Stable Throughput Region and Admission Control for Device-to-Device Cellular Coexisting Networks

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***Abstract*—Device-to-device (D2D) communication is proposed as a vital technique to enhance system capacity in cellular networks, which requires efficient interference modeling and managements to improve spectral efficiency. In practice, even when two wireless connections share the same resources, the interference between them may not always exist if there is no conflict at packet-level transmissions. To explore the real effect of interference, in this paper, we establish a cross-layer model for D2D communications underlaying cellular network and derive the closed-form stable throughput region. Then, we formulate an optimization problem to obtain the maximal achievable packet rate for cellular link, which determines whether the D2D pair can share the same resources with a specific cellular link. By dividing the original optimization problem into several simplified subproblems, the optimal solution can be calculated with low complexity. Subsequently, our model is extended to a generalized scenario where multiple D2D pairs share the same resources with one cellular link. Due to the complexity of obtaining closed-form expressions on stable throughput regions, we propose an algorithm to determine whether the transmissions of the cellular link and the multiple D2D pairs can satisfy the QoS requirements simultaneously. Furthermore, a low-complexity dynamic admission control strategy is introduced to deal with the admission process for new D2D requests. As a consequence, the cellular spectrum can allow access of many more D2D pairs than what the conventional model can. The significant improvements are verified by numeral simulations.**

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***Index Terms*—Device-to-device communication, resource reusing, stable throughput region, admission control.**

I. Introduction

DEVICE-to-device (D2D) communications allow direct transmissions between users underlaying cellular networks, without the data passing through the base station (BS) [1], [2]. Since it can enhance spectral efficiency, reduce transmission powers and achieve high data rates, D2D serves as a promising technique to improve the overall system capacity.

In a D2D-enabled cellular network, the resources can be allocated to D2D links based on three strategies [3]–[6]:

1) Orthogonal Sharing Mode (OSM): one-hop transmission, and orthogonal resources are assigned to D2D links,
2) Cellular Mode (CM): two-hop transmissions, where D2D pairs act the same way as cellular users (CUEs) (i.e., data flows go through D2D transmitter-BS-D2D receiver links), and
3) Non-Orthogonal Sharing mode (NOSM): one-hop transmission, and D2D pairs reuse the resources occupied by CUEs.

In a network with OSM, the interference management is simple, but the resource utilization may be less efficient. The second strategy is the conventional cellular mode. Due to spectral inefficiency of OSM and CM, most recent research focused mostly on NOSM, where D2D transmitters directly send information to the D2D receivers, reusing cellular resources. Since D2D users (DUEs) may simultaneously reuse an uplink or a downlink resource which is assigned to a CUE by the BS, D2D communications will result in severe interference to the CUE-BS link and vice versa. To prevent harmful intra-cell interference, efficient resources assignment strategies and power allocation schemes have been proposed in related works discussed below.

A. Related Work

In [7], by monitoring the common control channel, BS will identify the "near-far-risk" cellular users and broadcast the information to D2D pairs. The decisions of resources sharing are made by DUEs, rather than BS. As another distributed power control scheme, via minimizing the used sum power, the performance of OSM and NOSM is compared in [8] when the positions of both the D2D pair and the interfering CUE vary within the cell.

Since D2D pairs have access to licensed spectrum occupied by cellular networks, centralized control by BS will result in optimal performance. Hyunkee et al. proposed an interference limited area control scheme to manage interference from CUEs to D2D systems, where the method does not allow CUEs located in the same area to exploit the same resources as the DUEs, and receive mode selection among three strategies was analyzed in their works [9], [10]. However, they did not consider the interference from D2D pairs to cellular links. On the other hand, without involving cellular transmissions, power control among multiple D2D pairs was studied in [11]. Guaranteeing the quality-of-service (QoS) requirements for both D2D users and regular CUEs, the resource allocation problems were studied in [12], [13] to maximize the overall network throughput. Previous works are based on user-level, while recently, resource blocks-level resources allocation and power control schemes were proposed to achieve more flexible spectrum reuse [14]–[16]. In [17], [18], power control and channel allocation were studied for D2D communications using a game theoretic approach. The D2D spectrum sharing schemes were described and analyzed in [6], [19] using a stochastic geometry approach.

Under specific scenarios rather than general cases, cooperative communications could be introduced to deal with inter-link interference [20]–[23].

B. Motivation

There exist a major shortcoming in existing works. The admission processes of D2D pairs in their works [9]–[19] were based on information-theoretic studies where both D2D pairs and the cellular connection, which share the same resources, keep transmitting signals simultaneously and interfere with each other all the time. However, in practice, packets are generated and queued for transmission according to certain dynamic processes. Considering the possibility of the transmission queues being empty, all those connections may not access the channel simultaneously within each time slot even when they share the same resources. Such an issue is also addressed in [24], where interference scenarios among multiple links are characterized in distributed Ad Hoc networks. The underutilization of licensed spectrum has also stimulated the research on cognitive radio [25]–[27].

C. Contributions

In this paper, we propose a new cross-layer model to characterize the interference between D2D and cellular transmissions. The "cross-layer" notion represents that the proposed model is not only based on the physical layer in terms of signal-to-interference-plus-noise ratios (SINRs) and outage probabilities, but also refers to packet-level queueing and transmission process. We will firstly present the model and analysis with the scenario that only one D2D pair reuses the same resources with one cellular connection. Closed-form expressions on stable throughput region under this scenario are derived. An optimization problem is then formulated to find the maximal achievable packet arrival rate of the cellular link, which provides insights on the admission process for D2D connections. Through dividing the optimization problem into several simple subproblems, the optimal solution is obtained.

Subsequently, the model and analysis will be extended to the generalized case where multiple D2D pairs share the same cellular resources. Since it is difficult to derive the closed-form expressions on stable throughput regions, we propose an algorithm to determine whether those D2D pairs can share the same resources with the cellular connection. Furthermore, a low-complexity dynamic admission control scheme is introduced to deal with the admission process for D2D pairs.

As a consequence, the proposed model expands the stable throughput region among D2D connections and cellular links. In a single D2D pair scenario, the stable throughput region of the proposed model is the same as the conventional one when the inter-user interference is sufficiently small. Under this circumstance, both of them outperform TDMA transmissions. When the two links suffer severe interference from each other, the proposed model can achieve almost the same performance as that of TDMA while the conventional one can hardly admit D2D pairs. Furthermore, in the multiple D2D pairs scenarios, the proposed model outperforms both the conventional model and TDMA. With the increase of the number of D2D pairs that reuse the same cellular resources, the improvement of the proposed model becomes more significant. Therefore, more D2D pairs have access to cellular resources, enhancing the network capacity.

The proposed model and analysis are different from those in [28]–[31], which introduced stable throughput analysis into cognitive radio networks. In those works, secondary users have to sense and access the channels when they are not occupied by primary users (an overlay model). The analysis is based on a specific scheduling scheme to guarantee the QoS requirement of the primary users while the secondary users are saturated. Stable throughput region is determined by false alarm and misdetection errors of the secondary users. While in our scheme, we study an underlay model, where both D2D and cellular connections can be considered as the primary links. There is no channel sensing necessary in our model and the QoS requirements of both connections are satisfied.

The rest of paper is organized as follows: Section II depicts the system model where one D2D pair reuses the same resources with one cellular connection. Section III details the stable throughput region and admission control scheme based on our model. The model and analysis are extended to multiple D2D pairs scenario in Section IV. In Section V, simulation results are given to illustrate the system performance of our scheme. Finally, Section VI summarizes the paper.

