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Energy-Aware Radio Resource Management in D2D-Enabled Multi-Tier HetNets

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ABSTRACT Hybrid networks consisting of both millimeter wave (mmWave) and microwave (μW) capabilities are strongly contested for next-generation cellular communications. A similar avenue of current research is device-to-device (D2D) communications, where users establish direct links with each other rather than using central base stations. However, a hybrid network, where D2D transmissions coexist, requires special attention in terms of efficient resource allocation. This paper investigates dynamic resource sharing between network entities in a downlink transmission scheme to maximize energy efficiency (EE) of the cellular users (CUs) served by either (μW) macrocells or mmWave small cells while maintaining a minimum quality-of-service (QoS) for the D2D users. To address this problem, first, a self-adaptive power control mechanism for the D2D pairs is formulated, subject to an interference threshold for the CUs while satisfying their minimum QoS level. Subsequently, an EE optimization problem, which is aimed at maximizing the EE for both CUs and D2D pairs, has been solved. Simulation results demonstrate the effectiveness of our proposed algorithm, which studies the inherent tradeoffs between system EE, system sum rate, and outage probability for various QoS levels and varying densities of D2D pairs and CUs.

INDEX TERMS Device-to-device (D2D) communication, energy efficiency, fifth generation (5G) network, heterogeneous network, millimeter wave, multi objective optimization and radio resource management.

I. INTRODUCTION

The next generation wireless technology will consist of a mixture of network tiers of different sizes, transmission power levels, backhaul capabilities, and radio access technologies (RATs) [2], [3]. In recent years, traditional cellular networks have been utilizing sub-6GHz bands which are insufficient enough to meet the data demands of next generation networking, such as 5G, due to spectrum scarcity. Millimeter wave (mmWave) is considered as a key enabling technology for future generation networks due to its higher available bandwidth (in the range of 1-2 GHz) and the possibility of larger antenna arrays due to the smaller wavelength of mmWave signals [4]–[6].

Device-to-device (D2D) communication is a paradigm shift allowing its coexistence within the cellular infrastructure with a potential to enhance network performance, throughput and power utilization. It enables a dedicated direct link for the devices in close proximity to establish a connection [7]–[10], whereas in traditional cellular communication the entire traffic is routed through base stations (BSs). D2D communication systems have the potential to improve spectral resource utilization and reduce energy consumption, while providing support to new peer-to-peer and location-based applications and services [10], [11], such as public safety networks [12].

Recently, a lot of attention has been given to the radio resource management in traditional heterogeneous networks (HetNets) [13]–[18], where the small cells coexist with the macrocell both operating on μW band covering the same geographical area. Another facet of future 5G networks is the use of mmWave resources along with the μW resources. With the extreme shortage of available spectrum and demand for higher data rates, mmWave communication has triggered a great deal of interest. Indeed, the realization of a reliable communication network can only be achieved when mmWave network coexist with conventional μW networks. In past, the use of mmWave spectrum was not considered suitable for wireless communication due to its sensitivity to blocking and strong directionality requirements [19]. Moreover, [20], [21] summarizes the distinct characteristics of mmWave networks ranging from blockage models, initial access design, beamforming and radio resource management issues. In the recent literature, the coverage and rate trends are analyzed in mmWave cellular networks as outlined in [22]. It is also shown in [22] that the mmWave networks operate in noise limited regime in comparison to the traditional cellular networks operating in an interference limited regime. Furthermore, a cloud radio access network (CRAN) may also be considered a suitable candidate for 5G systems. It is envisioned that a 5G ultra dense cloud small cell network (UDCSNet) comprises densely deployed small cells and a CRAN. Zhang *et al.* [23] have highlighted the network architecture of such systems, laying special emphasis on their fronthaul infrastructure.

Another promising solution to improve the network capacity for the future generation network is the integration of D2D communication within the cellular infrastructure. The challenge in D2D communication is to devise a mode strategy that allows users to dynamically choose between either communicating directly or via the central access point (or BS). Lin *et al.* [24] have tackled this mode selection problem and have presented a tractable hybrid network model to derive an analytical rate expressions for the two D2D spectrum sharing scenarios, i.e., underlay and overlay. This work highlights that at higher D2D mode selection thresholds, the optimal spectrum partition is almost independent of the proportion of possible D2D users in the overlay spectrum sharing scenario. Similarly, the design of innovative and novel power control strategies for D2D links are of paramount importance in improving the performance of the D2D-enabled systems. In this respect, [25] puts forth a random network model for a D2D underlaid cellular network to develop a centralized and distributed power control strategies. Here, the former strategy restricts the aggregate received interference from the D2D pairs whereas the latter strategy maximizes the sum-rate of its users. For instance, [26] studies such a system model in which D2D pairs coexist with the multiple-input multiple-output (MIMO)-enabled cellular infrastructure. This work investigates the spectral efficiency of both cellular and D2D tiers under the estimation errors in the channel state information (CSI) and it concludes that the spectral efficiency of cellular tier is affected by the underlay D2D tier.

Several investigations have been carried-out into various aspects of D2D communications [27]–[35]. For example, in [30], the resource allocation scheduling is modeled as an approximate dynamic programming algorithm which provides significant gains in terms of overall throughput, energy efficiency and quality-of-experience (QoE) for the users in contrast to the conventional techniques used in cellular systems. A context-aware and self-organizing algorithm is modeled as a matching game in [31] to optimize the resource utilization and traffic offloading using the social and wireless contextual information of the wireless users in D2D-enabled small cell networks to reduce the traffic congestion on the backhaul links. Similarly, Hoang *et al.* [32] have proposed the non-orthogonal dynamic spectrum sharing scheme in D2D underlaid cellular network and utilize the graph theory to maximize the weighted system capacity. Two possible approaches, namely *iterative rounding algorithm* and *optimal branch-and-bound (BnB) algorithm*, have been used to provide solution to the aforementioned problem. An energy-efficient power scheme is investigated for D2D communications underlaying within a cellular infrastructure, where the resources in the uplink transmission scheme reserved for the cellular users are shared among the multiple D2D pairs [33]. The original EE optimization problem is non-concave, which is transformed into the difference of two concave functions, following which the authors have proposed a sub-optimal approach with reasonable complexity to provide a near-optimal solution.

Zhou *et al.* [34] have studied the simultaneous wireless information and power transfer (SWIPT)-based D2D underlay networks to jointly investigate power and spectrum resource allocation problem. The joint optimization problem is formulated as a two-dimensional energy-efficient stable matching scheme and the solution is obtained using the Gale-Shapley (GS) algorithm. The energy efficient resource sharing procedure in the downlink (DL) transmission scheme is proposed to maximize the system EE with the aid of a matching scheme in D2D underlying cellular networks as outlined in [35].

A. APPROACH AND CONTRIBUTIONS

In this paper, we consider a network of multiple radio access technologies (RATs) where D2D pairs can share resources with CUs. Therefore, in order to enhance the QoS of CUs a dynamic power control strategy has been proposed for D2D pairs to satisfy a predefined interference threshold.

