Self-Adaptive Power Control Mechanism in D2D Enabled Hybrid Cellular Network with mmWave Small Cells: An Optimization Approach

Syed Ahsan Raza Naqvi*, Syed Ali Hassan*, Haris Pervaiz†, Qiang Ni† and Leila Musavian†
*School of Electrical Engineering & Computer Science, National University of Sciences & Technology (NUST), Pakistan
{11beesraza, ali.hassan}@seecs.edu.pk
†School of Computing & Communications, Lancaster University, UK
{h.pervaiz, q.ni, l.musavian}@lancaster.ac.uk

***Abstract*—Millimeter wave (mmWave) and Device-to-Device (D2D) communications have been considered as the key enablers of the next generation networks. We consider a D2D-enabled hybrid cellular network compromising of μW macro-cells co-existing with mmWave small cells. We investigate the dynamic resource sharing in downlink transmission to maximize the energy efficiency (EE) of the priority, or cellular users (CUs), that are opportunistically served by either macrocells or mmWave small cells, while satisfying a minimum quality-of-service (QoS) level for the D2D pairs. In order to solve this problem, we first formulate a self-adaptive power control mechanism for the D2D pairs subject to the interference threshold constraint set for the CUs, while maintaining its minimum QoS level. Subsequently, the original EE optimization problem, which aimed at maximizing the EE for both CUs and D2D pairs, has been broken up into two subproblems that manage the radio resource allocation for D2D pairs and maximize EE exclusively for CUs, in that order. We then propose an iterative algorithm to provide a near-optimal EE solution for CUs.**

I. INTRODUCTION

The fifth generation (5G) technology will comprise a mixture of network tiers of different sizes, transmission powers, backhaul connections and different radio access technologies (RATs) [1]. In the recent years, the traditional cellular networks have been operating in the ultra high frequency (UHF) bands which are generally insufficient to meet the data rate demands of 5G due to limited availability of spectral resources. Utilization of millimeter wave (mmWave) technology for future generation networks has recently gained attention due to its higher available bandwidth in the range of 1 GHz and the possibility of larger antenna arrays due to the smaller wavelength of mmWave signals [2]–[4].

Device-to-device (D2D) communication, on the other hand is a new paradigm underlying within the cellular networks with a potential to enhance network performance, spectrum efficiency (SE) and energy efficiency (EE). D2D communication allows mobile devices in close proximity to establish a dedicated direct link whereas the entire traffic is routed through BSs in traditional cellular communication. Several investigations have been carried-out into various aspects of D2D communications [5]–[7]. For instance, a random network model for D2D underlaid cellular network was utilized to develop centralized and distributed power control mechanisms as mentioned in [5]. Moreover, the authors in [6] proposed two radio resource allocation (RRA) schemes: the first scheme focused on mitigating the interference between the D2D pairs and CUs whereas the other scheme proposed an energy efficient resource allocation among the D2D pairs and CUs. In contrast, this work optimizes the EE of CUs only, with the D2D transmit powers being subjected to certain constraints.

In this paper, we consider a hybrid cellular network where each D2D pair can share resources with the CUs and propose a joint subcarrier and power allocation to maximize the EE of the CUs while satisfying a minimum quality-of-service (QoS) level of the D2D pairs. The CUs are treated as priority users with the D2D transmitters dynamically tuning their transmit powers to limit the interference experienced by CUs. By extension, system EE has been taken to be the ratio of the total system sum rate to the total power consumed in the network, including all circuit and transmit powers. We first derive a self-adaptive power control mechanism for D2D pairs in order to provide protection to the CUs subject to the predefined interference threshold constraint. We aim to optimize the EE of both CUs and D2D pairs. In doing so, we decompose this problem into two independent subproblems: first, to deal with the RRA of D2D pairs subject to their minimum rate requirement and the interference threshold of CUs and second, to maximize the EE of CUs, in light of the RRA of the D2D pairs.

It should be noted that the small cells are not considered to be a part of the optimization problem as they operate exclusively in the mmWave band. Using the proposed optimal power allocation for the CUs, the optimal subcarrier allocation is found using the Hungarian method. Utilizing these results, we further investigate the tradeoff between the outage probability of D2D pairs and the system EE for various required QoS levels for both CUs and D2D pairs. While earlier work has aimed to optimize the system sum rate [8] and incorporate mmWave technology [9] in a heterogeneous cellular system in the absence of D2D pairs, we will look into the tradeoff between system sum rate and system EE in such a network for different D2D pair to CU density ratios.

