Joint User Pairing and Power Control for C-NOMA with Full-Duplex Device-to-Device Relaying

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***Abstract*—This paper investigates the performance of cooperative non-orthogonal multiple access (C-NOMA) in cellular downlink systems. The system model consists of a base station (BS) that needs to serve multiple users within a region of service. A subset of the users, especially those located close to the cell edge, undergo severe fading and suffer from poor channel quality and low achievable rates. To overcome this problem, C-NOMA is proposed as the system design methodology, in which users that have the capability of full-duplex (FD) communication can assist the transmissions between the BS and users with poor channel quality through device-to-device (D2D) communications. To harness both the multiplexing gain from NOMA and the diversity gain from FD-D2D communications, we formulate and solve a novel optimization problem that jointly determines D2D user pairing and power allocation. The formulated problem is a mixed-integer non-linear program (MINLP) with prohibitively high complexity. To overcome this issue, a two-step policy is proposed to solve the problem in polynomial time. Our simulation results show that with reasonable assumptions, the proposed scheme always outperforms some existing schemes in the literature, and that, under undesirable conditions, e.g., poor D2D channel conditions or imperfect self-interference (SI) cancellation, the proposed scheme is reduced to conventional NOMA.**

***Keywords*—Cooperative NOMA, device-to-device communication, user pairing, power control.**

I. Introduction

5G networks are expected to meet challenging requirements that are fueled by the rapid growth of the Internet of Things (IoT) and mobile Internet [1]. Specifically, 5G wireless technologies need to support the three generic services, namely, enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC), each imposing different service requirements [2]. These stringent requirements for each of these services are the driving force behind the explorations of novel network architectures and new transmission techniques. Recently, non-orthogonal multiple access (NOMA) has been envisioned as one of the key enablers for 5G [3].

Non-orthognonal multiple access (NOMA) is capable of supporting more users than the number of available orthogonal resources [4], thereby leading to higher spectral efficiency and user fairness when compared to standard orthogonal multiple access (OMA) techniques.[1] The principle of NOMA leverages the concept of superposition coding (SPC) at the transmitter and successive interference cancellation (SIC) at the receiver [5]. However, an efficient multiple access technique alone still cannot adequately fulfill the demanding specifications of 5G and beyond. Thus, recent research aims to further enhance the performance of NOMA by integrating it into other advanced techniques such as multiple-input-multiple-output (MIMO) [6], hybrid automatic repeat request (HARQ) [7], or device-to-device (D2D) communications combined with full-duplex (FD) relaying, also known as cooperative NOMA (C-NOMA) [8], [9].

C-NOMA has been proposed to enhance network-wide fairness by enabling users with better channel conditions to act as relays to improve the received signal quality of users with poor channel conditions. In [9], the authors proposed a C-NOMA system consisting of a base station (BS) and multiple users, where the strongest users decode and relay the weakest users' message to increase the achievable rate at the weak users. Due to the high complexity for system design, [9] proposed performing user pairing and suggested that users can be paired in a way that the distinction of channel gains from the BS to them is the highest, following the conclusion of pairing policy for conventional NOMA [10]. This pairing method, however, is not ideal since the performance of C-NOMA does not only depend on NOMA but also on the D2D links. Under some scenarios, users with distinct channel gains may experience poor D2D channel conditions; thus, they cannot yield benefits from the D2D relaying and ultimately do not exploit the full potential of C-NOMA. It is worth noting that there has been some work that tackled the pairing problem for conventional NOMA as in [10]–[12] while other related works on C-NOMA including [9], [13], [14] only consider 2-user C-NOMA systems. Zhou *et al* consider C-NOMA with random pairing only.

In this paper, we consider the same problem investigated in [9], [13], [14] but for a number of cellular users higher than 2. Therefore, to the best of our knowledge, the present paper is the first that attempts to solve the joint user pairing and power control problem for multi-user C-NOMA. By adding the D2D communication as a design degree to the optimization prob-

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[1]In this paper, the term "NOMA" is restricted to power-domain NOMA as distinct from its code-domain NOMA counterpart.

lem, C-NOMA is promised to achieve better performance than conventional NOMA, and on the other hand, makes the problem more challenging due to its combinatorial and non-convex characteristics. Our contributions in this paper are as follows.