II. System Model

A. Networks and Links

We consider a hybrid multi-cell network, where direct D2D connections coexist with cellular transmissions in each cell. The discovery, resources allocation and power control of D2D pairs are performed at the BS. Firstly, we consider a single D2D pair scenario where one D2D pair coexists with one cellular

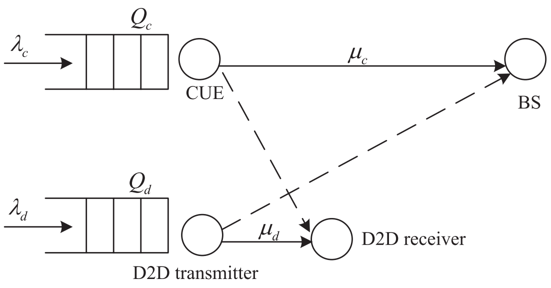


Fig. 1. Queuing and transmission model for single D2D pair scenario. Uplink resources are reused. The dotted lines represent the interference.

link, as shown in Fig. 1. The multiple D2D pairs scenario will be detailed in Section IV. Assuming slow flat fading channels, the instantaneous channel gain from the transmitter of link i to the receiver of link j ($i, j \in \{c, d\}$) accounts for the path-loss, shadow fading, and Rayleigh fading, determined by

$$G_{ij} = L_{ij}^{-\alpha}\beta \cdot |h_{ij}|^2, \tag{1}$$

where L_{ij} is the distance between node i and node j with path-loss exponent α, β is the slow fading gain with log-normal distribution (i.e., shadow fading), $h_{ij} \sim \mathcal{CN}(0, 1)$ is modeled as zero-mean complex Gaussian random variables with unit variance, characterizing the Rayleigh fading. Thus, G_{cc}, G_{dd}, G_{cd}, and G_{dc} represent the channel gains of the cellular link, the D2D link, the channel from the cellular transmitter to the D2D receiver, and the channel from the D2D transmitter to the cellular receiver, respectively. All channel coefficients are supposed to remain constant within one frame and vary independently from frame to frame. The corresponding noise at each receiver is assumed to be complex additive white Gaussian noise (AWGN) with noise power N_0.

B. Queueing Model

We consider slot-by-slot transmissions where one second is divided into T time slots (TSs). Without loss of generality, let the duration of one TS be one packet transmission period. Both uplink and downlink resources can be reused by D2D connections. As depicted in Fig. 1, packets are generated at the cellular transmitter and the D2D transmitter with average rate λ_c and λ_d (packets/TS), respectively, independent from each other, and independent and identically distributed (i.i.d.) over slots. The data queues at the transmitters of the cellular connection and the D2D pair are denoted by Q_c and Q_d, respectively, with infinite capacity for storing arriving packets.

Denote by Q_i^t the length of queue i at the beginning of time slot t. Based on the definition in [32]–[35], the queue is said to be stable if $\lim_{t\to\infty} \Pr\{Q_i^t < x\} = F(x)$ and $\lim_{x\to\infty} F(x) = 0$. The Loynes' Theorem [36] states that if the arrival and service processes of a queue are strictly stationary and ergodic, the queue is stable if and only if the average arrival rate is strictly less than the average service rate. Thus, the stable throughput region, where one D2D pair and one cellular link share the same resources, is expressed as

$$\mathcal{R} = \{(\lambda_c, \lambda_d) | \quad \lambda_c < \mu_c \quad \& \quad \lambda_d < \mu_d\}, \tag{2}$$

where μ_c and μ_d are the service rates of the cellular link and the D2D connection (packets/TS), respectively. We assume that acknowledgements (ACKs) are instantaneous and error-free. The packet that fails to be decoded by the desired receiver will stay in the queue for retransmission. The service rate of each connection is equal to the probability that one packet is successfully decoded at the receiver. Thus we have

$$\begin{aligned}\mu_c &= \Pr\{Q_d = 0\}(1-\rho_c) + \Pr\{Q_d > 0\}\left(1-\rho_c^{(I)}\right)\\ &\overset{(a)}{=} \left(1-\frac{\lambda_d}{\mu_d}\right)(1-\rho_c) + \frac{\lambda_d}{\mu_d}\left(1-\rho_c^{(I)}\right)\end{aligned} \tag{3}$$

and

$$\begin{aligned}\mu_d &= \Pr\{Q_c = 0\}(1-\rho_d) + \Pr\{Q_c > 0\}\left(1-\rho_d^{(I)}\right)\\ &\overset{(a)}{=} \left(1-\frac{\lambda_c}{\mu_c}\right)(1-\rho_d) + \frac{\lambda_c}{\mu_c}\left(1-\rho_d^{(I)}\right),\end{aligned} \tag{4}$$

where $Q_i = 0$ ($i \in \{c, d\}$) denotes that the transmission queue i is empty and no packet is sent within this TS and $Q_i > 0$ corresponds to the case that link i is occupying the channel to perform the transmission, ρ_c is the outage probability of the cellular link when it is free from the interference from D2D link and $\rho_c^{(I)}$ is the outage probability of the interference scenario. Likewise, ρ_d and $\rho_d^{(I)}$ correspond to the outage probabilities of the D2D connection under these two circumstances, respectively. The deducing (a) in (3) or (4) is based on the Little's Law [37], which states that the probability of queue size being equal to zero in a G/G/1 queue with arrival rate λ and service rate μ is $(1 - \frac{\lambda}{\mu})$. Thus, the first term of (3) or (4) denotes that when one of the links keeps silent within the slot, the service rate of the transmitting link is determined by the outage probability without intra-cell interference. While, the second terms characterize the interference scenario when both links carry out transmissions within the same slot. The overall service rate of each link is the weighted sum of the service rates corresponding to the two scenarios.

Although inter-cell interference can be handled via Inter-Cell Interference Coordination mechanisms [38], [39], it has always been a primary concern in the design of cellular systems due to the shrink of cells. Thus, we introduce inter-cell interference to our model. Assuming there exist N_I interfering nodes in the pre-defined certain area of the surrounding cells. Node I_i ($i \in \{1, 2, \ldots, N_I\}$) has transmission power P_{I_i} and the channel gain from I_i to the receiver of link $j \in \{c, d\}$ is $G_{I_i j}$. The BS may not know the detail transmission scenarios of other cells and it requires much more complicated computations when studying multiple interactional queues. Furthermore, in most scenarios, intra-cell interference determines system behaviors due to short distances between interfering links. Thus, we will not establish packet-level transmission models for inter-cell interference. The inter-cell interference is assumed to be existent within each slot. Then, the outage probabilities are calculated through

$$\rho_c = \Pr\left\{B\log\left(1+\frac{P_c G_{cc}}{N_0 + \sum_{i=1}^{N_I} P_{I_i} G_{I_i c}}\right) < R_c\right\}, \tag{5}$$

$$\rho_d = \Pr\left\{ B\log\left(1+\frac{P_dG_{dd}}{N_0+\sum_{i=1}^{N_I}P_{I_i}G_{I_id}}\right) < R_d\right\}, \tag{6}$$

$$\rho_c^{(I)} = \Pr\left\{ B\log\left(1+\frac{P_cG_{cc}}{P_dG_{dc}+N_0+\sum_{i=1}^{N_I}P_{I_i}G_{I_ic}}\right) < R_c\right\}, \tag{7}$$

and

$$\rho_d^{(I)} = \Pr\left\{ B\log\left(1+\frac{P_dG_{dd}}{P_cG_{cd}+N_0+\sum_{i=1}^{N_I}P_{I_i}G_{I_id}}\right) < R_d\right\}, \tag{8}$$

respectively, where B is the bandwidth, P_c and P_d are the transmission powers of the cellular transmitter and D2D transmitter, respectively, $R_c = S_cT$ with R_c being the threshold rate related to outage event of the cellular link and S_c being the number of bits contained in one packet sent by the cellular transmitter. Likewise, $R_d = S_dT$ corresponds to the D2D link. The primary notations are presented in Table I.