II. SYSTEM MODEL

We consider a DL scenario of two-tier heterogeneous networks (HetNets) consisting of υ_{b} μW macro-cells, distributed using a Poisson point process (PPP) with density Φ_{b}, and $4\upsilon_{\mathrm{b}}$ mmWave (mm) SBSs, with a total of m CUs with density Φ_{m} and D D2D pairs with density Φ_{d}. The index set of all BSs operating on μW and mm frequency bands is given by $q = \{1, \ldots, Q\}$ and $w = \{1, \ldots, W\}$, respectively. Each μW

BS has $N_{\mu W}$ subcarriers, whereas each mm small BS (SBS) has N_{mm} subcarriers such that $N_{\mu W} \bigcup N_{\text{mm}} = N$. The set for subcarriers is denoted as $n = \{1, \dots, N_{\mu W}, \cdots, N_{\text{mm}}\}$, the set of all CUs as $m = \{1, \dots, M\}$ and the set of all D2D pairs as $d = \{1, \dots, D\}$. Moreover, each user is expected to achieve a certain minimum data rate, which is given by R_{min}. In addition, all BSs (μW BSs and mm SBSs) in the hybrid HetNets operate independently of each other allowing them to find their optimal transmission power in a distributed manner [10].

In this work, the user association is done prior to the subcarrier allocation. In addition, the maximum transmit power of a BS, P_k^{max}, operating at frequency band $k \in \{\mu W, \text{mm}\}$ has been used to determine the biased received power as

$$\Gamma_m^k = \frac{\beta_k P_k^{\text{max}} G(\theta)}{\text{PL}_m^k}, \tag{1}$$

where β_k is the biasing factor of the BS operating at frequency band $k \in \{\mu W, \text{mm}\}$, θ is the azimuthal angle of the BS beam alignment and $G(.)$ is the antenna gain presented as a function of θ. $G(\theta)$ is assumed to be omnidirectional, i.e., $G(\theta) = 1$ for μW BS. Each user associates to the BS operating in frequency band k with the highest biased received power. Since the angle that provides the maximum received signal power is θ_{max}, hence the transmitter beam is taken to be perfectly aligned if $\theta \in [\theta_{\text{max}} - \frac{\Delta\omega}{2}, \theta_{\text{max}} + \frac{\Delta\omega}{2}]$ where $\Delta\omega$ denotes the half power beamwidth. A perfectly aligned transmitter beam has a gain of G_{max} but a misaligned beam has gain of G_{min}. The antenna sectoring model used in this paper is similar to the one adopted in [3].

In this work, an orthogonal subcarrier selection scheme is considered such that each subcarrier is exclusively assigned to a single CU within the same cell. The achievable rate of user m on subcarrier n associated with μW BS is given by,

$$r_{m,n}^{(\mu W)} = \Theta_{\mu W} B_{\mu W} \log_2(1 + \gamma_{m,n}^{(\mu W)} \times p_{m,n}^{(\mu W)}), \tag{2}$$

where $\Theta_{\mu W}$ is the proportion of bandwidth allocated to each subcarrier by μW BS, $B_{\mu W}$ indicates the total bandwidth available to the μW BS and $p_{m,n}^{(\mu W)}$ indicates the power allocated to user m on the subcarrier n associated with μW BS. The signal-to-interference plus noise ratio (SINR) of user m on subcarrier n associated with μW BS is denoted by $\gamma_{m,n}^{(\mu W)}$ and defined as

$$\gamma_{m,n}^{(\mu W)} = \frac{|\text{h}_{m,n}^{(\mu W)}|^2}{(\text{N}_0 \Theta_{\mu W} B_{\mu W} + I_{m,n}^{(\mu W)}) \text{PL}_m^{\mu W}}, \tag{3}$$

where $|\text{h}_{m,n}^{(\mu W)}|^2$ represents the squared envelope of the multi-path fading with the envelope following a Nakagami distribution between CU m, and μW BS at subcarrier n, N_0 is the thermal noise and $I_{m,n}^{(\mu W)}$ is the total cross-tier interference caused due to the subcarrier $n \in N_q$ being reused by a D2D pair within the coverage area of μW BS q. The path loss of a user m, located at $(x, y) \in \mathbb{R}^2$, associated with μW BS, at carrier frequency $f_{\mu W}$, denoted by $\text{PL}_m^{\mu W}$, can be expressed as

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

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

Similarly, the achievable rate of user m on subcarrier n associated with mm BS is given by

$$r_{m,n}^{(\text{mm})} = \Theta_{\text{mm}} B_{\text{mm}} \log_2(1 + \gamma_{m,n}^{(\text{mm})} \times p_{m,n}^{(\text{mm})}), \tag{5}$$

where Θ_{mm} is the proportion of bandwidth allocated to each subcarrier by mm BS, B_{mm} indicates the total bandwidth available to the mm BS and $p_{m,n}^{(\text{mm})}$ indicates the power allocated to user m on the subcarrier n associated with mm BS. The SINR of user m on subcarrier n associated with mm BS is denoted by $\gamma_{m,n}^{(\text{mm})}$ and defined as follows:

$$\gamma_{m,n}^{(\text{mm})} = \frac{|\text{h}_{m,n}^{(\text{mm})}|^2}{(\text{N}_0 \Theta_{\text{mm}} B_{\text{mm}} + I_{m,n}^{(\text{mm})}) \text{PL}_m^{\text{mm}}}, \tag{6}$$

