Energy Efficient Resource Allocation in mmWave D2D Enabled 5G Cellular Networks

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Abstract-**The current trend has seen the data capacity and traffic density increase due to the increased demand for multimedia services. Since this cannot be handled successfully by the current 4G networks, there is a need to integrate the mmWave and the Device-to-Device (D2D) communication 5G technologies to meet this increased demand and traffic density. However, there is the challenge of increased interference between dense D2D users and cellular users if D2D users are allowed to reuse the resources allocated to cellular users. This degrades the performance of the D2D users in terms of achievable data rate and Energy Efficiency (EE). The paper formulates a match theoretic resource allocation scheme to maximize the achievable D2D sum rate. In addition, an EE optimization problem is formulated for D2D users by considering the rate and power constraints. The EE optimization problem is solved by the Lagrangian dual decomposition method. The algorithms were simulated in MATLAB and the results were compared to Hungarian and heuristic optimization algorithms. The results showed that the match theoretic resource allocation is on average 1.82 times better than the Hungarian algorithm. At the same time, the match theoretic resource allocation algorithm increases fairness in resource allocation as it maintains a higher sum rate for low and high-density number of users. The proposed EE optimization algorithm improved the D2D performance by 8.2% compared to the heuristic algorithm.**

Keywords-D2D; energy efficiency; mmWave; matching theory; Lagrangian decomposition

I. INTRODUCTION

Mobile data traffic has been projected to rise over the next 10 years with the number of devices connected to each other and with the cloud reaching 50 billion. This exponential growth in the number of devices brings the challenge of managing the increased capacity required for multimedia communications. Despite these shortcomings, the implementation of the 5G technology can enhance coverage, energy efficiency and spectrum usage [1, 2]. This challenge can be solved by deploying Device-to-Device (D2D) communications which allow proximity users to share content directly without going through the Base Stations (BSs). This also ensures that there is better channel quality and lower transmit power for D2D communication [3, 4]. The integration of millimeter-wave (mmWave) and D2D communication ensures higher data rates, in the order of giga-bits per second, to be realized. The mmWave communication can address the challenge of implementing bandwidth-intensive applications such as interactive gaming and video streaming. The implementation of mmWave D2D networks may not only accomplish higher data rates but also reduce the energy consumption of the network [5]. The main merits of D2D communication is the provision of high data rates, better spectrum efficiency, lower latency, improved energy efficiency, and reduced power consumption. However, in D2D communication networks, there is limited battery life which requires the energy consumption to be taken into consideration in the design of D2D communication networks. Therefore, to reap the merits of D2D communication, resource and power allocation, mode selection, and interference control algorithms should be carefully developed to realize the optimal Quality of Service (QoS) guarantee for the Cellular Users (CUs) and D2D user pairs [6].

In this paper, a power control scheme for D2D communication network in the mmWave band is formulated for a single cell with multiple CUs and multiple D2D user pairs to improve performance in terms of sum rate and Energy Efficiency (EE). The EE, defined as the ratio of the achieved data rate (in b/s/Hz) and the total energy consumed, is an important metric for the future green 5G communication networks [7]. This study proposes a matching theory based on the Gale Shapley algorithm and a Lagrangian dual decomposition based EE maximization algorithm to allocate spectrum and power to the D2D user pairs and CUs in order to determine the optimal transmit power for each device in the network and to maximize sum rate and EE. The contributions of this study are:

- The formulation of a match-theoretic D2D solution for sum rate maximization and resource allocation optimization function for mmWave D2D communication, where D2D users share the uplink resources of cellular users.
- The formulation of an energy-efficient solution for resource allocation optimization function by considering minimum data rate, interference, and maximum power constraints.
- The validation of the proposed algorithm by comparing it with other resource allocation algorithms.

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II. RELATED WORK

There are studies which have implemented and analyzed mmWave D2D communication networks by optimizing EE and sum rate. In [8], a multiuser communication system consisting of cellular and D2D pairs was analyzed in order to optimize throughput under interference and transmit power constraints. The formulated nonlinear optimization problem was solved by a heuristic algorithm to obtain sub-optimal results while satisfying the minimum data rate requirement. This study was extended in [9] where a resource allocation for underlay D2D in outdoor mmWave scenario was studied with emphasis on fair distribution of resources in a cell while maximizing Spectrum Efficiency (SE). The power allocation for the D2D users in a single cell was done by applying an iterative water filling algorithm which considered the interference experienced in resource blocks with sub-optimal results being obtained. In [10], the objectives were to maximize the EE and to reduce transmission power. The optimization problem was mathematically formulated as a nonlinear fractional programming problem which was solved by an iterative power allocation algorithm for full duplex relay aided mmWave D2D communication. The study was extended by implementing a modified bottleneck effect elimination power algorithm for transmission power reduction and further improvement on the EE. In [11], a mode selection and resource sharing mechanism was implemented to maximize the sum logarithmic rate in a single cell based on Time Division Duplex (TDD) mmWave cellular network. The resource sharing solution was formulated as a mixed integer programming problem which was remodeled as a convex optimization problem. The Lagrangian dual technique was applied to obtain the solution. The adaptive mode selection was proposed after getting the solution of the resource sharing scheme. In [12], an EE maximization method with a trade-off between EE, system sum rate, and outage probability for various QoS levels and varying density of CUs and D2D pairs was studied. The energy-aware radio resource management scheme was formulated to jointly maximize the achievable rate and the EE of all CUs with a minimum QoS requirement and maximum input power constraint. The resource optimization problems reformulated to convex sub-problems by applying dual decomposition and Lagrange multipliers. Then the Karush Kuhn Tucker conditions were applied to find the optimal power allocation for microwave and mmWave BSs. The optimal power allocation for the microwave BS associated users was determined by multi-level water filling where the water level depended on the beam-level beamwidth for the transmitter and the receiver. The subcarrier allocation problem was solved with the Hungarian algorithm obtaining a near optimal solution. The concept of channel inversion was applied in [13] to develop an energy efficient outband D2D communication network in the mmWave band. It considered the effect of sectored antenna models and the number of elements in the uniform linear array antennas for SE and EE maximization. The analysis was based on stochastic geometry and the results showed that the EE can be improved by a factor of 23 in a dense user scenario compared to omnidirectional antennas.