We would like to point out that even when the D2D link reuses the same spectrum with the cellular link, the practical transmissions within each TS have two cases. Case 1: One of the transmitters sends a packet while the other one keeps silent, corresponding to the first term in (3) or (4). Case 2: both of the transmitters send packets, corresponding to the second term in (3) or (4). The "conventional model" in this paper refers to the common assumptions in existing works [10]–[19], where they only considered Case 2 (the worst case) when calculating SINRs or data rates. In the following, we will present the theoretical analysis and numerical results on the proposed model, which takes both Case 1 and Case 2 into considerations.

TABLE I
NOTATIONS

Notations	Description
G_{ij}	the channel gain from the transmitter of link i to the receiver of link j, $G_{ij} \sim \exp(1/\sigma_{ij}^2)$
L_{ij}	the distance between node i and node j
α	the path-loss exponent
h_{ij}	Rayleigh fading
β	shadowing fading
N_0	the AWGN power
$\mathcal{CN}(0,\sigma^2)$	circular symmetric complex Gaussian distribution with zero-mean and variance σ^2
$\exp(1/\sigma^2)$	exponential distribution with mean σ^2
T	the number of time slots per second
λ_i	the average packet arrival rate at the transmitter of link i
μ_i	the average packet service rate of link i
Q_i	the length of the data queue at the transmitter of link i
$\mathcal{R}$	stable throughput region
Pr{A}	the probability of event A
ρ_i	the outage probability of link i when free from intra-cell interference
$\rho_c^{(I)}$	the outage probability of link i when suffer from intra-cell interference
P_i	the transmission power at the transmitter of link i
N_I	the number of inter-cell interfering nodes
B	the bandwidth
R_i	the threshold rate related to outage event of link i
η_i	$\eta_i = 2^{\frac{R_i}{B}} - 1$
S_i	the packet size of the transmissions of link i, $S_i = R_i/T$
$\mathbb{E}$	mathematical expectation
$P_{tr}^{(i,t)}$	the *transmission probability* of the transmitter of link i at the beginning of slot t
r_i	the constraint on the ratio of link i occupying the channel
$X_i(a,b)$	the number of slots occupied by link i from slot a to slot b
$P_{i,th}$	the transmission power constraint for link i
N	the number of the D2D pairs which share the same resources with one cellular link
$\mathbf{v}_k^{(i)} = (v_{k,1}^{(i)}, v_{k,2}^{(i)}, \cdots, v_{k,N}^{(i)})$	the indicator vector of the interfering state for link i
$\rho_{\mathbf{v}_k^{(i)}}$	the outage probability of link i with interfering state $\mathbf{v}_k^{(i)}$
$\lvert x\rvert$	the absolute value of x
$\lvert\lvert\mathbf{x}\rvert\rvert_1$	$\lvert\lvert\mathbf{x}\rvert\rvert_1 = \sum_{i=1}^{N_{\mathbf{x}}} \lvert x_i\rvert$, where $\mathbf{x} = (x_1, x_2, \cdots, x_{N_{\mathbf{x}}})$

III. Stable Throughput Region and Admission Control

In this section, we will develop the stable throughput region for the above described scenario where one D2D pair share the same resources with one cellular connection. Then an admission control mechanism will be performed at the BS to determine whether the D2D link is allowed to access.

A. Stable Throughput Region

Firstly, we derive the stable throughput region. Although two queues are coupled, for each of them, the departure process is only determined by the packet delivery rate. According to (3) and (4), as long as λ_c, λ_d, P_c, and P_d are given, the average service rates are fixed and time-independent. Thus, we can use Loynes' Theorem to characterize the stable throughput region. Then, the composite effect of path loss, log-normal shadow fading and Rayleigh fading is analytically untractable. Thus, the theoretical analysis is based on path-loss and Rayleigh fading channel, while the performance of shadow fading is tested in simulations. Mathematically, according to (1) and the distribution of h_{ij}, channel gains are exponentially distributed. Thus we have $G_{cc} \sim \exp(1/\sigma_{cc}^2)$, $G_{dd} \sim \exp(1/\sigma_{dd}^2)$, $G_{cd} \sim \exp(1/\sigma_{cd}^2)$, $G_{dc} \sim \exp(1/\sigma_{dc}^2)$, $G_{I_ic} \sim \exp(1/\sigma_{I_ic}^2)$, and $G_{I_id} \sim \exp(1/\sigma_{I_id}^2)$. Before calculating the outage probabilities, we firstly introduce the following lemma.

Lemma 1: Suppose $t, t_1, t_2, \ldots, t_N$ $(N \geq 2)$ are independent exponentially distributed random variables with means $\sigma^2, \sigma_1^2, \sigma_2^2, \ldots, \sigma_N^2$, respectively. Then, we have

$$\Pr\left\{\sum_{n=1}^{N} t_n < a\right\} = 1 - \sum_{n=1}^{N} \frac{\sigma_n^{2(N-1)}}{\prod_{\substack{m=1,\\ m\neq n}}^{N} (\sigma_n^2 - \sigma_m^2)} e^{-\frac{a}{\sigma_n^2}} \tag{9}$$

and

$$\Pr\left\{\frac{t}{\sum_{n=1}^{N} t_n + a} < b\right\} = 1 - \sum_{n=1}^{N} \frac{\sigma^2 \sigma_n^{2(N-1)}}{\prod_{\substack{m=1,\\ m\neq n}}^{N} (\sigma_n^2 - \sigma_m^2)(b\sigma_n^2 + \sigma^2)} e^{-\frac{ab}{\sigma^2}}, \tag{10}$$

where $a > 0$ and $b > 0$.

