Energy Efficient D2D-Assisted Offloading with Wireless Power Transfer

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***Abstract*—Traffic offloading via device-to-device (D2D) communications has been proposed to improve the network capacity and alleviate the increasing traffic burden on cellular base stations (BSs). However, the success of D2D communications largely relies on the D2D transmitters' (D2D-Txs) willingness of sharing contents (due to the energy consumption for transmission). In this paper, we model and analyze wireless powered D2D-assisted offloading (WPDO) in underlying cellular networks, where the D2D-Tx is allowed to receive power from the nearest BS as well as other interfering BSs, and then D2D-Tx broadcasts the popular contents to nearby users. The average received power at D2D-Tx and the success probability of D2D-Tx transmission are derived. Furthermore, based on the proposed model, we maximize the network energy efficiency while guaranteeing users' required data rates. Our results confirm that the maximum energy efficiency of the WPDO network can be achieved by jointly optimizing the fraction of time for wireless power transfer and the offloading range of D2D-Tx.**

***Index Terms*—D2D communications, energy efficiency, traffic offloading, underlay, cellular networks, wireless power transfer.**

I. Introduction

With the upsurge growth of data traffic and the explosively increasing number of mobile devices, traffic offloading via device-to-device (D2D) communications has attracted great attention to improve the network capacity and alleviate the traffic burden of cellular networks by exploiting the physical proximity of communicating devices [1], [2]. In D2D communications, one of the most traffic demanding social networking applications is content sharing among multiple devices, such as video streaming [3].

However, the power/energy consumption to transmit shared contents creates concerns for D2D transmitters (D2D-Txs). In [1], an incentive framework for D2D based offloading was proposed, where the operator motivated D2D-Txs to broadcast popular contents to nearby users in order to maximize the operator's profit. In [4], the socially enabled D2D communication was studied, where the social interactions among users, who knew each other in real life or in social networks, were considered.

In the meanwhile, dedicated wireless power transfer (WPT) through electromagnetic (EM) radiation emerges as an attractive technology [5], as it can eliminate the hassle of connecting cables and act as a cost-effective technique to enable on-demand energy supplies and uninterrupted operations [6]. The existing literatures studied radio frequency (RF) energy harvesting-based D2D communications [7] as well as user equipment relay communications [8], where mobile devices were powered by the ambient RF signals for information transmission. In fact, it was shown in [9] that energy harvested from ambient RF signals can only power small sensors opportunistically with sporadic activities, while offering stable and fully controllable power needs to rely on the pointing beam, and thus dedicated WPT [6].

On the other hand, driven by both economical and environmental concerns, network designers pay more attention to the energy efficient green communications in order to curb the increasing power consumption of wireless networks [10]. With this in mind, we aim at maximizing the network energy efficiency when the D2D communications are actuated by the dedicated WPT.

In this paper, we propose an energy efficient wireless powered D2D-assisted offloading (WPDO) network, where the D2D-Tx is allowed to receive power from its nearest BS by pointing beam as well as other interfering BSs, and then D2D-Tx broadcasts the popular contents to users located in D2D-Tx's offloading region. In the offloading region, D2D users' required data rates can be guaranteed. We summarize the contributions of this paper as follows:

- Using stochastic geometry, we analytically characterize the average received power at D2D-Tx and derive the practical transmit power of BS by considering user's required data rate. In addition, the density of cellular users with the impact of D2D-assisted offloading is quantified.
- We analytically obtain the success probability of D2D-Tx transmission, and note the existence of optimal time allocation factor (the fraction of time allocated for WPT) that decreases with the D2D user's required data rate.
- We propose to jointly optimize the time allocation factor and the offloading range of D2D-Tx, such that the energy efficiency of WPDO network can be maximized.

The remainder of this paper is organized as follows. In Section II, system model is presented. Section III formulates the average received power at D2D-Tx and the practical transmit power of BS. Section IV analyzes the success probability of D2D-Tx transmission. The energy efficient WPDO network is proposed in Section V. Numerical results are shown in Section VI. Finally, conclusions are drawn in Section VII.

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II. System Model

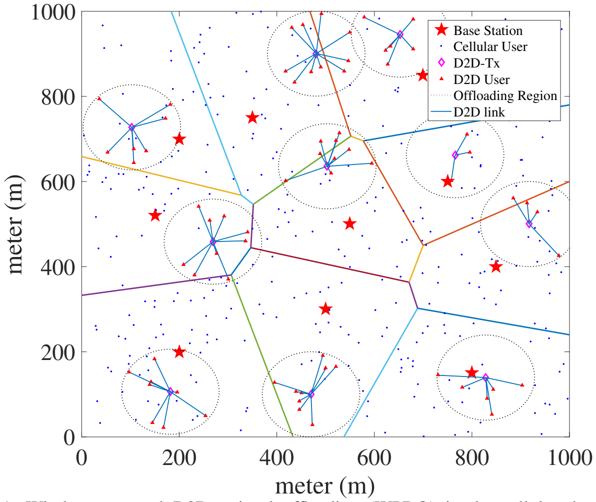

Fig 1: Wireless powered D2D-assisted offloading (WPDO) in the cellular downlink networks, where D2D-Txs can be powered by BSs with pointing beam as well as other interfering BSs and broadcast popular contents to the users in the offloading region with radius of R_D. In the offloading region, D2D users' required data rates can be guaranteed.