In [14], a downlink mmWave cellular communication network underlaid with multiple D2D user pairs was studied to optimize the outage probability and ergodic capacity. The Non-Orthogonal Multiple Access (NOMA) was integrated with multi-user MIMO in the developed D2D underlaid system model. The simulated model was then compared with the traditional TDMA with the results showing that NOMA had a better performance. An OFDMA cellular network with an integrated D2D communication was studied in [15] to optimize device association probability, coverage probability, spectral efficiency, and energy efficiency. The resource allocation scheme considered incorporated distance threshold, device association, antenna radiation pattern, and blockage effects with an out-of-cell interference constraint.

The present study formulates a match-theoretic resource allocation scheme for a mmWave D2D communication network to maximize sum rate. It also develops a Lagrangian based resource allocation scheme to optimize the energy efficiency of D2D users. The developed mmWave D2D communication model considers the D2D reuse and dedicated modes. This study addresses the challenge of interference and increased energy consumption in 5G D2D networks by developing an energy efficient scheme. The energy efficient optimization algorithm considers the distance of the D2D user pair from the BS, the distance of the CUs from the BS, and the maximum transmit power. The sum rate maximization algorithm considers the number of D2D user pairs, the number of resource blocks, and the cell radius variation.

III. SYSTEM MODEL

Consider D2D users (DUs) operating in dedicated mode for Line of Sight (LOS) conditions and cellular reuse mode when the interference threshold set for the D2D link is exceeded in non-LOS (NLOS) conditions, thereby sharing resources with the CUs. Figure 1 shows a single cell considered in this study which consists of a set of K CUs, $\mathcal{K} = \{1,2,3,\dots,K\}$ and a set of L DU pairs denoted by $\mathcal{L} = \{1,2,3,\dots,L\}$ sharing the available spectrum. When the DUs are not communicating due to severe signal blockage, they will shift to the reuse mode by sharing the uplink resources with the CUs in the same cell.

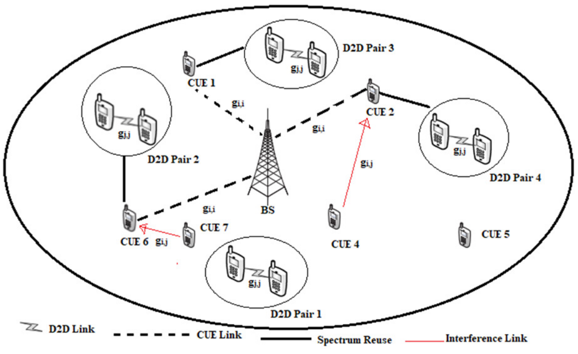

Fig. 1. System model.

The BS has N Resource Blocks (RBs) $\mathcal{N} = \{1,2,\dots,N\}$, each having a bandwidth B for communication. In this case, there are $\mathcal{N}$ RBs allocated to CUs and DUs denoted as n_s, where a cellular user $k \in \mathcal{K}$ can transmit with a resource block $n \in N$ at a transmit power $p_{k,n}$ with the transmit power constraint given as $\sum_{n \in N} p_{i,s} \leq p_i^c$, where p_i^c is the transmit power threshold for the cellular device and c denotes a cellular device. In the same way, the D2D user $L \in \mathcal{L}$ does its transmission with a resource block $n \in \mathcal{N}$ with a transmit power $p_{l,n}$ subject to the D2D user's own transmit power constraint which is given by $\sum_{n \in N} p_{j,s} \leq p_j^d$, with p_j^d being the transmit power threshold for a D2D device and d denotes the D2D device. In addition, the communication is assumed to use the uplink transmission resources for the CUs since the uplink cellular spectrum is lightly loaded in comparison with the downlink cellular spectrum. This implies that the interference originating from the spectrum sharing scheme can only affect the BS side. For a successful resource sharing and optimal power allocation, the CUs and the DUs must meet certain Signal-to-Interference-to-Noise Ratio (SINR) constraints before spectrum sharing is set up. It is also assumed that the number of DU pairs L is equal to the number of CUs K to attain a stable matching. The channel model takes into consideration the multipath propagation effects, i.e. fast fading, slow fading, and shadowing effect. Therefore, the channel gain between the cellular user, k_i and the BS can be given as [16]:

$$g_{i,b} = \Psi \beta_{i,b} \xi_{i,b} d_{i,b}^{-\alpha} \quad (1)$$

where Ψ is a constant value for determining the system parameter, $\beta_{i,b}$ is fast fading gain, $\xi_{i,b}$ is slow fading gain, $d_{i,b}$ is the distance between cellular user k_i and the BS, and α is the Path Loss Exponent (PLE). The channel gain between the DU transmitter and receiver L_j is denoted as g_j, the interference link between the DU transmitter and receiver L_j and the BS has its channel gain as $h_{i,b}$, the interference link between the cellular user k_i and DU L_j has a channel gain given as $h_{i,j}$.

