Energy-Efficient Device-to-Device Communication in Cellular Networks

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***Abstract*—Device-to-Device (D2D) communication is expected to satisfy the rapidly increasing capacity, and it can also alleviate the burden of base stations (BSs) by offloading onto direct links in a 5G mobile system, which can support high-speed data rate for local users and provide power-saving services, while enhancing the energy efficiency (EE) of the global network. Therefore, we model the EE of global network underlaid or overlaid D2D direct communications, where the explicit relationships between EE and the offloading strategy radius are signified by quantifying various network parameters (i.e., density of BSs and users, data-rate and system bandwidth, etc). More importantly, we analytically comprehend the EE and user's average transmission power in both D2D modes, that is, underlay and overlay. Furthermore, offloading probability of cellular users and active probability of D2D transmitters are analytically obtained. Simulations are carried out and show that global network EE can be significantly improved by using D2D communication. Moreover, in overlay mode, when the D2D bandwidth is same with underlay mode, users consume less power for transmission, because the inter-tier interference is eliminated at the price of saving gain on the energy and spectrum as the total bandwidth becomes larger.**

***Index Terms*—Device-to-Device communication, energy efficiency, mode selection.**

I. Introduction

With exponential growth of traffic, mobile cellular networks are facing the technology challenges to enable enormous data flows, high data rate, and large system capacity. Despite various application scenarios in mobile communication networks, effective local area communication inside a cell shall be predominant in the future systems. Noticeably, in order to meet diverse need, D2D communication has been proposed as a promising technology which allows users to alleviate traffic from base station inside a cell [1]-[3]. Two basic modes for D2D communication have been widely considered: underlay (spectrum shared with cellular users, uplink or downlink) and overlay (orthogonal spectrum with cellular networks)[4].

However, the increasing number of D2D transmitters can result in severe interference on same frequency band in hybrid D2D and cellular networks. Consequently, the energy efficiency of the system may be declined since users could consume additional power to achieve the quality of service requirement. Much more efforts have been done in early research about such offloading strategy. Resource allocation was jointly performed with mode selection in [5]-[8]. [9] proposed the mode switching algorithm for D2D communications based on the user's energy efficiency optimization. As green communication emerges [10]-[14], the mode selection strategy should not only reinforce the end-user throughput and system capacity, but also guarantee the improved energy efficiency with user's transmission power constraint. To evaluate the performance of global network EE on different offloading strategy becomes a critical but overlooking issue to adopt D2D communications, and serves the ultimate goal of this research.

In this study, we leverage stochastic geometry to model the position of base stations and users as independent homogeneous Poisson point processes (PPPs) with different density λ, and later interference analysis. Specifically, we consider the density of different network components (cellular user, D2D transmitter and BS), user date rate, system bandwidth and the offloading strategy radius which is the dominant variable through the theoretical model, and we discover delicate relationships between these network parameters. We further derive the more compact closed-form EE and average D2D transmitter power expressions, surprisingly finding that how energy saving gain can be captured with the respect of network parameters changing into different values. The theoretical framework is verified by simulations.

The remainder of this paper is organized as follows. Section II presents the system model and energy efficiency analysis. Section III formulates and derives the EE model of the hybrid network. Numerical results are shown and analyzed in section IV. Finally, the conclusions are summarized in section V.

II. System Model

We consider cellular downlinks and D2D communications coexisting in the hybrid network, where D2D transmitter can be activated to broadcast the information for local users as in Fig. 1. Macro BSs are randomly distributed in the entire plane $\mathbb{R}^2$ according to the homogeneous Poisson point process with density λ_b, which is denoted as the set of $\Psi_b = \{b_j, j = 0, 1, 2, ...\}$. The users are classified into cellular users (CUEs) and donor uers (DUEs), and they are also spatially scattered on the basis of independent PPPs denoted by different density λ_u and λ_D, indicated as Ψ_u and Ψ_D.