A. Network Topology

We consider the cellular downlink integrated with D2D communications, where D2D-Txs can broadcast popular contents to the users in proximity as in Fig. 1. BSs are modeled as a homogeneous Poisson Point Process (PPP) on the entire plane $\mathbb{R}^2$ with the density of λ_B and are denoted as the set of $\Phi_B = \{b_j, j = 0, 1, 2, ...\}$. Each BS has the maximum allowable transmit power represented as P_m and is equipped with N_t antennas. In addition, we assume that each BS can power one D2D-Tx in its cell area by maximal-ratio transmission (MRT) beamforming, and thus the density of D2D-Txs λ_D equals to BSs' (i.e., $\lambda_D = \lambda_B$). The cell area of j^{th} BS b_j is $V_j = \left\{x \in \mathbb{R}^2 \,|\|x - b_j\| \leq \|x - b_n\| \,, b_n \in \Phi_B \backslash b_j\right\}$, where $\|a - b\|$ represents the distance between a and b. Users, which consist of cellular users (connecting with BSs) and D2D users (using D2D links), denoted by Φ_U are scattered on $\mathbb{R}^2$ based on another independent PPP with the density of λ_u. Each user is assumed to be equipped with 1 antenna and has a rechargeable battery with large storage.

B. User's Association

We consider that both cellular users and D2D users have a common required data rate R_u Mbps as their practical traffic demand for the media service, where R_u can be interpreted as the average data rate in the entire network. Each cellular user connects to the closest BS. In addition, each D2D-Tx has the offloading region Ω_D with the radius of R_D. In the offloading region, D2D users' required data rates should be guaranteed. We define the probability $\mathbb{P}_{con}$ that the desired content of a typical user u_0 is the same with the broadcast information of an arbitrary D2D-Tx, also called *content popularity*. We suppose that the value of $\mathbb{P}_{con}$ can be statistically obtained by the operator. If a user's desired content is same with D2D-Tx's broadcast information, the user is transferred into D2D communication by the operator, and such vertical handover process is transparently performed for the user.

C. Channel Model

The bandwidth of cellular downlink is B MHz, while the bandwidth for D2D communications is B_D MHz, and $B_D = \rho B$ where ρ represents the frequency reuse factor [7]. We assume that each BS is capable of performing adaptive power control according to zero-delay channel state information (CSI). Therefore, according to Shannon's theorem, the transmit power $P_{i,j}^B$ of BS b_j for cellular user $u_{i,j}^c$ (i^{th} cellular user in j^{th} cell) is allocated to ensure the required data rate R_u, as follows [11]:

$$R_u = \frac{B}{N_j^c}\log_2\left(1 + SINR\left(u_{i,j}^c\right)\right)$$
$$SINR\left(u_{i,j}^c\right) = \frac{P_{i,j}^B\left\|\mathbf{h}_{b_j u_{i,j}^c}\right\|^2 H_\alpha\|b_j - u_{i,j}^c\|^{-\alpha}}{I_{u_{i,j}^c}^C + I_{u_{i,j}^c}^D + \sigma^2}, \tag{1}$$

where N_j^c denotes the total number of cellular users served by the BS b_j, $\mathbf{h}_{b_j u_{i,j}^c} \in C^{1\times N_t}$ is the small-scale fading channel vector[1], H_α is the path loss for a reference distance, α is the path loss exponent factor, $I_{u_{i,j}^c}^C$ indicates the interference from cellular BSs at $u_{i,j}^c$, $I_{u_{i,j}^c}^D$ denotes the interference from D2D-Txs and σ^2 is the additive noise. More specifically, we have

$$I_{u_{i,j}^c}^C = \sum_{b_n\in\Phi_B\backslash b_j} P_{i,n}^B\left|\mathbf{h}_{b_n u_{i,j}^c}\frac{\mathbf{g}_{b_n u_{i,n}^c}^H}{\left\|\mathbf{g}_{b_n u_{i,n}^c}\right\|}\right|^2 H_\alpha\|b_n - u_{i,j}^c\|^{-\alpha}, \tag{2}$$

$$I_{u_{i,j}^c}^D = \sum_{d_j\in\Phi_D} P_{d_j} h_{d_j u_{i,j}^c} H_\alpha\|d_j - u_{i,j}^c\|^{-\alpha}, \tag{3}$$

where $\mathbf{h}_{b_n u_{i,j}^c} \in C^{1\times N_t}$ is the small-scale fading interfering channel vector, and $\frac{\mathbf{g}_{b_n u_{i,n}^c}^H}{\left\|\mathbf{g}_{b_n u_{i,n}^c}\right\|}$ is the MRT beamforming vector of BS b_n, where $\mathbf{g}_{b_n u_{i,n}^c} \in C^{1\times N_t}$ is the small-scale fading channel vector from BS b_n to its associated user $u_{i,n}^c$. According to [12], $\mathbf{h}_{b_n u_{i,j}^c}\frac{\mathbf{g}_{b_n u_{i,n}^c}^H}{\left\|\mathbf{g}_{b_n u_{i,n}^c}\right\|}$ is a zero-mean complex Gaussian variable, such that $\left|\mathbf{h}_{b_n u_{i,j}^c}\mathbf{g}_{b_n u_{i,n}^c}^H \Big/ \left\|\mathbf{g}_{b_n u_{i,n}^c}\right\|\right|^2 \sim \exp(1)$.

