Multi-objective Resource Allocation for D2D and Enabled MC-NOMA Networks by Tchebycheff Method

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Abstract—This paper considers a resource allocation problem in device-to-device (D2D) communications sharing the same frequency spectrum. In particular, the CUs utilize non-orthogonal multiple access (NOMA) while DUs adopt the orthogonal frequency division multiple access (OFDMA). A multi-objective optimization problem (MOOP) is formulated, which jointly maximizes the sum rate of D2D and CUs (CUs) in uplink communications while taking into account the maximum transmit power budget and minimum data rate requirement for D2D and CUs. This MOOP is handled by the weighted Tchebycheff method, which converts it into a single-objective optimization (SOOP). Then, the monotonic optimization approach is employed to solve this SOOP optimally. Numerical results unveil an interesting tradeoff between D2D and CUs.

I. INTRODUCTION

Device-to-Device (D2D) communication is promoted as an innovative paradigm to improve the network performance as well as the system resources utilization in the fifth-generation (5G) cellular networks and beyond [1]. The power and channel allocation for D2D communication need elaborate coordination with cellular users (CUs), as D2D users (DUs) can impose interference to other users [2]. In practice, D2D communication operates either in the overlay or underlay modes along with existing CUs. In fact, the underlay mode is appealing as it follows the system to achieve higher spectral efficiency in which the spectrum is shared between DUs and CUs [3, 4].

Non-orthogonal multiple access (NOMA) has been proposed as one of the fundamental techniques for beyond 5G to achieve a better balance between system spectral efficiency (SE) and user fairness [5]. As a result, the integration between NOMA and D2D communication has significant attention in order to improve user connectivity as well as SE [6, 7, 15]. In this regard, resource allocation is one challenging problem which can appropriately mitigate interference, thereby improving the system SE. In [6], while using the successive interference cancellation (SIC) to detect the multiplexing signals, the resource block assignment and power allocation were optimized to maximize the sum data rate of the D2D pairs. In [7], according to interference status, different NOMA-aided spectrum-sharing modes (i.e., the D2D access scheme) for the paired DUs and CUs were considered. Then, a connectivity-maximization problem was formulated under mode selection, user pairing, and power control while guaranteeing the decoding thresholds of CUs and DUs to take advantage of the NOMA-and-D2D integrated structure. In [8], the authors offered an innovative resource allocation policy to enhance the performance of D2D communications underlaying CUs in the downlink (DL). For a network consisting of CUs and DUs in [9], the problem of power allocation and user clustering was studied while the sum-rate of the NOMA-based network was maximized. In [10], a joint power allocation and user scheduling for the D2D-enabled HetNets with NOMA was proposed to maximize the ergodic sum rate of the near users in the small cells, while guaranteeing the quality-of-service requirements of the far users and the macro-cell users. The authors in [11] offered a joint optimization framework for D2D-enabled NOMA networks, where the performance of the D2D communication was maximized while considering the SIC decoding order of the NOMA-based CU equipment. In [12], the mode selection and resource allocation problem for D2D-enabled NOMA cellular networks was considered. However, the inter-layer mode was introduced for D2D communications in NOMA system to maximize the system sum rate, which exploited the SIC to cancel the interference between D2D pairs and CUs. In [13], a NOMA-enhanced D2D communication scheme was considered and then the system sum-rate was maximized, while optimizing subchannel and power allocation. Then, a solution was proposed to assign subchannels to D2D groups and allocate power to receivers in each D2D group. The authors in [14] considered the resource allocation problem for an uplink multi-carrier NOMA in D2D underlaid cellular networks and then the maximization problem of the Nash product of each user was investigated as a Nash bargaining game.

Despite the fruitful results in the literature, the performance of the D2D communications can still be improved as the conflicting goals of D2D and cellular create a serious network performance bottleneck. In the literature, the framework of the multi-objective optimization problem (MOOP) was employed to address the conflicting objectives in wireless systems [15-18]. Regarding this, the authors in [15] proposed a MOOP for maximizing the signal-to-interference-plus-noise ratio (SINR) to determine the optimal power allocation for each D2D pair. A MOOP tradeoff was analyzed in [16] to investigate the tradeoff between EE and SE in a D2D underlying system. This problem was converted into a SOOP via the ε-method, and a two-stage iterative algorithm was proposed. Furthermore, in [17], a multi-objective cell association problem was considered for arranging several D2D links in a multi-cell network based on the fractional frequency reuse scheme. However, a non-trivial tradeoff between DUs and CUs would be expected. As a result, the spectrum sharing deployment under such networks suffers from inter-cell interference originated from the DUs and CUs in each cell which leads to an exciting optimization problem. Studying such a tradeoff between DUs and CUs leads to an interesting optimization problem that has not been reported in the literature yet.