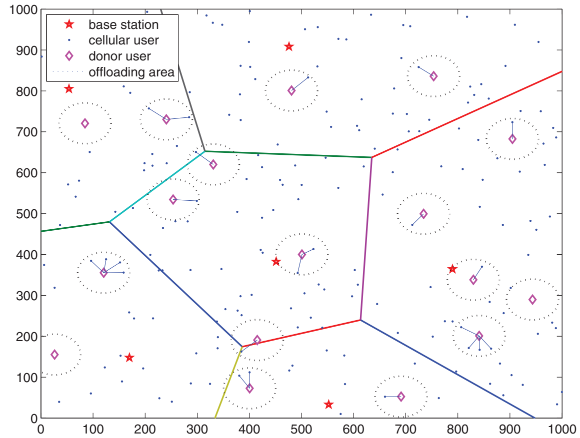

Fig 1: Cellular downlink with D2D transmitters which can be activated and broadcast information when CUE exists in his circular region of radius R_S

The set of BSs forms a Poisson-Voronoi tessellation as in Fig. 1. Each cellular user attached to one BS $(b_j \in \Psi_b)$ which is closer to the user than other BSs, and the cell area can be defined as the set of $V_j = \left\{x \in \mathbb{R}^2 \,|\, \|x - b_j\| \le \|x - b_k\|, b_k \in \Psi_b \backslash b_j\right\}$, where $\|a-b\|$ represents the distance between a and b. For D2D communication, special CUE $\left(u_i^d\right)$ connects to the DUE $\left(u_i^{DT}\right)$ which is located in the circular region Ω_i of radius R_S with the centre of u_i^d, and $\Omega_i = \left\{x \in \mathbb{R}^2 \,|\, \|x - u_i\| \le R_S, u_i \in \Psi_u\right\}$. If DUEs are located outside the designated offloading area of a reference u_i, this u_i will maintain the traditional cellular link. It's worth noting that one u_i can convert to the D2D receiver $\left(u_i^d\right)$ when the distance between u_i and u_i^{DT} is less than R_S.

A. Resource And Power

1)Cellular downlink: In an arbitrary cell, the whole CUEs can be denoted as $\Psi_{u,j}$, where $|\Psi_{u,j}| = N \in N^+$. The total bandwidth for downlink is B HZ, and it is equally divided into N sub-bands (i.e. each CUE has $B_i = B/N$ HZ), which enables the transmission links to be orthogonal. In each sub-band, the associated CUE $u_{i,j}^c \in \Psi_{u,j}$ requires a specific service rate $R_{i,j}^c$. We assume BS has the adaptive power control ability according to zero-delay *channel state information* (CSI). Therefore, the BS transmission power $P_{i,j}^B$ for $u_{i,j}$ on its sub-band is allocated to ensure the required service rate $R_{i,j}^c$, and the total transmission power for BS is:

$$\begin{aligned} &P_{cell}^j = \sum\nolimits_i P_{i,j}^B \;\; s.t. \;\; P_{cell}^j < P_M \\ &R_{i,j}^c = B_i \log_2\left(1 + \frac{P_{i,j}^B g_{i,j}^c}{N_0 + I_{i,j}^c}\right) \ge R_{\min}^c \end{aligned} \quad (1)$$

Where $g_{i,j}^c$ represents the power channel gains between user and BS, N_0 is the noise power and $I_{i,j}^c$ is the interference at $u_{i,j}^c$, P_M denotes the maximum transmission power at BS.

2)D2D link: D2D pairs can share the same resources $(B_d = B)$ with the existing cellular links or occupy the dedicated resources $(B_d = \omega B)$ that are orthogonal with CUEs. In the two modes, D2D bandwidth is divided into several sub-bands by the parameter β, and each u_i^{DT} can randomly access to one sub-bands. Uniformly, each D2D link has a particular data rate R_i^d which will be higher than $R_{i,j}^c$ on account of the proximity communication. Moreover, P_i^d is the transmission power at u_i^{DT} on D2D sub-band, satisfying the data rate R_i^d requirement:

$$R_i^d = \frac{B_d}{\beta}\log_2\left(1 + \frac{P_i^d g_i^d}{N_0 + I_i^d}\right) \ge R_{\min}^d \quad s.t. \; P_i^d \le P_D. \quad (2)$$

Where P_D is the user maximum transmission power, g_i^d represents the power channel gains between u_i^{DT} and u_i^d and I_i^d is the interference at D2D receiver u_i^d.

