Mode Selection for Device-to-Device Communications with Voronoi Tessellation

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***Abstract*—Due to the increasing demand for local wireless transmissions from proximity-based social or local-content sharing applications, direct communication between user equipment (UE), known as device-to-device (D2D) communication, is regarded as a key technology component in LTE-Advanced. Taking the advantages of short transmission distance, D2D transmission increases resource utilization as well as reduces transmission delay and power consumption. However, the introduction of D2D communication incurs extra interference to the UEs who make the traditional cellular connection with the base station (BS), which shall be carefully considered. This paper, therefore, investigates the very beginning and fundamental problem in D2D communications underlaying cellular network, that is, either establishing local D2D communications or make a traditional communication with BS. A novel mode selection mechanism is proposed to control the number of UEs performing D2D communications to achieve maximum average transmit data rate. We apply the recent innovation, stochastic geometry, to analyze the performance of the proposed mode selection mechanism. By including the realistic feature in cellular network, that is, UEs will associate the closet BS, a Poisson-Voronoi tessellation is comprised. We further derive a tractable result on tradeoff between link reliability and data rate. As a result, this work serves as a powerful and efficient tool for analyzing the effects of D2D mode selection.**

***Keywords*—Heterogeneous cellular networks, device-to-device communications, mode selection, stochastic geometry, Voronoi tessellation.**

I. Introduction

Device-to-Device (D2D) communication, direct communication between user equipment (UEs) makes a new technology for local wireless transmissions from proximity based social or local-content sharing applications. Without involving D2D data transmission, cellular infrastructure (i.e., base station; BS) plays the role of controlling UEs, which incurs minimum overheads while guaranteeing the quality of D2D transmission. Taking the advantages of short transmission distance [1], D2D transmission increases resource utilization and spectrum efficiency as well as reduces transmission delay, backhaul demand and power consumption.

However, when the UEs who perform D2D communications (known as DeUEs) and who make the traditional cellular connection with BS (known as CeUEs) share the same spectrum (considered as *in-band D2D* scenario), complicated interference among those UEs shall be carefully considered [2], [3]. As a result, how a UE selects D2D or cellular connection is related to how CeUEs and DeUEs share the spectrum [4]–[8], which acts the most fundamental problem. Typically, the centralized sophisticated resource allocation scheme is applied in LTE-Advanced [9]–[11] to achieve the mode selection, which inevitably incurs substantial control and computational overhead. As a result, a fully-distributed random access protocol for mode selection is desirable [12] and slotted Aloha protocols are typically applied [6], [13], [14]. That is, UE can attempt to transmit data whenever it has data to send, without any association procedure or dedicated control channel, and then select either D2D or cellular communications [15]. In particular, we consider distance-based D2D mode selection and use mode selection threshold to make a potential D2D pair can switch direct and normal cellular communication. As a result, UEs can simply switch the mode exploiting distance message, making the proposed model more realistic and convenient.

In this paper, by using stochastic geometry, we analytically derive the transmission power and spectral efficiency of D2D links underlaid with cellular network, considering both

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interference among DeUEs and interference from/to CeUEs. The recent innovation, Poisson point process (PPP), is adopted as the spatial distribution of BSs and UEs. In particular, we consider the realistic situation where the UEs connect to the closet BS, which leads a Voronoi Tessellation. Built on the Voronoi Tessellation, tractable results are derived. Moreover, we conduct simulation experiments to validate the proposed analytical model and evaluate the its performance of the proposed selection mechanism from the aspects of average data rate. The numerical results show that we can achieve the higher transmission data rate while choosing the suitable mode selection threshold in D2D communication underlaying cellular network.

The remainder of the paper is organized as follows. In Section II the system model is introduced. The proposed mode selection mechanism and the corresponding analysis is shown in Section III. Section IV evaluates the performance of the proposed mechanism, and finally, Section V concludes this work.