D. Wireless Power Transfer

A harvest-then-transmit protocol at D2D-Tx is considered [13]. Let T denote the duration of a communication block, where the sub-blocks of duration θT and $(1-\theta)T$ are allocated for WPT and information transmission, respectively, where $\theta\,(0 \leqslant \theta \leqslant 1)$ is the time allocation factor. During θT, D2D-Tx captures power from the nearest BS with pointing beam and other BSs. The instantaneous received power $P_{d_j}^R$ at D2D-Tx d_j in j^{th} cell is expressed as

$$P_{d_j}^R = P_{S_{b_j}} + P_{I_{BS}} = P_m\left\|\mathbf{h}_{b_j d_j}\right\|^2\frac{H_\beta}{\left(\max\{\|b_j - d_j\|, v\}\right)^\beta} + \sum_{b_n\in\Phi_B\backslash b_j} P_m\left|\mathbf{h}_{b_n d_j}\frac{\mathbf{g}_{b_n d_n}^H}{\|\mathbf{g}_{b_n d_n}\|}\right|^2\frac{H_\beta}{\left(\max\{\|b_n - d_j\|, v\}\right)^\beta}, \tag{4}$$

[1]With a slight abuse of notation we will use $\mathbf{h}_{\mathrm{xy}}$ to denote the small-scale fading channel vector from x to y, where the channels are assumed to experience Rayleigh fading such that $\|\mathbf{h}_{\mathrm{xy}}\|^2 \sim \mathrm{Gamma}\,(N_t, 1)$.

where $P_{S_{b_j}}$ denotes the received power of pointing beam, and $P_{I_{BS}}$ is the received power from other BSs. During θT, we assume that BSs transmit at P_m in order to supply the reliable power at D2D-Txs. β is the path loss exponent factor for WPT, and $v \geqslant 1$ is a constant value. It is worth noting that the carrier frequencies of WPT and information transmission can be different. This may indicate that the path loss indexes of these two types of signals (i.e., α and β) should be clarified separately, and thus H_β is the path loss for a reference distance.

To simplify the notations in the analytical result, here we consider that D2D-Txs with large battery capacity transmit at the average received power $\overline{P_d} = \phi \mathbb{E}\left\{P_{d_j}^R\right\}$ [14], where $\phi = \eta \frac{\theta}{1-\theta}$ and η is the RF-to-DC conversion efficiency [15]. In D2D-Tx's information transmission, the signal-to-interference-plus-noise (SINR) ratio at the D2D user $u_{i,j}^d$ connected with d_j is given by

$$SINR\left(u_{i,j}^d\right) = \frac{\overline{P_d} h_{d_j u_{i,j}^d} H_\alpha \left\|d_j - u_{i,j}^d\right\|^{-\alpha}}{I_{u_{i,j}^d}^C + I_{u_{i,j}^d}^D + \sigma^2}, \quad (5)$$

where

$$I_{u_{i,j}^d}^C = \sum_{b_n \in \Phi_B} P_{i,n}^B \left| \mathbf{h}_{b_n u_{i,j}^d} \frac{\mathbf{g}_{b_n u_{i,j}^d}^H}{\left\|\mathbf{g}_{b_n u_{i,j}^d}\right\|} \right|^2 H_\alpha \left\|b_n - u_{i,j}^d\right\|^{-\alpha}, \quad (6)$$

$$I_{u_{i,j}^d}^D = \sum_{d_n \in \Phi_D \setminus d_j} \overline{P_d} h_{d_n u_{i,j}^d} H_\alpha \left\|d_n - u_{i,j}^d\right\|^{-\alpha}, \quad (7)$$

where $h_{d_j u_{i,j}^d} \sim \exp(1)$ is the channel power gain, $I_{u_{i,j}^d}^C$ denotes the interference from cellular networks and $I_{u_{i,j}^d}^D$ indicates the interference from D2D communications.

In order to reflect the powering efficiency and the reliability of D2D-Tx information transmission, we define that the success transmission of D2D-Tx occurs when the data rate at the edge of the offloading region Ω_D exceeds the predetermined user's required data rate R_u during a communication block T. The success probability of D2D-Tx transmission is given by

$$P_{suc}^D = \Pr\left\{ \frac{(1-\theta)T}{T} B_D \cdot \log_2\left(1 + \frac{\overline{P_d} h_{d_j u_{i,j}^d} H_\alpha {R_D}^{-\alpha}}{I_{u_{i,j}^d}^C + I_{u_{i,j}^d}^D + \sigma^2}\right) \geqslant R_u \right\}. \quad (8)$$

In the next section, we characterize the average received power $\overline{P_d}$ and the BS practical transmit power $P_{i,j}^B$ from system-level perspective.