B. SIR

Since the total interference at a user is higher than the noise power, we will not consider the effects of noise. The path-loss is taken into account and is modeled by $L_\alpha(r) = Ar^{-\alpha}\,(A > 0)$, where r is the distance from transmitter to receiver, and α is attenuation factor. Correspondingly, fast-fading is omitted for the convenience of analysis. For convenience, we focus on the worst-case scenario where intruders transmit on their maximum power.

With underlay mode, the interference at $u_{i,j}^c$ is generated from other BSs as the set of $\{\Psi_b \backslash b_j\}$ and DUEs which are broadcasting his information and sharing the same resources with cellular links. The SIR of $u_{i,j}^c$ on the downlink of B_i bandwidth is given in the following:

$$SIR_{i,j}^c = \frac{L_\alpha\left(\left\|u_{i,j}^c - b_j\right\|\right) P_{i,j}^B}{\begin{bmatrix} \sum_{b_k \in \{\Psi_b \backslash b_j\}} L_\alpha\left(\left\|u_{i,j}^c - b_k\right\|\right) P_{\max} \\ + \sum_{u_k^{DT} \in \{\Psi_D^I\}} L_\alpha\left(\left\|u_{i,j}^c - u_k^{DT}\right\|\right) P_D \end{bmatrix}}. \quad (3)$$

and the received SIR for D2D user u_i^d is given as follows:

$$SIR_i^d = \frac{L_\alpha\left(\left\|u_i^d - u_i^{DT}\right\|\right) P_i^d}{\begin{bmatrix} \sum_{b_k \in \{\Psi_b\}} L_\alpha\left(\left\|u_i^d - b_k\right\|\right) P_{\max} \\ + \sum_{u_k^{DT} \in \{\Psi_D^I \backslash u_i^{DT}\}} L_\alpha\left(\left\|u_i^d - u_k^{DT}\right\|\right) P_D \end{bmatrix}}. \quad (4)$$

Furthermore, in overlay mode, the denominator of SIR expression (3) retains first term and (4) retains second term since inter-tier interference eliminates.

III. Energy Efficient D2D Hybrid Networks

In this section, we derive the global network EE based on the aggregate transmission power in an arbitrary BS and the average transmission power of an arbitrary DUE. Firstly, we give the probability (P_{OL}) of one cellular user offloading to D2D link:

$$P_{OL} = \int_0^{R_S} f(r)dr = 1 - e^{-\pi\lambda_D {R_S}^2}, \quad (5)$$

where $f(r) = 2\pi\lambda_D r e^{-\pi\lambda_D r^2}$ denotes probability density function (PDF) of the distance between u_i^d and its associated D2D transmitter u_i^{DT}. Furthermore, once there is a cellular user in the scope of R_S centered in accordance with the reference DUE, it will be active. Next, the probability $\left(P_D^{act}\right)$ of any one DUE being active to broadcast his information can be expressed as:

$$P_D^{act} = \int_0^{R_S} 2\pi\lambda_u r e^{-\pi\lambda_u r^2} dr = 1 - e^{-\pi\lambda_u R_S{}^2}. \quad (6)$$

A. Transmission power of BS and DUE

In order to obtain the BS transmission power, we aim at the n^{th} user $u_{n,j}^c$ at the origin in V_n, which is separated by the distance $\left\|u_{n,j}^c - b_j\right\|$ from its associated BS b_j. According to Shannon theorem that is similar to (1), service rate of $u_{n,j}^c$ can be given by ignoring noise N_0.

$$R_{n,j}^c = B_n \log_2\left(1 + \frac{P_{n,j}^B \left\|u_{n,j}^c - b_j\right\|^{-\alpha}}{I_{n,j}^c}\right), \quad (7)$$

where $I_{n,j}^c$ represents total interferences at $u_{n,j}^c$. Then, the required transmission power $P_{n,j}^B$ in its sub-band B_n can be obtained as follow:

$$\mathbb{E}\left[P_{n,j}^B\right] = \frac{\left(2^{NR_{n,j}^c/B} - 1\right)\mathbb{E}\left[I_{n,j}^c\right]}{\left\|u_{n,j}^c - b_j\right\|^{-\alpha}}. \quad (8)$$