Proof: The proof of this lemma is provided in Appendix A. ■

According to (9) and (10), the outage probabilities ρ_c and ρ_d are given by

$$\rho_c = 1 - \sum_{i=1}^{N_I} \frac{P_c \sigma_{cc}^2 (P_{I_i} \sigma_{I_i c}^2)^{N_I - 1}}{\prod_{\substack{m=1,\\ m\neq i}}^{N_I} (P_{I_i} \sigma_{I_i c}^2 - P_{I_m} \sigma_{I_m c}^2)(\eta_c P_{I_i} \sigma_{I_i c}^2 + P_c \sigma_{cc}^2)} e^{-\frac{\eta_c N_0}{P_c \sigma_{cc}^2}}, \tag{11}$$

and

$$\rho_d = 1 - \sum_{i=1}^{N_I} \frac{P_d \sigma_{dd}^2 (P_{I_i} \sigma_{I_i d}^2)^{N_I - 1}}{\prod_{\substack{m=1,\\ m\neq i}}^{N_I} (P_{I_i} \sigma_{I_i d}^2 - P_{I_m} \sigma_{I_m d}^2)(\eta_d P_{I_i} \sigma_{I_i d}^2 + P_d \sigma_{dd}^2)} e^{-\frac{\eta_d N_0}{P_d \sigma_{dd}^2}}, \tag{12}$$

respectively, where

$$\eta_c = 2^{\frac{R_c}{B}} - 1 \tag{13}$$

and

$$\eta_d = 2^{\frac{R_d}{B}} - 1. \tag{14}$$

Then, with interference scenario, the outage probabilities of the cellular link and D2D connection are given by

$$\rho_c^{(I)} = 1 - \sum_{i=0}^{N_I} \frac{P_c \sigma_{cc}^2 (P_I \sigma_{I_i c}^2)^{N_I}}{\prod_{\substack{m=0,\\ m\neq i}}^{N_I} (P_{I_i} \sigma_{I_i c}^2 - P_{I_m} \sigma_{I_m c}^2)(\eta_c P_{I_i} \sigma_{I_i c}^2 + P_c \sigma_{cc}^2)} e^{-\frac{\eta_c N_0}{P_c \sigma_{cc}^2}}, \tag{15}$$

and

$$\rho_d^{(I)} = 1 - \sum_{i=1}^{N_I+1} \frac{P_d \sigma_{dd}^2 (P_I \sigma_{I_i d}^2)^{N_I}}{\prod_{\substack{m=1,\\ m\neq i}}^{N_I+1} (P_{I_i} \sigma_{I_i d}^2 - P_{I_m} \sigma_{I_m d}^2)(\eta_d P_{I_i} \sigma_{I_i d}^2 + P_{dd} \sigma_{dd}^2)} e^{-\frac{\eta_d N_0}{P_d \sigma_{dd}^2}}, \tag{16}$$

respectively, where, for the simplicities of the expressions, we substitute the notation "d" in (7) with "I_0" in (15) and substitute the notation "c" in (8) with "I_{N_I+1}" in (16).

Then, we can determine the stable throughput region by the following **Theorem 1**.

Theorem 1: The stable throughput region $\mathcal{R} = \{(\lambda_c, \lambda_d) | \lambda_c < \mu_c \;\&\; \lambda_d < \mu_d\}$, where one D2D pair with packet arrival rate λ_d shares the same resources with one cellular link with packet arrival rate λ_c, is characterized by

$$\mathcal{R} = \left\{(\lambda_c, \lambda_d) \,\middle|\, (\lambda_c, \lambda_d) \in \mathcal{R}_1 \bigcup \mathcal{R}_2\right\} \tag{17}$$

where

$$\mathcal{R}_1 = \left\{ \begin{array}{l} \text{(a)} : \lambda_c < (1 - \rho_c) - \lambda_d \dfrac{\rho_c^{(I)} - \rho_c}{1 - \rho_d^{(I)}} \\ \text{(b)} : \lambda_c < \dfrac{(1 - \rho_d - \lambda_d)(1 - \rho_c^{(I)})}{\rho_d^{(I)} - \rho_d} \end{array} \right\}, \tag{18}$$

and

$$\mathcal{R}_2 = \left\{ \begin{array}{l} \text{(a)} : \; \lambda_c \leq \dfrac{\left(\sqrt{\lambda_d(\rho_c^{(I)} - \rho_c)} - \sqrt{(1 - \rho_c)(1 - \rho_d)}\right)^2}{\rho_d^{(I)} - \rho_d} \\ \text{(b)} : \; \lambda_c < \dfrac{(1 - \rho_c)(1 - \rho_d) - \lambda_d(\rho_c^{(I)} - \rho_c)}{2 - \rho_d - \rho_d^{(I)}} \\ \text{(c)} : \; \lambda_d < \dfrac{(1 - \rho_d)(1 - \rho_c) - \lambda_c(\rho_d^{(I)} - \rho_d)}{2 - \rho_c - \rho_c^{(I)}} \end{array} \right\}. \tag{19}$$

Proof: The proof of this lemma is provided in Appendix B. ■

Remark: The stable throughput constraint is only determined by the packet arrival rate of each transmitter. Under certain circumstance, unpredictable and sudden arrival nature of the packets may results in the instantaneous arrival rate being much larger than the service rate. The packet dropout may occur at the source data queue. For many systems and applications, there exist requirements for the probability of packet dropout. Thus, we introduce a bias to the packet arrival rate, i.e., the targeted service rate of node $i \in \{c, d\}$ should be larger than the adjusted arrival rate, expressed as $\{\tilde{\lambda}_i | \tilde{\lambda}_i = \lambda_i + bias_i < \mu_i\}$ ($bias > 0$), where $\tilde{\lambda}_i$ ensures that the probability of instantaneous arrival rate being larger than the service rate is below a pre-defined threshold value $P_{th}^{(i)}$. This measurement not only maintains the stable constraint, but also captures the volatility of the packet arrival process, decreasing the probability of packet dropout. Different systems and applications have different distributions of the packet arrival process. For specific system and distribution, we can acquire the corresponding cumulative distribution function of the packet arrival process $F_i(x)$. Thus, $bias_i$ can be obtained through solving the equation $F_i(\lambda_i + bias_i) = P_{th}^{(i)}$. Without loss of generality, we still use notations λ_c and λ_d in the following derivations.

The above method is simple but increases the admission threshold for both links. Alternatively, we introduce another approach to deal with the bursty nature of packet arrival process. In the LTE networks, the QoS requirements are associated with the SINRs of both cellular and D2D links [40]. The transmission powers are limited to ensure that the SINR of each link is always larger than the pre-defined threshold. Such QoS requirements are deployed to limit the interference and guarantee the data rate. In our paper, the long-term statistical data rates are satisfied based on the stable throughput region. However, based on the unpredictable and sudden arrival nature of the packets, the instantaneous rates cannot be guaranteed. To be specific, if the cellular transmitter has a large amount of packets and accesses the channel in each slot within certain time period, the instantaneous service rate of the D2D link will significantly decrease. Mathematically, if $(\lambda_c, \lambda_d, P_c, P_d)$ satisfies the stable throughput constraint, μ_c, μ_d can be calculated through (3) and (4). For D2D link,

$$\mu_d = \left(1 - \frac{\lambda_c}{\mu_c}\right)(1-\rho_d) + \frac{\lambda_c}{\mu_c}\left(1-\rho_d^{(I)}\right)$$
$$= 1 - \rho_d - \left(\rho_d^{(I)} - \rho_d\right)\frac{\lambda_c}{\mu_c}. \tag{20}$$