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In the numerical results, we provide an interesting trade-off problem which is not investigated in [9]-[14]. In contrast to the existing literature e.g., [4]-[10], we study the performance tradeoff between DUs and CUs in D2D networks underlying NOMA CUs, by maximizing the throughput of DUs and CUs via a MOOP framework. This performance tradeoff can be obtained by adjustable weighting parameters to execute the resource allocation policy. The contributions of this letter are summarized as follows:

- We formulate a MOOP to maximize the sum data rate of the DUs and CUs simultaneously by jointly optimizing the transmit powers and subcarrier allocation policies.
- To solve the MOOP at hand, we first apply the weighted Tchebycheff method which converts the MOOP into a SOOP. Then, a monotonic optimization method is proposed to obtain the optimal resource allocation policy.
- In the numerical results, we provide an interesting tradeoff between CUs and DUs and also demonstrate the superiority of MC-NOMA scheme as compared to multi carrier orthogonal multiple access (MC-OMA) schemes. This also shows that our proposed scheme outperforms the proposed algorithm in [14].

II. System Model

In this paper, an uplink single-cell NOMA-based cellular network is considered which compromises of one BS to serve $M$ CUs and $K$ D2D links (DUs) given by $M = \{1, ..., M\}$ and $K = \{1, ..., K\}$, respectively. The total system bandwidth of $B$ Hz is divided into a set of subchannels denoted by $N = \{1, ..., N\}$, which is shared between CUs and DUs so that each subchannel has bandwidth of $B_c = B/N$ Hz. We define $h_{t_r}$ as the channel gain between transmitter $t$ and receiver $r$ over subcarrier $n$. For simplify, the channel gain between the transmitter and BS is defined as $h_{t}$. Denote the instantaneous channel power gains for the $k$-th DU to the BS as $h_{k,m}$ and the link between the $m$-th CU and the BS as $g_{m,n}$. The transmitted power from the $k$-th DU over subchannel $n$ is expressed by $p_{m,n}^k$ and for the $m$-th CU is given by $p_{m,n}$. Furthermore, the noise power spectral density is given by $N_0$. It should be noted that the D2D devices are performed based on the OFDMA protocol due to closing to each other, which indicates that the desired signal is more considerable than the interference terms. In this network, the BS can employ the SIC technique based on the descending order in the channel gain. The channel gains between the users and the BS should satisfy $g_m > h_k > g_i$, then the BS will decode the signals $x_m$, $x_k$, and $x_i$ sequentially by using the SIC technique. On the contrary, since the signal strength of $x_m$ at the D2D receiver $x_k$ is the strongest, the D2D receiver will directly decode its desired signal. This constraint ensures that the BS can perform SIC properly. As a result, the instantaneous SINR for each CU on subchannel $n$ is given by

$$\gamma_{m,\text{Cellular}}^n = \frac{\psi_m^np_m^n|g_m^n|^2}{N_0B_c + \sum_{t \in M\setminus m} \psi_t^n p_t^n|g_t^n|^2 + \sum_{j \in K\setminus j} \varphi_j^n p_j^n|h_j|^2},$$

where $\psi_m^t$ and $\varphi_j^n$ are the binary variables for subchannel allocation for the CU and DU, respectively. If $\psi_m^n = 1$, subchannel $n$ is allocated to the $m$-th CU and $\psi_m^n = 0$, otherwise. In a similar manner, if $\varphi_j^n = 1$, subchannel $n$ is assigned to the $j$-th DU and $\varphi_j^n = 0$, otherwise. In (1), the term $\sum_{j \in K\setminus j} \varphi_j^n p_j^n|h_j|^2$ is the interference term from the CUs due to operating on the same subchannel based on the NOMA scheme, and the term $\sum_{(i \neq m) \in M} g_{i,m}^n$ corresponds to the interference from the DUs. In addition, the instantaneous received SINR at the $k$-th DU on subchannel $n$ can be written as