II. System Model

A. Network Model

As show in Fig. 1, we consider a hybrid network model. The cochannel deployment and underlay sharing between CeUEs and potential DeUEs are assumed, that is, both CeUEs and potential DeUEs can utilize all the resources if interference constrained. The spatial distribution of BSs and UEs are assumed to follow a homogeneous Poisson Point Process (PPP) with density λ_B and λ_U, respectively. Let $\Phi_B = \{X_k\}$ and $\Phi_U = \{Y_k\}$ respectively denote the sets of locations of BSs and UEs. Similarly, we let P_C and P_D denote the transmit power of the CeUE and DeUE. We assume that each CeUE is associated with the closest BS and the consequent the coverage areas of BS comprise a Poisson Voronoi tessellation on the plane. Perfect synchronization in time is also assumed. The distance between an arbitrary CeUE and its serving BS is denoted as L_C, which has probability density function (PDF) as

$$f_C(r) = 2\pi\lambda_B r \cdot \exp(-\lambda_B \pi r^2), r \geq 0. \tag{1}$$

Let $\{P_i\}$ denote the transmit power of UEs. In this thesis, we use channel inversion for power control, i.e., $P_i = L_i^{\alpha}$, where $\alpha > 2$ denotes the path loss exponent. We assume that q is a simple indicator of the load of potential D2D traffic and each potential D2D receiver is randomly and independently placed around its associated potential D2D transmitter with isotropic

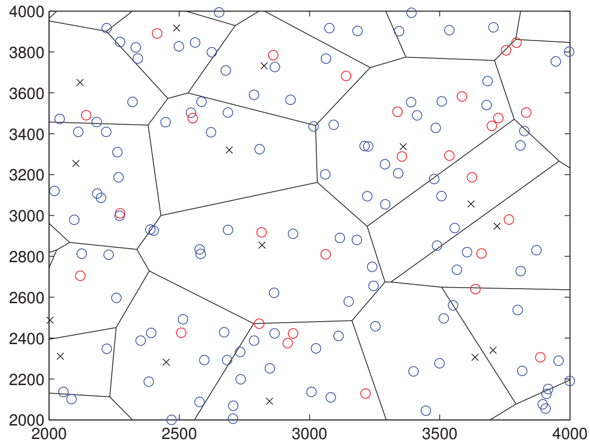

Fig. 1. A hybrid network model. Cross, blue circle and red circle denote BSs, uplink cellular transmitters and D2D transmitters, respectively.

direction and Rayleigh distributed distance L_D with PDF is given by

$$f_D(x) = 2\pi\xi x \cdot \exp(-\xi\pi x^2), x \geq 0. \tag{2}$$

And also, the effects of path loss attenuation, Rayleigh fading with unit average power $\mathcal{G}$ and background noise power N_0 in our channel model [16]. The successful reception of a transmission at a UE depends on if Signal-to-Interference-plus-Noise ratio (SINR) observed by the UE is larger than an SINR threshold (denoted by δ).

B. Transmit Scheduling

The cellular transmitters including CeUEs and potential DeUEs in cellular mode forms a PPP Φ_C with intensity $\lambda_C = (1-q)\lambda_U + q\lambda_U \mathbb{P}(D \geq \mu)$. We assume that only one CeUE uplink transmitter can active in each macrocell at a time by using orthogonal multiple access technique. Further, the potential DeUEs in D2D mode forms a PPP Φ_D with intensity $\lambda_D = q\lambda_U \mathbb{P}(D < \mu)$.

C. Performance Metrics

We introduce the SNR to denote the average received signal power normalized by noise power, i.e.,

$$\mathrm{SNR} = \frac{PL^{-\alpha}}{N_0 B_W} = \frac{1}{N_0 B_W}, \tag{3}$$

where B_W denotes the channel bandwidth. Moreover, we will analyze the average data rate of CeUEs and potential DeUEs, R_C, and R_D. Let $\hat{R_D}$ denote the transmission rate of potential DeUE in D2D mode. By definition, the average data rate of potential DeUEs has two parts: cellular mode and D2D mode. That is the average transmission data rate can be written as

$$R_D = \mathbb{P}(D \geq \mu) R_C + \mathbb{P}(D < \mu) \hat{R_D}. \tag{4}$$

III. Mode Selection and Analysis

We consider distance-based D2D mode selection: the potential DeUE will active cellular mode if $D \geq \mu$; otherwise, the D2D mode is selected. Recall we assume that each CeUEs are associated with the closest BS, while the potential DeUE pair transmits its data by direct D2D link if the distance between transmitter and receiver is closed enough; otherwise the potential DeUE transmitter will connect to the closest BS to transmit the data by using the uplink spectrum just like a normal CeUE do. By definition, we consider Rayleigh fading, i.e., $\mathcal{G} \sim \exp(1)$, and assume independent fading over space.