- We revisit the concept of C-NOMA and introduce a system model for a cellular network that incorporates C-NOMA. From this, we propose and formulate a joint pairing and power control optimization problem for C-NOMA-enabled downlink communications in cellular networks.
- Since the formulated problem is a mixed-integer non-linear program, which is generally NP-hard, we decompose it into two sub-problems, one of which can be solved analytically and the other using the well-known Hungarian algorithm. Thus, a low-complexity algorithm is developed to solve the original problem.
- Our simulation results shed some lights on the system operations under different channel conditions. Specifically, we reveal that the performance of our proposed scheme is lower-bounded by that of conventional NOMA, which occurs under unfavorable channel gain and poor self-interference cancellation.

The rest of the paper is organized as follows. Section II presents the system model. Section III presents an analysis on the achievable rates. Section IV is the problem formulation and solution approach. Section V presents the simulation results and analysis under different scenarios of channel conditions. Finally, conclusions are drawn in section VI.

II. System Model

We consider a downlink communication system. The system model consists of one single-antenna BS in the center of the cell, and $2K$ ($K \in \mathbb{N}$) active users (AUs), each equipped with one receive and one transmit antenna as shown in Fig. 1. We assume that the $2K$ AUs can be grouped into K pairs, where each pair is served using power-domain NOMA [4], i.e., power-domain multiplexing at the BS and SIC at each AU. Each pair is composed of two AUs; the AU with higher channel gain is referred to as the strong AU and the AU with lower channel gain is referred to as the weak AU. In addition, we assume that the AUs have the capability of full-duplex communication in order to relay signals via D2D links. Therefore, in each pair, the strong AU can assist the communication between the BS and the weak AU through an additional D2D communication as in Fig. 2. Moreover, given that the total available cellular bandwidth at the BS is W, we assume that different pairs are served via OMA on different orthogonal sub-channels (SCs) with a bandwidth $B = \frac{W}{K}$. We refer to these pairs as C-NOMA pairs. Within each C-NOMA pair, D2D communication operates on the same SC as BS-AU communication.

The superimposed transmitted signal for a given C-NOMA pair is given, at each channel use $n \in \mathbb{N}$, by

$$s[n] = \sqrt{P_{\mathrm{w}}[n]}s_{\mathrm{w}}[n] + \sqrt{P_{\mathrm{s}}[n]}s_{\mathrm{s}}[n], \tag{1}$$

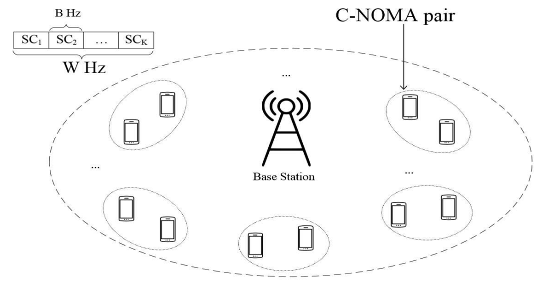

Fig. 1. An illustration of the proposed downlink C-NOMA communication systems

where $s_{\mathrm{w}}[n]$ and $s_{\mathrm{s}}[n]$ represent the intended signals for the weak AU and the strong AU, respectively, such that $\mathbb{E}(|s_{\mathrm{w}}[n]|^2) = \mathbb{E}(|s_{\mathrm{s}}[n]|^2) = 1$; $P_{\mathrm{w}}[n]$ and $P_{\mathrm{s}}[n]$ represent the transmit powers allocated to the weak AU and the strong AU, respectively. As shown in Fig. 2, for a given C-NOMA pair, we denote the channel coefficients from the BS to the weak AU, from the BS to strong AU and from the strong AU to the weak AU (D2D link) by $h_{\mathrm{w}}[n]$, $h_{\mathrm{s}}[n]$, $h_{\mathrm{d}}[n]$, respectively; moreover, we denote the SI channel coefficient at the strong AU as $h_{\mathrm{SI}}[n]$. Further, we assume that all the channel coefficients h_{w}, h_{s}, h_{d} and h_{SI} follow independent Rayleigh distributions. It is noted that there are two phases of transmissions for C-NOMA in Fig. 2. The first phase is the NOMA transmission phase (the solid lines), which corresponds to the transmission of the total superimposed signal $s[n]$ for each C-NOMA pair from the BS to the two NOMA AUs. The second phase is to the D2D cooperative phase (the dashed line). In this phase, the strong AU performs SIC to decode the signal $s_{\mathrm{w}}[n]$ intended to the weak AU and cancels this interference, decodes its own signal $s_s[n]$ and forwards the signal $s_{\mathrm{w}}[n]$ to the weak AU. In this case, the signal reception at the weak AU is improved due to the additional diversity resulting from the cooperation of the strong AU. Although the two phases can take place simultaneously since the strong AU is operating in a full-duplex mode, there is a cost of inducing self-interference (SI) at the strong AU user (the dotted line).