The spectrum sharing between any DU and a CU is made possible when the minimum SINR requirement is satisfied between a DU transmitter and receiver or a CU. The additive white Gaussian noise power spectral density is assumed for all the cases to be N_o. The SINR for communication between the DU and the BS is:

$$\gamma_j^d = \frac{p_j^d g_j}{\rho_{i,j} p_i^c h_{i,j} + N_o} \quad (2)$$

The SINR for the cellular user and BS communication can be expressed as:

$$\gamma_i^c = \frac{p_i^c g_{i,b}}{\rho_{i,j} p_j^d h_{j,b} + N_o} \quad (3)$$

The maximum sum rate for the D2D network in reuse mode can then be formulated as:

$$\max_{\rho_{i,j}, p_i^c, p_j^d} \sum_{k=1}^{K} \sum_{l=1}^{L} W_i \left[\log_2\left(1+\gamma_j^c\right) + \rho_{i,j} \log_2(1+\gamma_j^d)\right] \quad (4)$$

$$s.t \;\; \gamma_j^d = \frac{p_j^d g_j}{\rho_{i,j} p_j^d h_{i,j} + N_o} \geq \gamma_{j,min}^d \quad \forall L_j \in \mathcal{L} \quad (5)$$

$$\gamma_i^c = \frac{p_i^c g_{i,b}}{\rho_{i,j} p_j^d h_{j,b} + N_o} \geq \gamma_{i,min}^c \;\; \forall k_i \in \mathcal{K} \quad (6)$$

$$\sum_{L_j \in L} \rho_{i,j} \leq 1, \;\; \rho_{i,j} \in \{0,1\} \quad \forall\, k_i \in \mathcal{K} \quad (7)$$

$$\sum_{k_i \in K} \rho_{i,j} \leq 1, \;\; \rho_{i,j} \in \{0,1\} \quad \forall\, L_j \in \mathcal{L} \quad (8)$$

$$p_j^d \leq p_{max}^d, \; \forall L_j \in \mathcal{L} \quad (9)$$

$$p_i^c \leq p_{max}^c, \forall k_j \in \mathcal{K} \quad (10)$$

The binary variable $\rho_{i,j}$ is defined such that $\rho_{i,j} = 1$ if the RB of cellular user is shared with a DU L_j operating on the same RB n otherwise $\rho_{i,j} = 0$. The optimization function of (4) incorporates the CUs and DUs' interference constraint. The formulated problem is a Mixed Integer Nonlinear Problem (MINLP) whose objective function is non-convex. This problem is non-convex due to the existence of the interference term in the denominator of the objective function. The complexity of the solution method increases exponentially with the number of DUs and sub channels. The sub channel and power allocation variables are coupled together. Therefore, the formulated optimization problem will be decomposed into two sub problems where one deals with the sub channel assignment and the other with the power allocation to the receivers. The spectrum assignment and power allocation problems are solved by applying matching theory and Lagrangian dual decomposition.

A. Admission Control Scheme

This scheme is used to determine the admissible pairs which have one CU and one DU pair. The membership to the set of these admissible pairs is possible only when both the CUs and the DUs transmit powers have satisfied the minimum SINR requirements. The equations which govern the admissible sets are given by:

$$\left.\begin{array}{l} \gamma_j^d = \frac{p_j^d g_j}{\rho_{i,j} p_j^d h_{i,j} + N_o} \geq \gamma_{j,min}^d \\ \gamma_i^c = \frac{p_i^c g_{i,b}}{\rho_{i,j} p_j^d h_{j,b} + N_o} \geq \gamma_{i,min}^c \\ p_j^d \leq p_{max}^d, p_i^c \leq p_{max}^c \end{array}\right\} \quad (11)$$

B. Optimal Power Allocation

For every admissible pair between the cellular users and the D2D user pair, the optimal power allocation is determined. The optimal pair can be expressed by:

$$\left(p_i^{c*}, p_j^{d*}\right) = \arg\max_{p_i^c, p_j^d \in \mathcal{Q}_{admin}} f\left(p_i^c, p_j^d\right) \quad (12)$$

with $f\left(p_i^c, p_j^d\right) = W_i\left[\log_2\left(1+\gamma_j^c\right) + \rho_{i,j} \log_2(1+\gamma_j^d)\right]$, where $\mathcal{Q}_{admin}$ is a set containing all the transmission power pairs for the cellular users and D2D pairs. If the function $f\left(p_i^c, p_j^d\right)$ is defined as $f\left(p_i^c, p_j^d\right) = W_i\left[\log_2\left(1+\gamma_j^c\right) + \rho_{i,j} \log_2(1+\gamma_j^d)\right]$, then $f\left(\xi p_i^c, \xi p_j^d\right)$ can be derived such that $f\left(\xi p_i^c, \xi p_j^d\right) = W_i\left[\log_2\left(1+\gamma_j^c\right) + \rho_{i,j} \log_2(1+\gamma_j^d)\right]$ if $\xi > 1$. This implies that, at least one value exists for the transmission power in $\left(p_i^{c*}, p_j^{d*}\right)$ which is bounded by the maximum power values. Therefore, the function $f\left(p_i^c, p_j^d\right)$ can be maximized by allowing only one user to transmit at the maximum transmit power value. It has been shown that $f\left(p_i^c, p_j^d\right)$ is a convex function over either p_i^c or p_j^d when the other power value is fixed [17].