It is worthwhile to note that the original problem proposes to maximize the EE of both CUs and D2D pairs. However, it has been broken down into two independent subproblems, i.e., the the radio resource management of D2D pairs in order to satisfy their minimum QoS, and the predefined interference threshold set for the CUs. In the second subproblem, we aim to jointly optimize the two conflicting objectives, i.e., maximizing the system EE and maximizing the system sum rate, in light of the resource allocation to the D2D pairs. The transformed radio resource allocation problem is formulated as a multi-objective optimization problem (MOP) to derive an optimal power allocation strategy for the CUs. The MOP is transformed into a single-objective optimization problem using the *weighted-Tchebycheff* method in order to achieve a Pareto-optimal solution resulting in a complete

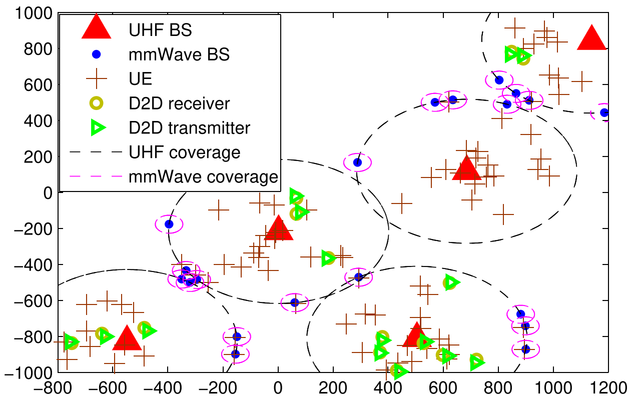

FIGURE 1. **A snapshot of BS and user deployment.**

Pareto-Frontier curve by tuning the weights of both conflicting objectives. Furthermore, the mmWave-based small cells are assumed to operate exclusively in the mmWave band with a chosen power control strategy to maximize the sum rate of their associated users. Using the formulated approach, the optimal power allocation for the CUs are computed and the Hungarian method has been utilized to select the best available subcarriers for the CUs. The simulation results demonstrate the relationship between the coverage probability of D2D pairs and the system EE for a varying minimum QoS for both CUs and D2D pairs. Finally, the impact of density ratios of D2D pairs to CUs on the system sum rate and system EE has also been investigated. The results illustrate the effectiveness of our proposed mechanism in comparison to the traditional rate maximization and power minimization schemes.

The rest of the paper is organized as follows. Section II outlines the system model, whereas Sections III and IV provide detailed information on power allocation mechanisms for the D2D pairs and the CUs. Section V describes the simulation results and Section VI concludes the paper.

II. SYSTEM MODEL

Consider a DL transmission scheme consisting of k_b μW macro-cells, distributed using a Poisson point process (PPP) with density Φ_b, overlaid with 4 k_b mmWave (mmWave) small base stations (SBSs), with $|\mathcal{M}|$ CUs with density Φ_m and D D2D pairs with density Φ_d as shown in Fig. 1. The set of CUs, denoted by $\mathcal{M}$, consists of U wireless virtual reality users and C normal wireless users such that $\mathcal{M} = \mathcal{U} \cup \mathcal{C}$. The BSs operating on μW and mmWave frequency bands are denoted by $\mathcal{B} = \{1, \ldots, B\}$ and $\mathcal{W} = \{1, \ldots, W\}$, respectively such that $\mathcal{L} = \mathcal{B} \cup \mathcal{W}$. Each μW BS has $N_{\mu W}$ subcarriers, whereas each mm small BS has N_mm subcarriers such that $N_{\mu W} = N_\mathrm{mm} = N$. The set of subcarriers for each BS $l \in \mathcal{L}$ is denoted by $\mathcal{N}_l = \{1, 2, \cdots, N\}$, the set of all CUs by $\mathcal{M} = \{1, \ldots, M\}$ and the set of all D2D pairs by $\mathcal{D} = \{1, \ldots, D\}$. Moreover, each user $m \in \mathcal{M}$ must satisfy a minimum QoS, which is given by $R^{(m)}_\mathrm{min}$. In addition, (μW BSs and mm SBSs) operate independently of each other which aids in finding their optimal power allocation in a distributed manner. It should be noted that one of the major objectives of this work is to provide a framework where each BS can choose whether to maximize its own throughput or EE and the D2D transmitters dynamically adjust their transmission power in order to protect the QoS of cellular users. In this work, it is assumed that the mmWave BSs will maximize their own throughput whereas the μW BSs will maximize their own energy efficiency.

Herein, we provide some of our antenna assumptions specially for mmWave SBSs. It is assumed that the transmitters and receivers are perfectly aligned with each other and have an antenna gain of G_max whereas a misaligned beam has an antenna gain of G_min. Therefore, the effective antenna gain $G^y_{m,w}$ for $y \in \{t, r\}$, where t and r represents the transmitter and receiver, respectively, can be described as follows

$$G^t_{m,w} = \begin{cases} G_\mathrm{max} = \dfrac{2\pi - (2\pi - \Delta\omega^t_w)\, G_\mathrm{min}}{\Delta\omega^t_w}, & \text{if } |\theta^t_{m,w}| \leq \dfrac{\Delta\omega^t_w}{2} \\ G_\mathrm{min}, & \text{Otherwise.} \end{cases} \tag{1a}$$

and

$$G^r_{m,w} = \begin{cases} G_\mathrm{max} = \dfrac{2\pi - (2\pi - \Delta\omega^r_m)\, G_\mathrm{min}}{\Delta\omega^r_m}, & \text{if } |\theta^r_{m,w}| \leq \dfrac{\Delta\omega^r_m}{2} \\ G_\mathrm{min}, & \text{Otherwise.} \end{cases} \tag{1b}$$

In this work, it is assumed that each subcarrier is exclusively assigned to a single CU within the same BS. The achievable rate of user $m \in \mathcal{M}$ on subcarrier $n \in \mathcal{N}$ associated with μW BS $b \in \mathcal{B}$ is given by

$$r^{(b)}_{m,n} = \Theta_b Bw_b \log_2(1 + \gamma^{(b)}_{m,n} \times p^{(b)}_{m,n}), \tag{2}$$

where the proportion of bandwidth allocated to each subcarrier by μW BS b is denoted by Θ_b, Bw_b indicates the total bandwidth available to the μW BS b and $p^{(b)}_{m,n}$ indicates the power allocated to user m associated with μW BS b on subcarrier n. The signal-to-interference plus noise ratio (SINR) of user m on subcarrier n associated with μW BS b, $\gamma^{(b)}_{m,n}$ is defined as

$$\gamma^{(b)}_{m,n} = \frac{|\mathrm{g}^{(b)}_{m,n}|^2/\mathrm{PL}^b_m}{(\mathrm{N}_0 \Theta_b Bw_b + I^{(b)}_{m,n})} = \frac{|\mathrm{g}^{(b)}_{m,n}|^2/\mathrm{PL}^b_m}{(\sigma^2 + P^\mathrm{min}_{d,n} \times \mathrm{g}^{(m)}_{d,n})}, \tag{3}$$

where $|\mathrm{g}^{(b)}_{m,n}|^2$ follows a Nakagami distribution at subcarrier n between CU m, and μW BS b, N_0 is the noise spectral density and the total cross-tier interference caused due to the subcarrier $n \in N_b$ being reused by a D2D pair within the coverage area of μW BS b is given by $I^{(b)}_{m,n} = P^\mathrm{min}_{d,n} \times \mathrm{g}^{(m)}_{d,n}$. More details about the computation of $P^\mathrm{min}_{d,n}$ can be found in Section III. The path loss of a user m at carrier frequency $f_{\mu W}$, associated with μW BS, denoted by $\mathrm{PL}_m^{\mu W}$, can be expressed as

$$\mathrm{PL}_m^{\mu W} = 20\log\left(\frac{4\pi}{\lambda_{\mu W}}\right) + 10\alpha^{\mu W}\log(d) + \epsilon^{\mu W}, \quad (4)$$

where $\lambda_{\mu W}$ is the wavelength, $\alpha^{\mu W}$ is the path loss exponent for the μW frequency band, d is the distance between user m and μW BS, and $\epsilon^{\mu W}$ represents the shadowing (in dB) which is a Gaussian random variable with zero mean and variance ξ_1^2.