where $|\text{h}_{m,n}^{(\text{mm})}|^2$ represents the squared envelope of the multi-path fading with the envelope following a Nakagami distribution between CU m and mm BS at subcarrier n, with parameter 3 [4] for non line-of-sight (NLoS) and parameter 1 for line-of-sight (LoS) links, N_0 is the thermal noise and $I_{m,n}^{(\text{mm})}$ is the total cross-tier interference. As mm networks are generally considered to be noise limited due to negligible impact of interference and a greater available bandwidth, this paper takes $I_{m,n}^{(\text{mm})}$ to be equal to 0. The path loss of a user m located at $(x, y) \in \mathbb{R}^2$ associated with mm BS, at carrier frequency f_{mm}, denoted by PL_m^{mm} is given by,

$$\text{PL}_m^{\text{mm}} = \begin{cases} \rho + 10\alpha_L^{\text{mm}} \log(d) + \chi_{\text{L}}^{\text{mm}}, & \text{if Link is LoS,} \\ \rho + 10\alpha_N^{\text{mm}} \log(d) + \chi_{\text{N}}^{\text{mm}}, & \text{Otherwise.} \end{cases} \tag{7}$$

In (7), $\chi_{\text{L}}^{\text{mm}}$ and $\chi_{\text{N}}^{\text{mm}}$ represents the shadowing in mm band (in dB) for the LoS and NLoS links, respectively. $\chi_{\text{L}}^{\text{mm}}$ and $\chi_{\text{N}}^{\text{mm}}$ are a Gaussian random variable with zero mean and variance ξ_z^2, where $z \in \{\text{LoS}, \text{NLoS}\}$ which models the effects of blockages. The fixed path loss in PL_m^{mm} is given by $\rho = 32.4 + 20\log(f_{\text{mm}})$. The path loss exponents for LoS and NLoS links in mm band are denoted by α_L^{mm} and α_N^{mm}, respectively.

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

$$\overline{R_m} = \sum_{k \in \{\mu W, \text{mm}\}} \sum_{n=1}^{N_m} \sigma_{m,k} r_{m,n}^{(k)}, \tag{8}$$

where $\sigma_{m,k} = 1$, if the user m is associated with network k and 0, otherwise and N_m is the total number of subcarriers allocated to user m by network k. Similarly, the total power consumed by user m is denoted by $\overline{P_m}$ and given by $\overline{P_m} = \sum_{k \in \{\mu W, \text{mm}\}} \sum_{n=1}^{N_m} \sigma_{m,k} p_{m,n}^{(k)}$. Similarly, the system EE is taken to be given by the expression,

$$\text{EE} = \frac{\sum\limits_{m=1}^{M} \overline{R_m} + \sum\limits_{d=1}^{D} \overline{R_d}}{\sum\limits_{m=1}^{M} \overline{P_m} + Q \times P_C^{(q)} + D \times P_C^{(d)} + \sum\limits_{d=1}^{D} \Lambda_{d,n}^{(*)}}, \tag{9}$$

where $\overline{R_d}$ is the total rate of D2D pair d, $P_C^{(q)}$ is the circuit power for BS q, $P_C^{(d)}$ is the circuit power for the D2D transmitter. Details about $\Lambda_{d,n}^{(*)}$ may be found in Section III.

III. POWER ALLOCATION MECHANISM FOR D2D PAIRS

In order to guarantee the QoS of the CUs associated with μW BS, we impose a maximum interference threshold constraint I_t such that the total cross-tier interference caused by the D2D transmitter to the CU sharing a subcarrier should always be less than or equal to I_t. The transmission power of each D2D transmitter should be chosen in such a manner that the CUs can satisfy their minimum rate requirement is calculated as,

$$\log_2\left(1+\frac{p^{(q)}_{m,n}|\mathrm{h}^{(q)}_{m,n}|^2}{\left(\sigma^2+\frac{\Lambda_{d,n}}{\mathrm{PL}^{\mu W}_{d,m}}|\mathrm{h}^{(d)}_{m,n}|^2\right)\mathrm{PL}^{\mu W}_{m}}\right)\geq R_{\text{min}} \qquad (10)$$

$$\Lambda_{d,n}\leq\frac{\mathrm{PL}^{\mu W}_{d,m}}{|\mathrm{h}^{(d)}_{m,n}|^2}\left(\frac{p^{(q)}_{m,n}|\mathrm{h}^{(q)}_{m,n}|^2}{(2^{R_{\text{min}}}-1)\mathrm{PL}^{\mu W}_{m}}-\sigma^2\right), \qquad (11)$$

where $\Lambda_{d,n}$ is the transmit power of the d^{th} D2D transmitter at subcarrier n, which it shares with CU m, $p^{(q)}_{m,n}$ is the cellular power transmitted by the BS at the given subcarrier n to the CU m and R_{min} is the minimum rate requirement for the CU.

The second value of the D2D transmit power is computed using a predetermined interference threshold, I_t. This provision allows for the transmit power of the D2D transmitter to be controlled dynamically as follows:

$$\overline{\Lambda}_{d,n}\leq\frac{I_t\,\mathrm{PL}^{\mu W}_{d,m}}{|\mathrm{h}^{(d)}_{m,n}|^2}, \qquad (12)$$

where $\overline{\Lambda}_{d,n}$ is the transmit power of the d^{th} D2D transmitter corresponding to the interference threshold I_t and $\mathrm{PL}^{\mu W}_{d,m}$ is the path loss experienced between the d^{th} D2D transmitter and the m^{th} CU sharing the subcarrier n.