III. Achievable Rate Analysis

Based on the previous section, the received signal at the strong AU is expressed, for each C-NOMA pair and at each channel use $n \in \mathbb{N}$, as

$$\begin{aligned} y_{\mathrm{s}}[n] &= h_{\mathrm{s}}[n](\sqrt{P_{\mathrm{w}}[n]}s_{\mathrm{w}}[n] + \sqrt{P_{\mathrm{s}}[n]}s_{\mathrm{s}}[n]) \\ &\quad + h_{\mathrm{SI}}[n]\sqrt{P_{\mathrm{d}}[n]}s_{\mathrm{d}}[n] + \omega_{\mathrm{s}}[n] \end{aligned} \tag{2}$$

where $s_{\mathrm{d}}[n]$ represents the forwarded signal from the strong AU to the weak AU through the D2D link, such that $\mathbb{E}(|s_{\mathrm{d}}[n]|^2 = 1)$, $P_d[n]$ is the D2D transmit power allocated to the signal $s_{\mathrm{d}}[n]$ and $\omega_{\mathrm{s}}[n]$ is an additive complex Gaussian noise that is $\mathcal{CN}(0,1)$ distributed. According to NOMA principle, and by applying SIC, this AU first decodes the message of the weak AU by treating its own message as noise. Thus, the signal-to-interference-plus-noise ratio (SINR) of the strong AU to decode the the weak AU's message is expressed as

$$\Gamma_{\mathrm{s,w}}[n] = \frac{P_{\mathrm{w}}[n]\gamma_{\mathrm{s}}[n]}{P_{\mathrm{s}}[n]\gamma_{\mathrm{s}}[n] + P_{\mathrm{d}}[n]\gamma_{\mathrm{SI}}[n] + 1} \tag{3}$$

where $\gamma_{\mathrm{s}}[n] = |h_{\mathrm{s}}[n]|^2$ and $\gamma_{\mathrm{SI}}[n] = |h_{\mathrm{SI}}[n]|^2$. Consequently, the achievable rate of the strong AU to decode the message of the weak AU is given by

$$R_{\mathrm{s,w}}[n] = B\log(1 + \Gamma_{\mathrm{s,w}}[n]) \tag{4}$$

Then, after successfully decoding and cancelling the message of the weak AU, the strong AU decodes his own message $s_{\mathrm{s}}[n]$. Therefore, the SINR for the strong user to decode its own signal is expressed as

$$\Gamma_{\mathrm{s,s}}[n] = \frac{P_{\mathrm{s}}[n]\gamma_{\mathrm{s}}[n]}{P_{\mathrm{d}}[n]\gamma_{\mathrm{SI}}[n] + 1} \tag{5}$$

Hence, the achievable rate at the strong AU is given by

$$R_s[n] = B\log(1 + \Gamma_{\mathrm{s,s}}[n]) \tag{6}$$

After decoding the message of the weak AU, the strong AU can forward it to the weak AU. We denote τ as the processing delay from the SIC process. Thus, at each channel use n, the weak AU receives the message $s_{\mathrm{w}}[n]$ from the BS and the message $s_{\mathrm{d}}[n-\tau]$ from the strong user. Therefore, the total received signal at the weak AU can be written as

$$\begin{aligned} y_{\mathrm{w}}[n] = h_{\mathrm{w}}[n](\sqrt{P_{\mathrm{w}}[n]}s_{\mathrm{w}}[n] + \sqrt{P_{\mathrm{s}}[n]}s_{\mathrm{r}}[n]) \\ + h_{\mathrm{d}}[n]\sqrt{P_d}s_{\mathrm{w}}[n-\tau] + \omega_{\mathrm{w}}[n] \end{aligned}$$

where $\omega_{\mathrm{w}}[n]$ is an additive complex Gaussian noise that is $\mathcal{CN}(0,1)$ distributed. In this work, we assume that the weak AU can successfully co-phase and combine the signals from the BS and the strong user by a proper diversity-combining technique such as maximal ratio combining (MRC) [15]. Consequently, the SINR of the weak AU to decode the message $s_{\mathrm{w}}[n]$ transmitted from the BS can be expressed as

$$\Gamma_{\mathrm{b,w}}[n] = \frac{P_{\mathrm{w}}[n]\gamma_{\mathrm{w}}}{P_{\mathrm{s}}[n]\gamma_{\mathrm{w}} + 1} \tag{7}$$

where $\gamma_{\mathrm{w}}[n] = |h_{\mathrm{w}}[n]|^2$. Thus, the corresponding achievable rate can be expressed as