Similarly, the achievable rate of user $m \in \mathcal{M}$ on subcarrier $n \in \mathcal{N}$ associated with mmWave SBS $w \in \mathcal{W}$ is given by

$$r_{m,n}^{(w)} = \left(1 - \frac{\tau_{m,w}}{T}\right)\Theta_w Bw_w \log_2\left(1 + \gamma_{m,n}^{(w)} \times p_{m,n}^{(w)}\right), \quad (5)$$

where the proportion of bandwidth allocated to each subcarrier by mmWave SBS w is denoted by Θ_w, Bw_w indicates the total bandwidth available to the mmWave SBS w and $p_{m,n}^{(w)}$ indicates the power allocated to user m associated with mmWave SBS w on the subcarrier n. The beam alignment overhead $\tau_{m,w}$ between user m and mmWave SBS w can be defined as

$$\tau_{m,w}\left(\Delta\omega_w^t, \Delta\omega_m^r\right) = \frac{\Delta s_w^t \Delta s_m^r T_p}{\Delta\omega_w^t \Delta\omega_m^r}, \quad (6)$$

where it should be noted that $\Delta\omega_w^t\Delta\omega_m^r \geq \frac{T_p \Delta s_w^t \Delta s_m^r}{T}$ in order to make sure that $\tau_{m,w} \leq T$ and T_p is the duration of the pilot transmission. From this condition, we can infer that the minimum value of $\Delta\omega$ is given by $\Delta\omega_{\text{lower}} \triangleq \frac{T_p \Delta s_w^t \Delta s_m^r}{T}$. Since the beam level alignment takes place within the sector level beamwidths, therefore, $\Delta\omega_w^t \leq \Delta s_w^t$ and $\Delta\omega_m^r \leq \Delta s_m^r$. From these conditions, we can infer that the maximum value of $\Delta\omega$ is given by $\Delta\omega_{\text{upper}} \triangleq \Delta s_w^t \Delta s_m^r$. Since we assume that the multi-user interference is negligible, the joint optimization of operating beamwidths for all mmWave SBS-CU pairs can be simplified to be the independent optimization for each mmWave SBS-CU pair. Hence, the feasible region of optimal beam-level beamwidth $\Delta\omega^*$ for each SBS-CU pair to maximize the throughput defined in (5) can be given by

$$\frac{T_p \Delta s_w^t \Delta s_m^r}{T} \leq \Delta\omega^* \leq \Delta s_w^t \Delta s_m^r,$$

Lemma 1: The signal-to-noise ratio (SNR) of a user m on subcarrier n associated with mmWave BS w is denoted by $\gamma_{m,n}^{(w)}$ *and is given by*

$$\gamma_{m,n}^{(w)} \triangleq \frac{\left(|g_{m,n}^{(w)}|^2/PL_m^w\right)\left(\frac{\Omega}{\Delta\omega} + G_{min}^2\right)}{N_0 \Theta_w Bw_w}. \quad (7)$$

Proof: We assume that the multi-user interference is negligible due to the pseudo-wired abstraction of mmWave communications. The SNR of a user m on subcarrier n associated with mmWave BS w can be defined as

$$\gamma_{m,n}^{(w)} = \frac{\left(|g_{m,n}^{(w)}|^2/\mathrm{PL}_m^w\right) G_{m,w}^t G_{m,w}^r}{N_0 \Theta_w Bw_w}$$

$$= \frac{\left(\frac{|g_{m,n}^{(w)}|^2}{\mathrm{PL}_m^w}\right)\left(\frac{2\pi-(2\pi-\Delta\omega_w^t)G_{\min}}{\Delta\omega_w^t}\right)\left(\frac{2\pi-(2\pi-\Delta\omega_m^r)G_{\min}}{\Delta\omega_m^r}\right)}{N_0\Theta_w Bw_w}$$

$$= \frac{\left(\frac{|g_{m,n}^{(w)}|^2}{\mathrm{PL}_m^w}\right)\left(\frac{\Omega^{1/2}+\Delta\omega_w^t G_{\min}}{\Delta\omega_w^t}\right)\left(\frac{\Omega^{1/2}+\Delta\omega_m^r G_{\min}}{\Delta\omega_m^r}\right)}{N_0\Theta_w b_w}$$

$$= \frac{\left(\frac{|g_{m,n}^{(w)}|^2}{\mathrm{PL}_m^w}\right)\left(\frac{\Omega^{1/2}}{\Delta\omega_w^t} + G_{\min}\right)\left(\frac{\Omega^{1/2}}{\Delta\omega_m^r} + G_{\min}\right)}{N_0\Theta_w Bw_w}$$

$$= \frac{\left(\frac{|g_{m,n}^{(w)}|^2}{\mathrm{PL}_m^w}\right)\left(\frac{\Omega}{\Delta\omega} + \frac{\Omega^{1/2}G_{\min}}{\Delta\omega_m^r} + \frac{\Omega^{1/2}G_{\min}}{\Delta\omega_w^t} + G_{\min}^2\right)}{N_0\Theta_w Bw_w}$$

$$= \frac{\left(\frac{|g_{m,n}^{(w)}|^2}{\mathrm{PL}_m^w}\right)\left(\frac{\Omega}{\Delta\omega} + \frac{\Omega^{1/2}G_{\min}(\Delta\omega_w^t+\Delta\omega_m^r)}{\Delta\omega_w^t\Delta\omega_m^r} + G_{\min}^2\right)}{N_0\Theta_w Bw_w}$$

$$= \frac{\left(\frac{|g_{m,n}^{(w)}|^2}{\mathrm{PL}_m^w}\right)\left(\frac{\Omega}{\Delta\omega} + \frac{\Omega^{1/2}G_{\min}(\Delta\omega_w^t+\Delta\omega_m^r)}{\Delta\omega} + G_{\min}^2\right)}{N_0\Theta_w Bw_w}$$

$$\gamma_{m,n}^{(w)} \triangleq \frac{\left(\frac{|g_{m,n}^{(w)}|^2}{\mathrm{PL}_m^w}\right)\left(\frac{\Omega}{\Delta\omega} + G_{\min}^2\right)}{N_0\Theta_w Bw_w}, \quad \text{if } G_{\min}\left(\Delta\omega_w^t + \Delta\omega_m^r\right) \ll \Omega^{1/2},$$

where $\Omega = (2\pi - 2\pi G_{\min})^2$ and $\Delta\omega = \Delta\omega_w^t\Delta\omega_m^r$. ■

The path loss of a user m located associated with mmWave SBS w, at carrier frequency f_w, denoted by PL_m^w is given by [38],

$$\mathrm{PL}_m^{\text{mmW}} = \begin{cases} \rho + 10\alpha_L^{\text{mmW}}\log(d) + \epsilon_L^{\text{mmW}}, & \text{if Link is LoS,} \\ \rho + 10\alpha_N^{\text{mmW}}\log(d) + \epsilon_N^{\text{mmW}}, & \text{Otherwise.} \end{cases} \quad (8)$$

In (8), ϵ_L^{mmW} and ϵ_N^{mmW} represent the shadowing in mmW band (in dB) for the line-of-sight (LoS) and non line-of-sight (NLoS) links, respectively. The ϵ_L^{mmW} and ϵ_N^{mmW} are Gaussian random variables with zero mean and variances ξ_z^2, where $z \in \{\text{LoS}, \text{NLoS}\}$ model the effects of blockages, $\rho = 32.4 + 20\log(f_{\text{mmW}})$.

The total rate of a user m, associated with either μW BS b or mmWave SBS w, can be written as,

$$\overline{R_m} = \sum_{l\in\mathcal{L}}\sum_{n\in\mathcal{N}_m}\sigma_{m,l}r_{m,n}^{(l)}, \quad \forall m \quad (9)$$

Similarly, the total power consumed by user m is denoted by $\overline{P_m}$ and given by

$$\overline{P_m} = \sum_{l\in\mathcal{L}}\sum_{n\in\mathcal{N}_m}\sigma_{m,l}p_{m,n}^{(l)}. \quad (10)$$

Similarly, the system EE can be defined as

$$\eta_{EE} = \frac{\sum_{m\in\mathcal{M}} \overline{R_m} + \sum_{d\in\mathcal{D}} \overline{R_d}}{\sum_{m\in\mathcal{M}} \overline{P_m} + (B+W)\times P_C + D\times P_C^{(d)} + \sum_{d\in\mathcal{D}} P_d^{(*)}}, \tag{11}$$

where $\overline{R_d}$ is the total rate of D2D pair d, P_C is the circuit power for both μW and mmWave BSs, $P_C^{(d)}$ is the circuit power for the D2D transmitter. More information about $P_d^{(*)}$ are described in detail later in Section III. Each user depending on their category has a minimum QoS requirement as detailed below:

$$R_{\min}^{(m)} = \begin{cases} R_{\min}, & \forall m \in \mathcal{U} \\ \frac{(n_{\text{pixels}} \times s_{\text{pixels}} \times u_{\text{rate}})}{c_{\text{rate}}}, & \forall m \in \mathcal{C}. \end{cases} \tag{12}$$

where n_{pixels} is the number of pixels for a panoramic image, s_{pixels} is the number of bits used to store each pixel, u_{rate} is the refresh rate of the image and c_{rate} is the compression rate.