Similarly, each D2D pair needs to transmit at a specific minimum transmission power in order to achieve its minimum rate requirement. This minimum power is given by,

$$\Lambda^{\text{min}}_{d,n}=\frac{\mathrm{PL}_d}{|\mathrm{h}_{d,n}|^2}\left(2^{R_{\text{min}}}-1\right)\left(\sigma^2+\frac{p^{(q)}_{m,n}|\mathrm{h}^{(d)}_{m,n}|^2}{\mathrm{PL}^{\mu W}_{m,d}}\right), \qquad (13)$$

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

$$\Lambda^{(*)}_{d,n}=\begin{cases}\min\left(\overline{\Lambda}_{d,n},\max\left(\Lambda_{d,n},\Lambda^{\text{min}}_{d,n}\right),\Lambda^{\text{max}}_{d,n}\right), \text{if} A\geq\Lambda^{\text{min}}_{d,n},\\ \text{Infeasible}, \qquad \text{Otherwise},\end{cases} \qquad (14)$$

where $A=\min\left(\Lambda_{d,n},\overline{\Lambda}_{d,n}\right)$. Finally, the achievable rate of the d^{th} D2D pair on the subcarrier n can be computed as follows:

$$r_{d,n}=\log_2\left(1+\Lambda^{(*)}_{d,n}\gamma_{d,n}\right), \qquad (15)$$

where $\gamma_{d,n}=\dfrac{|\mathrm{h}_{d,n}|^2}{(\sigma^2+I_{d,n})\,\mathrm{PL}_d}$, with $I_{d,n}$ being the interference experienced by the D2D receiver from the BS at subcarrier n. Additionally, the total sum rate for a D2D pair is given by,

$$\overline{R_d}=\sum_{n=1}^{N_d}r_{d,n}. \qquad (16)$$

The subcarrier allocation for D2D pairs is accomplished in a similar manner to that for CUs as outlined in Algorithm 2.

IV. POWER ALLOCATION MECHANISM FOR CUS

Our goal is to simultaneously optimize achievable rate and EE of all the CUs associated with μW BSs subject to the maximum transmission power constraint and minimum required QoS level. The joint optimization problem to maximize the achievable rate and EE is equivalent to maximizing the sum rate and minimizing the total power consumption. The proposed optimization problem in DL transmission scheme is formulated as a MOP which is further transformed into a single objective optimization problem (SOP) using the weighted sum method by normalizing the two objectives by R_{norm} and P_{norm}, respectively, to ensure a consistent comparison as shown below:

$$\textbf{(P1)}\max_{\mathbf{p}}\phi\frac{\sum\limits_{q\in Q}\sum\limits_{m\in M_q}\sum\limits_{n\in N_q}\sigma_{m,n}r^{(q)}_{m,n}}{R_{\text{norm}}}-(1-\phi)\frac{P}{P_{\text{norm}}}, \qquad (17)$$

subject to

$$\begin{aligned}&\text{C1: }\sum_{m\in M_q}\sum_{n\in N_q}p^{(q)}_{m,n}\leq P^{\text{max}}_q,\forall q\\ &\text{C2: }R_m\geq R_{\text{min}},\forall m,\\ &\text{C3: }p^{(q)}_{m,n}\geq 0,\forall m,\forall n,\forall q.\\ &\text{C4: }\sigma_{m,n}\in\left[0,1\right],\forall m,\forall n.\end{aligned}$$

where M_q represents the total number of users associated with BS q such that $\sigma_{m,q}=1$ and N_q represents the total number of available subcarriers to BS q. It is worthwhile to mention that while the user association has already been achieved beforehand, the subscript q has been used to improve the readability. Since each CU can share at most one subcarrier with the D2D pair, the problem **(P1)** can be decomposed into two subproblems (i) the power allocation problem for the CUs and D2D pairs, and (ii) the subcarrier allocation problem for the CUs associated with each μW BS q. The power allocation problem can be formulated as follows:

$$\textbf{(P1-1)}\ \max_{\mathbf{p}}\phi\frac{\sum\limits_{q\in Q}\sum\limits_{m\in M_q}\sum\limits_{n\in N_q}r^{(q)}_{m,n}}{R_{\text{norm}}}-(1-\phi)\frac{P}{P_{\text{norm}}}, \qquad (18)$$

subject to

C1-C3

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

$$T(\mathbf{p},\boldsymbol{\mu},\boldsymbol{\eta})=\frac{\phi}{R_{\text{norm}}}\sum_{q\in Q}\sum_{m\in M_q}\sum_{n\in N_q}r^{(q)}_{m,n}-\frac{(1-\phi)}{P_{\text{norm}}}P$$
$$+\sum_{q\in Q}\mu_q\left(P^{\text{max}}_q-\sum_{m\in M_q}\sum_{n\in N_q}p^{(q)}_{m,n}\right)+\sum_{m\in M_q}\eta_m(R_m-R_{\text{min}}), \qquad (19)$$

where $P_q^{\max}$ is the maximum transmit power of BS q. Using (2), (19) may be rewritten as (20) given at the top of the next page.