Thus, to meet the service rate $\mu_d > \lambda_d$, the ratio of cellular link occupying the channel ($\frac{\lambda_c}{\mu_c}$) should be no larger than $\frac{1-\rho_d-\lambda_d}{\rho_d^{(I)}-\rho_d}$. Likewise, to meet the service rate μ_c, the ratio of D2D link occupying the channel ($\frac{\lambda_d}{\mu_d}$) should be no larger than $\frac{1-\rho_c-\lambda_c}{\rho_c^{(I)}-\rho_c}$. The stable throughput region can only guarantee the long-term requirements for both ratios. Therefore, if we want to guarantee the instantaneous rates for both links, we introduce a *transmission probability* for each transmitter to control the instantaneous interference to its reusing partner. To do so, cellular transmitter has a *transmission probability* $P_{tr}^{(c)}$, which means that if the cellular transmitter has a packet to send at the beginning of a slot, it will transmit with probability $P_{tr}^{(c)}$ and keep silent with probability $(1 - P_{tr}^{(c)})$. And $P_{tr}^{(d)}$ is deployed at the D2D transmitter. Since $P_{tr}^{(c)}$ and $P_{tr}^{(d)}$ are associated with instantaneous transmission rate, they should be updated at the beginning of each time slot. Meanwhile, the estimation of the instantaneous ratio requires a series of time slots. Thus, we divide the entire transmission period into many cycles, where one cycle consists of K time slots. $P_{tr}^{(c,t)}$ denotes the *transmission probability* of cellular transmitter in time slot t. Within the mth cycle, $(m-1)K < t \le mK$, $P_{tr}^{(c,t)}$ is given by

$$P_{tr}^{(c,t)} = \begin{cases} 1 & \text{if} \quad \frac{Q_c^t}{\mu_c} \le r_c K - X_c((m-1)K, t-1) \\ \tilde{P}_{tr} & \text{if} \quad \frac{Q_c^t}{\mu_c} > r_c K - X_c((m-1)K, t-1) \\ 0 & \text{if} \quad X_c((m-1)K, t-1) \ge r_c K \end{cases}, \tag{21}$$

where $\tilde{P}_{tr} = \min\left\{\frac{r_c K - X_c((m-1)K, t-1)}{mK-t+1}, 1\right\}$. $X_c((m-1)K, t-1)$ denotes the amount of slots which are occupied by the cellular transmitter from slot $(m-1)K$ to slot $t-1$, and $r_c = \frac{1-\rho_d-\lambda_d}{\rho_d^{(I)}-\rho_d}$ is the constraint on the ratio of cellular link occupying the channel. As mentioned before, to meet the service rate of D2D link, the ratio of cellular link occupying the channel ($\frac{\lambda_c}{\mu_c}$) should be no larger than r_c. Thus, the slots that occupied by the cellular link throughout the entire K slots should be less than $r_c K$. In (21), $X_c((m-1)K, t-1)$ is the slots consumption from the beginning of the mth cycle to slot $t-1$. Thus, to meet the rate requirement of D2D link, the available slots which can be occupied by the cellular link from slot t to mK (i.e., the rest of this cycle) is $r_c K - X_c((m-1)K, t-1)$. Meanwhile, $\frac{Q_c^t}{\mu_c}$ denotes the amount of the slots needed to successfully deliver the packets in the data queue. Since we cannot predict the incoming packets in the future, the *transmission probability* is configured based on the past and present. In the first line of the above equation, if the slots needed for the delivery of Q_c^t packets are less than the remaining accessible slots in this cycle, the source will transmit with probability 1. If the slots needed for the delivery of Q_c^t packets are more than the available slots, the source will transmit with probability $\frac{r_c K - X_c((m-1)K, t-1)}{mK-t+1}$, where $mK - t + 1$ is the rest slots in this cycle. Once $X_c((m-1)K, t-1)$ is equal to or larger than $r_c K$, the source is prohibited to transmit in this cycle. As a result, the access ratio of the cellular link in each cycle is no larger than $\frac{\lceil r_c K \rceil}{K}$. The similar configuration can be done at the D2D transmitter.

Subsequently, we prove that the deployments of *transmission probabilities* will not change the stable throughput region. If λ_d is fixed, based on **Theorem 1** in our paper, we obtain the stable throughput region for the cellular link, denoted as $\{\lambda_c | \lambda_c \le \lambda_{c,max|_{\lambda_d}}\}$.

1) For any $\lambda_c < \lambda_{c,max|_{\lambda_d}}$, we have $\mu_c = 1 - \rho_c - (\rho_c^{(I)} - \rho_c)\frac{\lambda_d}{\mu_d} > \lambda_c$ and $\mu_d = 1 - \rho_d - (\rho_d^{(I)} - \rho_d)\frac{\lambda_c}{\mu_c} > \lambda_d$. We assume that the system with the deployments of *transmission probabilities* cannot satisfy the stable throughput constraint. Thus, we have $\lim_{t\to\infty} Q_c^t = \infty$ and $\mu_{c,tr} < \lambda_c$, where $\mu_{c,tr}$ is the mean service rate of the system with *transmission probabilities*. According to the configuration in the above equation, to limit the interference to the D2D link, the cellular transmitter will have an average *transmission probability* $P_{tr}^{(c)} = r_c = \frac{1-\rho_d-\lambda_d}{\rho_d^{(I)}-\rho_d}$ since the data queue of the cellular transmitter is saturated when $t \to \infty$. Thus, the service rate of the cellular link can be calculated as $\mu_{c,tr} = r_c \mu_c'$, where

$$\mu_c' = (1 - \Pr\{\text{D2D} \quad \text{transmits}\})(1-\rho_c)$$
$$+ \Pr\{\text{D2D} \quad \text{transmits}\}(1-\rho_c^{(I)})$$
$$= 1 - \rho_c - (\rho_c^{(I)} - \rho_c)\Pr\{\text{D2D} \quad \text{transmits}\} \tag{22}$$

If the D2D transmitter sends a packet with *transmission probability* 1, $\Pr\{\text{D2D} \quad \text{transmits}\} = \frac{\lambda_d}{\mu_d}$, otherwise $\Pr\{\text{D2D} \quad \text{transmits}\} < \frac{\lambda_d}{\mu_d}$ due to $P_{tr}^{(d)} < 1$. Then, we have

$$\mu_c' \ge 1 - \rho_c - (\rho_c^{(I)} - \rho_c)\frac{\lambda_d}{\mu_d} = \mu_c. \tag{23}$$

As a result,

$$\mu_{c,tr} \ge r_c \mu_c = \frac{1-\rho_d-\lambda_d}{\rho_d^{(I)}-\rho_d}\mu_c > \frac{1-\rho_d-\mu_d}{\rho_d^{(I)}-\rho_d}\mu_c$$
$$= \frac{\lambda_c}{\mu_c}\mu_c = \lambda_c, \tag{24}$$

which is against the assumption $\mu_{c,tr} < \lambda_c$. Thus, for any $\lambda_c < \lambda_{c,max|_{\lambda_d}}$, the system with the deployments of *transmission probability* can still maintain the stability constraint.

2) For any $\lambda_c > \lambda_{c,max|_{\lambda_d}}$, we cannot achieve a service rate pair (μ_c, μ_d) which satisfies $\mu_c > \lambda_c$ and $\mu_d > \lambda_d$. Thus, even we can limit the access ratio of either the cellular link or the D2D link to obtain the stability of its partner, its own rate cannot be satisfied.

Likewise, when λ_c is fixed, the stable throughput region of λ_d remains unchanged. Based on the above discussions, the *transmission probability* introduced at each link not only meets the long-term statistical stability, but also satisfies the QoS requirements on instantaneous rates. It serves as an effective method to well handle the bursty nature of the packet arrival process.

B. Admission Control

When a D2D pair with data arrival rate λ_d requests to access the spectrum occupied by specific cellular link, the BS will determine whether this D2D connection can be admitted, on condition that both transmission queues should satisfy the stable throughput constraints. This can be achieved by comparing λ_c with the maximum acceptable data arrival rate of the cellular link (λ_c^*). Mathematically, λ_c^* can be obtained by solving the following optimization problem (i.e., when λ_d is given, we obtain the maximal λ_c according to $\mathcal{R}$ in (17)):

$$\text{(OP)}\quad \lambda_c^* = \max_{P_c, P_d} \lambda_c, \tag{25a}$$
$$\text{s.t.}\quad \mathcal{R}, \tag{25b}$$
$$P_c \le P_{c,th}, \tag{25c}$$
$$P_d \le P_{d,th}, \tag{25d}$$

where $P_{c,th}$ and $P_{d,th}$ are the maximal transmit powers of the cellular and D2D transmitters, respectively. This original problem (OP) is non-convex and is intractable in its original form.