III. SELF-ADAPTIVE POWER CONTROL STRATEGY FOR D2D PAIRS

In order to preserve the QoS of the CUs associated with μW BS, a maximum predefined interference threshold I_t is imposed for the D2D transmitter reusing the same subcarrier with the CUs. The transmission power of the D2D transmitter is also constrained such that the CUs can satisfy their minimum QoS and can be given as,

$$\log_2\left(1 + \frac{p_{m,n}^{(b)}|g_{m,n}^{(b)}|^2}{\left(\sigma^2 + \frac{P_{d,n}}{PL_{d,m}^{\mu W}}|g_{m,n}^{(d)}|^2\right) PL_m^{\mu W}}\right) \geq R_{\min}^{(m)} \tag{13}$$

$$P_{d,n} \leq \frac{PL_{d,m}^{\mu W}}{|g_{m,n}^{(d)}|^2}\left(\frac{p_{m,n}^{(b)}|g_{m,n}^{(b)}|^2}{(2^{R_{\min}^{(m)}}-1)PL_m^{\mu W}} - \sigma^2\right), \tag{14}$$

where $P_{d,n}$ is the transmission power of the d^{th} D2D transmitter at subcarrier n, which it shares with CU m and $p_{m,n}^{(b)}$ is the cellular power transmitted by the BS at the given subcarrier n to the CU m.

The D2D transmission power is also limited due to a predetermined interference threshold, I_t. Due to this provision, the transmit power of the D2D transmitter can be computed as

$$\overline{P}_{d,n} \leq \frac{I_t\, PL_{d,m}^{\mu W}}{|g_{m,n}^{(d)}|^2}, \tag{15}$$

where $\overline{P}_{d,n}$ is the transmit power of the d^{th} D2D transmitter corresponding to I_t and $PL_{d,m}^{\mu W}$ is the path loss between the d^{th} D2D transmitter and the m^{th} CU sharing the same subcarrier n. Similarly, each D2D pair needs to transmit at a specific power level in order to achieve its minimum QoS which is given by,

$$P_{d,n}^{\min} = \frac{PL_d}{|g_{d,n}|^2}\left(2^{R_{\min}^{(m)}} - 1\right)\left(\sigma^2 + \frac{p_{m,n}^{(b)}|g_{m,n}^{(d)}|^2}{PL_{m,d}^{\mu W}}\right), \tag{16}$$

where PL_d is the path loss between the transmitter and receiver of a D2D pair. Hence, the final constrained transmission power of d^{th} D2D pair is then given by,

$$P_{d,n}^{(*)} = \begin{cases} \min\left(\overline{P}_{d,n}, \max\left(P_{d,n}, P_{d,n}^{\min}\right), P_d^{\max}\right), & \text{if } \Lambda \geq P_{d,n}^{\min}, \\ \text{Infeasible}, & \text{Otherwise}, \end{cases} \tag{17}$$

where $\Lambda = \min\left(P_{d,n}, \overline{P}_{d,n}\right)$. Finally, the total sum rate of a D2D pair is given by

$$\overline{R_d} = \sum_{n=1}^{\mathcal{N}_d} r_{d,n} = \sum_{n=1}^{\mathcal{N}_d} \sigma_{d,n} \log_2\left(1 + P_{d,n}^{(*)}\gamma_{d,n}\right), \tag{18}$$

where $\gamma_{d,n} = \frac{|h_{d,n}|^2}{(\sigma^2 + I_{d,n})\, PL_d}$. The allocation of subcarriers for D2D pairs can also be obtained using the Hungarian algorithm.

IV. PROPOSED ENERGY AWARE RADIO RESOURCE MANAGEMENT PROCEDURE IN D2D-ENABLED MULTI-TIER HETNETS

The objective of this work is to jointly maximize the achievable rate and EE of all the CUs, subject to a maximum input power constraint and minimum QoS requirement. This formulated problem is equivalent to maximizing the sum rate and minimizing the total power consumption. The proposed optimization problem is formulated as a MOP which is further transformed into a single objective optimization problem (SOP) using the *weighted-Tchebycheff* method by normalizing the two objectives by R_{norm} and P_{norm}, respectively, to ensure a consistent comparison as shown below:

$$\begin{aligned} \textbf{(P1)} \quad & \max_{\mathbf{p},\sigma,\Delta\omega} \ \phi \frac{\sum_{l\in\mathcal{L}}\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}} \sigma_{m,n}^{(l)} r_{m,n}^{(l)}}{R_{\text{norm}}} - (1-\phi)\frac{P}{P_{\text{norm}}}, \\ & \text{subject to C1: } \sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}} p_{m,n}^{(l)} \leq P_l^{\max}, \forall l \\ & \text{C2: } R_m \geq R_{\min}^{(m)}, \quad \forall m, \\ & \text{C3: } p_{m,n}^{(l)} \geq 0, \quad \forall m,\ \forall n,\ \forall l. \\ & \text{C4: } \sigma_{m,n}^{(l)} \in [0,1], \quad \forall m,\ \forall n,\ \forall l \end{aligned} \tag{19}$$

The optimization problem **(P1)** as outlined in (19) can be decomposed into two subproblems. Firstly, optimizing over the operating beamwidth and transmission power for all BS-CU pairs to find their optimal transmission power $p_{m,n}^{(l,\text{opt})}$ which is dependent on the SINR, which is defined as the function of the operating beamwidth as depicted in (7). Each BS-CU pair can optimize its own operating beamwidth independently due to the negligible multi-user interference in order to maximize its achievable throughput at the expense of reduced beam alignment overhead. Finally, substituting $p_{m,n}^{(l,\text{opt})}$ into a reformulated optimization problem as outlined later in **(P1-2)** to find the optimal allocation for the CUs. The joint optimization problem of operating beamwidth and transmission power in DL transmission scheme can be formulated as

$$\textbf{(P1-1)}\quad \max_{\mathbf{p},\Delta\omega} \phi \frac{\sum_{l\in\mathcal{L}}\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}} r_{m,n}^{(l)}}{R_{\text{norm}}} - (1-\phi)\frac{P}{P_{\text{norm}}}, \quad \text{subject to C1-C3} \tag{20}$$

From (20), we can also observe that the formulated problem **(P1-1)** can be transformed into a power minimization problem by setting $\phi = 0$. Similarly, the formulated problem **(P1-1)** can be varied from the power minimization problem to the rate maximization problem by dynamically adjusting the weighting coefficient from $\phi = 0$ to 1 to obtain a complete Pareto-optimal solution. It is important to mention that an energy efficient solution of the problem **(P1-1)** can be obtained by selecting $\phi = \phi_{\text{EE}}$.