C. Gale-Shapley Algorithm for Stable Matching

The sum rate optimization problem is modeled as a one-to-one matching game and then a stable marriage is applied to match the D2D users with the CUs and mappings [18]. The Gale Shapley (GS) algorithm [19] is applied in this stable marriage game to determine a stable solution. A stable matching is defined as a complete matching between a DU transmitter and a DU receiver that admits no blocking pair. The basis of the GS algorithm is that one DU transmitter makes a series of proposals to the other set of CUs. This implies that each DU transmitter and receiver pair proposes, in order, to CUs which are in their preference list and waits for the CUs to consider the proposal, but continues if the proposal is rejected. The CU receives the proposal and rejects it, if there is already an existing better proposal, otherwise it holds it for another consideration. The process terminates if all the proposals have been considered and no other request can be made from the D2D pairs. The admissible pairs and the optimal transmit power can be determined after admission and power control. The cellular users' sum rate is given by $W_i \log_2(1+\gamma_i^c)$ during spectrum sharing with D2D users, L_j being used to show the $k_i's$ preference over L_i. Similarly, the D2D user sum rate $W_i \log_2(1+\gamma_j^d)$ is used to show the $L_j's$ preference over k_i. Thus, defining the preference relation for k_i, which is between k_i with $k_{i'}$ and preference relation forL_j, which is between L_j with $L_{j'}$.

Definition 1: The CU k_i prefers L_j to L_j' if the achievable rate of L_j is greater than that of L_j' , $W_i \log_2(1+\gamma_j^d) > W_i \log_2(1+\gamma_{j'}^d)$ which is denoted as $l_j \succ_{k_i} l_{j'}$ for $k_i \in \mathcal{K}$, $l_j, l_{j'} \in \wp_i^c$, $j \neq j'$, where $\wp_i^c$ is a set of DUs admitted by CU k_i.

Definition 2: The D2D user, l_j prefers k_i to k_i' if $W_i \log_2(1+\gamma_i^c) > W_i \log_2(1+\gamma_{i'}^c)$ which is denoted as $k_i \succ_{l_j} k_i'$ for $l_j \in \mathcal{L}$, $k_j, k_{j'} \in \wp_i^d$, $i \neq i'$, with $\wp_i^d$ denoting the set of DUs admitted by DU l_j. The rank which is denoted as (k_i, l_j) shows the position of l_j in the $k_i's$ preference list, $\mathcal{PL}_i^c$ and rank (l_j, k_i) as the position of k_i in $l_i's$ preference list, $\mathcal{PL}_j^d$.

Definition 3: The matching $\mathcal{M}$ is said to be stable, if there is no blocking pair (k_i, l_j) such that $l_j \succ_{k_i} \mathcal{M}(k_i)$ and $k_i \succ_{l_j} \mathcal{M}(l_j)$ where $\mathcal{M}(k_i)$ denotes $k_i's$ partner in $\mathcal{M}$ and $\mathcal{M}(l_j)$ represents $l_i's$ partner in $\mathcal{M}$.

The matching-theoretic sum rate maximization algorithm is summarized in Algorithm 1.

Algorithm 1: Sum Rate Maximization

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1. Input: D2D user set, $\mathcal{L}$, Cellular user set, $\mathcal{K}$, Number of RBs, $\mathcal{N}$ and Number of D2D links, $\mathcal{V}$, $p_{max}^d$, $p_{max}^c$.
Begin
2. Set, $\rho_{i,j} = 0, \forall k_i \in \mathcal{K}\ and\ \forall L_j \in \mathcal{L}$
3. for $k_i \in \mathcal{K}$ ; $L_j \in \mathcal{L}$
4. if SINR condition is met, then
5. $\rho_{i,j} = 1$
6. Count how many times a node is chosen
7. for $j=1: \mathcal{V}$ do
8$N_j^d = sum(x_{j,}1:\mathcal{N})$.
9. end
10. for i=1: $\mathcal{N}$, do
11. $N_i^c = sum(x_{i,}1:\mathcal{V})$
12. end
13. D2D link, $j_o$with minimum $N_{j_0}^d$ is selected
14. for i=1: $\mathcal{N}$, do
15. if $\rho_{i,j_o} = 1$, then
16. $CU - k_i$ with minimal $N_i^c$selected for D2D link-$j_o$
17. Maximize $R_{i,j_o}$ by optimizing $p_i^c, p_j^d$
18. end
19. end
20. Delete DU-CU reuse pair already used from the set
21. Update $\mathcal{N}$, $\mathcal{V}$.
22. Go to step 13 till $\mathcal{N}$ =0 or $\mathcal{V}$ =0
23. end
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D. Energy Efficiency Optimization for D2D User Devices

The reuse mode is selected and the n^{th} RB is allocated to the k_i CU. The n^{th} RB that is allocated to the CU is then reused by the L_j D2D pair. The transmit power from the transmitter of the L_j D2D pair on the n^{th} RB is denoted as $p_{j,n}^d$. The achieved data rate by the L_j D2D users on the n^{th} RB can be given as:

$$R_d = B \log_2\left(1 + \frac{p_{j,n}^d g_{j,j}}{p_i^d g_{i,j} + N_o}\right) \quad (13)$$

where B is the bandwidth of the n^{th}considered RB, $g_{j,j}$ is the channel gain between DU L_j, $g_{i,j}$ is the interference channel gain from the k_i CU to the L_j DU pair and N_o is the noise power. The total D2D data rate can be denoted as R_D which can be given by:

$$R_D = \sum_{l=1}^{L} \sum_{n=1}^{N} R_d \quad (14)$$

The total radiated power, $p_{j,t}^d$, for the L_j D2D pair can be expressed as:

$$p_{j,t}^d = \sum_{l=1}^{L} \sum_{n=1}^{N} p_{j,n}^d \quad (15)$$

where $l \in \mathcal{L}$ the number of D2D users is, $n \in \mathcal{N}$ is the number of RBs.

