved by the proposed partial L-NOMA and conventional L-NOMA schemes versus different power allocation factors a_1 for transmit SNR as $\rho = 15$ dB

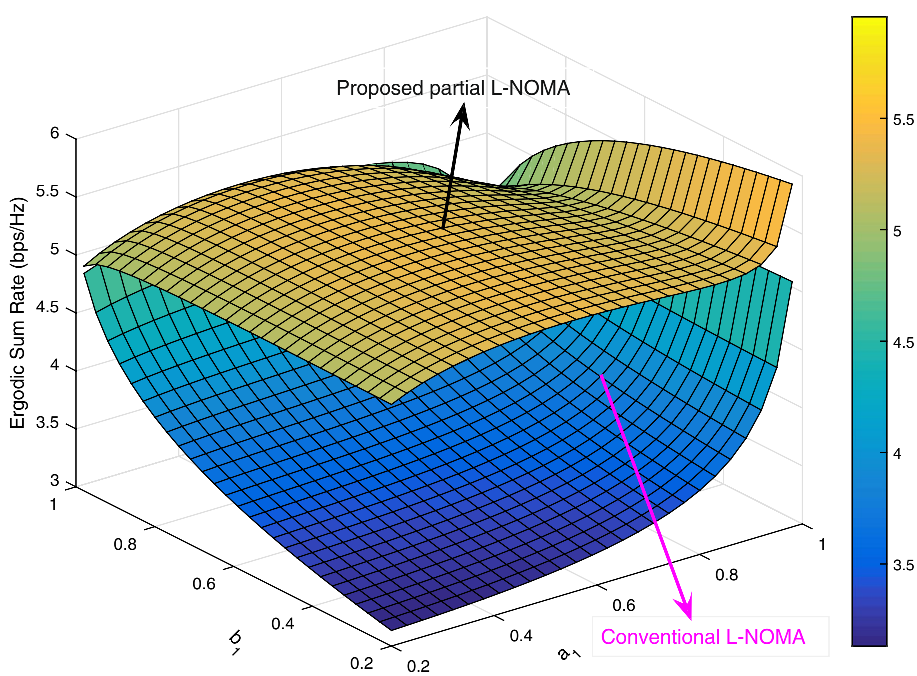

Fig. 6 The ergodic SRs achieved by the proposed partial L-NOMA and conventional L-NOMA schemes versus different power allocation factors a_1 and b_1 for transmit SNR as $\rho = 15$

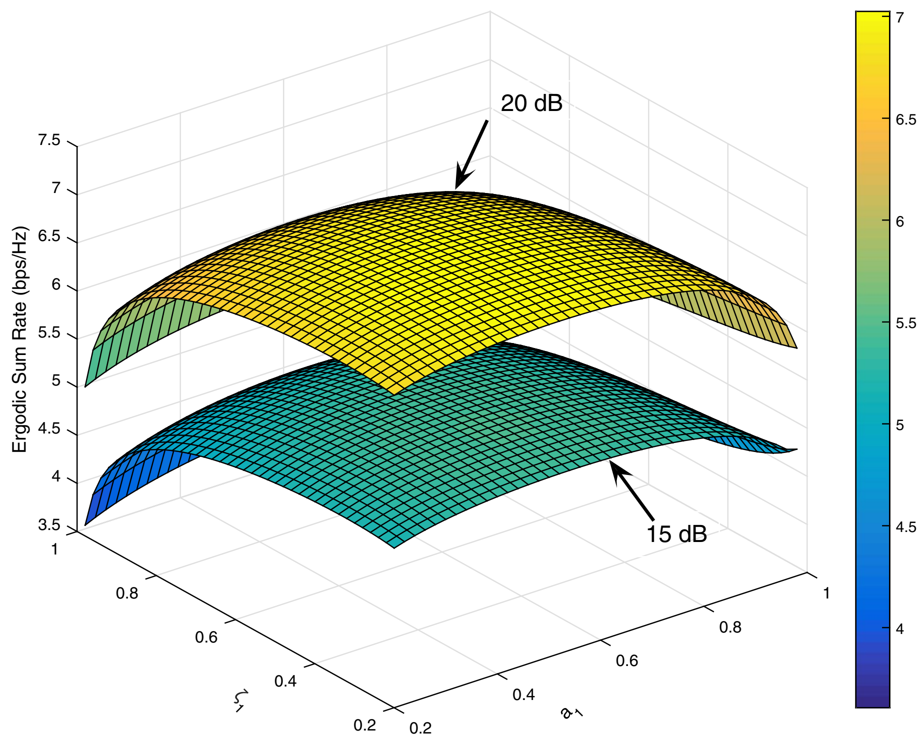

Fig. 7 The ergodic SRs achieved by the proposed partial L-NOMA scheme versus different power allocation factors a_1/b_1 and partial rates ζ for transmit SNR as $\rho = 15$ and $\rho = 20$ dB