A. Analysis of Transmit Power

Due to the channel inversion, i.e., $P \cdot L^{-\alpha} = 1$ [14], the transmit power won't be a constant, and we have to analyze the average transmit powers of CeUEs and potential DeUEs. Let $\mathbb{E}[P_C]$, $\mathbb{E}[P_D]$ and $\mathbb{E}[\hat{P_D}]$ denote the average transmit power of a typical CeUE, a potential DeUE and a potential DeUE in D2D mode, respectively. $\mathbb{E}[P_C]$ is given by

$$\begin{aligned} \mathbb{E}[P_C] &\overset{(a)}{=} \mathbb{E}[L_C^\alpha] \\ &\overset{(b)}{=} \int_0^\infty r^\alpha 2\pi\lambda_B r e^{-\lambda_B \pi r^2} dr \\ &= 2\pi\lambda_B \int_0^\infty r^{\alpha+1} e^{-\lambda_B \pi r^2} dr, \end{aligned} \tag{5}$$

where (a) is due to the channel inversion and (b) follows (1). And $\mathbb{E}[\hat{P_D}]$ is given by

$$\begin{aligned} \mathbb{E}[\hat{P_D}] &\overset{(c)}{=} \mathbb{E}[L_D^\alpha | D < \mu] = \frac{1}{\mathbb{P}(D < \mu)} \mathbb{E}[L_D^\alpha] \\ &\overset{(d)}{=} \int_0^\mu r^\alpha 2\pi\xi r e^{-\lambda_B \pi r^2} dr \\ &= \frac{1}{1 - e^{-\xi\pi r^2}} 2\pi\xi \int_0^\mu r^{\alpha+1} e^{-\xi\pi r^2} dr, \end{aligned} \tag{6}$$

where (c) is due to the channel inversion and (d) follows (2). And $\mathbb{E}[P_D]$ is given by

$$\begin{aligned} \mathbb{E}[P_D] &= \mathbb{P}[D \geq \mu]\mathbb{E}[P_C] + \mathbb{P}[D < \mu]\mathbb{E}[\hat{P_D}] \\ &= e^{-\xi\pi r^2}\mathbb{E}[P_C] + [1 - e^{-\xi\pi r^2}]\mathbb{E}[\hat{P_D}]. \end{aligned} \tag{7}$$

B. Analysis of Success Probability

Recall that the successful reception of a transmission at a UE depends on if SINR is larger than an SINR threshold or not. Then we use the success probability to describe the quality of the link for both CeUEs and DeUEs.

$$\begin{aligned} P_{suc}^C &= \mathbb{P}[\mathrm{SINR}_C \geq x] \\ &= \mathbb{P}\left[\frac{P_C \mathcal{G} L_C^{-\alpha}}{I_C + N_0} \geq x\right] \\ &= \mathbb{P}[\mathcal{G} \geq x(I_C + N_0)] \\ &\overset{(a)}{=} \mathbb{P}[\mathcal{G} \geq x(I_{CC} + I_{DC} + N_0)] \\ &\overset{(b)}{=} \mathbb{E}[e^{-xN_0} e^{-xI_{CC}} e^{-xI_{DC}}] \\ &= e^{-xN_0} \mathcal{L}_{I_{CC}}(x) \mathcal{L}_{I_{DC}}(x), \end{aligned} \tag{8}$$

where (a) I_{CC}, I_{DC} and N_0 are independent, and (b) is due to that $\mathcal{G} \sim \exp(1)$. In (8), $\mathcal{L}_{I_{CC}}(x)$ is the Laplace transfrom of I_{CC}, i.e., the interference from the other CeUEs to cellular BS, and is derived as follow.

$$\begin{aligned} \mathcal{L}_{I_{CC}}(x) &= \mathbb{E}[e^{-x \sum_{x_i \in \Phi_C \cap A^c} P_{Ci} \mathcal{G} \|x_i\|^{-\alpha}}] \\ &\overset{(a)}{=} \mathbb{E}\left[\prod_{x \in \Phi_C \cap A^c} e^{P_C \mathcal{G} \|x\|^{-\alpha}}\right] \\ &\overset{(b)}{=} \exp(-2\pi\lambda_B \int_R^\infty (1 - \mathbb{E}[e^{-xP_C \mathcal{G} r^{-\alpha}}]) r dr) \\ &= \exp(-2\pi\lambda_B \int_R^\infty x\mathbb{E}[P_C]\mathbb{E}[\mathcal{G}] r^{-\alpha+1} dr), \end{aligned} \tag{9}$$

where

$$R = \int_0^\infty 2\pi\lambda_B r^2 e^{-\lambda_B \pi r^2} dr, \tag{10}$$

and (a) is from Slivnyak's theorem and (b) is due to the generating functional of PPP. $\mathcal{L}_{I_{DC}}(x)$ is the Laplace transform of I_{DC}, i.e., the interference from DeUE to cellular BS, and is derived as follow.