The optimal value $p_{m,n}^{(q)}$ can then be computed as

$$p_{m,n}^{(q)} = \left[\frac{\left(\frac{\phi}{R_{\text{norm}}} + \eta_m\right) \Theta_q B_q}{\left(\mu_q + \frac{1-\phi}{P_{\text{norm}}}\right)(\ln 2)} - \frac{1}{\gamma_{m,n}^{(q)}} \right]^+ , \forall m \in M_q, \forall n \in N_q, \tag{21}$$

where μ_q and η_m are the Lagrangian multipliers associated with constraints C1 and C2, respectively, which can be updated using sub-gradient method as follows:

$$\mu_q(j+1) = \left[\mu_q(j) - s_1 \left(P_q^{\max} - \sum_{m=1}^{M_q} \sum_{n=1}^{N_q} p_{m,n}^{(q)} \right) \right]^+ . \tag{22a}$$

$$\eta_m(j+1) = \left[\eta_m(j) - s_2 \left(R_m - R_{\min} \right) \right]^+ . \tag{22b}$$

where $[x]^+ = \max(0, x)$. Further details about the power allocation mechanism are given in Algorithm 1.

Algorithm 1 : Power Allocation mechanism for CUs associated with μW BSs

```
Set $j = 0$ and $j_{max} = 10^4$, initialize $p_{m,n}^{(q)} = 10^{-6}$, $\eta_m = 10^{-2}$, $\forall m$ and $\mu_q = 10^{-2}$, $\forall q$.
while $\eta_m$ and $\mu_q$ have not converged or $j < j_{max}$ do
    Compute $p_{m,n}^{(q)}$ using (14)
    Update $\eta_m(j+1)$ according to (15a)
    Update $\mu_q(j+1)$ according to (15b)
end while
End
```

Using the $p_{m,n}^*$ as an optimal power allocation solution corresponding to **(P1-1)** for the CUs associated with $q \in Q$, the subcarrier allocation problem for each μW BS q can be modelled as below:

$$\textbf{(P1-2)} \ \max_{\sigma} \sum_{m \in M_q} \sum_{n \in N_q} \sigma_{m,n} p_{m,n}^*, \tag{23}$$

subject to

$$\text{C4: } \sigma_{m,n} \in [0, 1], \forall m, \forall n.$$

The problem **(P1-2)** can be solved using the Hungarian Algorithm [11] for each μW BS $q \in Q$, as outlined in Algorithm 2, resulting in $\boldsymbol{\sigma} = \left[\boldsymbol{\sigma}^{(1)}, \boldsymbol{\sigma}^{(2)}, \cdots, \boldsymbol{\sigma}^{(Q)}\right]$ where $\boldsymbol{\sigma}^{(Q)}$ is a subcarrier allocation indicator matrix for μW BS Q whose size is $M_Q \times N_Q$.

The maximum transmission power of each mm BS w, $P_w^{\max}$, is assumed to be uniformly distributed among all the subcarriers N_w. Hence, the power allocation for CUs associated with mm BS w denoted by $p_{m,n}^{(\text{w})}$ can be given as follows:

$$p_{m,n}^{(\text{w})} = \frac{P_w^{\max}}{N_w}, \tag{24}$$

where N_w is the total number of subcarriers available to mm BS w. The subcarrier allocation indicator matrix for mm BS $w \in W$ can also be found using Hungarian Algorithm in a manner similar to that for μW BS. The model presented in this work can be applied to accommodate D2D pairs as priority users by dynamically adjusting the CUs transmission power for given I_t according to the details mentioned in Section III and solving the problem **(P1)** for the D2D pairs.

Algorithm 2 : Subcarrier allocation for CUs associated with μW BS to maximize EE

```
Initialize $e$ to 1
Initialize set of all BSs, $q = \{1 \dots Q\}$
for $e$ = 1 to $Q$ do
Determine $M_q$, the set of CUs associated with BS $e$
Populate a $M_q \times N_q$ matrix, $\kappa_e$, with the optimal transmission power allocated at each subcarrier for each user obtained through (14)
Apply the Hungarian algorithm on $\kappa_e$
    if $e = Q$ then
        Concatenate $\kappa_j$, where $j : 1 \longrightarrow Q$
    end if
end for
End
```