III. System-level performance evaluation

A. Average received power at D2D-Tx

Proposition 1. *In the WPDO network, given the BS density λ_B, the number of antennas N_t and the transmit power P_m, the average received power at D2D-Tx is given in (9) at the top of the next page.*

Proof: The average instantaneous received power $\mathbb{E}\left\{P_{d_j}^R\right\}$ in (4) can be expressed as

$$\mathbb{E}\left\{P_{d_j}^R\right\} = \mathbb{E}\left\{P_{S_{b_j}}\right\} + \mathbb{E}\left\{P_{I_{BS}}\right\}. \quad (10)$$

In addition, we have

$$\begin{aligned} \mathbb{E}\left\{P_{S_{b_j}}\right\} &= \mathbb{E}\left\{P_m \left\|\mathbf{h}_{b_j d_j}\right\|^2 H_\beta (\max\{\|b_j - d_j\|, v_1\})^{-\beta}\right\} \\ &\overset{(a)}{=} P_m N_t H_\beta \left[\int_0^{v_1} v_1^{-\beta} f_{\|b_j - d_j\|}(x) dx + \int_{v_1}^{\infty} x^{-\beta} f_{\|b_j - d_j\|}(x) dx\right] \quad (11) \\ &\overset{(b)}{=} \frac{P_m N_t H_\beta v_1^{-\beta}}{\left(1 - e^{-\pi\lambda_B v_1^2}\right)^{-1}} + \frac{P_m N_t H_\beta}{(\pi\lambda_B)^{-\frac{\beta}{2}}} \Gamma\left(1 - \frac{\beta}{2}, \pi\lambda_B v_1^2\right), \end{aligned}$$

where $f_{\|b_j - d_j\|}(x) = 2\pi\lambda_B x e^{-\pi\lambda_B x^2}$ $(x > 0)$, (a) is obtained by using $\mathbb{E}\left\{\left\|\mathbf{h}_{b_j d_j}\right\|^2\right\} = N_t$ and the Campbell's Theorem of PPP. In (b), $\Gamma(\cdot,\cdot)$ is the incomplete Gamma function.

Besides, $\mathbb{E}\{P_{I_{BS}}\}$ is obtained as follows:

$$\begin{aligned} \mathbb{E}\{P_{I_{BS}}\} &= \sum_{b_n \in \Phi_B \setminus b_j} \mathbb{E}\left\{P_m \left|\mathbf{h}_{b_n d_j} \frac{\mathbf{g}_{b_n d_n}^H}{\|\mathbf{g}_{b_n d_n}\|}\right|^2 H_\beta\right\} \cdot \mathbb{E}\left\{(\max\{\|b_n - d_j\|, v_1\})^{-\beta}\right\} \\ &\overset{(a)}{=} P_m H_\beta \mathbb{E}_{\Phi_B}\left\{\sum_{b_n \in \Phi_B \setminus b_j} (\max\{\|b_n - d_j\|, v_1\})^{-\beta}\right\} \\ &= P_m H_\beta 2\pi\lambda_B \int_0^\infty r(\max\{r, v_1\})^{-\beta} dr \\ &= P_m H_\beta 2\pi\lambda_B \left[\int_0^{v_1} v_1^{-\beta} r dr + \int_{v_1}^\infty r^{1-\beta} dr\right] \\ &= P_m H_\beta \pi\lambda_B v_1^{2-\beta}\left(1 + \frac{2}{\beta - 2}\right), \end{aligned} \quad (12)$$

where (a) follows from $\left|\mathbf{h}_{b_n d_j} \frac{\mathbf{g}_{b_n d_n}^H}{\|\mathbf{g}_{b_n d_n}\|}\right|^2 \sim \exp(1)$.

Combining (11) and (12) into (10), we have the desired result in (9). ■

B. BS practical transmit power

To characterize the practical transmit power of BS, we give the following Lemma which specifies the density of cellular users (i.e., users that are unable to offload) λ_u^c in the D2D-assisted offloading networks.

Lemma 1. *In the WPDO network, given the BS density λ_B, the offloading radius R_D and the content popularity $\mathbb{P}_{con}$, the density of cellular users λ_u^c is given by*

$$\lambda_u^c = e^{-\mathbb{P}_{con}\pi\lambda_B (R_D)^2} \lambda_u. \quad (15)$$

Proof: A typical user u_0 can offload onto D2D communication only if the two requirements are satisfied. First, the distance between u_0 and D2D-Tx is within the D2D communication range of radius R_D. Second, the desired content of u_0 is the same as the broadcast information of D2D-Tx. We suppose that D2D-Txs are distributed with a PPP, and thus

$$\overline{P_d} = \frac{\phi P_m N_t H_\beta v_1^{-\beta}}{\left(1-e^{-\pi\lambda_B v^2}\right)^{-1}} + \frac{\phi P_m N_t H_\beta}{\left(\pi\lambda_B\right)^{-\frac{\beta}{2}}}\Gamma\left(1-\frac{\beta}{2},\pi\lambda_B v_1^2\right) + \phi P_m H_\beta \pi\lambda_B v_1^{2-\beta}\left(1+\frac{2}{\beta-2}\right), \tag{9}$$

$$\mathbb{E}\left\{\overline{P_{i,j}^B}\right\} = \left(2^{\frac{N_j^c R_u}{(1-\theta)B}}-1\right)\frac{2H_\alpha\Gamma\left(\frac{\alpha}{2}+1\right)}{(\alpha-2)\,N_t(\pi\lambda_B)^{\frac{\alpha}{2}-1}}\left[\frac{P_m(\pi\lambda_B)^{\frac{\alpha}{2}-1}}{\Gamma\left(\frac{\alpha}{2}+1\right)} + \overline{P_d}v_2{}^{2-\alpha}\left(\frac{1}{2}+\frac{1}{\alpha-2}\right)+\sigma^2\right], \tag{13}$$