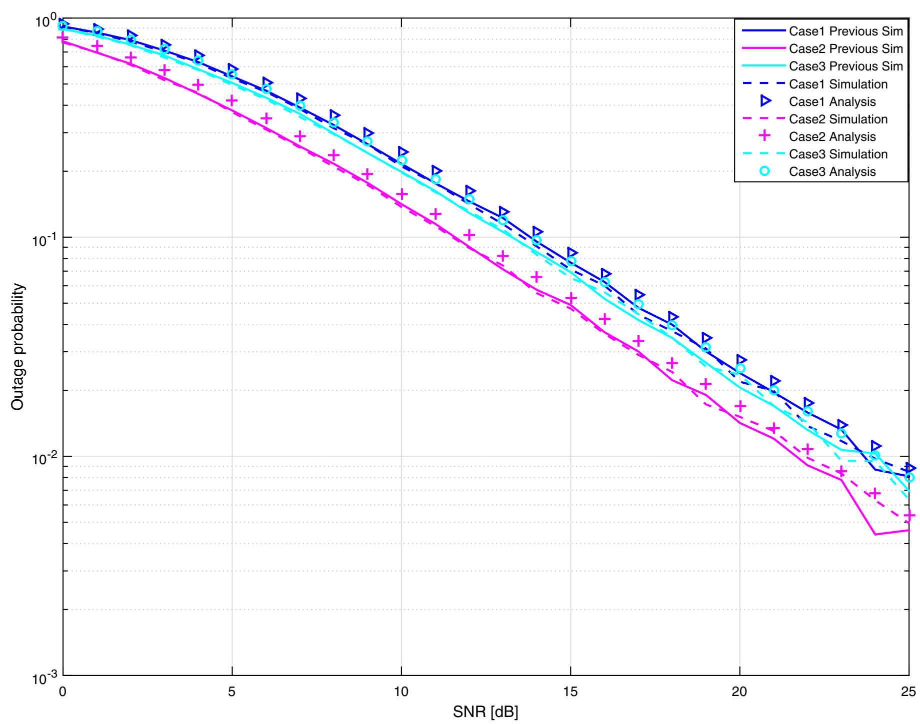

Fig. 8 The outage probability for group 1 (O_1) in three cases. Case 1 versus the target rate as 0.6 with fixed $\lambda_{SD_1} = 10$, $\lambda_{D_{11}} = 4$ and $\lambda_{D_{12}} = 6$, as well as $\lambda_{SD_2} = 6$ and $\lambda_{D_{21}} = 6$. Case 2 versus the same target rate in case 1 with fixed $\lambda_{SD_1} = 18$, $\lambda_{D_{11}} = 6$ and $\lambda_{D_{12}} = 10$, as well as $\lambda_{SD_2} = 10$ and $\lambda_{D_{21}} = 5$. Case 3 versus the target rate as 0.75 with the same channel parameters in case 2

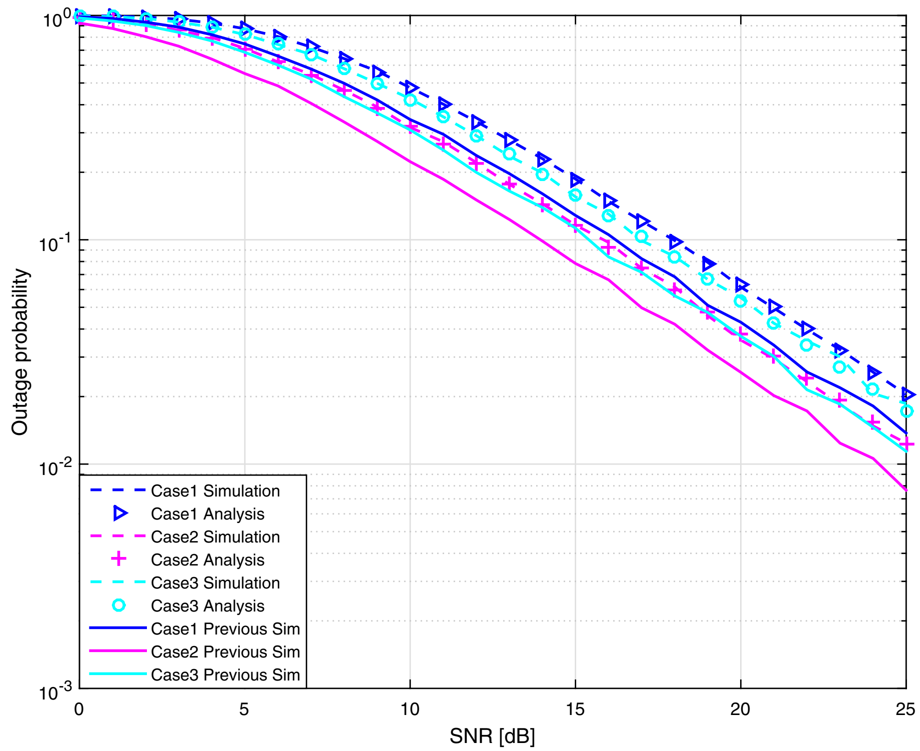

Fig. 9 The outage probability for group 2 (O_2) in the above three cases as in Fig. 8 versus the transmit SNR