In order to obtain the optimal solution, we divide the problem into several subproblems to reduce the complexity.

Proposition 1: According to **Theorem 1**, where $\mathcal{R} = \mathcal{R}_1 \bigcup \mathcal{R}_2$, the OP can be divided into the following two subproblems (P-1 and P-2)

$$\text{(P-1)}\quad \lambda_{c\text{-}1}^* = \max_{P_c, P_d} \lambda_c, \tag{26a}$$
$$\text{s.t.}\quad \mathcal{R}_1, \tag{26b}$$
$$P_c \le P_{c,th}, \tag{26c}$$
$$P_d \le P_{d,th}, \tag{26d}$$

and

$$\text{(P-2)}\quad \lambda_{c\text{-}2}^* = \max_{P_c, P_d} \lambda_c, \tag{27a}$$
$$\text{s.t.}\quad \mathcal{R}_2, \tag{27b}$$
$$P_c \le P_{c,th}, \tag{27c}$$
$$P_d \le P_{d,th}. \tag{27d}$$

The solution of OP can be obtained through

$$\lambda_c^* = \max\{\lambda_{c\text{-}1}^*, \lambda_{c\text{-}2}^*\}. \tag{28}$$

Proof: The optimization solution of OP λ_c^* must satisfy $(\lambda_c^*, \lambda_d) \in \mathcal{R}$. According to **Theorem 1**, where $\mathcal{R} = \mathcal{R}_1 \bigcup \mathcal{R}_2$, $(\lambda_{c\text{-}1}^*, \lambda_d) \in \mathcal{R}_1$ results in $(\lambda_{c\text{-}1}^*, \lambda_d) \in \mathcal{R}$. Thus, $\lambda_{c\text{-}1}^*$ is a feasible solution of the OP, i.e., $\lambda_{c\text{-}1}^* \le \lambda_c^*$. Likewise, $\lambda_{c\text{-}2}^* \le \lambda_c^*$. Thus, $\max\{\lambda_{c\text{-}1}^*, \lambda_{c\text{-}2}^*\} \le \lambda_c^*$. Meanwhile, if $(\lambda_c^*, \lambda_d) \in \mathcal{R}_1$, λ_c^* is no larger than the optimal value of P-1, i.e., $\lambda_c^* \le \lambda_{c\text{-}1}^*$. Likewise, if $(\lambda_c^*, \lambda_d) \in \mathcal{R}_2$, we have $\lambda_c^* \le \lambda_{c\text{-}2}^*$. Thus, $\max\{\lambda_{c\text{-}1}^*, \lambda_{c\text{-}2}^*\} \ge \lambda_c^*$. Based on the above discussions, we have $\max\{\lambda_{c\text{-}1}^*, \lambda_{c\text{-}2}^*\} = \lambda_c^*$. ∎

Subsequently, to obtain the solution of P-1 and P-2, further simplifications are necessary. We take P-1 for an example. Based on (18), we have

$$\lambda_c < \min\left\{(1-\rho_c) - \lambda_d \frac{\rho_c^{(I)} - \rho_c}{1 - \rho_d^{(I)}}, \frac{(1-\rho_d-\lambda_d)(1-\rho_c^{(I)})}{\rho_d^{(I)} - \rho_d}\right\}. \tag{29}$$

Thus, the optimization problem P-1 can be further divided into two parts as

$$\text{(P-1-1)}\quad \lambda_{c\text{-}1\text{-}1}^* = \max_{P_c, P_d} (1-\rho_c) - \lambda_d \frac{\rho_c^{(I)} - \rho_c}{1 - \rho_d^{(I)}}, \tag{30a}$$
$$\text{s.t.}\ (1-\rho_c) - \lambda_d \frac{\rho_c^{(I)} - \rho_c}{1 - \rho_d^{(I)}} \le \frac{(1-\rho_d-\lambda_d)(1-\rho_c^{(I)})}{\rho_d^{(I)} - \rho_d}, \tag{30b}$$
$$P_c \le P_{c,th}, \tag{30c}$$
$$P_d \le P_{d,th}, \tag{30d}$$

and

$$\text{(P-1-2)}\quad \lambda_{c\text{-}1\text{-}2}^* = \max_{P_c, P_d} \frac{(1-\rho_d-\lambda_d)(1-\rho_c^{(I)})}{\rho_d^{(I)} - \rho_d}, \tag{31a}$$
$$\text{s.t.}\quad (1-\rho_c) - \lambda_d \frac{\rho_c^{(I)} - \rho_c}{1 - \rho_d^{(I)}} > \frac{(1-\rho_d-\lambda_d)(1-\rho_c^{(I)})}{\rho_d^{(I)} - \rho_d}, \tag{31b}$$
$$P_c \le P_{c,th}, \tag{31c}$$
$$P_d \le P_{d,th}, \tag{31d}$$

and through the similar analysis as that of **Proposition 1**, it is easy to prove that the solution of P-1 is given by

$$\lambda_{c\text{-}1}^* = \max\{\lambda_{c\text{-}1\text{-}1}^*, \lambda_{c\text{-}1\text{-}2}^*\}. \tag{32}$$

Likewise, we can divide P-2 with the same method, which will not be detailed here.

Before calculating the solutions of P-1-1 and P-1-2, we introduce the following proposition.

Proposition 2: Let P_c^* and P_d^* be the transmit powers of the cellular transmitter and D2D transmitter, respectively, when the optimal solution λ_c^* is obtained. Then we have

$$\{P_c^*, P_d^*\} = \{P_{c,th}, P_d^*\} \quad \text{or} \quad \{P_c^*, P_d^*\} = \{P_c^*, P_{d,th}\}. \tag{33}$$

Proof: If $P_c^* < P_{c,th}$ and $P_d^* < P_{d,th}$, there exists a positive real number $\alpha > 1$ which satisfies $\alpha P_c^* \le P_{c,th}$ and $\alpha P_d^* \le$

$P_{d,th}$. Then we plug αP_c^* and αP_d^* into (5)–(8) and find out that all the outage probabilities are smaller than those with P_c^* and P_d^*. The decrease of outage probabilities means that fewer TSs are needed to successfully transmit the packets, resulting in less interference from/to the transmission partner. As a consequence, the service rates increase. Thus, the maximal achievable data arrival rates also increase, which is against the assumption. Therefore, to achieve the optimal solution of OP, at least one of the two transmitters sends its signals with its largest power. ■