Let P_c represent the total power consumption by the device circuitry of all the D2D users under consideration and is independent of the radiated power. The total EE, η_{EE} of the D2D communication pairs can be expresses as:

$$\eta_{EE} = \frac{R_D}{p_{j,t}^d + P_c} \quad (16)$$

where P_c, is the power consumed by the device circuitry. The binary variable $\rho_{j,n}$ indicates when the resources are allocated to the D2D users, is such that $\rho_{j,n} = 1$ when a resource has been allocated to a D2D user and zero otherwise. The EE optimization problem can then be formulated as:

$$\max_{\rho_{j,n}, p_{j,n}^d} \eta_{EE} \quad (17)$$

subject to:

$$R_D \geq R_{D,min}, \forall \rho_{j,n} = 1 \quad (18)$$

$$p_{j,n}^d g_{i,j} \leq \tau, \forall \rho_{j,n} = 1 \quad (19)$$

$$\sum_{l=1}^{L}\sum_{n=1}^{N} p_{j,n}^{d} \leq p_{max}^{d} \quad (20)$$

where $R_{d,min}$ is the minimum data rate requirement for every D2D pair, τ is the interference threshold between the CU and the D2D pair, and p_{max}^{d} is the maximum transmit power for every D2D pair transmitter. Since the optimization problem has a binary variable, it falls in the category of MINLP which is complex to solve. In addition, the fractional energy efficiency optimization problem is a non-convex function. The optimal value of EE for the D2D pairs can be denoted as η^* and is expressed as:

$$\eta^* = \max_{\{\rho_{j,n},p_{j,n}^{d}\}\in\Omega} \frac{R_D}{p_{j,t}^{d}+P_c} \quad (21)$$

where Ω is the feasible region of the constraints.

The objective function can be transformed by applying the following theorems [20].

Theorem 1: The maximum value of EE, η^* can be attained if and only if:

$$\max_{\{\rho_{j,n},p_{j,n}^{d}\}\in\Phi} \Phi(\eta) = \{R_D - \eta^*(p_{j,t}^{d} + P_c)\} = 0 \quad (22)$$

The equivalent subtractive function can be obtained for the fractional optimization problem by utilizing the fractional programming techniques. The equivalent objective function is convex and can be solved by the Lagrange dual decomposition technique. The Lagrange dual function can be expressed as:

$$\mathcal{L}(p_{j,n}^{d},,\delta,\theta,\beta) = R_D - \eta(\sum_{l=1}^{L}\sum_{n=1}^{N} p_{j,n}^{d} + P_c) + \delta(R_D - R_{D,min}) + \theta(\sum_{i\neq j}^{N} p_{j,n}^{d} g_{i,j} - \tau) + \beta(\sum_{l=1}^{L}\sum_{n=1}^{N} p_{j,n}^{d} - p_{max}^{d}) \quad (23)$$

where δ, θ, β are the Lagrange multipliers for the constraints given in (18)-(20). The Lagrange dual optimization function can then be formulated as:

$$\min_{\delta,\theta,\beta} \max_{p_{j,n}^{d}} \mathcal{L}(p_{j,n}^{d},,\delta,\theta,\beta) \quad (24)$$

$$s.t\ \delta,\theta,\beta \geq 0 \quad (25)$$

The Karush Kuhn conditions for the optimization problem given by (22) result in a series of nonlinear equations which are complex to solve. Therefore, an efficient numerical iteration method should be proposed to optimally solve the problem in (22). The optimal power allocation to maximize energy efficiency can be determined by taking the first derivative of (23) with respect to $p_{j,n}^{d}$:

$$\frac{\partial L}{\partial p_{j,n}^{d}} = \frac{(1+\delta)g_{j,j}}{\left[(\eta+\theta)+\beta\sum_{i\neq j}^{N} p_{j,n}^{d} g_{i,j}\right] In\ 2} - p_{j,n}^{d} - \sum_{i\neq j}^{N} p_{j,n}^{d} g_{i,j} + N_o \quad (26)$$

Then, equating the first derivative to zero and rearranging gives the optimal power allocation as:

$$p_{j,n}^{d*} = \frac{(1+\delta)}{\left[(\eta+\theta)+\beta\sum_{i\neq j}^{N} p_{j,n}^{d} g_{i,j}\right] In\ 2} - \frac{\sum_{i\neq j}^{N} p_{j,n}^{d} g_{i,j} + N_o}{g_{j,j}} \quad (27)$$

This is the solution of the optimization problem given in (23). The values of δ, θ and β that can minimize the dual objective function (24) can be determined by applying the sub-gradient method [21, 22]:

$$\delta(m+1) = [\delta(m) - \Delta(R_D - R_{D,min})] \quad (28)$$

$$\theta(m+1) = [\theta(m) - \Delta(p_{j,n}^{d} g_{i,j} - \tau)] \quad (29)$$

$$\beta(m+1) = [\beta(m) - \Delta(\sum_{l=1}^{L}\sum_{n=1}^{N} p_{j,n}^{d}(m) - p_{max}^{d}] \quad (30)$$

where m is the iteration index and Δ is a positive parameter which is the Newton decreasing step size. This shows that as the value of m increases, the value of power p converges to some fixed point. The Newton decreasing step size Δ is determined as:

$$\Delta = \frac{\partial\mathcal{L}(p_{j,n}^{d},,\delta,\theta,\beta) / \partial p_{j,n}^{d}}{\partial^2\mathcal{L}(p_{j,n}^{d},,\delta,\theta,\beta) / \partial(p_{j,n}^{d})^2} \quad (31)$$

The stopping criteria for the iterative optimization algorithm is determined as:

$$\varepsilon = \frac{\left(\partial\mathcal{L}(p_{j,n}^{d},,\delta,\theta,\beta) / \partial p_{j,n}^{d}\right)^2}{\partial^2\mathcal{L}(p_{j,n}^{d},,\delta,\theta,\beta) / \partial(p_{j,n}^{d})^2} \quad (32)$$

The energy efficiency optimization problem is solved by Algorithm 2.