$$R_{\mathrm{b,w}}[n] = B\log(1 + \Gamma_{\mathrm{b,w}}[n]) \tag{8}$$

Similarly, the SINR of the weak AU to decode the message $s_{\mathrm{d}}[n]$ forwarded from the strong AU is expressed as $\Gamma_{\mathrm{w,s}}[n] = P_{\mathrm{d}}[n]\gamma_{\mathrm{d}}[n]$, where $\gamma_{\mathrm{d}}[n] = |h_{\mathrm{d}}[n]|^2$. After applying MRC, the SINR of the weak AU is the summation of the SINRs resulting from decoding its message from different sources. Thus, the achievable rate when applying MRC can be written as

$$R_{\mathrm{MRC,w}}[n] = B\log(1 + \Gamma_{\mathrm{b,w}}[n] + \Gamma_{\mathrm{w,s}}[n]) \tag{9}$$

Based on the above analysis and the result in [16], the achievable rate at the weak AU is given by

$$R_{\mathrm{w}}[n] = \min\left(R_{\mathrm{b,w}}[n], R_{\mathrm{MRC},w}[n]\right) \tag{10}$$

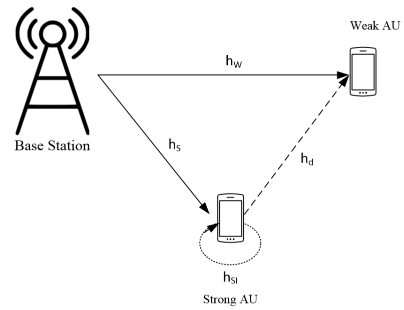

Fig. 2. Illustration of C-NOMA within a C-NOMA pair

Finally, recall that the channel coefficients h_{w}, h_{s}, h_{d} and h_{SI} follow independent Rayleigh distributions. Therefore, the channel gains γ_{w},γ_{s}, γ_{r} and γ_{d} follow independent exponential distributions.

IV. Problem Formulation and Solution Approach

A. Problem Formulation

The total number of AUs in the considered cellular system is $2K$. Therefore, in one channel use, there are $(2K-1)!! = (2K-1)(2K-3)...1$ possible pairing configurations. Assuming that user pairing procedure was performed, let us consider a given pair (m,n) from the generated $2K$ pairs. Considering only one channel realization, we introduce the $2K \times 2K$ matrix $\mathbf{A} = (a_{m,n})_{1\le m,n\le 2K}$, where $\forall m,n \in [\![1,2K]\!]$, $a_{m,n} \in \{0,1\}$. Note that, $\forall m,n \in [\![1,2K]\!]$, $a_{m,n} = 1$ implies that the m-th AU is paired with the n-th AU and $a_{m,n} = 0$ otherwise. Let $R_{\mathrm{w}}^{(m,n)}$ and $R_s^{(m,n)}$ be the achievable rate of weak AU and the strong AU that are computed using (6) and (10), respectively, among the mth and the nth AUs. Furthermore, we define $P^{(m,n)} \triangleq \{P_{\mathrm{w}}^{(m,n)}, P_{\mathrm{s}}^{(m,n)}, P_{\mathrm{d}}^{(m,n)}\}$ as the power allocation of the pair (m,n) when the m-th AU and the n-th are paired. Based on the above, the problem of maximizing the sum of minimum achievable rates among all pairs of AUs with respect to user pairing strategy and power allocation can be formulated as follows.

$$\max_{\mathbf{A}} \quad \sum_{n=1}^{2K}\sum_{m=n+1}^{2K} a_{mn} \max_{P^{(m,n)}} \min_{i\in\{\mathrm{s,w}\}} R_i^{(m,n)} \tag{11a}$$

$$\text{s.t.} \quad P_{\mathrm{w}}^{(m,n)} + P_{\mathrm{s}}^{(m,n)} \le P_B,\ \forall m,n \in \{1,2,...,2K\} \tag{11b}$$

$$P_R^{(m,n)} \le P_D,\ \forall m,n \in \{1,2,...,2K\} \tag{11c}$$

$$P^{(m,n)} \ge 0 \tag{11d}$$

$$a_{mn} \in \{0,1\},\ \forall m,n \in \{1,2,...,2K\} \tag{11e}$$

$$a_{mn} = a_{nm}, \forall m,n \in \{1,2,...,2K\} \tag{11f}$$

$$a_{mm} = 0, \forall m,n \in \{1,2,...,2K\} \tag{11g}$$

$$\sum_{m=1}^{2K} a_{mn} = 1,\ \forall n \in \{1,2,...,2K\} \tag{11h}$$

$$\sum_{n=1}^{2K} a_{mn} = 1,\ \forall m \in \{1,2,...,2K\} \tag{11i}$$

where (11b) represents the total power budget of NOMA links, (11c) represents the maximum power budget of D2D links, (11f) guarantees the symmetric pairing relationship between AUs, (11g) guarantee that each AU cannot be paired with itself, and (11h) and (11i) guarantees that each user can only belong to a single pair.