Using [36], the Lagrangian function of problem **(P1-1)** subject to the constraints C1 – C3 can be written as,

$$T(p,\boldsymbol{\mu},\boldsymbol{\eta},\boldsymbol{\Delta\omega}) = \frac{\phi}{R_{\text{norm}}}\sum_{l\in\mathcal{L}}\sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}} r_{m,n}^{(l)} - \frac{(1-\phi)}{P_{\text{norm}}}P + \sum_{l\in\mathcal{L}}\mu_l\left(P_l^{\max} - \sum_{m\in\mathcal{M}}\sum_{n\in\mathcal{N}} p_{m,n}^{(l)}\right) + \sum_{m\in\mathcal{M}}\eta_m(R_m - R_{\min}^{(m)}), \tag{21}$$

where $P_l^{\max}$ is the maximum transmit power of BS l, $\boldsymbol{\mu}$ is the Lagrange multiplier vector of dimensions L corresponding to the minimum data requirement of CUs, $\boldsymbol{\eta}$ is the Lagrange multiplier vector of dimensions M corresponding to the maximum transmission power constraint of BS and $\boldsymbol{\Delta\omega}$ is the vector of beam-level beamwidth for all the links within the system with a dimension of $M \times W$. Using (2), (21) can be rewritten as (22), shown on the bottom of the next page. The corresponding Lagrangian dual function is

$$t(\boldsymbol{\mu},\boldsymbol{\eta}) = \max_{\mathbf{p},\Delta\omega} \quad T(p,\boldsymbol{\mu},\boldsymbol{\eta},\boldsymbol{\Delta\omega}), \tag{23}$$

and the dual problem is

$$\min_{\boldsymbol{\mu},\boldsymbol{\eta}} \; t(\boldsymbol{\mu},\boldsymbol{\eta}) \quad \text{subject to } \boldsymbol{\mu} \geq 0, \boldsymbol{\eta} \geq 0. \tag{24}$$

It is worthwhile to highlight that since the dual problem is convex, hence the dual decomposition method is used to solve this problem. This dual problem can be decomposed into N independent sub-problems as

$$t(\boldsymbol{\mu},\boldsymbol{\eta}) = \max_{\mathbf{p},\Delta\omega}\left\{\sum_{n\in\mathcal{N}} t_n(\boldsymbol{\mu},\boldsymbol{\eta}) - \frac{(1-\phi)(L\times P_C)}{P_{\text{norm}}} + \sum_{l\in\mathcal{L}}\mu_l P_l^{\max} - \sum_{m\in\mathcal{M}}\eta_m R_{\min}^{(m)}\right\}, \tag{25}$$

where

$$t_n(\boldsymbol{\mu},\boldsymbol{\eta}) = \sum_{l\in\mathcal{L}}\sum_{m\in\mathcal{M}}\left[(1+\eta_m)\,\Theta_l B w_l \log_2\left(1+\gamma_{m,n}^{(l)}p_{m,n}^{(l)}\right) - \left(\mu_l + \frac{(1-\phi)}{P_{\text{norm}}}\right)p_{m,n}^{(l)}\right]$$

It should be noted that $t_n(\boldsymbol{\mu},\boldsymbol{\eta})$ is convex with respect to $p_{m,n}^{(l)}$ and these N subproblems can be solved independently. Using the Karush-Kuhn-Tucker (KKT) conditions, the optimal power allocation for μW BS $l \in \mathcal{L}$ and mmWave BS $l \in \mathcal{W}$ can then be computed respectively as (26a)-(26c), shown on the bottom of the next page, where $[y]^+ = \max(0, y)$ and $p_{m,n}^{(l,\text{opt})} \in [0, p_{m,n}^{(l,\max)}]$.

The transmission power of the D2D transmitter cannot exceed $P_d^{\max}$ which can also limit the maximum permissible transmission power of the CUs which is denoted by $p_{m,n}^{(l,\max)}$. This quantity may be computed as follows:

$$p_{m,n}^{(l,\max)} = \min\left\{P_d^{\max}, \frac{\text{PL}_{m,d}^{\mu W}}{|g_{m,n}^{(d)}|^2}\left(\frac{|g_{d,n}|^2 P_d^{\max}}{\text{PL}_d\left(2^{R_{\min}^{(m)}}-1\right)} - \sigma^2\right)\right\}$$

The optimal power allocation for users associated with μW BS $l \in \mathcal{B}$ as shown in (26b) is in the form of multi-level water filling where the water-level depends on both dual variables μ and η, both rate and power normalization factors, i.e., R_{norm} and P_{norm}, weighting factor ϕ and the channel gain. Similarly, the optimal power allocation for users associated with mmWave BS $l \in \mathcal{W}$ as shown in (26c) is in the form of multi-level water filling where the water-level depends on the beam-level beamwidth for both transmitter and receiver, i.e., $\Delta w \triangleq \Delta\omega_w^t \Delta\omega_m^r$, side lobe antenna gain $G_{\min}$, both dual variables μ and η, both rate and power normalization factors, i.e., R_{norm} and P_{norm}, weighting factor ϕ and the channel gain. Further details about the joint optimal beam-level beamwidth and optimal power allocation mechanism for D2D-enabled Multi-Tier HetNets are given in Algorithm 1.

Then, substituting the $p_{m,n}^{(l,\text{opt})}$ as an optimal power allocation solution from (26) corresponding to **(P1-1)** for the CUs associated with $l \in L$, the subcarrier allocation problem for each BS l can be modeled as below:

$$\textbf{(P1-2)}\quad \max_{\sigma}\sum_{l\in L}\sum_{m\in M}\sum_{n\in N}\sigma_{m,n}^{(l)}p_{m,n}^{(l,\text{opt})}, \quad \text{subject to C4: } \sigma_{m,n}^{(l)} \in [0,1], \quad \forall m, \forall n, \forall l. \tag{27}$$

It can be shown that (27) is a linear assignment problem with respect to $\sigma_{m,n}^{(l)}$ and can be effectively solved optimally using the standard integer point methods. The problem **(P1-2)** can be solved using the Hungarian Algorithm [37] for each BS $l \in L$, resulting in $\boldsymbol{\sigma} = [\boldsymbol{\sigma}^{(1)}, \boldsymbol{\sigma}^{(2)}, \cdots, \boldsymbol{\sigma}^{(L)}]$ where $\boldsymbol{\sigma}^{(L)}$ is a subcarrier allocation indicator matrix for BS L whose size is $M_L \times N_L$. It is worthwhile to mention that the constraint (C4) that was not considered in the partial Lagrangian are included in (27). The obtained solution is an asymptotically optimal solution.

Algorithm 1 Joint Optimal beamwidth and Power Allocation Mechanism for D2D-Enabled Multi-Tier HetNets

1: Set $i = 0, j = 0, i_{max} = 10^4$ and $j_{max} = 10^4$, initialize $\delta = 10^{-4}$, $p^{(l)}_{m,n} = 10^{-6}$, $\eta_m = \min_{l \in \mathcal{L}, n \in \mathcal{N}} \left(|g^{(l)}_{m,n}|^2 \right) + \delta$, $\forall m$ and $\mu_l = \delta$, $\forall l$.
2: Set $\Delta\omega_{\text{lower}} = \frac{T_p \Delta s^t_w \Delta s^r_m}{T}$ and $\Delta\omega_{\text{upper}} = \Delta s^t_w \Delta s^r_m$
3: **while** $\left(\frac{|\eta_{\text{EE}}(i+1) - \eta_{\text{EE}}(i)|}{|\eta_{\text{EE}}(i+1)|} \right) \le 10^{-4}$ **do**
4: $\overline{\Delta\omega} = \frac{\Delta\omega_{\text{lower}} + \Delta\omega_{\text{upper}}}{2}$
5: **while** η_m and μ_b have not converged or $j < j_{max}$ **do**
6: Compute $p^{(l,\text{opt})}_{m,n}$ by substituting $\Delta\omega = \overline{\Delta\omega}$ using (26)
7: Update $\mu_l(j+1)$ according to (29a)
8: Update $\eta_m(j+1)$ according to (29b)
9: **end while**
10: Calculate $\eta_{\text{EE}}(i+1)$ using (11)
11: if ($\eta_{\text{EE}}(i+1) > \eta_{\text{EE}}(i)$)
12: $\Delta\omega_{\text{lower}} = \overline{\Delta\omega}$
13: Else
14: $\Delta\omega_{\text{upper}} = \overline{\Delta\omega}$
15: End if
16: go to Step 3
17: **end while**
18: End