$$\gamma_{k,\text{D2D}}^n = \frac{\varphi_k^n p_k^n|h_k|^2}{N_0B_c + \sum_{m \in M} \psi_m^n p_m^n|g_{m,k}^n|^2 + \sum_{j \in K\setminus k} \varphi_j^n p_j^n|h_{j,k}^n|^2},$$

where $g_{m,k}^n$ is the channel power gain between the $m$-th CU and the $k$-th DU receiver over subchannel $n$, and $\sum_{m \in M} \psi_m^n p_m^n|g_{m,k}^n|^2$ is the interference term arising from the CUs. Besides, $\sum_{j \in K\setminus k} \varphi_j^n p_j^n|h_{j,k}^n|^2$ denotes the interference term resulting from the other D2D pairs, where $h_{j,k}^n$ is the instantaneous channel power gain from the $j$-th DU transmitter to the $k$-th DU receiver on subchannel $n$.

III. Problem Formulation

In this section, to strike a tradeoff between the system performance of DUs and CUs, we formulate a MOOP in which jointly the sum rate of the DUs, $R_{DU}$, and CUs, $R_{CU}$, are maximized. The proposed MOOP framework aims to obtain power allocation as well as the subchannel assignment strategy to study the performance tradeoff between conflicting system objectives. This joint optimization can be formulated through the following MOOP:

$$\max_{\{p,\psi,\varphi\}} \sum_{k=1}^{K} R_{DU,k} \quad (3a)$$

$$\max_{\{p,\psi,\varphi\}} \sum_{m=1}^{M} R_{CU,m} \quad (3b)$$

s.t. $\sum_{n=1}^{N} \varphi_k^n p_k^n \leq p_{\text{max,DU},2D}, \quad \sum_{n=1}^{N} \psi_m^n p_m^n \leq p_{\text{max,Cellular}},$ (3c)

$$\varphi_k^n \in \{0, 1\}, \quad \forall k, n, \quad \psi_m^n \in \{0, 1\}, \quad \forall m, n,$$ (3d)

$$\sum_{n=1}^{N} \varphi_k^n \leq 1, \quad \forall k, \quad \sum_{n=1}^{N} \psi_m^n \leq 1, \quad \forall m,$$ (3e)
$\sum_{k=1}^{K} \varphi^m_k + \sum_{m=1}^{M} \psi^m_n \leq L_{\text{max}}, \quad \forall n,$

(3f)

$R_{\text{CU},m} \geq R^o_{\text{DU},\text{min}}, \forall m$ \quad $R_{\text{DU},k} \geq R^o_{\text{DU},\text{min}}, \forall k,$

(3g)

where $R_{\text{CU},m} = \sum_{n=1}^{N} \ln (1 + \gamma^m_{n,\text{Celluar}})$ and $R_{\text{DU},k} = \sum_{n=1}^{N} \ln (1 + \gamma^k_{n,\text{D2D}})$. To facilitate the system design, we define $\varphi \in \mathbb{Z}^{KN \times 1}$ and $\psi \in \mathbb{Z}^{MN \times 1}$ as the vectors of subchannel assignment variables in D2D and cellular networks, respectively. Furthermore, variables $p \in \mathbb{R}^{KN \times 1}$ and $\tilde{p} \in \mathbb{R}^{MN \times 1}$ are the collections of power allocation variables in D2D and cellular networks, respectively. Variables $P_{\text{max},\text{D2D}}$ and $P_{\text{max},\text{Cellular}}$ are the maximum total power for the DUs and CUs, respectively. $L_{\text{max}}$ denotes the maximum number of CUs that can be paired on a subchannel under spectrum sharing scheme. Note that the optimization problem (3) is a mixed-integer non-linear programming (MINLP) because of the interference in the rate function, and the presence of the binary constraints.

IV. PROPOSED SOLUTION

One approach to solve a MOOP is the weighted Tchebycheff technique [19], which offers an auxiliary optimization variable, $\chi$ for (3) as follows

$$\min_{\{p,\tilde{p},\varphi,\psi,\chi\}} \chi$$

s.t. (3c) - (3g),

(4a)

$$\frac{R_{\text{DU},\text{max}}}{(R_{\text{DU},\text{max}} - R_{\text{DU}}) - \chi} \leq 0,$$

(4b)

$$\frac{R_{\text{CU},\text{max}}}{(R_{\text{CU},\text{max}} - R_{\text{CU}}) - \chi} \leq 0,$$

(4c)

where $\alpha$, and $1 - \alpha$ are the weighting coefficients indicating the impact of the different objectives. The weighted Tchebycheff method ensures to produce a set of Pareto-optimal solutions when $R_{\text{DU},\text{max}}$ and $R_{\text{CU},\text{max}}$ are the utopian objective points as the maximum of each objective, respectively [19]. In the following, to solve the highly nonconvex optimization problem in (4) globally, we apply a global optimization approach known as the monotonic optimization method. By exploiting monotonicity or hidden monotonicity in the objective function as well as constraints, this method guarantees the convergence [20].