B. Solution Approach

It is important to clarify that, in this work, we are not optimizing the power and SC bandwidth allocation for each AU pair; thus, fairness is only guaranteed within each pair. The optimization problem in (11) involves two optimization problems. The inner problem corresponds to maximizing the minimum achievable rate $R_i^{(m,n)}$ for a given pair (m,n) with respect to the power coefficients $P^{(m,n)}$, whereas the outer problem corresponds to maximizing the sum of obtained max-min achievable rate with respect to the pairing strategy $\mathbf{A}$. Then, the optimization variables $\mathbf{A}$ and $P^{(\mathrm{m,n})}$ in problem (11) are not coupled, neither in the objective function (11a) nor in the constraints. Thus, problem (11) can be rewritten as

$$\begin{aligned} \max_{\mathbf{A}} \quad & \sum_{n=1}^{2K} \sum_{m=n+1}^{2K} a_{mn} R_{\text{opt}}^{(m,n)} \\ \text{s.t.} \quad & \text{(11b)} - \text{(11d)} \end{aligned} \tag{12}$$

where $R_{\text{opt}}^{(m,n)}$ is given by

$$\begin{aligned} R_{\text{opt}}^{(m,n)} = \max_{P^{(m,n)}} \quad & \min_{i \in \{\mathrm{s,w}\}} R_i^{(m,n)}(P^{(m,n)}) \\ \text{s.t.} \quad & \text{(11e)} - \text{(11i)} \end{aligned} \tag{13}$$

Therefore, we follow a two-step policy by first solving power allocation problem (13) for a fixed pair of AUs. Then, after obtaining the optimal power $\tilde{P}^{(m,n)}$ from problem (13), we inject the optimal max-min achievable rate $R^{(m,n)}(\tilde{P}^{(m,n)})$ into the objective function of problem (12) and we solve it with respect to the pairing strategy $\mathbf{A}$. In the following subsections, we start by solving problem (13) and then we investigate the solution of problem (12) to conclude about the optimal solution of the original problem in (11).

C. Problem (13)*: Power Allocation for a C-NOMA Pair*

We consider in this subsection the optimization problem in (13), which corresponds to a max-min fairness problem for a 2-user C-NOMA. We note that the max-min fairness problem in 2-user conventional NOMA system is a quasi-concave problem [17]. However, enabling D2D communication between the strong and the weak AUs renders the problem non-convex. Nevertheless, optimal solution for (13) can be found analytically. Following [8], the optimal power allocation for problem (13) can be written as follows

$$\text{if } \beta_0^* < \beta_1^* \begin{cases} P_{\mathrm{d}} = \nu^*, \\ P_{\mathrm{w}} = \dfrac{(\gamma_{\mathrm{SI}}\nu^* + 1)(\beta_1^* - \gamma_{\mathrm{d}}\nu^*)\beta_1^*}{\gamma_{\mathrm{s}}} + \\ \qquad \dfrac{(\beta_1^* - \gamma_{\mathrm{d}})\nu^*}{\gamma_{\mathrm{w}}}, \\ P_{\mathrm{s}} = \dfrac{(\gamma_{\mathrm{SI}} + 1)\beta_1^*}{\gamma_{\mathrm{s}}}, \end{cases} \tag{14}$$

$$\text{if } \beta_0^* \geq \beta_1^* \begin{cases} P_{\mathrm{d}} = 0, \\ P_{\mathrm{w}} = \beta_0^*(\dfrac{1}{\gamma_{\mathrm{w}}} + \beta_0^*), \\ P_{\mathrm{s}} = \dfrac{\beta_0^*}{\gamma_{\mathrm{s}}}, \end{cases} \tag{15}$$

where β_0^* is the optimal max-min SINR of the conventional NOMA and β_1^* is the optimal max-min SINR of the D2D cooperative NOMA. β_0^* and β_1^* can be obtaining by respectively finding the positive root of the following equations