$$P_{suc}^D = \exp\left\{-\psi\left(\theta,R_u\right)\sigma^2 - \frac{2\lambda_B\left(\mathbb{E}\left\{\overline{P_{i,j}^B}\right\}\right)^{\frac{2}{\alpha}}\pi^2}{\alpha\sin\left(\frac{2\pi}{\alpha}\right)}\left(\psi\left(\theta,R_u\right)\right)^{\frac{2}{\alpha}} - \pi\lambda_B\zeta\left(\psi\left(\theta,R_u\right),R_D,\overline{P_d}\right)\right\}, \tag{14}$$

the Probability Density Function (PDF) of the distance $r_{i,j}^d$ between u_0 and its nearest D2D-Tx is

$$f_{r_{i,j}^d}(r) = 2\pi\lambda_D r e^{-\pi\lambda_D r^2}, r>0. \tag{16}$$

Then we have the probability P_{OL} that the distance $r_{i,j}^d$ is less than R_D, i.e., the probability that u_0 is located in at least one of the offloading regions of D2D-Txs, as follows:

$$P_{OL} = \int_0^{R_D} f_{r_{i,j}^d}(r)dr = 1-e^{-\pi\lambda_D(R_D)^2}. \tag{17}$$

Recall that the content popularity $\mathbb{P}_{con}$ defined in Section II-B, and suppose that there are m D2D-Txs in a circular region with the radius of R_D centered for u_0. λ_u^c is given by

$$\lambda_u^c = \left(1-P_{OL}\right)\lambda_u + \mathbb{E}_{m\geqslant 1}\left[\left(1-\mathbb{P}_{con}\right)^m\right]\lambda_u, \tag{18}$$

where we regard the cellular users as the PPP with the density of λ_u^c for mathematical tractability.

According to Poisson distribution of D2D-Txs, the Probability Mass Function (PMF) of m is given by

$$\mathbb{P}\left(N_{D2D-Tx}=m\right) = \frac{\left[\pi\lambda_D(R_D)^2\right]^m}{m!}e^{-\pi\lambda_D(R_D)^2}. \tag{19}$$

Therefore, we have

$$\begin{aligned}&\mathbb{E}_{m\geqslant 1}\left[\left(1-\mathbb{P}_{con}\right)^m\right]\\ &= \sum_{m=1}^{\infty}\left(1-\mathbb{P}_{con}\right)^m\mathbb{P}\left(N_{D2D-Tx}=m\right)\\ &= e^{-\mathbb{P}_{con}\pi\lambda_D(R_D)^2} - e^{-\pi\lambda_D(R_D)^2}.\end{aligned} \tag{20}$$

Note that in the WPDO network, the density of D2D-Txs λ_D equals to BSs' (i.e., $\lambda_D=\lambda_B$). Substituting (20) and (17) into (18) gives us the desired result in Lemma 1. ■

We are now in the position of describing the procedure for computing the practical transmit power of BS b_j for a typical cellular user $u_{i,j}^c$.

Proposition 2. *In the WPDO network, given the BS density λ_B, the number of antennas N_t and the user's required data rate R_u, the practical transmit power of BS b_j is given in (13) at the top of the page, where $N_j^c = \frac{\lambda_u^c}{\lambda_B}$ and λ_u^c is given in Lemma 1, $\overline{P_d}$ is given in (9).*

Proof: Given a typical cellular user $u_{i,j}^c$ which requests data rate R_u during the communication block T, the practical transmit power at its serving BS b_j during the sub-block $(1-\theta)T$ is given by a transformation of (1) as

$$\mathbb{E}_I\left\{P_{i,j}^B\right\} = \frac{2^{\frac{R_u N_j^c}{(1-\theta)B}}-1}{\left\|b_j-u_{i,j}^c\right\|^{-\alpha}N_t}\mathbb{E}\left\{I_{u_{i,j}^c}^C + I_{u_{i,j}^c}^D + \sigma^2\right\}, \tag{21}$$

where $\mathbb{E}_I[x]$ denotes taking expectation of variable x on the interference I, and we have utilized $\mathbb{E}\left\{1\Big/\left\|\mathbf{h}_{b_j u_{i,j}^c}\right\|^2\right\} = \frac{1}{N_t}$, which characterizes the average performance in channel.

We consider the worst-case scenario, where the interferers transmit at the maximum allowable power, and thus we have

$$\begin{aligned}&\mathbb{E}\left\{I_{u_{i,j}^c}^C\right\} \leqslant \mathbb{E}_{h,\Phi_B}\left\{\sum_{b_n\in\Phi_B\setminus b_j}P_m H_\alpha\left\|b_n-u_{i,j}^c\right\|^{-\alpha}\right\}\\ &\overset{(a)}{=}\frac{P_m H_\alpha}{\left(2\pi\lambda_B\right)^{-1}}\int_{y_{i,j}^{BS}}^{\infty}x^{1-\alpha}dx = \frac{2\pi\lambda_B P_m H_\alpha}{(\alpha-2)\left(y_{i,j}^{BS}\right)^{\alpha-2}},\end{aligned} \tag{22}$$

where (a) is obtained by using Campbell's Theorem, and we have utilized $\mathbb{E}\left\{\left|\mathbf{h}_{b_n u_{i,j}^c}\frac{\mathbf{g}_{b_n u_{i,n}^c}^H}{\left\|\mathbf{g}_{b_n u_{i,n}^c}\right\|}\right|^2\right\} = 1$. $y_{i,j}^{BS} = \left\|b_j-u_{i,j}^c\right\|$ is the distance between $u_{i,j}^c$ and its nearest BS.