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Algorithm 2: Energy Efficiency Optimization
1. Input: $\delta = 0.001, \theta = 0.001, \beta = 0.001$
2. while, $|\mathcal{L}(p_{j,n}^{d},,\delta,\theta,\beta)| \geq \varepsilon$ or $q \leq q_{max}$
3. repeat
4. find $p_{j,n}^{d}$ using (27)
5. update $\delta$, $\theta$, and $\beta$ using (28), (29), and (30) respectively
6. until $\delta$, $\theta$ and $\beta$ converge
7. update $\eta(q+1) = \frac{R_D}{p_{j,t}^{d}+P_c}$
8. update $\mathcal{L}(p_{j,n}^{d},,\delta,\theta,\beta)$
9. $q = q + 1$
10. end while
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IV. SIMULATION RESULTS AND DISCUSSION

This section presents the simulated results of a mmWave D2D communication network in terms of sum rate and EE performance metrics. The mmWave D2D model illustrated in Figure 1 was simulated in MATLAB version R2018b using the settings given in Table I. The simulation procedure starts by drawing a circular single cell with the BS at the center. Then, the D2D users and CUs are randomly distributed within the cell by a Poisson point distribution process for a cell radius of 250m. The users' admission criteria given in (11) are used to define the selection of users within the network. For the D2D user pairs, an additional criterion of minimum distance between them is defined. For this study, the minimum distance between a D2D user pair was taken as d_0=4m. The energy consumption of the D2D user pairs which consists of the radiated transmission power and the circuit power was determined for maximization of the energy efficiency. The D2D performance analysis is based on the mathematical expressions presented above and the proposed algorithms for LOS and NLOS scenarios. The D2D sum rate for dedicated and reuse modes was simulated by Algorithm 1 and the energy efficiency by Algorithm 2. The results of the proposed Gale Shapley and the Lagrangian dual decomposition based algorithms were compared to Hungarian and heuristic algorithms respectively. The mmWave channel model was modeled with (1) with the parameters α_n, α_l being the path loss exponents for LOS and NLOS conditions. The path loss parameters and shadowing standard deviation in dB are based on the New York University (NYU) mmWave model presented in [23]. The mmWave D2D simulation settings such as maximum transmit power and number of resource blocks are based on [24, 25].

TABLE I. SIMULATION PARAMETERS

Parameter	Notation	Value
Maximum radius of the cell	R	250m
Maximum transmit power of DU	P^d_{max}	23dBm
Carrier frequency	f_c	28GHz
Noise power (dBm)	N_o	-174
Bandwidth per RB	B	20MHz
System bandwidth	W	1GHz
Number of RBs	N	50
SINR threshold, DU	τ_d	4dB
D2D link distance	d_L	5-50m
Path Loss Exponent (PLE)	α_l, LOS $\alpha_n, NLOS$	2 2.92
Number of D2D users	L	50
Fading standard deviation	LOS $NLOS$	5.8dB, 8.7dB

E. Sum Rate Maximization

The D2D communication was simulated in MATLAB with the CUE and D2D devices being distributed randomly in a single cell network. Figure 2 gives the variation of D2D sum rate when the number of D2D pairs is increased for reuse and dedicated modes in a cell radius of 250m. The D2D communication under LOS conditions was simulated for dedicated mode where the D2D user pairs operate in a dedicated channel which is free from the interference of the CUs. This shows that the D2D deployment as an overlay (outband) to the cellular network in the mmWave band can achieve higher data rates compared to other operating modes. When the D2D users are implemented as an underlay to the CUs, the interference between the CUs and the D2D user pairs is taken into consideration and reduces the achievable sum rate by the D2D pairs which are reusing the resources already allocated to the CUs. The NLOS conditions were also considered in the mmWave D2D network scenario. The results showed that the dedicated mode of operation from the D2D user pairs performs well when the number of pairs is less 30 as shown in Figure 3. This is because with the densification of the D2D user pairs, the interference which was assumed to be so small for an overlaid implementation starts to increase. This reduces the sum rate attainable for the dedicated mode.

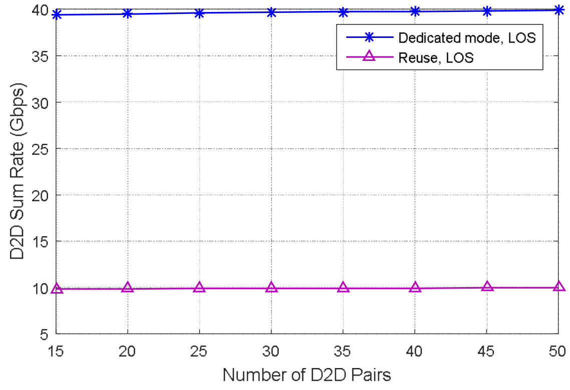

Fig. 2. Sum rate versus number of D2D pairs for LOS.

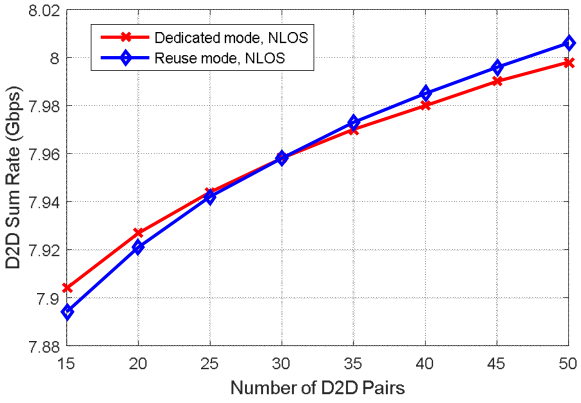

Fig. 3. Sum rate versus D2D pairs for NLOS.