After computing the optimal power allocation and subcarrier allocation, the dual problem can be solved using subgradient method. The subgradients of the dual function in (23) are given as follow:

$$\Delta\mu_l(j) = P^{\max}_l - \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} \sigma^{(l)}_{m,n} p^{(l)}_{m,n}, \quad \forall l, \tag{28a}$$

$$\Delta\eta_m(j) = \sigma^{(l)}_{m,n} \Theta_l B w_l \log_2 \left(1 + \gamma^{(l)}_{m,n} p^{(l)}_{m,n} \right) - R^{(m)}_{\min}, \quad \forall m, \tag{28b}$$

The dual variables in the $j+1^{\text{th}}$ iteration are updated by

$$\mu_l(j+1) = \left[\mu_l(j) - s_1(j) \times \Delta\mu_l(j) \right]^+, \quad \forall l, \tag{29a}$$

$$\eta_m(j+1) = \left[\eta_m(j) - s_2(j) \times \Delta\eta_m(j) \right]^+, \quad \forall m, \tag{29b}$$

where $s_1(j)$ and $s_2(j)$ are the appropriate positive small step sizes, respectively, according to the non-summable diminishing step length policy. It is assumed that $s_1(j) = s_2(j) = \frac{0.5}{\sqrt{i}}$, where i denotes the iteration index. We also like to mention that the subgradient method can guarantee a globally optimum solution only for the convex optimization problem for small step size.

In this work, we have utilized the dual decomposition method to solve (24). In the dual decomposition method, the inner subproblem is first solved in order to obtain the subcarrier and power allocation variables using the given values of dual variables (or Lagrangian multipliers) such as μ_l and η_m. The outer problem is solved to update the Lagrangian multipliers using the obtained values of subcarrier and power allocation variables. This procedure is repeated until the convergence is achieved.

V. PERFORMANCE EVALUATION

The simulations consider actual building locations from the NUST campus, Islamabad, Pakistan, in order to incorporate real blockage effects and environmental geometry. In the considered setup, there are K mmWave SBSs randomly deployed at the cell edge of each μW BS. The simulation parameters and their considered values are shown in Table I. It should be noted that $\Gamma_m = 2^{R_{\min,t}} - 1$, for $t \in \{\mathcal{U}, \mathcal{C}\}$.

Fig. 2 demonstrates the variation of achievable system EE versus varying Γ_m for different power control strategies. The power minimization strategy ($\phi = 0$) ensures that all CUs achieve their minimum QoS, i.e., they strictly operate at Γ_m. The rate maximization strategy ($\phi = 1$) allocates

$$T(p, \boldsymbol{\mu}, \boldsymbol{\eta}, \boldsymbol{\Delta\omega}) = \frac{\phi}{R_{\text{norm}}} \sum_{l \in \mathcal{L}} \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} \Theta_l B w_l \log_2 \left(1 + \gamma^{(l)}_{m,n} p^{(l)}_{m,n} \right) - \frac{(1-\phi)}{P_{\text{norm}}} \left(\sum_{l \in \mathcal{L}} \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} p^{(l)}_{m,n} + L \times P_{\text{C}} \right)$$
$$+ \sum_{l \in \mathcal{L}} \mu_l \left(P^{\max}_l - \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} p^{(l)}_{m,n} \right) + \sum_{m \in \mathcal{M}} \eta_m \left(\sum_{l \in \mathcal{L}} \sum_{n \in \mathcal{N}} \Theta_l B w_l \log_2 \left(1 + \gamma^{(l)}_{m,n} p^{(l)}_{m,n} \right) - R^{(m)}_{\min} \right) \tag{22}$$

$$\frac{dt_n(\boldsymbol{\mu}, \boldsymbol{\eta})}{dp^{(l)}_{m,n}} = 0, \tag{26a}$$

$$p^{(l,\text{opt})}_{m,n} = \left[\frac{\left(\frac{\phi}{R_{\text{norm}}} + \eta_m \right) \Theta_l B w_l}{\left(\mu_l + \frac{1-\phi}{P_{\text{norm}}} \right) \ln(2)} - \frac{\left(\text{N}_0 \Theta_l B w_l + I^{(l)}_{m,n} \right) \text{PL}^l_m}{|g^{(l)}_{m,n}|^2} \right]^+, \quad \forall l \in \mathcal{L}, \tag{26b}$$

$$p^{(l,\text{opt})}_{m,n} = \left[\frac{\left(\frac{1}{R_{\text{norm}}} + \eta_m \right) \Theta_l b_l}{\mu_l \ln(2)} - \frac{\text{N}_0 \Theta_l B w_l \text{PL}^l_m}{|g^{(l)}_{m,n}|^2 \left(\frac{\Omega}{\Delta\omega} + G^2_{\min} \right)} \right]^+, \quad \forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall l \in \mathcal{W}, \tag{26c}$$

TABLE 1. Simulation parameters.

Parameter	Value	Parameter	Value
f_{mm}	28 GHz	Bw_{mm}	2 GHz [5]
$f_{\mu W}$	2.4 GHz	$Bw_{\mu W}$	20 MHz
$P_b^{\max}$	46 dbm [17]	N_0	-174 dBm/Hz
Φ_{m}	200/km^2	$R_{\mu W}$	400 m
Φ_{b}	1/km^2	Φ_{d}	40/km^2
Std($\epsilon_{\text{L}}^{\text{mm}}$)	5.2 dB [5]	Std($\epsilon_{\text{N}}^{\text{mm}}$)	7.2 dB [38]
Std($\epsilon^{\mu W}$)	4 dB	$P_C^{(d)}$	0.1 W
$P_d^{\max}$	1 W	P_C	0.4 W
I_t	10^{-12} W	$N_{\mu W} = N_{\text{mm}}$	128
$r_d^{\max}$	25 m,	$\alpha^{\mu W}$	3.3
α_L^{mm}	2 [5]	α_N^{mm}	3.3 [5]
β_{mm}	5 dB	Γ_m	5 dB unless stated otherwise
R_{mm}	50 m	K	4
$G_{\max}$	18 dB	$G_{\min}$	-2 dB
n_{pixels}	1920 × 1080	s_{pixels}	24 bits
u_{rate}	60 images/s	c_{rate}	300

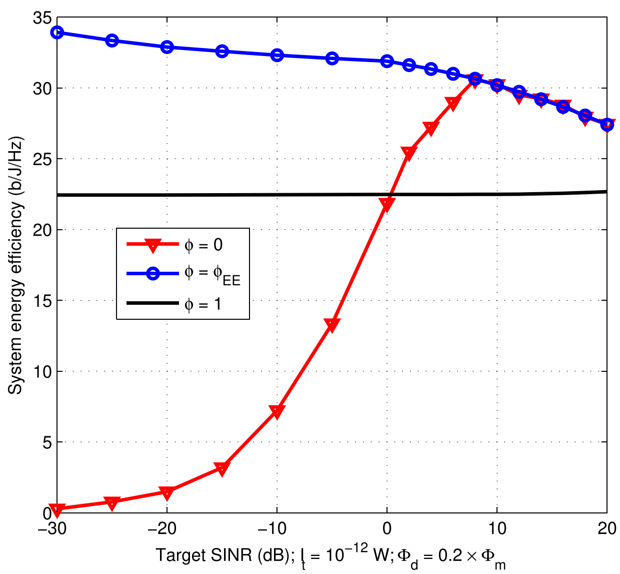

FIGURE 2. System energy efficiency versus target SINR for various power control mechanisms.