Proposition 1. *With underlay, when the system bandwidth B is given in a relatively large value and the service rate of each cellular user is R_c $\left(\forall R_{i,j}^c{=}R_c\right)$, the averaged aggregate transmission power of BS b_j in the cell area S_j can be expressed as follow:*

$$\begin{aligned}\mathbb{E}\left[P_j^B\right] = &\left\{\exp\left[\left(2^{R_c/B} - 1\right)(1 - P_{OL})\lambda_u S_j\right] - 1\right\} \\ &\times \left(\frac{2P_M}{\alpha - 2} + \frac{\alpha\Gamma(\alpha/2)\pi^{\frac{2-\alpha}{2}}\lambda_D^{act} P_D R_S^{2-\alpha}}{(\alpha - 2)\lambda_b{}^{\frac{\alpha}{2}}}\right),\end{aligned} \quad (9)$$

where $\Gamma(x)$ is the standard gamma function, and $\lambda_D^{act} = P_D^{act} \times \lambda_D$ represents the density of active D2D transmitters. The attenuation factor α should be greater than 2 as a condition through this model. This can be obtained by calculating the sum of per user's power and averaging the number of users. More details will be illustrated in future works.

In Proposition 1, we observe that either denser cellular user or less BS deployment accounts for the higher average transmission power of BS since the sub-band B_n for each user declines to satisfy the required service rate.

Proposition 2. *With underlay, by assuming the data-rate of each D2D link is equal to R_d $\left(\forall R_i^d{=}R_d\right)$, the average transmission power of active DUE can be obtained as follow:*

$$\begin{aligned}\mathbb{E}\left[P_i^D\right] = &\left[\frac{2\lambda_b{}^{\frac{\alpha}{2}} P_M \Gamma\left(\frac{4-\alpha}{2}\right)\gamma\left(\frac{2+\alpha}{2}, \pi\lambda_D^{act} R_S{}^2\right)}{\beta(\alpha - 2)\lambda_D^{act\,\frac{\alpha}{2}}}\right. \\ &\left. + \frac{2\lambda_D^{act} P_D}{(\alpha - 2)\beta}\left(\frac{P_{OL}}{\lambda_D^{act}} - \pi R_S{}^2(1 - P_{OL})\right)\right]\left(2^{\beta R_d/B} - 1\right),\end{aligned} \quad (10)$$

where $\gamma(z, x)$ is the incomplete gamma function as the following $\gamma(z, x) = \int_0^x t^{z-1} e^{-t} dt$. This can be obtained by considering interferences from two-tier and invoking the PDF of Poison points. Details are in last page. From proposition 2 we note that the transmission power of D2D user is effected by several network parameters (e.g. the density of BSs and DUEs, offloading radius R_S and service-rate, etc), and more detailed influences are shown in the following simulations.

B. Global EE for the hybrid network

In this subsection, we mathematically model the energy efficiency of downlink resource sharing network in the area $\mathbb{R}^2$ in the following Proposition, where P_{OM} indicates non-transmission power of BS b_j, which is a constant value in practice, including baseband processing, battery backup, BS cooling, and etc. Meanwhile, R_c and R_d represent the average service rate of cellular users and D2D users over the entire plane $\mathbb{R}^2$ respectively. To quantify the aggregate power of BS b_j, we use the coverage area $|V_j|$ is effected by the BS density in the network model, and we utilize the PDF of gamma distribution, as follows: $f_{S_j}(t) = (K\lambda_b)^K \frac{t^{K-1}}{\Gamma(K)} e^{-K\lambda_b t}$. Therefore, we can get a closed-form expression of global network EE in proposition 3.

Proposition 3. *With underlay, the global network EE is:*

$$\eta_{EE} = \frac{(1 - P_{OL}) R_c + P_{OL} R_d}{(\xi + \psi) B}, \quad (11)$$

when assuming the following substitutions:

$$\begin{aligned}\xi = &\left[\frac{2P_M\lambda_b}{(\alpha - 2)\lambda_u} + \frac{\alpha\Gamma(\alpha/2)\lambda_D^{act} P_D (1 - P_{OL})}{(\pi\lambda_b)^{(\alpha-2)/2}(\alpha - 2)\lambda_u R_S{}^{\alpha-2}}\right] \\ &\times \left[\frac{(K\lambda_b)^K}{\left[K\lambda_b - \left(2^{R_c/B} - 1\right)(1 - P_{OL})\lambda_u\right]^k} - 1\right] + \frac{\lambda_b}{\lambda_u} P_{OM}\end{aligned} \quad (12)$$