TABLE I: Simulation Parameters

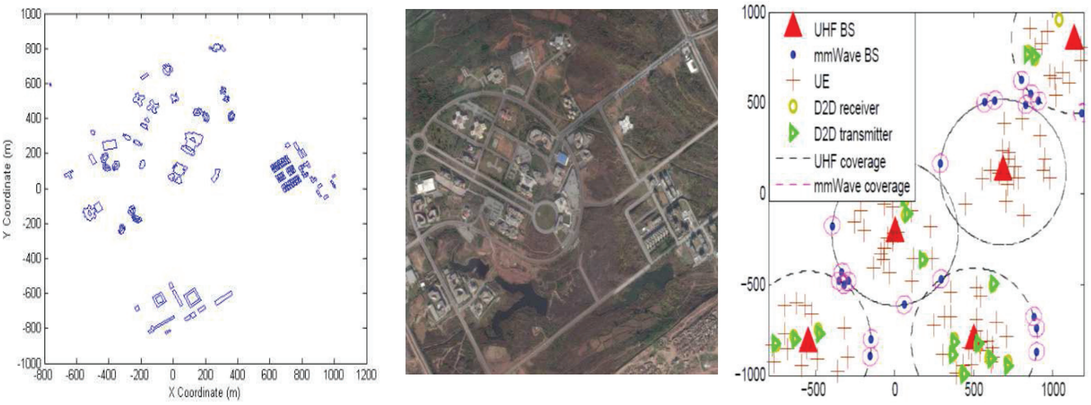
Parameter	**Value**	**Parameter**	**Value**
f_{mm}	28 GHz	B_{mm}	2 GHz [3]
$f_{\mu W}$	2.4 GHz	$B_{\mu W}$	20 MHz
$P_q^{\max}$	46 dBm [12]	N_0	-174 dBm/Hz
Φ_{m}	200/km^2	$\Delta\omega$	10°
Φ_{b}	1/km^2	Φ_{d}	40/km^2
Std($\chi_{\text{L}}^{\text{mm}}$)	5.2 dB [3]	Std($\chi_{\text{N}}^{\text{mm}}$)	7.2 dB
Std($\chi^{\mu W}$)	4 dB	$P_C^{(d)}$	0.1 W
$\Lambda_{d,n}^{\max}$	1 W	$P_C^{(q)}$	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 [3]	α_N^{mm}	3.3 [3]
β_{mm}	5 dB	τ	5 dB
$\beta_{\mu W}$	0 dB	K	4

V. PERFORMANCE EVALUATION

In this work, a DL transmission scheme of a hybrid cellular network, consisting of BSs operating at either μW or mm frequency bands has been considered. Each D2D receiver is randomly distributed within a maximum proximity distance of $r_d^{\max}$ [m] from their respective D2D transmitter. K mm SBSs are randomly deployed at the cell edge of each μW BS. Unless otherwise stated, system parameters are assigned values as shown in Table I.

In this simulation, the actual building locations from the National University of Sciences and Technology (NUST) campus, Islamabad, Pakistan, are used as shown in Fig. 1. This incorporates real blockage effects and environmental geometry into our analysis. Fig. 1(a) depicts the NUST campus as seen in Google Earth, whereas Fig. 1(b) shows the actual building locations of the campus. The initial shape file has been processed into a smaller shape file consisting of only the region of interest (RoI), that is, the NUST campus. The resultant shape file is then analyzed to obtain the actual building locations by using a script written in MATLAB. The detailed steps and

$$T(\mathbf{p},\boldsymbol{\mu},\boldsymbol{\eta}) = \sum_{q\in Q}\left(\frac{\phi\Theta_q B_q}{R_{\text{norm}}}\sum_{m\in M_q}\sum_{n\in N_q}\log_2(1+\gamma_{m,n}^{(q)}p_{m,n}^{(q)})\right) - \sum_{q\in Q}\left(\frac{(1-\phi)}{P_{\text{norm}}}\sum_{m\in M_q}\sum_{n\in N_q}(p_{m,n}^{(q)}+Q\times P_{\text{C}}^{(q)})\right)$$
$$+\sum_{q\in Q}\mu_q\left(P_q^{\max}-\sum_{m\in M_q}\sum_{n\in N_q}p_{m,n}^{(q)}\right)+\sum_{m\in M_q}\eta_m\left(\sum_{q\in Q}\sum_{n\in N_q}\Theta_q B_q\log_2(1+\gamma_{m,n}p_{m,n}^{(q)})-R_{\min}\right) \tag{20}$$



(a)
Map obtained through MATLAB

(b)
Google Earth image

(c)
Network Snapshot

Fig. 1: Building locations in NUST campus.

procedures to achieve the actual building locations have been omitted from the paper due to space limitations. Finally, Fig. 1(c) is a sample deployment scenario for the considered system.

In the assumed system, the mm SBSs are located along the circumference of the coverage parameter of μW BSs. The radius of this parameter has been fixed at 400 m for μW BSs and at 50 m for mm SBSs. The diagram also shows that the number of D2D pairs is only a fraction of that of CUs, as confirmed by Table I.