In addition, we have

$$\begin{aligned}&\mathbb{E}\left\{I_{u_{i,j}^c}^D\right\} = \mathbb{E}_{h,\Phi_D}\left\{\sum_{d_j\in\Phi_D}\frac{\overline{P_d}h_{d_j u_{i,j}^c}H_\alpha}{\left(\max\left\{\left\|d_j-u_{i,j}^c\right\|,v_2\right\}\right)^\alpha}\right\}\\ &\overset{(a)}{=}2\pi\lambda_D\overline{P_d}H_\alpha\left(\int_0^{v_2}v_2{}^{-\alpha}xdx + \int_{v_2}^{\infty}x^{-\alpha}xdx\right)\\ &= \overline{P_d}H_\alpha\pi\lambda_D v_2{}^{2-\alpha}\left(1+\frac{2}{\alpha-2}\right),\end{aligned} \tag{23}$$

where (a) follows from $h_{d_j u_{i,j}^c} \sim \exp(1)$.

Combining (23) and (22) into (21) and noting that $\lambda_D = \lambda_B$, we obtain the approximate $\mathbb{E}_I\left\{P_{i,j}^B\right\}$ as follows:

$$\begin{aligned}\mathbb{E}_I\left\{P_{i,j}^B\right\} &\approx \left(2^{\frac{N_j^c R_u}{(1-\theta)B}}-1\right)\frac{2\pi\lambda_B H_\alpha}{(\alpha-2)\left(y_{i,j}^{BS}\right)^{-\alpha}N_t}\\ &\cdot\left[\frac{P_m}{\left(y_{i,j}^{BS}\right)^{\alpha-2}} + \overline{P_d}v_2{}^{2-\alpha}\left(\frac{1}{2}+\frac{1}{\alpha-2}\right)+\sigma^2\right].\end{aligned} \tag{24}$$

Considering that the PDF of $y_{i,j}^{BS}$ is $f_{y_{i,j}^{BS}}(y) = 2\pi\lambda_B y e^{-\pi\lambda_B y^2}$ $(y>0)$, we obtain $\mathbb{E}_I\left\{\overline{P_{i,j}^B}\right\}$ as follows:

$$\mathbb{E}_I\left\{\overline{P_{i,j}^B}\right\} = \int_0^{\infty}\mathbb{E}_I\left\{P_{i,j}^B\right\}f_{y_{i,j}^{BS}}(y)dy. \tag{25}$$

By calculating (25), we get the desired result in (13). ■

IV. SUCCESS PROBABILITY OF D2D-TX

Recall that the success transmission of D2D-Tx occurs when the data rate at the edge of the offloading region exceeds the required data rate R_u during communication block T, which is defined in (8). Therefore, we have

$$P_{suc}^{D} = \Pr\left\{ SINR\left(u_{i,j}^{d}\right) \geqslant \gamma_{th}\left(\theta\right) \middle| R_D \right\}, \tag{26}$$

where the SINR threshold $\gamma_{th}(\theta)$ is

$$\gamma_{th}\left(\theta\right) = 2^{\frac{R_u}{(1-\theta)B_D}} - 1. \tag{27}$$

Proposition 3. *In the WPDO network, given the time allocation factor θ and the user's required data rate R_u, the success probability of D2D-Tx transmission P_{suc}^{D} is given in (14) at the top of the previous page, where $\mathbb{E}\left\{\overline{P_{i,j}^{B}}\right\}$ is given in (13) and $\overline{P_d}$ is given in (9), and*

$$\begin{aligned} \psi\left(\theta, R_u\right) &= \frac{2^{\frac{R_u}{(1-\theta)B_D}} - 1}{\overline{P_d} H_\alpha {R_D}^{-\alpha}} \\ \zeta\left(\psi\left(\theta, R_u\right), R_D, \overline{P_d}\right) &= \frac{2\psi\left(\theta, R_u\right)\overline{P_d}{R_D}^{2-\alpha}}{\alpha - 2} \\ &\cdot {}_2F_1\left[1, 1 - \frac{2}{\alpha}; 2 - \frac{2}{\alpha}; -\frac{\psi\left(\theta, R_u\right)\overline{P_d}}{{R_D}^{\alpha}}\right]. \end{aligned} \tag{28}$$

Proof: Based on (26), we have

$$\begin{aligned} P_{suc}^{D} &= \Pr\left\{ \frac{\overline{P_d} h_{d_j u_{i,j}^d} H_\alpha {R_D}^{-\alpha}}{I_{u_{i,j}^d}^{C} + I_{u_{i,j}^d}^{D} + \sigma^2} \geqslant \gamma_{th}\left(\theta\right) \right\} \\ &= \Pr\left\{ h_{d_j u_{i,j}^d} \geqslant \psi\left(\theta, R_T\right)\left(I_{u_{i,j}^d}^{C} + I_{u_{i,j}^d}^{D} + \sigma^2\right)\right\} \\ &\overset{(a)}{=} e^{-\psi(\theta,R_u)\sigma^2} \mathcal{L}_{I_{u_{i,j}^d}^{C}}\left\{\psi\left(\theta, R_u\right)\right\} \mathcal{L}_{I_{u_{i,j}^d}^{D}}\left\{\psi\left(\theta, R_u\right)\right\}, \end{aligned} \tag{29}$$

where $\psi(\theta, R_u)$ is given in (28), (a) follows from $h_{d_j u_{i,j}^d} \sim \exp(1)$, $\mathcal{L}_{I_{u_{i,j}^d}^{C}}\{\cdot\}$ and $\mathcal{L}_{I_{u_{i,j}^d}^{D}}\{\cdot\}$ denotes the Laplace transform of $I_{u_{i,j}^d}^{C}$ and $I_{u_{i,j}^d}^{D}$, respectively.