with the previous layered NOMA (L-NOMA). In Fig. 4, the differences of inter-group and inner-group rates are demonstrated under different PA factors and partial rates. In Fig. 5, the two-dimensional diagram of the SRs versus power allocation factors with fixed transmit SNR is investigated, whereas Fig. 6 corresponds to the three-dimensional diagram. Furthermore, the ergodic SRs versus partial rate ζ is considered under two different transmit SNRs, as shown in Fig. 7. In addition, the outage performance of the proposed layered D2D P-NOMA scheme and the difference with the previous scheme [19] are studied in Fig. 8 for O_1 and in Fig. 9 for O_2, separately. Finally, Fig. 10 illustrates the improvement of system outage performance by comparing the proposed partial layered NOMA scheme in this paper with the conventional NOMA, the previous L-NOMA [19] and the partial NOMA schemes.

4.1 Ergodic SR

Figure 3 shows the ergodic rates of the proposed partial L-NOMA and conventional L-NOMA schemes with fixed channel parameters when $a_1 = 0.9$, $a_2 = 1 - a_1$, as well as $b_1 = a_1$, $b_2 = a_2$, $c_1 = 1$ and $\zeta = 0.6$, $\eta = 1 - \zeta$. Due to the approximation of the analytical formula, at low transmit SNR, the theoretical analysis of the exact average rate is not in perfect agreement with the simulation results. However, in the high SNR region, especially $\rho \geq 15$ dB, the asymptotic results match the simulation results well, which is consistent with the practical situation. Hence, the advantages of our proposed scheme are also evident in the high SNR region. Obviously, the simulation

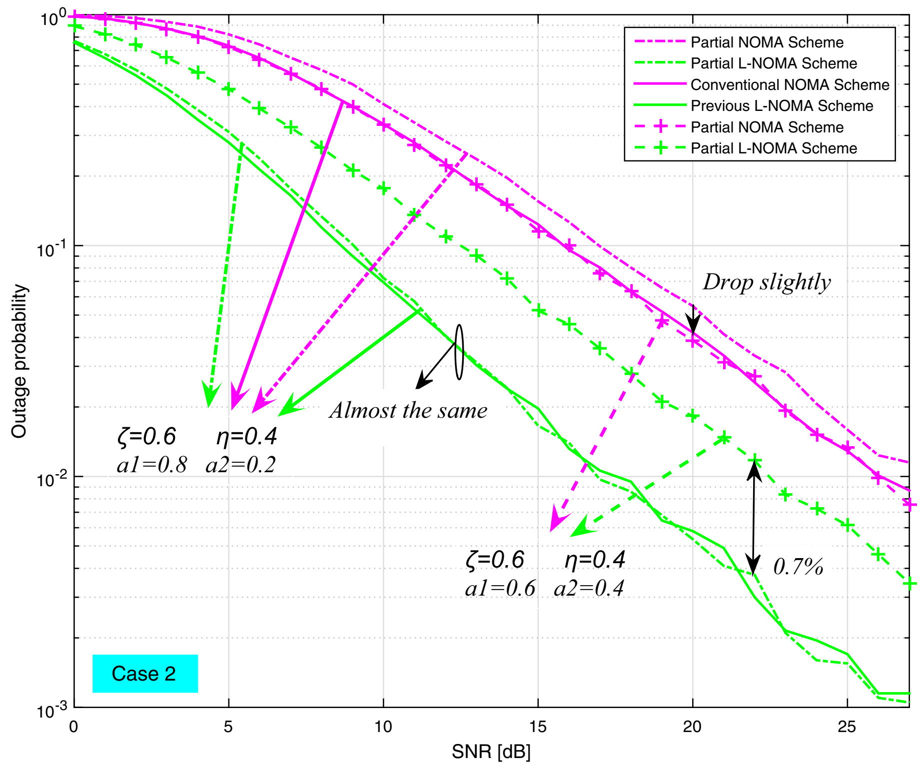

Fig. 10 Comparison of the outage probability for whole system between the proposed scheme and three other previous NOMA schemes versus different power allocation factors a_1 /b_1 with particular partial rate ζ =0.6 in case 2 in Fig. 8