A. Simulation Results

In this paper, a target SINR has been set which should be achieved by all CUs and D2D pairs. This target SINR, τ, is given simply by,

$$\tau = 2^{R_{\min}} - 1. \tag{25}$$

Fig. 2 depicts the variation of achievable system EE with varying τ for different power control schemes. The power minimization scheme ($\phi = 0$) forces all users to strictly operate at τ. Also, the rate maximization scheme ($\phi = 1$) allocates a power of $P_q^{\max}/N$ at each subcarrier, thereby ensuring that each user attains the maximum possible rate. Finally, the system EE optimization approach ($\phi = \phi_{\text{EE}}$) allocates power to each subcarrier using (21). As is obvious from the curve, the achievable system EE for $\phi = 1$ remains constant, as the power consumed by the network remains independent of τ. The curve for $\phi = 0$, however, has an achievable system EE close to 0 at -30 dB, as users operate at negligible rates irrespective of channel state. An increasing trend is then observed at higher values of τ, with the $\phi = 0$ curve overtaking that of $\phi = 1$, in terms of SEE, for $\tau > 0$ dB. Beyond a target SINR of 10 dB, the power minimization curve starts to approach the achievable system EE of the rate maximization approach. The curve for $\phi = \phi_{\text{EE}}$ has an achievable system EE which is greater than that of the $\phi = 1$ curve by nearly 60% at τ = -30 dB. Moreover, for $\tau > 9$ dB, the curves for $\phi = \phi_{\text{EE}}$ and $\phi = 0$ follow the same trend.

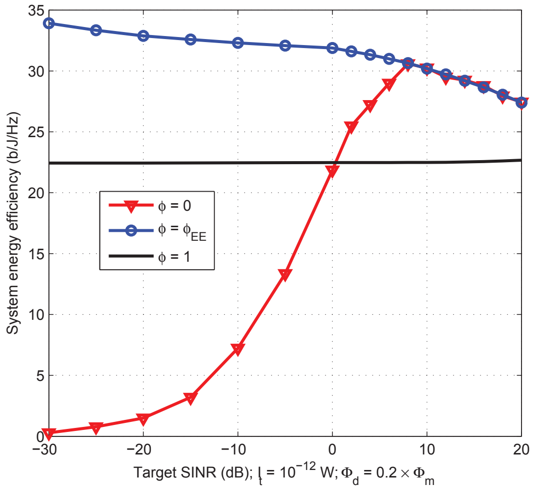


Fig. 2: System Energy Efficiency versus target SINR, for various power control mechanisms.

Fig. 3 analyzes the outage probability of D2D pairs and the achievable system EE for different values of τ. A D2D pair is taken to be in 'outage' if $A < \Lambda_{d,n}^{\min}$ as mentioned earlier in (14)[1]. It demonstrates that the outage probability increases with an increase in τ for different interference thresholds I_t. D2D pairs exhibit higher outage probabilities for lower values of I_t. The figure reveals that $I_t = 10^{-16}$ W results in an outage probability of 20% at $\tau = -20$ dB whereas the same outage

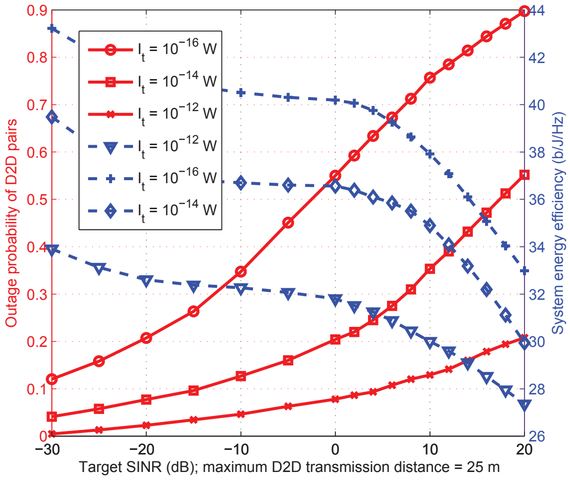


Fig. 3: Outage probability of D2D pairs and System Energy Efficiency versus target SINR at different I_t for $\phi = \phi_{\mathrm{EE}}$.

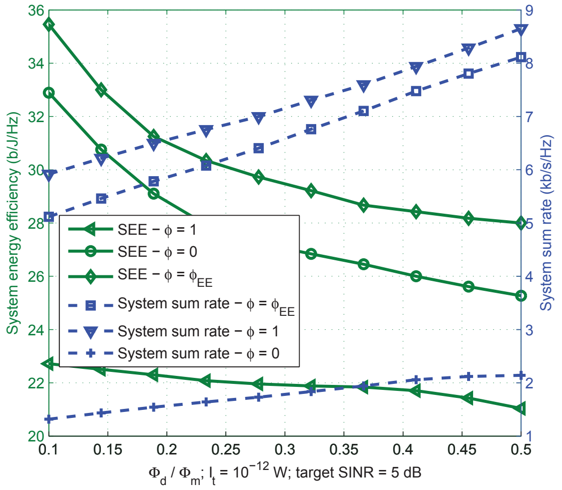


Fig. 4: System Energy Efficiency and System Sum Rate versus the D2D pair to CU density ratio.

probability is achieved at $\tau = 0$ dB and $\tau = 20$ dB for $I_t = 10^{-14}$ W and $I_t = 10^{-12}$ W, respectively. In conjunction with this trend, Fig. 3 also shows that the achievable system EE, for all values of I_t under consideration, generally decreases for increasing τ. As a further observation, the achievable system EE for $I_t = 10^{-16}$ W is generally higher than that for both $I_t = 10^{-14}$ W and $I_t = 10^{-12}$ W. In fact, the system EE for $I_t = 10^{-16}$ W at $\tau = 10$ dB is nearly 25% greater than that for $I_t = 10^{-12}$ W. This is due to the fact that the CUs are considered as priority users, a trade-off always exist between achievable system EE and D2D outage probability for a given I_t.