Note that (4) is not a monotonic optimization problem in canonical form since (4b) and (4c) are not monotonic. To facilitate the presentation, we rewrite these constraints as follows:

$$\sum_{k=1}^{K} \sum_{n=1}^{N} \ln \left(1 + \frac{\tilde{p}^n_k \psi^n_k}{N_0 B_c + \sum_{m \in \mathcal{M}} \tilde{p}^m_{\text{DU}} |g^m_{n,k}|^2 + \sum_{j \in \mathcal{K} \setminus k} \tilde{q}^j^n |h^m_{j,k}|^2} \right) \geq \frac{R_{\text{DU},\text{max}} - \chi}{\alpha},$$

(5)

$\frac{R_{\text{CU},\text{max}} - \frac{\sum_{n=1}^{N} \ln (1 + \gamma^m_{n,\text{Celluar}})}{\gamma^m_{n,\text{Celluar}}}}{1 - \alpha} \geq R_{\text{CU},\text{max}} - \frac{\sum_{n=1}^{N} \ln (1 + \gamma^m_{n,\text{Celluar}})}{1 - \alpha},$

(6)

where $\tilde{p}^m_k = \psi^n_m \tilde{p}^m_n$ and $\tilde{q}^j^n_k = \varphi^n_k \tilde{q}^j^n$. Note that optimization problem (4a) is not monotonic as a result of constraints (4b) and (4c). First, the optimization problem in (4a) can be rewritten as a monotonic optimization problem, and then we adopt the polyblock algorithm [20] to obtain a globally optimal solution. To do so, let us define $\mathcal{P}_{\text{Max}} = \{p_{\text{max},\text{D2D}}\}$, and $\mathcal{Q}_{\text{Max}} = \{q_{\text{Max},\text{Cellular}}\}$, $\forall m$ as the maximum transmit power for each user over all subchannels. Moreover, the relations in (5), (6), and (3g) can be equivalently stated as the following single constraints:

$$\sum_{i=1}^{M} \left( c^+_{\mathcal{P}} (\tilde{p}) - c^−_{\mathcal{P}} (\tilde{p}) \right) + R_{\text{DU},\text{max}} - \frac{\chi R_{\text{DU},\text{max}}}{\alpha} \geq 0,$$

(7)

$$\sum_{j=1}^{K} \left( c^+_{\mathcal{Q}} (\tilde{q}) - c^−_{\mathcal{Q}} (\tilde{q}) \right) + R_{\text{CU},\text{max}} - \frac{\chi R_{\text{CU},\text{max}}}{1 - \alpha} \geq 0,$$

(8)

$$\min_{i \in 1, \ldots, K} \left[ c^+_i (\tilde{p}) + \sum_{i \in K \setminus k} c^−_i (\tilde{p}) - \sum_{i \in \mathcal{K}} c^−_i (\tilde{p}) - R^t_{\text{DU},\text{min}} \geq 0, \right.$$

(9)

$$\min_{j \in 1, \ldots, M} \left[ c^+_j (\tilde{q}) + \sum_{j \in \mathcal{M} \setminus m} c^−_j (\tilde{q}) - \sum_{j \in \mathcal{M}} c^−_j (\tilde{q}) - R^t_{\text{CU},\text{min}} \geq 0, \right.$$

(10)

where $c^+_i (\tilde{p}), c^−_i (\tilde{p}), c^+_j (\tilde{q}),$ and $c^−_j (\tilde{q})$ are increasing in $\tilde{p}$ and $\tilde{q}$ given at the top of the next page. Bear in mind that equations (7) and (8) are the difference of two increasing functions. However, the constraint (3g) is a binary constraint which is intractable. To tackle it, we rewrite (3g) in the equivalent form as:

$$0 \leq \varphi^n_k \leq 1, \sum_{k=1}^{K} \sum_{n=1}^{N} \psi^n_m - (\varphi^n_k)^2 \leq 0,$$