$$\begin{aligned} \mathcal{L}_{I_{DC}}(x) &= \mathbb{E}[e^{-x \sum_{x_i \in \Phi_D} \hat{P_{Di}} \mathcal{G} \|x_i\|^{-\alpha}}] \\ &= \mathbb{E}\left[\prod_{x \in \Phi_D} e^{\hat{P_{Di}} \mathcal{G} \|x\|^{-\alpha}}\right] \\ &= \exp(-2\pi\lambda_D \int_R^\infty x\mathbb{E}[\hat{P_{Di}}]\mathbb{E}[\mathcal{G}] r^{-\alpha+1} dr) \\ &= \exp\left(-\frac{\pi\lambda_D}{\mathrm{sinc}(\frac{2}{\alpha})} \mathbb{E}[\hat{P_{Di}}^{\frac{2}{\alpha}}] x^{\frac{2}{\alpha}}\right). \end{aligned} \tag{11}$$

Similar to (8), The success probability of D2D link will be

$$P_{suc}^D = e^{-xN_0} \mathcal{L}_{I_{CD}}(x) \mathcal{L}_{I_{DD}}(x). \tag{12}$$

In (12), $\mathcal{L}_{I_{CD}}(x)$ is the Laplace transform of I_{CD}, i.e., the interference from CeUE to DeUE receiver, and is derived as follow.

$$\begin{aligned}\mathcal{L}_{I_{CD}}(x) &= \mathbb{E}[e^{-x\sum_{x_i\in\Phi_C} P_{Ci}\mathcal{G}\|x_i\|^{-\alpha}}] \\ &= \mathbb{E}\left[\prod_{x\in\Phi_C} e^{P_C\mathcal{G}\|x\|^{-\alpha}}\right] \\ &= \exp(-2\pi\lambda_B\int_0^\infty(1-\mathbb{E}[e^{-xP_C\mathcal{G}r^{-\alpha}}])rdr) \\ &= \exp(-2\pi\lambda_B\int_0^\infty x\mathbb{E}[P_C]\mathbb{E}[\mathcal{G}]r^{-\alpha+1}dr) \quad (13)\end{aligned}$$

$\mathcal{L}_{I_{DD}}(x)$ is the Laplace transform of I_{DD}, i.e., the interference from DeUE transmitter to DeUE receiver, and is derived as follow.

$$\begin{aligned}\mathcal{L}_{I_{DD}}(x) &= \mathbb{E}[e^{-x\sum_{x_i\in\Phi_D\setminus\{0\}} \hat{P_{Di}}\mathcal{G}\|x_i\|^{-\alpha}}] \\ &= \mathbb{E}\left[\prod_{x\in\Phi_D\setminus\{0\}} e^{\hat{P_{Di}}\mathcal{G}\|x\|^{-\alpha}}\right] \\ &= \exp(-2\pi\lambda_D\int_R^\infty x\mathbb{E}[\hat{P_{Di}}]\mathbb{E}[\mathcal{G}]r^{-\alpha+1}dr) \\ &= \exp\left(-\frac{\pi\lambda_D}{\text{sinc}(\frac{2}{\alpha})}\mathbb{E}[\hat{P_{Di}}^{\frac{2}{\alpha}}]x^{\frac{2}{\alpha}}\right). \quad (14)\end{aligned}$$

C. The Link Spectral Efficiency

Recall that $\text{SINR} = \frac{S}{I+N_0}$, were $S = P\mathcal{G}L^{-\alpha} = \mathcal{G} \sim \exp(1)$. If S and I are independent [14],

$$\mathbb{E}[\log(1+\text{SINR})] = \int_0^\infty \frac{e^{N_0x}}{1+x}\mathcal{L}_I(x)dx, \quad (15)$$

where $\mathcal{L}_I(s) = \mathbb{E}[e^{sI}]$ denotes the Laplace transform of I. The interference at the typical BS and the receiver of D2D pair are given by

$$I_C = \sum_{x_i\in\Phi_C\cap A^c} P_{Ci}\mathcal{G}\|x_i\|^{-\alpha} + \sum_{x_i\in\Phi_D} \hat{P_{Di}}\mathcal{G}\|x_i\|^{-\alpha}$$
$$I_D = \sum_{x_i\in\Phi_C} P_{Ci}\mathcal{G}\|x_i\|^{-\alpha} + \sum_{x_i\in\Phi_D\setminus\{o\}} \hat{P_{Di}}\mathcal{G}\|x_i\|^{-\alpha}$$