In addition, we have

$$\begin{aligned} \mathcal{L}_{I_{u_{i,j}^d}^{C}}\left\{s\right\} &= \mathbb{E}\left\{ \exp\left(-s \sum_{b_n \in \Phi_B} P_{i,n}^{B} \right.\right. \\ &\quad \left.\left. \cdot \left| \mathbf{h}_{b_n u_{i,j}^d} \mathbf{g}_{b_n u_{i,j}^d}^{H} \middle/ \left\| \mathbf{g}_{b_n u_{i,j}^d} \right\| \right|^2 H_\alpha \left\| b_n - u_{i,j}^d \right\|^{-\alpha} \right) \right\} \\ &= \exp\left\{ -2\lambda_B \left(s\mathbb{E}\left\{\overline{P_{i,j}^{B}}\right\}\right)^{\frac{2}{\alpha}} \pi^2 \middle/ \left(\alpha \sin\left(\frac{2\pi}{\alpha}\right)\right)\right\}, \end{aligned} \tag{30}$$

where we suppose that each interfering BS transmit with the power $\mathbb{E}\left\{\overline{P_{i,j}^{B}}\right\}$ based on (13).

Further, $\mathcal{L}_{I_{u_{i,j}^d}^{D}}$ is given by

$$\begin{aligned} \mathcal{L}_{I_{u_{i,j}^d}^{D}}\left\{s\right\} &= \mathbb{E}\left\{ \exp\left(-s \sum_{d_n \in \Phi_D \backslash d_j} \frac{\overline{P_d} h_{d_n u_{i,j}^d} H_\alpha}{\left\| d_n - u_{i,j}^d \right\|^{\alpha}} \right)\right\} \\ &\approx \exp\left\{-\pi \lambda_B \zeta\left(s, R_D, \overline{P_d}\right)\right\}, \end{aligned} \tag{31}$$

where we approximate that the interfering D2D-Txs are located outside a circular region with radius R_D centered of the $u_{i,j}^d$, and $\zeta(\cdot)$ is similar to (28) by considering $s = \psi(\theta, R_u)$.

Combining (31) and (30) into (29), we have (14). ∎

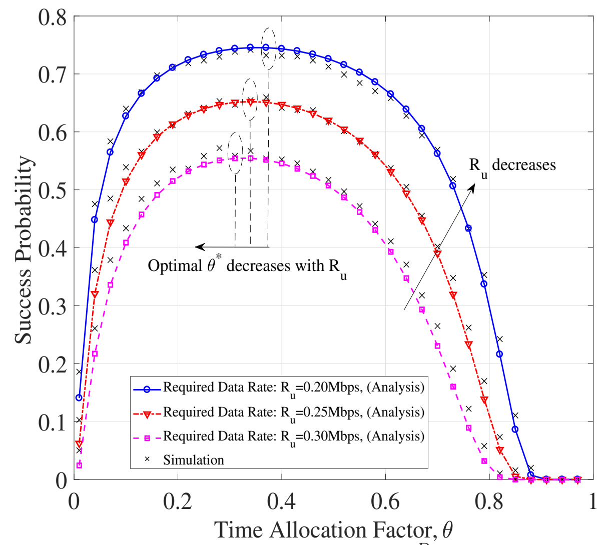

Fig 2: The success probability of D2D-Tx transmission P_{suc}^{D} given in (14) with respect to time allocation factor θ under various required data rates R_u. As R_u gets large, the optimal value of θ decreases, suggesting that a large fraction of time should be allocated for information transmission to optimize the success probability of D2D-Tx.

V. ENERGY EFFICIENT WPDO NETWORK

In this section, we propose an energy efficient WPDO network to achieve the maximum energy efficiency. The optimization problem is given as follows:

$$\begin{aligned} \max_{\theta, R_D} : \eta_{EE} &= \frac{R_u + P_{suc}^{D}\left(\theta, R_D\right) N_j^d R_u}{\mathbb{E}\left\{\overline{P_{i,j}^{B}}\right\}\left(\theta\right) + P_m} \\ s.t.\ \text{C1: } & P_{suc}^{D}\left(\theta, R_D\right) \geqslant \varepsilon \\ \text{C2: } & \mathbb{E}\left\{\overline{P_{i,j}^{B}}\right\}\left(\theta\right) \leqslant P_m \\ \text{C3: } & \overline{P_d}\left(\theta\right) \leqslant P_d, \end{aligned} \tag{32}$$

where the first term of the numerator in (32) denotes the throughput of cellular link during T, the second term of the numerator is the throughput of D2D links during T. $P_{suc}^{D}(\theta, R_D)$ is the success probability given in (14). $N_j^d = \frac{\lambda_u - \lambda_u^c}{\lambda_B}$ is the average number of D2D users in a cell, where λ_u^c is given in (15). The denominator is the sum of the power for BS information transmission and WPT, respectively, where $\mathbb{E}\left\{\overline{P_{i,j}^{B}}\right\}(\theta)$ is given in (13). The constraint C1 guarantees that the minimum success probability, where ε is a constant value. The constraints C2 and C3 insure that the transmit powers of BS and D2D-Tx could not exceed their corresponding maximum allowable transmit power P_m and P_d, respectively.