$$\begin{aligned}\psi = \frac{\lambda_D^{act} P_D^{act}}{\lambda_u} &\left[\frac{2\lambda_b{}^{\frac{\alpha}{2}} P_M \Gamma\left(\frac{4-\alpha}{2}\right)\gamma\left(\frac{2+\alpha}{2}, \pi\lambda_D^{act} R_S{}^2\right)}{\beta(\alpha - 2)\lambda_D^{act\,\frac{\alpha}{2}}}\right. \\ &\left. + \frac{2\lambda_D^{act} P_D}{\beta(\alpha - 2)}\left(\frac{P_{OL}}{\lambda_D^{act}} - \pi R_S{}^2(1 - P_{OL})\right)\right]\left(2^{\frac{\beta R_d}{B}} - 1\right)\end{aligned} \quad (13)$$

By calculating the aggregate transmission power at BS b_j, we can obtain the above expressions. Proposition 3 quantifies the network EE in underlay mode where D2D users share the resources with traditional cellular links. Furthermore, we consider the overlay mode where the interference is only generated from intra-tier companions, and it's more tractable for us to analyze the network EE model. Next, the closed-form EE expression is given in corollary 1.

Corollary 1. *For an overlay system, the global network EE can be expressed as the following:*

$$\eta_{EE} = \frac{(1 - P_{OL}) R_c + P_{OL} R_d}{(\xi + \psi)(1 + \omega) B}, \quad (14)$$

when assuming the following substitutions:

$$\xi = \left[\frac{(K\lambda_b)^K}{\left[K\lambda_b - \left(2^{R_C/B} - 1\right)(1 - P_{OL})\lambda_u\right]^K} - 1\right]\frac{2P_M\lambda_b}{(\alpha - 2)\lambda_u} \quad (15)$$

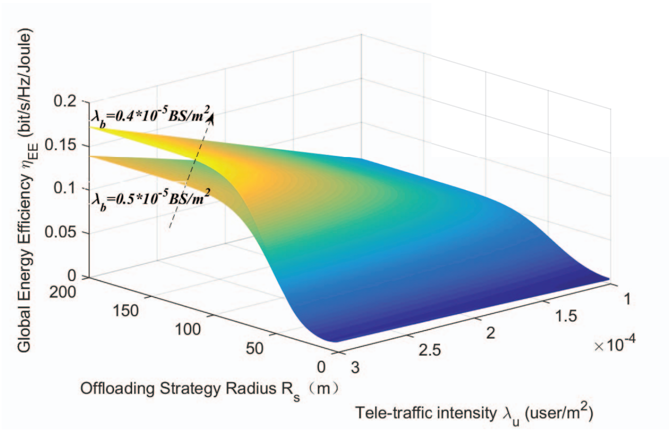

Fig 2: The hybrid network EE with underlay D2D vs. R_S, λ_u in different BS density λ_b.

$$\psi = \frac{2\pi P_D \left(2^{\beta R_D/(\omega B)} - 1\right)}{\left(\lambda_D^{act}\right)^{-2} \lambda_u \left(\alpha - 2\right) \beta} \left[\frac{P_{OL}}{\pi \lambda_D^{act}} - \frac{1 - P_{OL}}{{R_S}^{-2}}\right] + \frac{\lambda_b}{\lambda_u} P_{OM} \tag{16}$$

The detailed proof will not be given. However, this corollary can be easily proved by noting that the interferences at CUE which are generated from D2D pairs can be eliminated, and correspondingly the interferences at D2D receiver are originated from D2D links. Next, we present some numerical examples to illustrate our EE model conducted in this paper.

IV. Numerical Simulations and Discussions

In this section, we provide extensive simulations in order to clearly illustrate the results of our proposed EE model in section III with diverse practical network parameters. For all the cases that will be considered next, we choose $B = 20MHz$, α=3, $R_c = 0.1Mbps$, $R_d = 1Mbps$, λ_D=$0.1 \times 10^{-3} user/m^2$, $\omega = 1$, $P_M = 10W$, $P_D = 0.5W$, and $P_{OM} = 20W$, unless specified otherwise.