The spectral efficiency R_C of cellular links is given by

$$\begin{aligned}R_C &\overset{(a)}{=} \mathbb{E}[\frac{1}{N}\log(1+\text{SINR}_C)] \\ &\overset{(b)}{=} \frac{\lambda_B}{\lambda_C}(1-e^{-\frac{\lambda_C}{\lambda_B}})\int_0^\infty \frac{1}{1+x} \\ &\quad\cdot[\mathcal{L}_{CC}(B_Wx)+\mathcal{L}_{DC}(B_Wx)]dx, \quad (16)\end{aligned}$$

where (a) is by Shannon-Hartley theorem, (b) is by (15), and N is the random number of potential uplink transmitters located in the cell. Let N' denote the number of other potential uplink transmitters located in the cell except the one under consideration, i.e., $N = N' + 1$.

$$\begin{aligned}\mathbb{E}[\frac{1}{N}] &= \sum_{n=1}^\infty \frac{1}{n}\mathbb{P}(N=n) = \sum_{n=1}^\infty \frac{1}{n}\mathbb{P}(N'=n-1) \\ &= \sum_{n=1}^\infty \frac{1}{n}\frac{(\frac{\lambda_C}{\lambda_B})^{n-1}}{(n-1)!}e^{-\frac{\lambda_C}{\lambda_B}} = \frac{\lambda_B}{\lambda_C}\sum_{n=1}^\infty \frac{(\frac{\lambda_C}{\lambda_B})^n}{n!}e^{-\frac{\lambda_C}{\lambda_B}} \\ &= \frac{\lambda_B}{\lambda_C}(1-e^{-\frac{\lambda_C}{\lambda_B}}), \quad (17)\end{aligned}$$

Like (16), the spectral efficiency R_D of D2D links is is derived as follow.

$$\begin{aligned}R_D &\overset{(a)}{=} \mathbb{E}[\log(1+\text{SINR}_C)] \\ &\overset{(b)}{=} e^{-\xi\pi\mu^2}R_C + (1-e^{-\xi\pi\mu^2})\hat{R_D} \\ &\overset{(c)}{=} e^{-\xi\pi\mu^2}R_C + (1-e^{-\xi\pi\mu^2})\int_0^\infty \frac{1}{1+x} \\ &\quad\cdot[\mathcal{L}_{CC}(B_Wx)+\mathcal{L}_{DC}(B_Wx)]dx, \quad (18)\end{aligned}$$

where (a) is by Shannon-Hartley theorem, (b) is due to (15), and (c) is by (4).

TABLE I
NUMERICAL PARAMETERS

Density of macrocells λ_B	$(\pi 500)^{-1}$ m^{-2}
Density of UEs λ_U	$10 \cdot (\pi 500)^{-1}$ m^{-2}
Potential D2D parameter ξ	$10 \cdot (\pi 500)^{-1}$ m^{-2}
Potential D2D factor q	0.2
Path loss exponent α	4
Mode selection threshold μ	200 m
AWGN N_0	-174 dBm
Channel bandwidth B_W	1 MHz
Area Width	5000.0 m
Area Length	5000.0 m

IV. NUMERICAL RESULTS

As show in Fig. 2, the average power of a CeUE (resp. DeUE) transmitter can be obtained by multiplying (5) (resp. (6)) with scaling factor $N_0B_W \cdot SNR$. We also can find that compared to CeUE transmitters, DeUE transmitters can save lots of transmitting power as reaching the same SNR target. In other words, it describes the advantage of energy efficiency in D2D communication.

In Fig. 3, it confirms the analytical result of the complementary cumulative distribution function (CCDF) of the SINR of D2D link. Moreover, Fig. 3 also compares the grid model and PPP model at the same scenario. We can find that the success probability of DeUE decrease while the SINR threshold increases. When the mode selection threshold increase, the success probability of DeUE decrease. The reason is that there will be more interference in D2D link as more potential DeUE