According to **Proposition 2**, both P-1-1 and P-1-2 can be further simplified. For P-1-1, setting $P_d = P_{d,th}$, it can be transformed to

$$(\text{P-1-1}_{\text{P}_{\text{d,th}}}) \quad \lambda^*_{c\text{-}1\text{-}1_{P_{d,th}}} = \max_{P_c \in \mathcal{A}_{P_c,\text{P-1-1}_{\text{P}_{\text{d,th}}}}} (1-\rho_c) - \lambda_d \frac{\rho_c^{(I)} - \rho_c}{1-\rho_d^{(I)}}, \tag{34}$$

where the range of P_c ($\mathcal{A}_{P_c,\text{P-1-1}_{P_{d,th}}}$) is calculated through setting $P_d = P_{d,th}$ and replacing ρ_c ρ_d, $\rho_c^{(I)}$, and $\rho_d^{(I)}$ in (30b) with (11), (12), (15), and (16), respectively. The optimization objective in (34) is a one-dimension differentiable continuous function on P_c with finite interval. Due to the complicated expressions of ρ_c ρ_d, $\rho_c^{(I)}$, and $\rho_d^{(I)}$, it is difficult to analyze its convexity by evaluating second derivative. Whereas, the objective function is a continuous-differential function within a finite interval. It is known that for any continuously differentiable function $f(x)$, the minimum value ($\min f(x)$) or the maximum value ($\max f(x)$) within finite interval can be obtained in one of the extreme value points of $f(x)$ or the boundary points. Thus, the optimal solution of the above problem can be calculated by solving for the derivative being zero and comparing the extreme value points with the boundary points. Alternatively, we can perform one-dimensional exhaustive search on P_c within the finite interval. Assuming the iteration precision of transmission power is $1/M_{po}$ (i.e., $P_c \in \{\frac{1}{M_{po}} P_{c,th}, \frac{2}{M_{po}} P_{c,th}, \ldots, \frac{M_{po}}{M_{po}} P_{c,th}\}$), we have a computational complexity of $O(M_{po})$, which is acceptable for practical deployment.

Likewise, setting $P_c = P_{c,th}$, we can obtain another simplified subproblem, whose solution is denoted as $\lambda^*_{c\text{-}1\text{-}1_{P_{c,th}}}$. Then the solution of P-1-1 can be obtained as

$$\lambda^*_{c\text{-}1\text{-}1} = \max\left\{\lambda^*_{c\text{-}1\text{-}1_{P_{c,th}}}, \lambda^*_{c\text{-}1\text{-}1_{P_{d,th}}}\right\}. \tag{35}$$

Likewise, $\lambda^*_{c\text{-}1\text{-}2}$ can be obtained by the same way.

According to (28), (32), and (35), the solution to the OP can be achieved through the combinations of the solutions to the aforementioned several simplified subproblems.

Consequently, if the actual λ_c (QoS requirement) is smaller than λ_c^*, the D2D connection can be admitted by this cellular link.

In our paper, the transmission rate is equivalent to the packet size in one slot. If we change the packet size, the achievable throughput will be different. Thus, we can optimize the stable throughput via adjusting the packet size. Since S_c denotes the packet size of cellular link and $S_c = R_c/T$, the throughput can be expressed as $S_c\lambda_c$ (bit/slot). The optimization problem (25) can be rewritten as

$$S_c^*\lambda_c^* = \max_{P_c, P_d, S_c, S_d} S_c\lambda_c, \quad \text{(bit/s)} \tag{36a}$$

$$\text{s.t.} \quad \mathcal{R}, \tag{36b}$$

$$P_c \le P_{c,th}, \quad P_d \le P_{d,th} \tag{36c}$$

$$S_c > 0, \quad S_d > 0, \tag{36d}$$

where $S_d = R_d/T$ is the packet size of the D2D link. This problem can still be divided into those subproblems. Take the following subproblem ((P-1-1$_{P_{d,th}}$)) for example.

$$(\text{P-1-1}_{\text{P}_{\text{d,th}}}) \quad S^*_{c\text{-}1\text{-}1_{P_{d,th}}} \lambda^*_{c\text{-}1\text{-}1_{P_{d,th}}} = \max_{S_c, S_d, P_c \in \mathcal{A}_{P_c,\text{P-1-1}_{\text{P}_{\text{d,th}}}}} S_c \left((1-\rho_c) - \lambda_d \frac{\rho_c^{(I)} - \rho_c}{1-\rho_d^{(I)}}\right), \tag{37}$$

the solution of which requires a large amount of iterations since it is difficult to obtain useful properties to simplify this high-dimension mixed integer non-convex optimization problem. We assume the largest packet size is M_{pa} and the iteration precision of transmission power is $1/M_{po}$ (i.e., $P_c \in \{\frac{1}{M_{po}} P_{c,th}, \frac{2}{M_{po}} P_{c,th}, \ldots, \frac{M_{po}}{M_{po}} P_{c,th}\}$), which generate a computational complexity of $O(M_{po}M_{pa}^2)$. The complexity will exponentially increase with the admissions of multiple D2D pairs, which makes the problem intractable. We consider the fact that a practical system always has finite discrete packet lengths due to finite coding and modulation strategies. Thus, we have finite (S_c, S_d) pairs and the optimization remains to be a one-dimension search problem with complexity $O(M_{po})$. We will provide the simulation results to show the throughput performance with different packet sizes.

Remark: In an OFDMA-based LTE network, the resources are allocated in the unit of "resource blocks" (RBs). One RB consists of 15 sub-carriers. The transmissions of the symbols on different sub-carriers are independent from each other. For admission control in our paper, we can separately obtain the maximal achievable packet arrival rate for each sub-carrier. Then, we compare the sum of all these rates with the overall requirement for the packet arrival rate to determine the admission decision.

C. Discussions

The underlaying transmission process between the D2D link and the cellular link is shown in Fig. 2(a). In the conventional model, the SINRs or data rates are calculated under the interference scenario within each TS, which is equivalent to the transmissions depicted in Fig. 2(b), where the blue dotted packets may not exist in practice. Fig. 2(c) characterizes the TDMA transmissions.

It is known that if the D2D link and the cellular link are close to each other, TDMA transmissions will achieve better performance when simultaneously transmissions suffer from severe inter-link interference. Thus, with conventional assumptions, most of the D2D requests will be rejected. Instead, under the same circumstance, the proposed analysis significantly expands

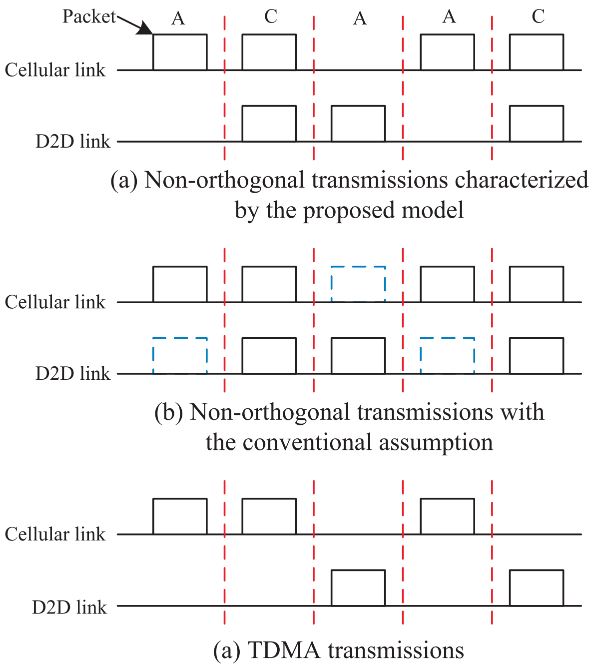


Fig. 2. Packet-level transmission processes of different schemes.

the stable throughput region of the conventional model via successfully capturing the real underlaying transmission and interference scenarios. Consequently, the proposed region can achieve almost the same performance as that of TDMA while the conventional one have the worst behavior. This will be verified in Section V.