Fig.2. shows the network EE, which is measured as bit/s/Hz/Joule, versus offloading radius R_S and tele-traffic intensity λ_u respectively in various macro BS density λ_b. Given in a certain λ_u, more cellular users will detect DUEs with the increase of the offloading radius R_S. Therefore, users are willing to offload their traffic from traditional cellular link to D2D link, which results in the rise of global network EE. In addition, we note that deploying sparser BSs enables higher energy saving gain due to reducing non-transmission power.

In Fig. 3., D2D transmitter power is showed with respect to the different R_S under varying cellular user intensity in both underlay and overlay. Obviously, higher user intensity leads to the increase of DUE transmission power consumption regardless of which mode is selected. This is because that more serious interferences can be generated from D2D pairs if a large number of CUEs offload to D2D communication. More significantly, in overlay, when the dedicated D2D bandwidth is almost the same with that in underlay, D2D transmitters can achieve more energy saving gain in the overlay mode, because the interferences from BSs are eliminated. However, with overlay mode, if the dedicated D2D bandwidth is relatively small (e.g. $\omega = 0.6$), D2D transmitter power will increase and

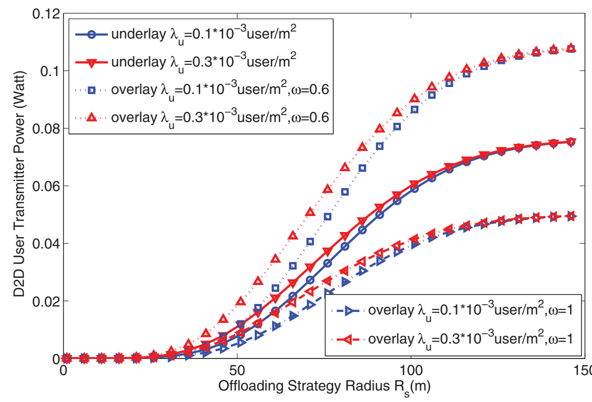

Fig 3: Comparison of DUE transmission power with respect to R_S into different cellular user intensity λ_u in underlay and overlay mode.

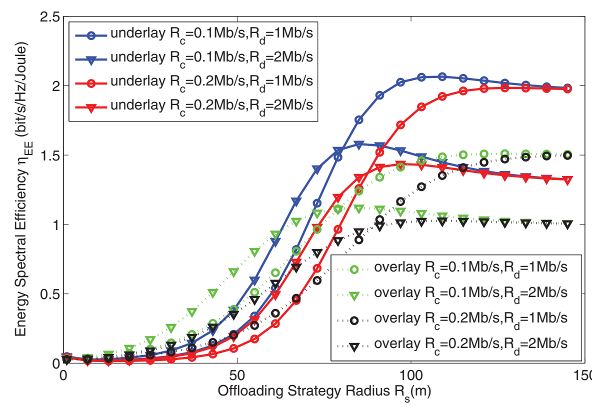

Fig 4: Network EE in both modes with R_S increased under varying service rate (R_c, R_d) where λ_b=$0.5 \times 10^{-5} BS/m^2$, λ_u=$0.3 \times 10^{-3} user/m^2$ and $P_{OM} = 0W$

surpass the power in underlay mode for the sake of satisfying specified service rate requirement.

In Fig. 4., the network energy efficiency is showed by varying R_S in both modes with $P_{OM} = 0W$, which represents the transmission period. We note that more power consumption at DUE results in lower energy efficiency when R_S is relatively large, although the higher D2D traffic speed can make the network throughput increase much faster. More specifically, there exists an optimal offloading strategy radius to maximize network energy efficiency. Therefore, given a specific value of required data rate, we can choose an appropriate R_S to enhance network performance. In addition, when R_S is small, the overlay mode can acquire high energy efficiency. However, using underlay mode can obtain much energy saving gain when R_S is large.