$$\begin{aligned} & \frac{\beta_1(1+\nu^*\gamma_{\mathrm{SI}})(\beta_1 - \gamma_{\mathrm{d}}\nu^*)}{\gamma_{\mathrm{s}}} + \frac{\beta_1 - \gamma_{\mathrm{d}}\nu^*}{\gamma_{\mathrm{w}}} \\ & + \frac{\beta_1 - \gamma_{\mathrm{d}}\nu^*}{\gamma_{\mathrm{w}}} - P_{\mathrm{B}}^{\max} = 0 \end{aligned} \tag{16}$$

$$\frac{\beta_0^2}{\gamma_{\mathrm{s}}} + \frac{\beta_0}{\gamma_{\mathrm{w}}} + \frac{\beta_0}{\gamma_{\mathrm{s}}} + \frac{\beta_1(\gamma_{\mathrm{d}}\nu^* + 1)}{\gamma_{\mathrm{s}}} - P_{\mathrm{B}}^{\max} = 0 \tag{17}$$

where $\nu^* = \min\{P_{\mathrm{d}}^{\max}, \lambda(\hat{\beta})\}$ and $\hat{\beta}$ is the root of the following equation

$$\frac{\beta(\beta+1)}{\gamma_{\mathrm{s}}}(\gamma_{\mathrm{SI}}\lambda(\beta) + 1) - P_{\mathrm{B}}^{\max} = 0 \tag{18}$$

and $\lambda(\beta)$ is defined as

$$\begin{aligned} \lambda(\beta) = & \frac{-\gamma_{\mathrm{s}}\gamma_{\mathrm{d}} - \gamma_{\mathrm{w}}\gamma_{\mathrm{d}}\beta - \gamma_{\mathrm{s}}\gamma_{\mathrm{SI}}\beta}{2\gamma_{\mathrm{w}}\gamma_{\mathrm{d}}\gamma_{\mathrm{SI}}\beta} \\ & + \frac{\sqrt{[\gamma_{\mathrm{s}}\gamma_{\mathrm{d}} + \beta\gamma_{\mathrm{w}}(\gamma_{\mathrm{d}} + \gamma_{\mathrm{SI}})]^2 + 4\gamma_{\mathrm{w}}\gamma_{\mathrm{d}}\gamma_{\mathrm{SI}}(\gamma_{\mathrm{s}} - \gamma_{\mathrm{w}})\beta}}{2\gamma_{\mathrm{w}}\gamma_{\mathrm{d}}\gamma_{\mathrm{SI}}\beta} \end{aligned} \tag{19}$$

It is trivial to verify that the left-hand-side of (18) is a monotonically increasing function. Thus, the root β^* can be obtained by using root-finding method such as bisection. Since equations (16) and (17) are both quadratic, closed-form expressions for β_0^* and β_1^* can be easily obtained.

D. Problem (12)*: Pairing Policy*

Although the optimal power allocation for each pair can be analytically derived, i.e $R_{\text{opt}}^{(m,n)}$ can be efficiently computed with negligible complexity, (12) is still a combinatory optimization problem for which finding the global optimum requires exhaustive search with a complexity $\mathcal{O}((2K-1)!!)$. Thus, we propose a low-complexity pairing policy as follows

First, without loss of generality, we assume the users' channel gains are sorted as $\gamma_1 \leq \gamma_2 \leq ....\gamma_{2K}$. We divide the AUs into two sets, namely the weak set including AU 1 to AU K and the strong set including AU $K+1$ to AU $2K$.

Second, since the AUs in the strong set have better channel gains than those in the weak set, each of the AU in the former can be selected to serve each in latter for our proposed scheme. Besides, since we can analytically obtain the rate in the max-min fairness problem for any possible pair of users, our problem can be reduced to finding which strong user should be assigned to each weak users, or in other words, to a classic assignment problem.

Algorithm 1 Low-complexity user pairing and power control for a C-NOMA system.