(14)

$$0 \leq \psi^n_m \leq 1, \sum_{m=1}^{M} \psi^n_m - (\psi^n_m)^2 \leq 0.$$

(15)

It can be perceived that right hand side of (14) and (15) are non-convex as well as non-monotonic. To tackle this issue, we introduce two slack variables $\nu$ and $\mu$ and rewrite as:

$$\sum_{k=1}^{K} \sum_{n=1}^{N} (\varphi^n_k)^2 + \nu \geq \mathcal{R}_1,$$

(16)

$$\sum_{m=1}^{M} \sum_{n=1}^{N} (\psi^n_m)^2 + \mu \geq \mathcal{R}_2,$$

(17)

$\sum_{k=1}^{K} \sum_{n=1}^{N} \varphi^n_k$ and $\sum_{m=1}^{M} \psi^n_m$ denote the priorities of CUs and DUs in the resource allocation policy specified in the media access control (MAC) layer to achieve a certain notion of fairness, especially for users who suffer from poor channel conditions.

1It can be perceived that at most $(L_{\text{max}} - 1)$ CUs share on the same subchannel.

2The non-negative weight $\alpha$ denotes the priorities of CUs and DUs in the resource allocation policy specified in the media access control (MAC) layer to achieve a certain notion of fairness, especially for users who suffer from poor channel conditions.
where $\mathcal{R}_1$ and $\mathcal{R}_2$ are constant. We note that the left hand sides of (14) and (15) are monotonically increasing with respect to $\nu$ and $\mu$, respectively. Consequently, by introducing the auxiliary variable $s_1$, $s_2$, $s_3$, and $s_4$ the problem in (4) can be then reformulated as following:

\[
\text{minimize} \quad \left\{ \mathbf{p}, \mathbf{q} \mid s_1 \leq c_1 - (\mathbf{P}_{\text{Max}}) - c_2(0), \right. \\
\left. 0 \leq s_1 \leq c_1 - (\mathbf{P}_{\text{Max}}), \right. \\
\left. c(\hat{\mathbf{p}}) + s_1 \leq c(\hat{\mathbf{P}}_{\text{Max}}), \right. \\
\left. c(\hat{\mathbf{p}}) + s_1 \leq c(\hat{\mathbf{P}}_{\text{Max}}), \right. \\
\left. 0 \leq s_2 \leq c_2 - (\mathbf{q}_{\text{Max}}), \right. \\
\left. 0 \leq s_2 \leq c_2 - (\mathbf{q}_{\text{Max}}), \right. \\
\left. c(\hat{\mathbf{q}}) + s_2 \geq c(\hat{\mathbf{q}}_{\text{Max}}), \right. \\
\left. c(\hat{\mathbf{q}}) + s_2 \geq c(\hat{\mathbf{q}}_{\text{Max}}), \right. \\
\left. \hat{p}_m^n \geq 0, \hat{q}_m^n \geq 0, V_m, k, n, \right. \\
\left. \sum_{n=1}^{N} \hat{q}_m^n \leq P_{\text{Max}, \text{D2D}}, \sum_{n=1}^{N} \hat{p}_m^n \leq P_{\text{Max}, \text{Cellular}}, \right. \\
\left. 0 \leq \varphi^n_k \leq 1, 0 \leq \psi^n_m \leq 1, \right. \\
\left. K \sum_{n=1}^{N} (\varphi^n_k)^2 + \nu \geq \mathcal{R}_1, \right. \\
\left. M \sum_{n=1}^{N} (\psi^n_m)^2 + \mu \geq \mathcal{R}_2, \right. \\
\left. \sum_{k=1}^{N} (\varphi^n_k)^2 + \nu \geq \mathcal{R}_1, \right. \\
\left. \sum_{m=1}^{N} (\psi^n_m)^2 + \mu \geq \mathcal{R}_2, \right. \\
\eqn{3e} - \eqn{3f}, \\
0 \leq s_3 \leq r_+ - (\mathbf{P}_{\text{Max}}) - r_-(0), \\
r_+ - (\hat{\mathbf{p}}) + s_3 \leq r_+ - (\mathbf{P}_{\text{Max}}), \\
r_+ - (\hat{\mathbf{q}}) + s_3 \geq r_+ - (\mathbf{q}_{\text{Max}}), \\
0 \leq s_4 \leq r_+ - (\mathbf{q}_{\text{Max}}), \\
r_+ - (\hat{\mathbf{p}}) + s_4 \leq r_+ - (\mathbf{P}_{\text{Max}}), \\
r_+ - (\hat{\mathbf{q}}) + s_4 \geq r_+ - (\mathbf{q}_{\text{Max}}). \\
\eqn{3g} - \eqn{3f},
\]
Algorithm 1 Bisection Projection Search Algorithm