Fig. 4 investigates the impact of the ratio of the D2D pair to CU density on the achievable system EE and the system sum rate. Higher values of this ratio result in an increase in system sum rate and a decrease in system EE for all power control approaches. However, for all the values of the ratio, the system EE optimization approach offers the greatest achievable SEE, followed by the power minimization and rate maximization approaches. If the system EE to be achieved is 26 b/J/Hz, then the required value of the density ratio for $\phi = 0$ is nearly 0.41, with the system sum rate being approximately 2 kb/s/Hz. Similarly, for an achievable system sum rate of 6 kb/s/Hz, the density ratio should be nearly 0.22 for $\phi = \phi_{\mathrm{EE}}$ with the achievable system EE being close to 30.5 b/J/Hz. Furthermore, the $\phi = 1$ curve experiences only a gentle decrease in its system EE resulting in approximately 75% of the $\phi = \phi_{\mathrm{EE}}$ curve at $\Phi_{\mathrm{d}}/\Phi_{\mathrm{m}} = 0.5$. At the same density ratio, the system sum rate at $\phi = 1$ is nearly 6% higher than that for $\phi = \phi_{\mathrm{EE}}$. The tradeoff between system EE and system sum rate for varying density ratios are quite obvious from this figure.

VI. CONCLUSION

In this paper, we have developed an efficient and self-adaptive radio resource management scheme for the D2D underlying hybrid cellular network to maximize the EE of the priority or cellular users while guaranteeing the minimum QoS level of non-priority or D2D pairs. This paper analyzes the system EE and system sum rate in a hybrid cellular network with traditional macrocells operating at μW band and small cells operating at mmWave band. The CUs sharing resources with the D2D pair are prone to interference which increases with an increase in D2D pair to the CU density ratio. The interference threshold constraint can be used effectively to limit the interference caused to the priority users from the non-priority users resulting in a better network performance. Simulation results show that our proposed approach outperforms the traditional schemes such as those aimed at maximizing system sum rate and minimizing the power consumption.

REFERENCES

[1] E. Hossain, et al., "Evolution toward 5G multitier cellular wireless networks: An interference management perspective," *in Wireless Commun.*, vol. 21, no. 3, pp. 118-127, 2014.

[2] T. Rappaport, R. Heath Jr., R. Daniels and J. Murdock, *Millimeter Wave Wireless Communication*, Prentice Hall, 2014.

[3] S. Singh, M. Kulkarni, A. Ghosh and J. Andrews, "Tractable model for rate in self-backhauled millimeter wave cellular networks," *in IEEE J. Sel. Areas Commun.*, vol. 33, no. 10, pp. 2196-2211, Oct. 2015.

[4] T. Bai, A. Alkhateeb and R. Heath Jr., "Coverage and capacity of millimeter-wave cellular networks," *IEEE Commun. Mag.*, vol. 52, no.9, pp. 70-77, Sep. 2014.

[5] N. Lee, X. Lin, J. Andrews and R. Heath Jr., "Power control for D2D underlaid cellular networks: Modeling, algorithms, and analysis," *in IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 1-13, Jan. 2015.

[6] S. Mumtaz, K. Huq, A. Radwan, J. Rodriguez and R. Aguiar, "Energy efficient interference-aware resource allocation in LTE-D2D communication," *in IEEE Int. Conf. on Commun. (ICC)*, pp. 282-287, Jun. 2014.

[7] M. Sheng, Y. Li, X. Wang, J. Li, and Y. Shi, "Energy efficiency and delay tradeoff in device-to-device communications underlaying cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 1, pp. 92-106, Jan. 2016.

[8] H. Munir, S. Hassan, H. Pervaiz and Q. Ni, "A game theoretical network-assisted user-centric design for resource allocation in 5G heterogeneous networks," *IEEE 83rd Vehicular Technology Conference (VTC Spring)*, pp. 1-5, May 2016.

[9] M. Omar, M. Anjum, S. Hassan, H. Pervaiz and Q. Ni, "Performance analysis of hybrid 5G cellular networks exploiting mmWave capabilities in suburban areas," *IEEE International Conference on Communications (ICC)*, May 2016.

[10] N. Abuzainab and W. Saad, "Cloud radio access meets heterogeneous small cell networks: A cognitive hierarchy perspective," arXiv:1606.04198v1 [cs.IT], Jun. 2016.

[11] H. Kuhn, "The Hungarian method for the assignment problem," *Naval Research Logistics Quarterly 2*, pp. 83-97, 1955.

[12] K. Huq, S. Mumtaz, J. Bachmatiuk, J. Rodriguez, X. Wang and R. Aguiar, "Green HetNet CoMP: Energy efficiency analysis and optimization," *IEEE Trans. on Veh. Technol.*, vol. 64, no. 10, pp. 4670-4683, Nov. 2014.

---

[1] The design goal of this work is to treat CUs as priority users resulting in a tradeoff between the outage probability of D2D pairs and the system EE for varying SINR target.