results agree well with the corresponding analysis results. Clearly, the sum rate of users in group 1 shown as the blue lines is greater than that in group 2 shown as the cyan lines. Considering the performance in terms of ergodic SR, the total SR of the proposed partial L-NOMA scheme is superior to the conventional L-NOMA SR after the SNR of $\rho = 15$ dB, as shown by the trend of the black and red lines. As you can see, Fig. 4 considers the SR for each group and for the entire system, involving three cases termed Cases I, II and III. In comparison with Case I, the total SR of the system in Case II increases when a_1 appropriately reduces. Hence, moderate PA factors, such as $a_1 = 0.65$ $a_2 = 0.35$, can effectively improve the total SR of whole system as shown in Case III. Meanwhile, three graphics show the same trend despite the differences between groups. As the power allocations a_1 and b_1 decrease, the rates in group 1 decrease while the rates in group 2 increase, and the increment has more effect on the total SR than the decrement as described earlier.

Figures 5 and 6 show the ergodic SR with respect to PA factors a_1 and b_1 for the proposed partial L-NOMA and conventional L-NOMA schemes with fixed transmit SNR as shown in figures, respectively. Clearly, in both the two-dimensional and the three-dimensional graphs, there are always optimal values of a_1 and b_1 that maximize the SR of the entire communication system. As can be seen from the figures, the corresponding a_1 and b_1 for the optimal ergodic SR are no longer close to 1, since partial strategy used in the first stage fully exploiting resource efficiency, which is more practical in the process of NOMA power allocation. Moreover, Figs. 5 and 6 demonstrate that the proposed scheme surpasses the conventional one and is applicable across a wide range of PA coefficients. The greatest advantage is observed at moderate PA values, approximately 0.5. However, it should be noted that the improved SR performance of the proposed scheme comes at the cost of increased system complexity, particularly in the first phase. Additionally, Fig. 7 expresses that increasing medium ζ will reduce the SR performance, which is due to the fact that a larger ζ results in more OMA and less NOMA, leading to greater performance degradation.

4.2 Outage probability

Figures 8 and 9 demonstrate the outage probability performance of the proposed partial L-NOMA and the previous conventional L-NOMA schemes for groups 1 and 2 with three cases, where the PA factors are $a_1 = b_1 = 0.8$, $a_2 = 1 - a_1$, as well as $b_2 = a_2$, $c_1 = 1$ and $\zeta = 0.6$, $\eta = 1 - \zeta$. The impact of channel parameters and thresholds on the outage probability performance has been investigated. In Fig. 8, with the increasing of channel gains as well as decreasing of the threshold in transmission, the performance of the considered schemes is improved, whereas the impact of partial rates on the performance in group 1 is insignificant. Another important observation from Fig. 9 is that the impact of partial rates ζ and η for users in group 2 is obvious, which is due to the low availability of resources for group 2 during the partial NOMA stage. Meanwhile, case 2 with the optimal outage probability can serve as a benchmark for comparing various schemes, including conventional NOMA, previous L-NOMA and partial NOMA, as well as the proposed partial L-NOMA, which is demonstrated in Fig. 10. As depicted in Fig. 10, the proposed partial L-NOMA scheme, as well as the previous L-NOMA scheme, exhibits superior performance compared to conventional NOMA and partial NOMA schemes. Furthermore, incorporating a combination of partial and layered transmission in NOMA system enhances performance, which is consistent with the observations presented in the aforementioned figures.

5 Conclusions

This paper investigated an efficient partial NOMA transmission scheme for a layered D2D system. By employing a partial strategy during the first layer, subcarrier signals can be flexibly overlapped instead of being completely covered with orthogonal or non-orthogonal signals as in OMA or NOMA schemes. Various resource allocation and overlap rate scenarios are analyzed to identify the key factors influencing the advantages of the proposed scheme. Nevertheless, integrating partial and layered transmission in D2D NOMA enhances both system performance and flexibility, enabling different trade-offs between system performance and complexity.

Abbreviations

AWGN	Additive white Gaussian noise
BS	Base station
CSI	Channel state information
CCDF	Complementary cumulative distribution function
D2D	Device-to-device
NOMA	Non-orthogonal multiple access
L-NOMA	Layered non-orthogonal multiple access

OMA	Orthogonal multiple access
P-NOMA	Partial NOMA
PA	Power allocation
QoS	Quality of services
SIC	Successive interference cancelation
SNR	Signal-to-noise ratio
SINR	Signal-to-interference-plus-noise ratio
SR	Sum rate

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Author contributions
J. Ju conceived and designed the study. J. Ju and Q. Sun performed the simulations. J. Ju wrote the paper. Q. Sun reviewed the manuscript. All authors read and approved the manuscript.

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Availability of data and materials
The authors declare that the data and materials in this study are available on request from the corresponding author.

Competing interests
The authors declare that they have no conflict of interest.

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