As illustrated in Fig. 5., the performance of energy efficiency is compared in varying λ_D from 0.0001, 0.00015 to 0.0002 $user/m^2$ when $R_S = 50m$. We note that increasing λ_D can achieve higher EE by encouraging more CUEs to offload onto D2D links. More interestingly, there exists an optimal ω to maximize the EE, regardless of the specific value λ_D. This reason is that transmit power increases with the decrease of D2D bandwidth, and large bandwidth results in more spectrum consumption. We can also observe that more

$$\mathbb{E}\left[P_j^D\right] = \int_0^{R_S}\int_0^{+\infty} \frac{\left(2^{\beta R_d/B_d}-1\right)2\pi}{r^{-\alpha}\left(\alpha-2\right)} \left(\frac{\lambda_b P_M}{\beta} v^{2-\alpha} + \frac{\lambda_D^{act}P_D}{\beta} l^{2-\alpha}\right) 2\pi\lambda_b v e^{-\pi\lambda_b v^2} 2\pi \lambda_D^{act} l e^{-\pi\lambda_D^{act} l^2} dvdl \tag{19}$$

$$= \frac{(2\pi)^3\left(2^{\beta R_d/B_d}-1\right)}{\alpha-2}\int_0^{R_S}\lambda_D^{act} l^{1+\alpha} e^{-\pi\lambda_D^{act}l^2}\int_0^{+\infty}\lambda_b{}^2\frac{P_M}{\beta}v^{3-\alpha}e^{-\pi\lambda_b v^2}+\lambda_b\lambda_D^{act}\frac{P_D}{\beta}l^{2-\alpha} v e^{-\pi\lambda_b v^2} dvdl \tag{20}$$

$$= \frac{(2\pi)^3\left(2^{\beta R_d/B_d}-1\right)}{\alpha-2}\int_0^{R_S}\lambda_D^{act} l^{1+\alpha} e^{-\pi\lambda_D^{act}l^2}\left[\lambda_b{}^2\frac{P_M}{\beta}\frac{\Gamma\left(\frac{4-\alpha}{2}\right)}{2(\pi\lambda_b)^{\frac{4-\alpha}{2}}} + \frac{P_D}{\beta}\frac{\lambda_b\lambda_D^{act}}{2\pi\lambda_b} l^{2-\alpha}\right] dl \tag{21}$$

$$= \frac{(2\pi)^2\left(2^{\beta R_d/B_d}-1\right)}{\alpha-2}\left[\frac{P_M\Gamma\left(\frac{4-\alpha}{2}\right)\lambda_D^{act}}{\lambda_b{}^{-\frac{\alpha}{2}}\pi^{\frac{2-\alpha}{2}}\beta}\int_0^{R_S} l^{1+\alpha}e^{-\pi\lambda_D^{act}l^2}dl + \frac{(\lambda_D^{act})^2 P_D}{\beta}\int_0^{R_S} l^3 e^{-\pi\lambda_D^{act}l^2} dl\right] \tag{22}$$

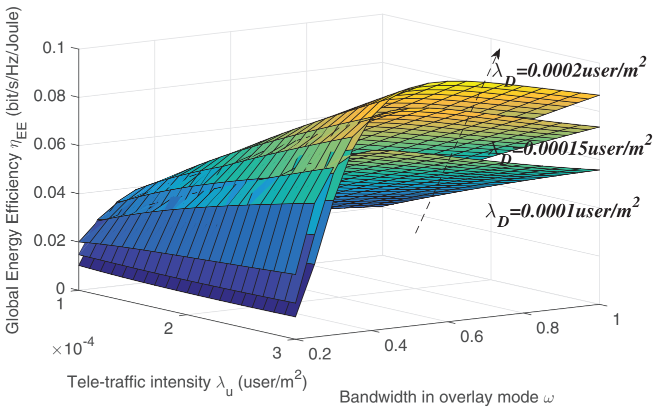

Fig 5: The hybrid network EE with overlay D2D vs. ω, λ_u in different DUE density λ_D where $R_S = 50m$

users' intensity lead to higher network energy efficiency.

V. Conclusions

In this paper, we study global network energy efficiency with D2D communication and develop the EE model by analyzing the interferences from two tiers network (i.e., macro and D2D). The proposed model integrates user density, service data rate and network deployment parameters (i.e., BSs' density, bandwidth, etc.), where the tractable closed-form expressions are given for both D2D modes (i.e., underlay and overlay). In our numerical simulation results, we evaluate the energy efficiency in two modes with varying system parameters and offloading radius, which reflects the superiority of using D2D communication in energy spectrum efficiency in future 5G. More detailed results will be illustrated in future woks.

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