Require: Channel gain vector $\mathbf{g} \in \mathbb{R}^{+1\times 2K}$, D2D channel gain matrix $\mathbf{G} \in \mathbb{R}^{+2K\times 2K}$
Ensure: $\mathbf{A}^*$, $\mathbf{P}^*$
  Initialize empty matrices $\mathbf{A}^*$, $\mathbf{P}^*$, $\mathbf{C}$, $\mathbf{A}_{\mathrm{H}}$
  for $m = 1 : K$ **do**
    for $n = (K+1) : 2K$ **do**
      compute $\tilde{P}^{(m,n)}$ using equations (14)-(19).
      compute $R_{\text{opt}}^{(m,n)}$ based on $\tilde{P}^{(m,n)}$
      Compute cost matrix entry $\mathbf{C}(m, n-k) \leftarrow -R_{\text{opt}}^{(m,n)}$
    end for
  end for
  Solve optimal pairing matrix $\mathbf{A}_{\mathrm{H}}$ using Hungarian algorithm with cost matrix $\mathbf{C}(m, n-k)$
  for $m = 1 : K$ **do**
    for $n = 1 : K$ **do**
      $\mathbf{A}^*(m, n+K) \leftarrow \mathbf{A}_{\mathrm{H}}(m,n)$
      $\mathbf{A}^*(n+K, i) \leftarrow \mathbf{A}_{\mathrm{H}}(m,n)$
      $\mathbf{A}^*(m,n) \leftarrow 0$
      if $\mathbf{A}_{\mathrm{H}}(m,n) == 1$ **then**
        $\mathbf{P}^* \leftarrow \left[\mathbf{P}^*, P^{(m,n)}\right]$
      end if
    end for
  end for

Finally, we employ the well-known Hungarian algorithm [18], which has a polynomial-time complexity of $\mathcal{O}(K^2)$, for our assignment problem.

E. Proposed Algorithm

First, we define $\mathbf{g} \in \mathbb{R}^{1\times 2K}$ as the channel gain vector from the BS to the AUs, which are sorted in an ascending order. We also define $\mathbf{G} \in \mathbb{R}^{+2K\times 2K}$ as the channel gain matrix that characterized the whole D2D communications in our system. Specifically, $\mathbf{G}(i,j), \forall i,j \in \{1,...,2K\}$ is the channel gain from the i-th AU to the j-th AU , while $\mathbf{G}(i,i)$ is the SI channel gain of AU i. It is noted that the Hungarian algorithm requires a $K \times K$ cost matrix $\mathbf{C}$ as the input and provides an assignment matrix $\boldsymbol{A}_{\mathrm{H}}$ as the output, where $\boldsymbol{A}_{\mathrm{H}}(i,j) = 1$ indicates that the i-th user in the strong set of users is paired with the j-th user in the weak set of users. In our algorithm, we define the cost of pairing two users as the opposite value of the computed max-min rates obtained by solving (13). Let matrix $\mathbf{A}^*$ represent the optimal pairing policy and $\mathbf{P}^*$ is the corresponding optimal power control scheme. The proposed algorithm is presented in Algorithm 1.

V. Simulation Results

In this section, we validate our proposed scheme. The total number of AUs in the network is $2K = 20$. The channel gains of BS-to-weak-AUs γ_{w}, BS-to-strong-AUs γ_{s}, strong-AUs-to-weak AUs γ_{d}, and SI γ_{SI} are generated randomly through independent exponential distributions, with means λ_{w}, λ_{s}, λ_{d}, and λ_{SI}, respectively. Unless otherwise stated, $\lambda_{\mathrm{w}} = 0$dB, $\lambda_{\mathrm{s}} = 10$dB, $\lambda_{\mathrm{d}} = 10$dB, $\lambda_{\mathrm{SI}} = -10$dB, $P_{\mathrm{d}} = 20$dBm. Simulation results are performed over 10^4 independent Monte-Carlo trials on the channel realizations.

Fig. 3 presents the sum of minimum rates achieved by the C-NOMA and conventional NOMA with different pairing schemes versus the power budget at the base station P_{B}. For conventional NOMA, AUs within each are served via NOMA while different pairs are served via OMA and there is no involved D2D communication. Besides, we compare our pairing policy with three different pairing schemes. For benchmark pairing scheme 1, we pair the k-th AU $(1 \leq k \leq K)$ with the $(2K-k+1)$-th, e.g, the weakest AU is paired with the strongest AU, the second weakest is paired with the second strongest, and so on. Note that this scheme has been proposed in [12] as being optimal for the sum rate maximization for conventional NOMA. For benchmark pairing scheme 2, we pair the k-th AU $(1 \leq k \leq K)$ with the $(K+k)$-th AU, e.g, the k-th weakest AU in the weak set is paired with the k-th weakest user in the strong set. This scheme intuitively gives the best fairness among AU pairs. For random pairing scheme, a randomly selected AU in the weak set is paired with a chosen AU in the strong set. As is illustrated, our proposed scheme always outperforms the others. Another observation is that, without a proper pairing scheme, C-NOMA can still be outperformed by NOMA (with good pairing) when the power budget at the base station is significantly larger than the D2D power budget (the NOMA component becomes more dominant than the D2D component).