Input: $\pi^{(l)}$ and $G$

Output $\lambda$ such that $\lambda = \arg \max \{ \lambda > 0 \mid \lambda \pi^{(l)} \in G \}$

1: Set $\lambda_{\text{min}} = 0$, $\lambda_{\text{max}} = 1$, and the error tolerance $\delta < 1$.
2: repeat
3: Let $\lambda = \frac{\lambda_{\text{min}} + \lambda_{\text{max}}}{2}$.
4: Solve the feasibility problem $\{23\}$.
5: If
6: Check if $\lambda$ is feasible, i.e., $\lambda \pi^{(l)} \in G$, then set $\lambda_{\text{max}} = \lambda$.
7: else
8: Set $\lambda_{\text{min}} = \lambda$.
9: until $\lambda_{\text{max}} - \lambda_{\text{min}} < \delta$.
10: Output $\lambda = \lambda_{\text{min}}$.

Algorithm 2 Outer Poly-block Approximation Algorithm

Input: An function $f(\cdot)$, a compact normal set $G$ and a closed conormal set $\mathcal{H}$, such that $\mathcal{G} \cap \mathcal{H} \neq \emptyset$.

Output: An $\epsilon$-optimal solution $x^*$.

1: Initialize iteration index $l = 0$, poly-block $\Omega^{(l)}$ be box $[0, b]$ that encloses $\mathcal{G} \cap \mathcal{H}$ with vertex set $\omega^{(l)} = \{b\}$. $\epsilon$ is a small positive number $V^{(l)} = -\infty$.
3: Repeat
4: From $\omega^{(l)}$, select, $\pi^{(l)} \in \arg \max \{ f(\pi) \mid \pi \in \omega^{(l)} \}$.
5: Obtain the projection of $\pi^{(l)}$, i.e., $\phi(\pi^{(l)})$ on the upper boundary of $G$.
6: If $\phi(\pi^{(l)}) \in \mathcal{G} \cap \mathcal{H} \neq \emptyset$ and $f(\phi(\pi^{(l)})) \geq V^{l-1}$, then let then best value be $\hat{x}^{l} = \phi(\pi^{(l)})$ and $V^{l} = f(\phi(\pi^{(l)}))$. Otherwise, $\hat{x}^{l} = \hat{x}^{l-1}$ and $V^{l} = V^{l-1}$.
10: Let $x = \phi(\pi^{(l)})$ and $w^{(l+1)} = (w^{(l)}) \nabla (\pi^{(l)}) \cup \{ z^{(i)} = z + (z^{(i)} - z^{(l)}) \epsilon_{i} \}$ \( z \in w^{(l)} \setminus \{ z \in w^{(l)} \mid z > x \} \).
11: Remove from $w^{(l+1)}$ the improper vertices and the vertices $\{ z \in w^{(l+1)} \mid z < \hat{x}^{l} \}$.
12: end
13: Set $l = l + 1$.
14: Until $|f(\pi^{(l)}) - V^{l}| \leq \epsilon$.
15: Return $x^* = \hat{x}^{l}$.

V. COMPUTATIONAL COMPLEXITY

In this section, we aim to provide the computational complexity of the polyblock algorithm, which significantly depends on the structure of the objective function and the constraints that form the normal set. We note that the proposed algorithm includes the following steps. In the first step, we obtain the best vertex with its projection belonging to the normal set. Next, we obtain the projection of the selected vertex. Finally, having the improper vertices removed, the new vertex set is found. We assume that the dimension of the optimization problem is $L_1$, the number of iterations in the overall polyblock algorithm for convergence is $L_2$ while the number of iterations for the projection of each vertex is $L_3$. Then, the complexity order can be expressed as $O(L_2 (L_2 \times L_1 + L_3))$ \cite{20, 21}.

VI. SIMULATION RESULTS

In this section the performance of our proposed algorithm via simulations is examined. We assume that each subchannel experiences Rayleigh flat fading which includes the path-loss model. The simulation parameters are given in Table I unless otherwise specified.