the transmission power such that each CU attains its maximum possible rate. Finally, the EE maximization strategy ($\phi = \phi_{\text{EE}}$) allocates transmission power to each subcarrier according to the optimal power allocation strategy defined in (26). The achievable system EE curve remains constant irrespective of Γ_m for $\phi = 1$. At a target SINR of 10 dB, the power minimization curve approaches the achievable system EE curve of the EE maximization strategy ($\phi = \phi_{\text{EE}}$). The curve for $\phi = \phi_{\text{EE}}$ has an achievable system EE which

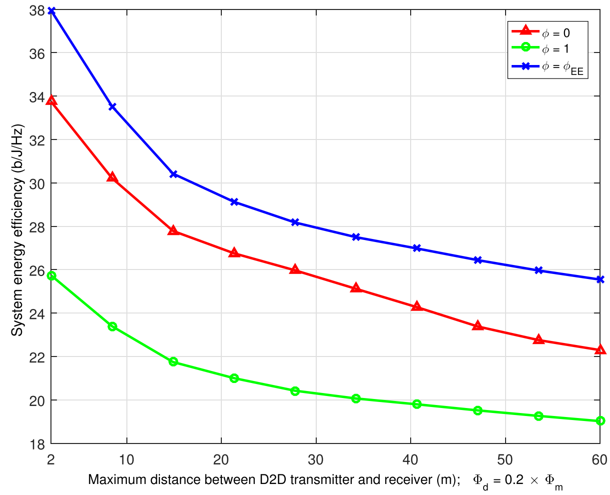

FIGURE 3. System energy efficiency versus $r_d^{\max}$ for various power control mechanisms.

is approximately 60% greater than the $\phi = 1$ curve at $\Gamma_m =$ -30 dB. Moreover, for $\Gamma_m > 9$ dB, the curves for $\phi = \phi_{\text{EE}}$ and $\phi = 0$ follow a similar trend.

Fig. 3 depicts the system EE versus variation in the maximum proximity distance between the D2D pair $r_d^{\max}$ at $\Phi_{\text{d}}/\Phi_{\text{m}} = 0.2$ and Γ_m =5 dB for the three proposed power control strategies. The power minimization power control strategy ($\phi = 0$) results in an achievable EE of approximately 34 b/J/Hz and it decreases with an increase in $r_d^{\max}$. The same trend can also be observed for the remaining two power control strategies as well. The EE maximization power control strategy ($\phi = \phi_{\text{EE}}$) achieves better performance in terms of achievable EE in comparison to the other two power control strategies irrespective of the $r_d^{\max}$. On the other hand, the rate maximization power control strategy ($\phi = 1$) attains far higher rate of 8 kb/s/Hz in contrast to the two other power control strategies as shown in Fig. 4. It is also evident that the achievable rate of the power minimization control strategy always remains constant irrespective of the variation in $r_d^{\max}$ as each user is only interested in achieving its minimum QoS requirement. The achievable rates of the other two power control strategies show a non-increasing trend with respect to an increase in $r_d^{\max}$. These simulation results demonstrate that the $r_d^{\max}$ can be tuned in order to attain a specific level of achievable rate and EE. For example, in order to attain an achievable EE of 28 b/J/Hz (or achievable rate of 5.3 kb/s/Hz) for a given Γ_m=5 dB and $\Phi_{\text{d}}/\Phi_{\text{m}} = 0.2$, the $r_d^{\max}$ can be chosen as 30 m.

Fig. 5 analyzes the system EE versus the interference threshold, I_t, with $r_d^{\max}$ at $\Phi_{\text{d}}/\Phi_{\text{m}} = 0.2$ and Γ_m =5 dB for various power control mechanisms. As the interference threshold I_t increases, the achievable rate of the priority users, i.e., CUs, decreases due to the fact that the maximum allowable transmission power of D2D transmitter is limited by I_t as shown in (15). An increase in I_t allows the transmission power of the non-priority users (or D2D pairs) to be

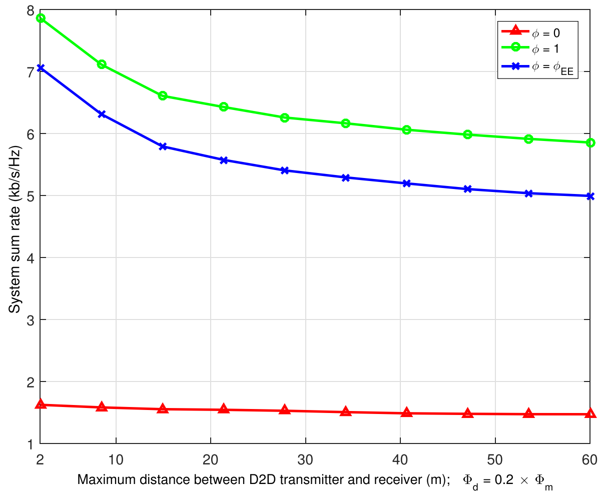

FIGURE 4. System sum rate versus r_d^{max} for various power control mechanisms.

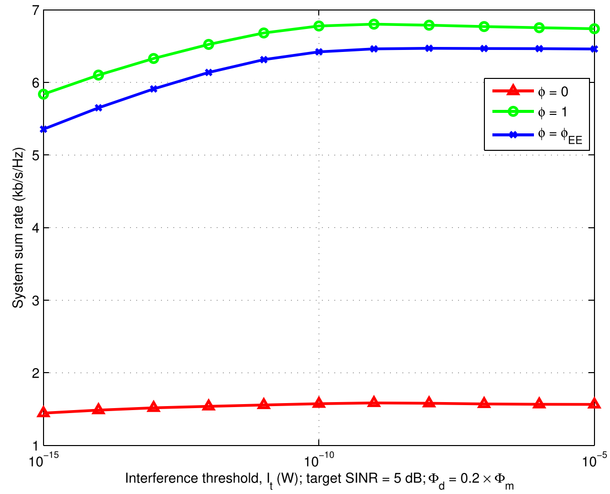

FIGURE 6. System sum rate versus interference threshold, I_t, for various power control mechanisms with $r_d^{max} = 25$ m.

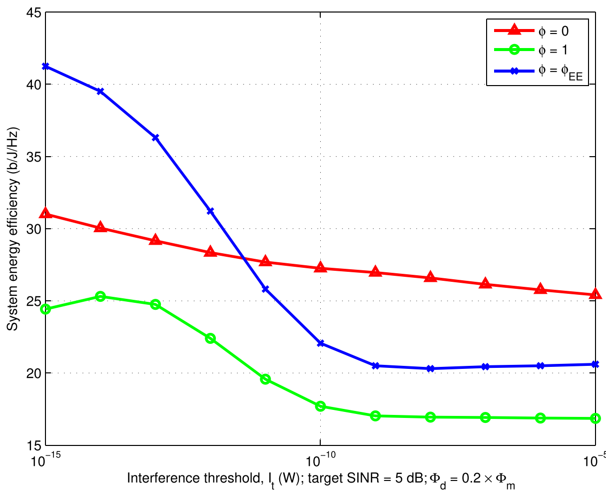

FIGURE 5. System EE versus interference threshold I_t for various power control mechanisms with $r_d^{max} = 25$ m.