VI. NUMERICAL EXAMPLES

The network operates at $B = 10$MHz, $\rho = 1$, $\lambda_B = 1 \times 10^{-5}$BSs/m^2, $\lambda_u = 4 \times 10^{-4}$users/m^2, $P_m = 24$dBm, $P_d = 20$dBm, $N_t = 64$, $v_1 = v_2 = 5$m, $\alpha = 3$, $\beta = 2.5$, $\sigma^2 = 1 \times 10^{-11}$W, $\eta = 1$, $\mathbb{P}_{con} = 0.2$, $R_u = 0.3$Mbps, $\varepsilon = 0.4$, unless otherwise stated.

In Fig.2, we observe that the success probability of D2D-Tx transmission can be maximized by adjusting the time allocation factor θ, and we conduct Monte Carlo (MC) simulations to validate the analytical results derived in this paper. Further,

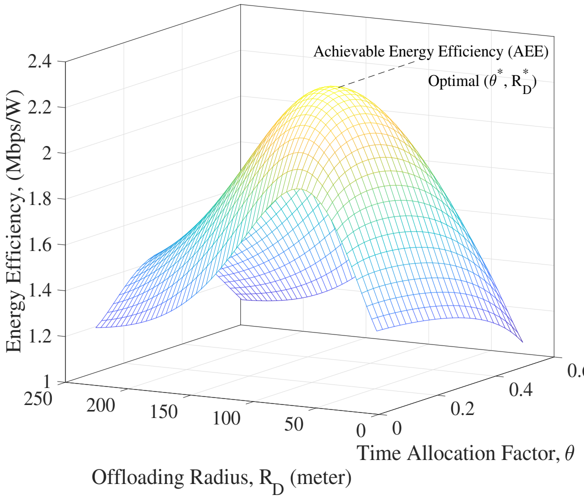

Fig 3: Network energy efficiency η_{EE} based on (32) as the function of the time allocation factor θ and the offloading radius R_D. The network achievable energy efficiency (AEE) is obtained by jointly optimizing θ and R_D.

when R_u gets large, it is desirable to divert more time fraction in a communication block to the information transmission at D2D-Tx, while a larger fraction of time needs to be portioned for the WPT when R_u is small.

In Fig.3, the network energy efficiency η_{EE} based on (32) is plotted regarding to the time allocation factor θ and the offloading radius R_D. The achievable energy efficiency (AEE) and the optimal strategy $(\theta^*, {R_D}^*)$ can be obtained. Specifically, when R_D gets large, although more traffic can be offload onto D2D links, the success probability decreases and the transmit power of BS $\mathbb{E}\left\{\overline{P_{i,j}^B}\right\}$ for cellular link increases, which results in the reduction of network energy efficiency.

In Fig.4, we observe that the AEE increases with the number of BS antennas N_t. This suggests that the performance of the network is greatly improved by using the massive antenna arrays at each BS. In addition, AEE increases with the content popularity $\mathbb{P}_{con}$, since more traffic can be offload onto D2D links, which is a cost-effective way and improves the network throughput. However, AEE decreases with the users density λ_u, since more power would be consumed to guarantee the cellular user's required data rate R_u, and thus AEE decreases.

VII. Conclusions

In this paper, we model and analyze the D2D-assisted offloading network with wireless power transfer. The average received power at D2D-Tx, the cellular users density, the BS practical transmit power and the success probability of D2D-Tx transmission are derived. Based on the proposed model, we develop an energy efficient WPDO network by jointly optimizing the time allocation factor and the offloading radius of D2D-Tx. The results provide significant insights into the design and application of the wireless power transfer enabled D2D-assisted offloading network.

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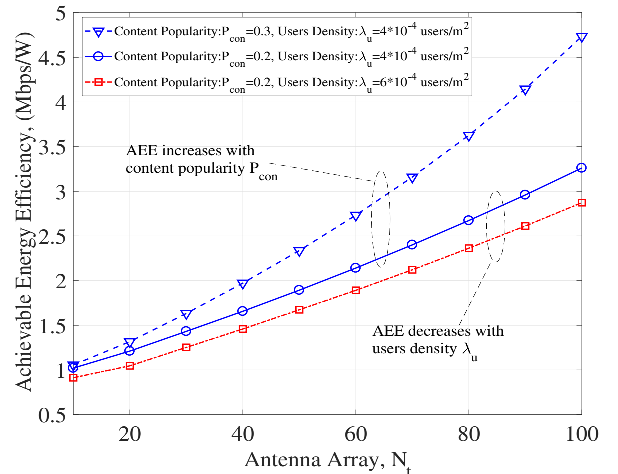

Fig 4: The achievable energy efficiency (AEE) with respect to antenna array N_t under various content popularity $\mathbb{P}_{con}$ and users density λ_u.

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