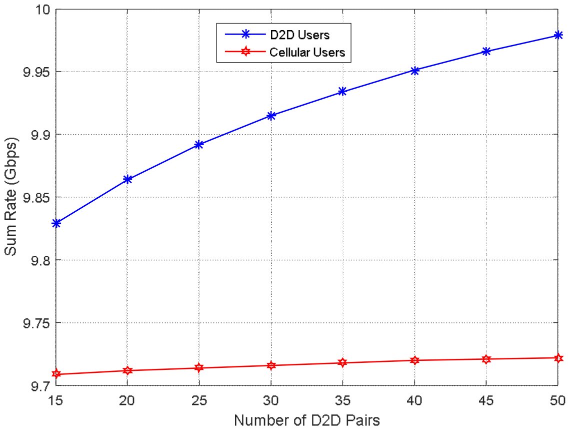

Fig. 4. Sum rate versus number of D2D pairs.

For the reuse mode, since the D2D user pairs are reusing the spectrum resources of the CUs, they are able to complete the communication. In this case, the CUs might not be encountering the NLOS conditions at the same time with the D2D pairs. This is the reason why the implementation of a reliable D2D communication network should incorporate both modes of operation so that in case of poor channel conditions it can able to switch between modes. The comparison of the sum rate obtained by both the D2D user pairs and CUs when the D2D users are operating in the LOS reuse mode is given in Figure 4. The cell radius is maintained at 250m. The Figure shows that the D2D achievable sum rate is higher compared to the CUs whose resources are reused. The higher data rate for D2D users is beneficial for meeting the high data rate requirements for the mmWave 5G networks. The study also considered the effect of varying cell radius from 100m to 500m as shown in Figure 5. The performance in terms of sum rate improved when the radius of the cell was reduced due to the existence of many D2D connections with the radius of 100m offering the best performance. This is very useful when the D2D communication is integrated with pico cells to improve sum rate and EE. In addition, this allows the densification of the D2D user equipment and pico cells for capacity enhancement in 5G networks.

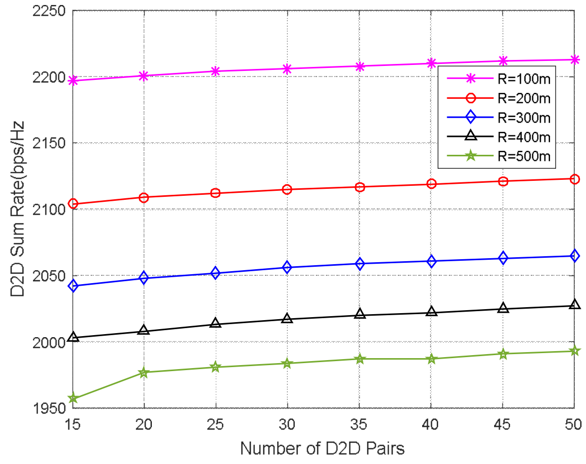

Fig. 5. Sum rate versus cell radius.

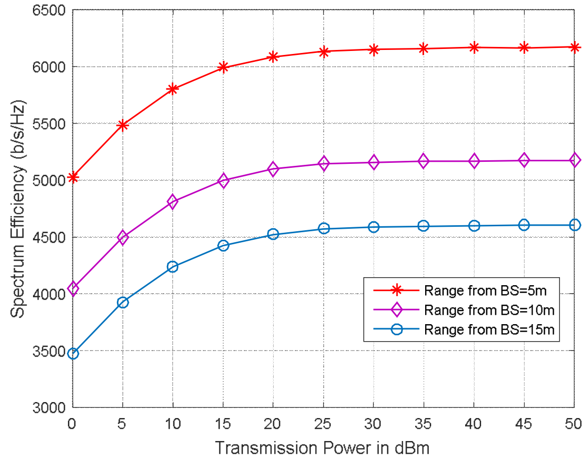

Fig. 6. Spectrum efficiency versus transmission power.

As shown in [23], the minimum cell radius for femto cells is 10m, for pico cells is 100m, and for micro cells it is 200m. The femto cells are only applied for indoor networks while the pico and micro cells are applied for both outdoor and indoor network scenarios. Therefore, the minimum radius used in this study is 100m, which is appropriate for pico cells. The deployment of pico cells is beneficial for D2D implementation as it can serve both indoor and outdoor users. Figure 6 shows that the range of a D2D pair from the BS has an impact on the obtained spectrum efficiency. It can be seen that when there is a range reduction, there is an increase of spectrum efficiency up to 25dBm. Beyond 25dBm the spectrum efficiency curve remains almost flat due to an interference increase as the transmission power goes beyond 25dBm.

F. Energy Efficiency Optimization

The energy efficiency for D2D users is presented in Figure 7 for various locations of the CUs from the BS whose resources are reused by the D2D users. The results show that as the location distance of the D2D user from the BS is increased, the EE is reduced due to the increased path losses and interference. In addition, when the CU location distance from the BS whose resources are reused is increased, the EE improves due to the reduction of interference contribution from the BS which might be communicating to other devices using the same channel. Figure 8 shows the variation of EE with the range of D2D users from the BS for different levels of RBs. The performance is better when 500 RBs are used. The use of more RBs reduces the interference experienced by the D2D user devices.