Fig. 1 shows the system sum-rate versus maximum transmit power of CUs for an equal weight of CUs and DUs i.e., $\alpha = 0.5$. It can be seen that by increasing $p^{\text{max,Cellular}}$, not only makes the CUs more easily meets the minimum requirement but also improves the system throughput. In fact with the increase $p^{\text{max,Cellular}}$, the system throughput increases monotonically due to enhancing the achievable rate for CUs which results in an enhancement of the total throughput of the system. This figure also shows that large value of $p^{\text{max,Cellular}}$ leads to releasing the potential of DUs that enables more D2D pairs to access the network. For comparison, we also consider three baseline schemes for the system sum rate. For baseline scheme 1, we adopt a subcarrier assignment randomly where the power allocation is obtained based on our proposed monotonic approach. For baseline scheme 2, we consider MC-OMA in which each subcarrier is allocated to at most one

| TABLE I SIMULATION PARAMETERS |
|-----------------------------|
| Parameter                  | Value                |
| Cell diameter              | 250 m                |
| Distance between D2D link   | 30 m                 |
| Number of CUs ($K_f$)      | 6                    |
| Number of DUS ($K_d$)      | 3                    |
| Number of sub-carriers ($N$)| 4                    |
| Noise power                | -120 dBm             |
| Sub-carrier bandwidth      | 180 kHz              |
| Path-loss model for cellular links | 128.1 + 37.6 log(d) |
| Path-loss model for D2D links | 148.1 + 40 log(d)   |
| Maximum transmit power of the DUs | 25 dBm               |
| Minimum data rate requirement ($R_{\text{min}}$) | 1 bps/Hz          |
user. For baseline scheme 3, we considered the proposed method in [14] in which an iterative algorithm is adopted to find the resource allocation policy. It can be perceived that our proposed algorithm outperforms the proposed algorithm in [14] due to performing a monotonic approach which gives us optimal resource allocation policy. Furthermore, we observe that the system sum rate for MC-OMA achieves a lower system sum rate compared to MC-NOMA due to underutilizing the orthogonal subcarrier assignment.

The trade-off between the total data rate of DUs and CUs is investigated in Fig. 2. This figure is obtained by solving problem (18) for different values of $\alpha \in [0, 1]$, with a step size of 0.1. It can be seen that a non-trivial trade-off between the total data rate of DUs and CUs exists. In particular, the total DUs data rate is a decreasing function versus the total CUs data rate. In other words, maximizing the total DUs data rate leads to a reduction in total CUs data rate due to conflicting objectives functions. In fact, by changing the weight factor, we can provide fairness between the cellular and DUs. This figure also demonstrates the superiority of the NOMA scheme as compared to the conventional OMA method.

VII. CONCLUSION

In this paper, we investigated the tradeoff between DUs and CUs in uplink underlaying CUs-enabled the NOMA network. We formulated a MOOP formulation which jointly maximizes the throughput of DUs and CUs simultaneously, to obtain power allocation strategy and subchannel assignment. The MOOP was converted into a SOOP using a weighted Tchebychef method and then solved via monotonic optimization to obtain an optimal solution. Simulation results not only unveiled an interesting tradeoff between the studied competing objective functions but also investigated the superiority of our proposed scheme as compared to MC-OMA.

REFERENCES

[1] V. W. Wong, R. Schober, D. W. K. Ng, and L.C.Wang, Key Technologies for 5G Wireless Systems. Cambridge University Press, 2017.

[2] F. Wang, C. Xu, L. Song, Q. Zhao, X. Wang, and Z. Han, “Energy-aware resource allocation for device-to-device uplink communication,” Proc.IEEE ICC, pp. 6076-6080, 2013.

[3] A. Asadi, Q. Wang, and V. Mancuso, “A survey on Device-To-Device communication in cellular networks,” IEEE Commun. Surveys Tuts., vol. 16, no. 4, pp. 1801-1819, Nov. 2014.

[4] C. Bockelmann, N. Pratas, H. Nikopour, K. Au, T. Svensson, C. Stefanovic, F. Popovski, and A. Dekorsy, “Massive machine-type communications in 5G: physical and MAC-layer solutions,” IEEE Commun. Mag., vol. 54, no. 9, pp. 59-65, Sep. 2016.

[5] J. Zhao, Y. Liu, K. K. Chai, A. Nallanathan, Y. Chen and Z. Han, “Spectrum allocation and power control for non-orthogonal multiple access in HetNets,” IEEE Trans. Wireless Commun., vol. 16, no. 9, pp. 5825-5837, Sept. 2017.