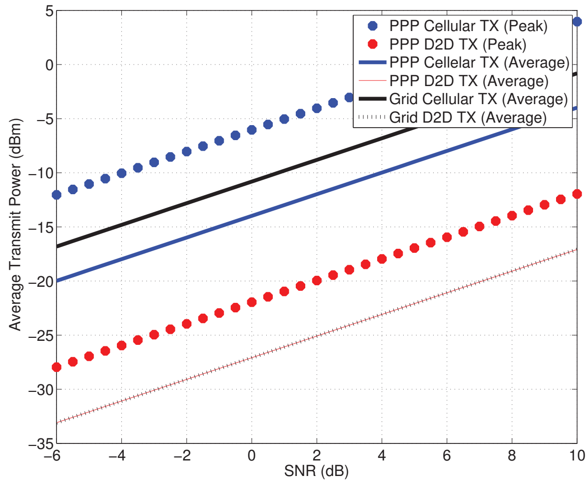

Fig. 2. The UE transmit power versus SNR with $N = -174$ dBm/Hz and $B_w = 1$ MHz

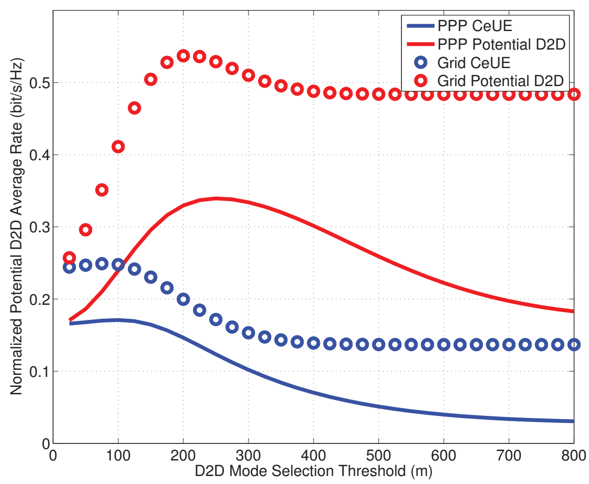

Fig. 4. Shows the average rates of cellular and potential D2D UEs versus D2D mode selection threshold.

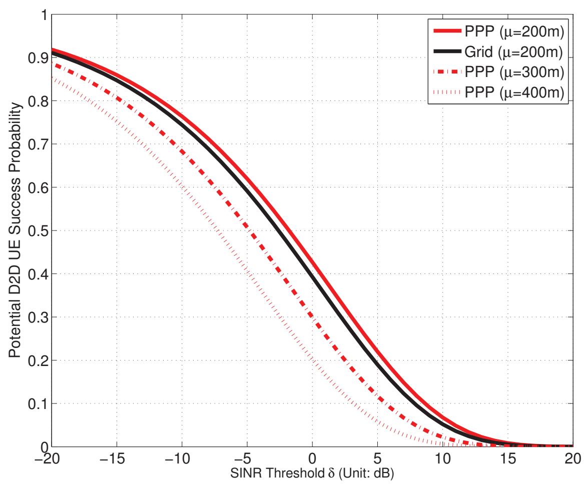

Fig. 3. Shows the CCDF of SINR in D2D link.

will active in D2D mode while the mode selection threshold increase.

Fig. 4 shows the average rates of CeUEs and potential DeUEs as a function μ in the underlying scenario. The average rate of CeUEs decreases as μ increases. This is because the CeUEs suffer from the interference caused by the underlaid DeUE transmitters. And the average rate of DeUE first increases and then decreases as μ increases. That is due to the average rate of potential DeUE is co-determined by its cellular-mode rate and D2D-mode rate: cellular-mode rate increases with μ while D2D-mode rate decreases with μ (cause by the increasing intra-tier interference). We also compare the different environment for both grid model and PPP moedel.

V. Conclusion and Future Work

In this thesis, we introduce a hybrid model that use stochastic geometry, PPP, models the spatial positions of BSs (UEs), and the channel inversion for power consumption. By involving underlaid D2D communication, both intra-tier and inter-tier interference are considered in our work. The numerical result shows not only the effect of interference but also the comparison for PPP model and grid network model. However, we consider the distance-based D2D model selection that can simply switch the direct D2D link and normal cellular uplink. By this mode selection strategy, we derive the analytical average transmit data rate and apply them to find a reliable D2D parameter and selection threshold. In the future, we may extend this work to heterogeneous networks model, multi-hop end-to-end communication, etc. And complex the strategy for mode selection by considering more environment parameters, e.g., the transmit power of UEs. Also, we will rise the trusty of our work by the support of simulation. Finally, we hope our work can be a stepping stone for this wide range of interesting cellular network and D2D communications.

VI. Acknowledgements

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