In Fig. 4, we compared the proposed C-NOMA scheme with conventional NOMA in terms of sum of minimum achievable rates with different D2D channel qualities. Specifically, we vary the mean value λ_{d} of the exponential distribution that generates γ_{d}. The higher values of λ_{d} characterize better channels (higher gains) on average. For a fair comparison, we assume that both C-NOMA and NOMA AUs follow our pairing policy. As is illustrated, with good D2D channels, the gain obtained from C-NOMA compared to NOMA is significant. For instance, with $\lambda_{\mathrm{d}} = 10$dB, the gain achieved can be over 100 percent. When the D2D channel condition is poor, i.e, $\lambda_{\mathrm{d}} = -10$, the gain from conventional NOMA is marginal. If we further lower the D2D channel gains, our scheme is reduced to conventional NOMA.

In Fig. 5, we observe the impact of SI channel on the performance gain between C-NOMA and NOMA. Similar to Fig. 4, we vary the value λ_{SI}. As opposed to the Fig. 4,

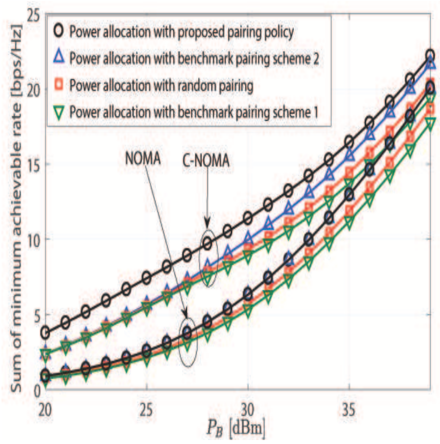

Fig. 3. Sum of minimum rates achieved by the C-NOMA and NOMA with optimal and random pairing versus the power budget at the base station P_{B}.

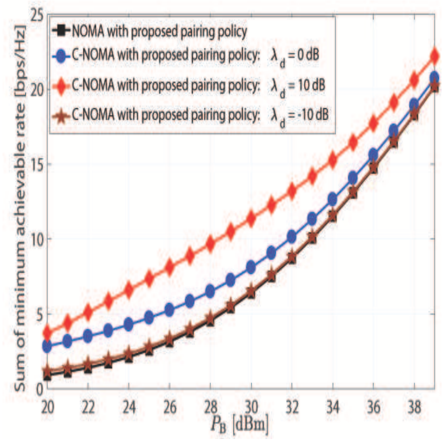

Fig. 4. A comparison between proposed C-NOMA scheme and conventional NOMA in terms of sum of minimum achievable rates with different mean values λ_{d} of D2D channel gains

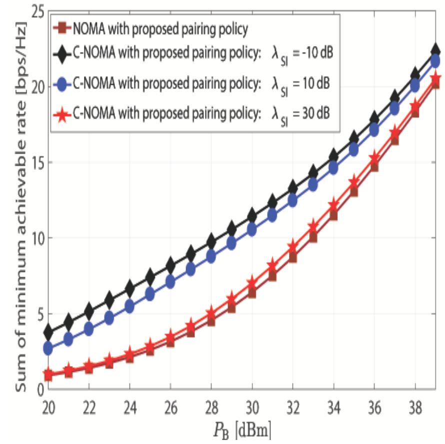

Fig. 5. A comparison between proposed C-NOMA scheme and conventional NOMA in terms of sum of minimum achievable rates with different mean values λ_{SI} of SI channel gains

higher SI channels result in a lower gain for C-NOMA as compared to NOMA and vice versa. High values of λ_{SI} may result from poor SI cancellation of FD devices (strong AUs). Thus, although the rates of the weak AUs are improved due to the messages relayed from the strong AUs, the rates of the strong AUs are reduced due to severe SI. Hence, with high SI channels gain, i.e 30dB, there is no significant performance gain of C-NOMA. In extreme case where SI is very severe, C-NOMA is reduced to NOMA. However, under these scenarios, the powers allocated to D2D links are close to 0. Thus, wasted devices' power is not an issue.

VI. Conclusion

In this paper, we have extended the framework of C-NOMA to the multi-user cellular system. To leverage the advantage of NOMA and D2D, we have formulated the joint pairing and power allocation problem, which is NP-hard. Thus, to overcome this issue, we have proposed a novel low-complexity joint power control and user pairing scheme. Simulation results showed the superiority of the proposed scheme when compared to the conventional NOMA in terms of user fairness with reasonable assumptions of channel gains. Under some extreme conditions with poor D2D channel gains or severe SI, our scheme can still achieve the same performance of conventional NOMA. Additional performance metrics can be considered as a future work on the topic of cooperative NOMA.

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