[6] Y. Pan, C. Pan, Z. Yang and M. Chen, “Resource allocation for D2D communications underlying a NOMA-based cellular network,” IEEE Wireless Commun. Letts., vol. 7, no. 1, pp. 130-133, Feb. 2018.

[7] D. Zhai, R. Zhang, Y. Wang, H. Sun, L. Cai, and Z. Ding, “Joint user pairing, mode selection, and power control for D2D-capable cellular networks enhanced by nonorthogonal multiple access,” IEEE Internet of Things Journal, vol. 6, no. 5, pp. 8919-8932, Oct. 2019.

[8] C. Xu et al., “Efficiency resource allocation for Device-to-Device underlay communication systems: A reverse iterative combinatorial auction based approach,” IEEE Journal on Selected Areas in Communications, vol. 31, no. 9, pp. 348-358, Sep. 2013.

[9] S. M. A. Kazmi, N. H. Tran, T. M. Ho, A. Manzoor, D. Niyato and C. S. Hong, "Coordinated device-to-device communication with non-orthogonal multiple access in future wireless cellular networks," IEEE Access, vol. 6, pp. 39860-39875, 2018.

[10] J. Liu et al., “Joint power allocation and user scheduling for device-to-device-enabled heterogeneous networks with non-orthogonal multiple access,” IEEE Access, vol. 7, pp. 62657-62671, 2019.

[11] J. Chen, J. Jia, Y. Liu, X. Wang, and A. H. Aghvami, “Optimal resource block assignment and power allocation for D2D-enabled NOMA communication,” IEEE Access, vol. 7, pp. 90023-90035, 2019.

[12] Y. Dai, M. Sheng, J. Liu, N. Cheng, X. Shen, and Q. Yang, “Joint mode selection and resource allocation for D2D-enabled NOMA cellular networks,” IEEE Trans Veh Technol, vol. 68, no. 7, pp. 6721-6733, Jul. 2019.

[13] J. Zhao, Y. Liu, K. K. Chai, Y. Chen and M. Elkhazali, “Joint subchannel and power allocation for NOMA enhanced D2D communications,” IEEE Trans Commun, vol. 65, no. 11, pp. 5081-5094, Nov. 2017.

[14] H. Zheng, S. Hou, H. Li, Z. Song, and Y. Hao, “Power allocation and user clustering for uplink MC-NOMA in D2D underlaid cellular networks,” IEEE Wireless Commun Letts, vol. 7, no. 6, pp. 1030-1033, Dec. 2018.

[15] M. W. Baidas, M. S. Bahbahani, E. Alsusia, K. A. Hamdi and Z. Ding, “Joint D2D group association and channel assignment in uplink multi-cell NOMA networks: A matching-theoretic approach,” IEEE Trans. Commun., vol. 67, no. 12, pp. 8771-8785, Dec. 2019.

[16] Y. Hao, Q. Ni, H. Li and S. Hou, “Robust multi-objective optimization for EE-SE tradeoff in D2D communications underlying heterogeneous networks,” IEEE Trans. Commun., vol. 66, no. 10, pp. 4936-4949, Oct. 2018.

[17] C. Vlachos and V. Friderikos, “MOCA: multiobjective cell association for device-to-device communications,” IEEE Trans. Veh. Technol., vol. 66, no. 10, pp. 9313-9327, Oct. 2017.

[18] M. R. Mili, A. Khalili, D. W. K. Ng, and H. Steendam, “A novel performance tradeoff in heterogeneous networks: A multi-objective approach,” IEEE Wireless Commun. Letts., vol. 8, no. 5, pp. 1402-1405, Oct. 2019.

[19] K. Miettinen, Nonlinear Multiobjective Optimization. Springer, 1999.

[20] Y. J. A. Zhang, L. P. Qiang, and J. W. Huang, “Monotonic optimization in communication and networking systems,” Foundations and Trends in Networking, vol. 7, no. 1, pp. 1-75, Now Publishers, Inc., 2013.

[21] J. Jalali and A. Khalili, “Optimal resource allocation for MC NOMA in SWIPT-enabled networks,” IEEE Commun. Letts., pp. 1–1, 2020.

[22] M. Grant, and S. Boyd, “CVX: Matlab Software for Disciplined Convex Programming, version 2.1.” http://cvxr.com/cvx Mar. 2014.