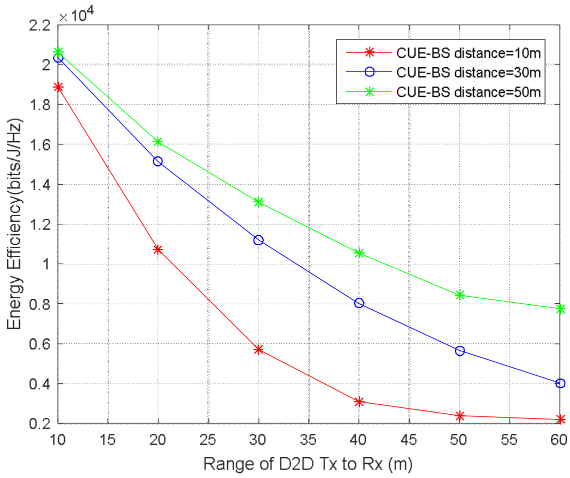

Fig. 7. Energy efficiency versus location of D2D users

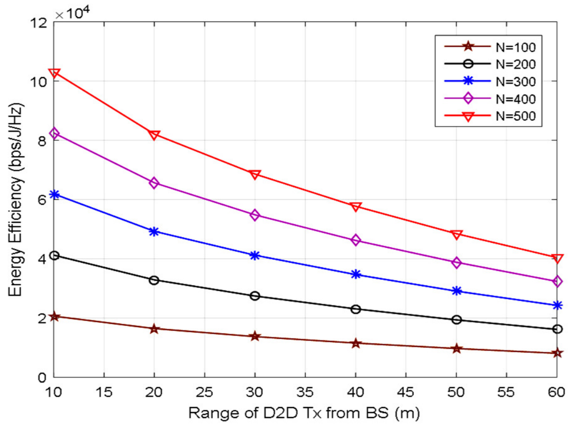

Fig. 8. EE versus number of RBs.

V. PERFORMANCE VALIDATION

The Gale Shapley based resource allocation optimization algorithm for sum rate maximization was compared with the Hungarian algorithm to validate the achieved performance. This was done by varying the number of D2D pairs. Figure 9 shows that the proposed algorithm performs better for any density of D2D users. The Hungarian algorithm only performs similarly for high density of D2D users. Therefore, the proposed Gale-Shapley algorithm increases fairness in resource allocation for attaining a higher D2D rate. Figure 10 shows the comparison of the EE obtained by varying maximum transmit power. The result shows that the proposed algorithm has an improved performance by an average of 8.2% compared to that of the heuristic algorithm presented in [8].

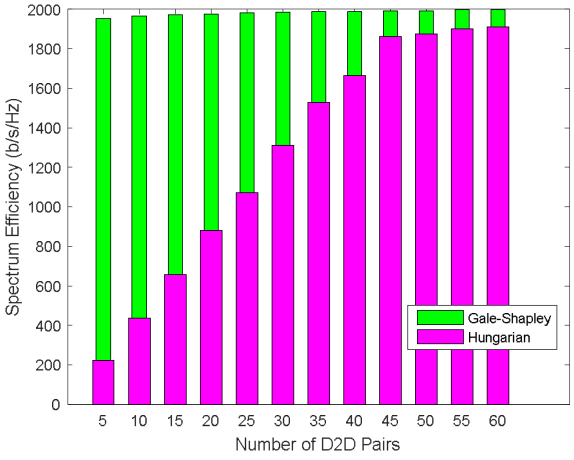

Fig. 9. Comparison of optimization algorithms for given numbers of D2D pairs.

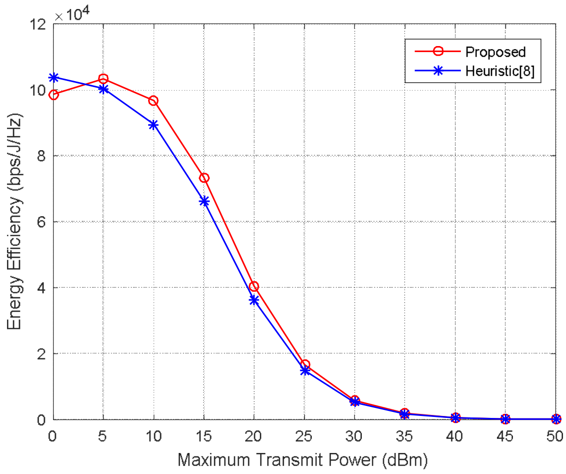

Fig. 10. Comparison of the proposed and the heuristic algorithm from [8].

VI. CONCLUSION

In this paper, the resource allocation problem was studied for mmWave D2D communication in frequency reuse and cellular mode. The main goal was to optimize the sum rate by applying the matching-theoretic algorithm. In addition, the EE of D2D users was maximized by varying the distance of a D2D transmitter from the BS.

The results showed that the Gale-Shapley algorithm had a performance which was averagely 1.82 times better when compared to the Hungarian algorithm. The Gale Shapley algorithm also ensured fairness in resource allocation for low density and high density scenarios. The Hungarian algorithm had a poor performance in the low density D2D user scenario. The spectral efficiency improved with the reduction of the cell radius. This showed that with densification of cells having a radius of between 50-100m, higher sum rates for D2D users can be obtained. The EE was found to decrease with an increase of the distance between the D2D transmitter and the BS due to the increase in path losses for D2D communication in the mmWave band. When the transmission power varied, it was found that the spectrum efficiency increased up to 30dBm and beyond that there was no further increase of the spectrum efficiency. When the EE was compared between the proposed algorithm and the heuristic algorithm from [8], the results showed that the proposed algorithm had a performance which was on average 8.2% better.

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