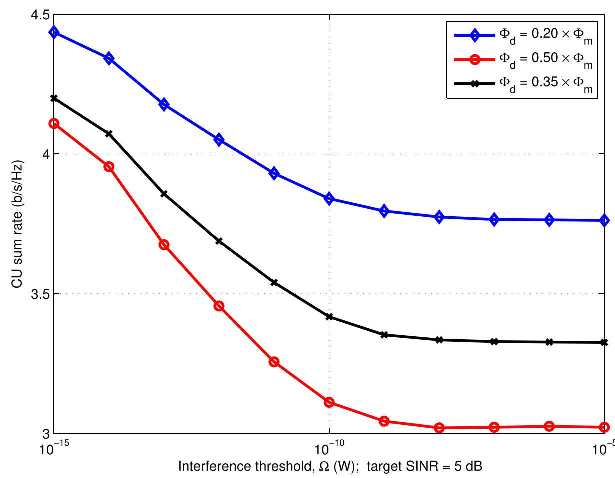

FIGURE 7. Average rate of CUs versus interference threshold I_t for various D2D pair to CU density ratio Φ_d/Φ_m with $r_d^{max} = 25$ m.

increased which can help them satisfy their minimum QoS level, resulting in better connectivity as depicted in (15) and (16) at the expense of reduced achievable rates of the CUs. As the density of the CUs Φ_m is 5 times greater than the density of D2D pairs Φ_d, the system EE decreases with an increase in I_t for all the proposed power control mechanisms. It is important to mention that a decrease in the system EE is quite gradual as the primary objectives of both priority and non-priority users are to satisfy their minimum QoS level reducing the impact of increase in I_t for the case of power minimization scheme ($\phi = 0$). We can also observe that after a certain value of I_t, the power minimization scheme ($\phi = 0$) outperforms in comparison to the EE maximization scheme ($\phi = \phi_{\text{EE}}$) and rate maximization scheme ($\phi = 1$).

The impact of the interference threshold I_t on the system sum rate with $r_d^{\max}$ at $\Phi_\text{d}/\Phi_\text{m} = 0.2$ and $\Gamma_m = 5$ dB for various power control mechanisms are illustrated in Fig. 6. The achievable rates of both CUs and D2D pairs increase with an increase in I_t for all the proposed power control mechanisms. The rate maximization scheme ($\phi = 1$) outperforms the other two proposed power control schemes as the D2D transmitters are allowed to transmit with more transmission power resulting in their high achievable data rates without degrading the QoS of CUs below the minimum acceptable level. This phenomenon results in an increased system power consumption which increases the system sum rate irrespective of the selected power control scheme (as depicted in Fig. 6) at the expense of a decrease in the achievable system EE as shown in Fig. 5.

Fig. 7 describes the average achievable rate of CUs versus I_t for various $\Phi_\text{d}/\Phi_\text{m}$ ratios with $r_d^{\max} = 25$ m. As the interference threshold I_t increases, the average achievable rate of CUs decreases due to the increased maximum allowable interference threshold from the D2D pairs. The CUs will need more allocated power from the access point in order

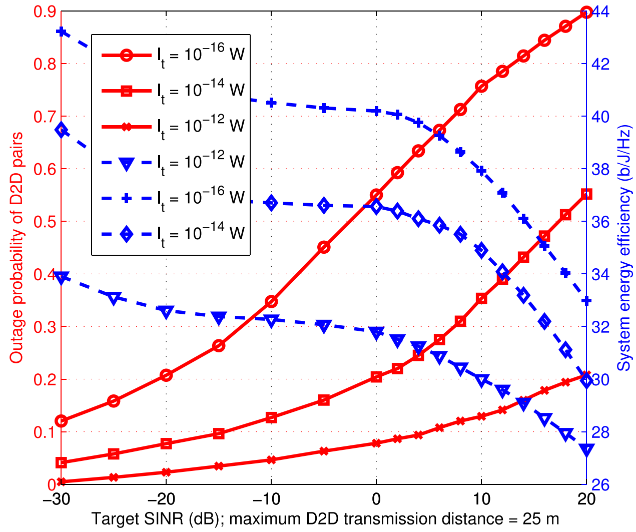

FIGURE 8. Outage probability of D2D pairs and system energy efficiency versus target SINR at different I_t for $\phi = \phi_{EE}$.

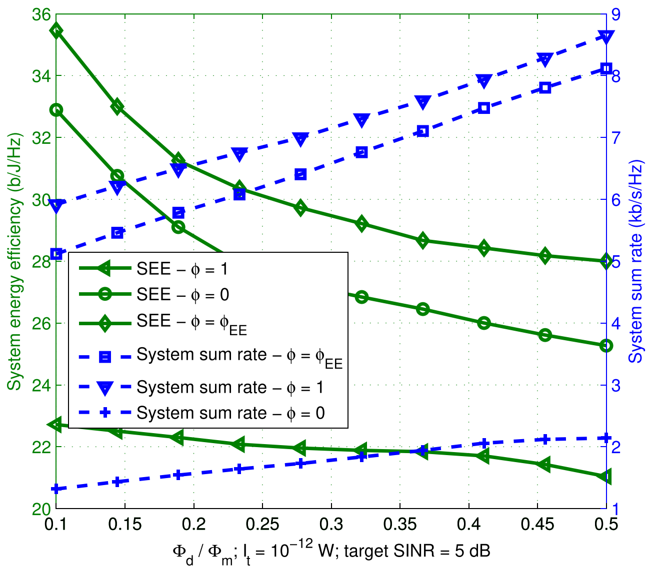

FIGURE 9. System energy efficiency and system sum rate versus the D2D pair to CU density ratio with $r_d^{max} = 25$ m.

to achieve their minimum rate requirement. This figure pinpoints that the average achievable rate of CUs decreases with an increase in I_t at a given fixed Φ_d/Φ_m. It is also important to mention that decreasing Φ_d/Φ_m, (i.e., decreasing the total number of CUs) results in decreasing the average achievable rate of the CUs. For example, the average achievable rate of CUs increases from 3.1 b/s/Hz to 3.8 b/s/Hz at $I_t = 10^{-10}$ W by decreasing the ratio from $\Phi_d/\Phi_m = 0.5$ to $\Phi_d/\Phi_m = 0.2$.

Fig. 8 analyzes the relationship between outage probability of D2D pairs and the achievable system EE versus I_t for various values of Γ_m. We can also observe that the coverage probability decreases with an increase in Γ_m for various values of interference thresholds I_t. It can also be seen that the probability of D2D pairs being in outage is higher at lower values of I_t. The figure highlights that in order to maintain an outage probability of 20%, the network operators can either tune the network parameters such as $I_t = 10^{-16}$ W and $\Gamma_m = -20$ dB whereas the same outage probability can also be achieved for $\Gamma_m = 0$ dB and $\Gamma_m = 20$ dB at $I_t = 10^{-14}$ W and $I_t = 10^{-12}$ W, respectively. It can also be observed from Fig. 8 that the achievable system EE generally decreases with an increase in Γ_m. It also demonstrates that the achievable system EE also decreases with an increase in I_t. In fact, the system EE can achieve nearly 25% gain at $\Gamma_m = 10$ dB with the help of interference mitigation techniques, i.e., reducing from $I_t = 10^{-16}$ W to $I_t = 10^{-12}$W.

Fig. 9 investigates the achievable system EE and the system sum rate versus the ratios of densities, i.e., ϕ_d/ϕ_m. The system sum rate increases with an increase in ϕ_d/ϕ_m. However, for all the values of density ratios, the system EE optimization approach offers the greatest achievable SEE, followed by the power minimization and rate maximization approaches. In order to achieve a system EE of 26 b/J/Hz for the power minimization strategy, i.e., $\phi = 0$, the optimal ϕ_d/ϕ_m density ratio should be 0.41, which will result in the achievable system sum rate of 2 Kb/s/Hz.

VI. CONCLUSION

Although 5G networks are anticipated to provide enhanced data rates and seamless connectivity, they pose critical challenges related to the resource allocation between various network entities. The problem becomes more pronounced especially if the network is truly heterogeneous in terms of diverse frequency bands, cell sizes, and modes of user communication. This article studied the resource allocation problem for such a network where D2D communications coexist with cellular communications and the BSs and CUs can operate on both sub 6 GHz as well as above 6 GHz frequency bands. Optimization routines have been developed to maximize both energy and spectral efficiencies of cellular as well as D2D users while guaranteeing a minimum QoS. The results heavily depend upon total power budget and the density of CUs and D2D pairs in the system. Future works include analyzing the system with more practical path loss models such as dual-slope models to cater for the effects of irregular patterns and geometry of cells. Similarly, user association for decoupled uplink/downlink can be studied where a CU can make disparate connections to different BSs in uplink and downlink, respectively.

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