When the distance between the D2D link and the cellular link is sufficiently large, the interference between them can be too weak to degrades the simultaneously transmission rates. Thus, TDMA suffers from spectral inefficiency while underlaying transmissions obtain much better performance. Under this circumstance, the region of the proposed model will not improve much than that of the conventional model, which is characterized by the following property.

Property 1: In a single D2D scenario, if the stable throughput region of the conventional model exceeds that of TDMA transmission, the stable throughput region of the proposed model in **Theorem 1** will be the same as the conventional one.

Proof: According to the condition, given λ_c, the maximal achievable λ_d with simultaneously transmissions ($\lambda^*_{d,\text{simult.}}$) is no less than that with TDMA transmissions ($\lambda^*_{d,\text{orth.}}$). In the proposed model, all the TSs can be divided into two categories: only one of the transmitters sending the signal (marked as "A" in Fig. 2(a)) and simultaneously transmission (marked as "C"). For those TSs marked as "A", the achievable packet rate of the D2D link will be no larger than $\lambda^*_{d,\text{orth.}}$. Likewise, for those TSs marked as "C", the achievable packet rate of the D2D link will be no larger than $\lambda^*_{d,\text{simult.}}$. As a result, the maximal achievable λ_d of the proposed model will be no larger than the conventional one. Meanwhile, the proposed model contains the simultaneously transmission scene. Therefore, the stable throughput region of the proposed model will be the same as the conventional one. ■

This property will also be verified by simulations in Section V.

IV. Multiple D2D Pairs

In this section, we develop the stable throughput region based admission control algorithm for multiple D2D pairs scenario.

A. Stable Throughput Region

In a multiple D2D pairs scenario, we assume N $(N > 1)$ D2D pairs share the same resource with one cellular link. We use λ_0 and μ_0 to denote the packet arrival and service rates of the cellular link, respectively. The packet arrival and service rates of D2D pair n $(n \in \{1, 2, \dots, N\})$ are respectively denoted by λ_n and μ_n. In addition, P_0 represents the transmission power of the cellular link and P_n corresponds to the transmission power of D2D pair n. The channel gain from the transmitter of connection i to the receiver of connection j $(i, j \in \{0, 1, 2, \dots, N\})$, where connection 0 stands for the cellular link, is $G_{ij} \sim \exp(1/\sigma^2_{ij})$.

The cellular transmissions suffer from the interferences from all D2D pairs. With packet arrival rate λ_n and service rate μ_n, D2D pair n either transmits (with probability $\frac{\lambda_n}{\mu_n}$) or keeps silent (with probability $1 - \frac{\lambda_n}{\mu_n}$) within each TS. Thus, for the cellular link, there exist 2^N interference states for each TS. We use 2^N vectors $\{\mathbf{v}^{(0)}_1, \mathbf{v}^{(0)}_2, \dots, \mathbf{v}^{(0)}_{2^N}\}$ to describe different states where $\mathbf{v}^{(0)}_k = (v^{(0)}_{k,1}, v^{(0)}_{k,2}, \dots, v^{(0)}_{k,N})$ $(k \in \{1, 2, \dots, 2^N\})$, and

$$v^{(0)}_{k,n} = \begin{cases} 1 & \text{D2D pair } n \text{ is transmitting} \\ 0 & \text{D2D pair } n \text{ keeps silent} \end{cases} \tag{38}$$

Consequently, the service rate of the cellular link can be calculated by

$$\mu_0 = \sum_{k=1}^{2^N} \Pr\{\mathbf{v}^{(0)}_k\}(1 - \rho_{\mathbf{v}^{(0)}_k}), \tag{39}$$

where $\Pr\{\mathbf{v}^{(0)}_k\}$ is the probability of state k and $\rho_{\mathbf{v}^{(0)}_k}$ is the corresponding outage probability. For D2D pair n, the probability of occupying the channel is $\Pr\{Q_n > 0\} = \frac{\lambda_n}{\mu_n}$, where Q_n is the transmission queue of D2D pair n. Thus we have

$$\Pr\left\{\mathbf{v}^{(0)}_k\right\} = \prod_{n=1}^{N} \left|1 - v^{(0)}_{k,n} - \frac{\lambda_n}{\mu_n}\right|. \tag{40}$$

$\rho_{\mathbf{v}^{(0)}_k}$ is given by

$$\rho_{\mathbf{v}^{(0)}_k} = \Pr\left\{B \log\left(1 + \frac{P_0 G_{00}}{\sum\limits_{n=1}^{N} v_{k,n} P_n G_{n0} + N_0 + \sum\limits_{i=1}^{N_I} P_{I_i} G_{I_i 0}}\right) < R_0\right\}, \tag{41}$$

where $\sum_{i=1}^{N_I} P_{I_i} G_{I_i 0}$ is the inter-cell interference. Without loss of generality, for the simplification of the expressions, we let $\{N+1, N+2, \dots, N+N_I\}$ be the indexes for the inter-cell interfering nodes and $v^{(0)}_{k,n} = 1$ for $\forall n \in \{N+1, N+2, \dots, N+N_I\}$. Then, based on **Lemma 1**, we have

$$\rho_{\mathbf{v}_k^{(0)}} = 1 - \sum_{n=1}^{N+N_I} \frac{v_{k,n}^{(0)} P_0\sigma_{00}^2 (P_n\sigma_{n0}^2)^{||\mathbf{v}_k^{(0)}||_1-1}}{\prod\limits_{\substack{i=1,\\ i\neq n,\\ v_{k,i}^{(0)}\neq 0}}^{N+N_I} (P_n\sigma_{n0}^2 - P_i\sigma_{i0}^2)(\eta_0 P_n\sigma_{n0}^2 + P_0\sigma_{00}^2)} e^{-\frac{\eta_0 N_0}{P_0\sigma_{00}^2}}, \tag{42}$$

where $||\mathbf{v}_k^{(0)}||_1 = \sum_{n=1}^{N+N_I} v_{k,n}$, $\eta_0 = 2^{\frac{R_0}{B}} - 1$ and R_0 is the threshold rate of the cellular connection.

Likewise, for D2D pair n, we have

$$\mu_n = \sum_{k=1}^{2^N} \Pr\{\mathbf{v}_k^{(n)}\}(1 - \rho_{\mathbf{v}_k^{(n)}}), \tag{43}$$

where $\mathbf{v}_k^{(n)} = (v_{k,0}^{(n)}, v_{k,1}^{(n)}, \ldots, v_{k,n-1}^{(n)}, v_{k,n+1}^{(n)}, \ldots, v_{k,N}^{(n)}, \ldots, v_{k,N+N_I}^{(n)})$ $(k \in \{1, 2, \ldots, 2^N\})$ and $v_{k,m}^{(n)} = 1$ for $\forall m \in \{N+1, N+2, \ldots, N+N_I\}$. The outage probability is calculated by

$$\rho_{\mathbf{v}_k^{(n)}} = 1 - \sum_{\substack{m=0,\\ m\neq n}}^{N+N_I} \frac{v_{k,m}^{(n)} P_n\sigma_{nn}^2 (P_m\sigma_{mn}^2)^{||\mathbf{v}_k^{(n)}||_1-1}}{\prod\limits_{\substack{i=0,\\ i\neq n,\\ i\neq m\\ v_{k,i}^{(n)}\neq 0}}^{N+N_I} (P_m\sigma_{mn}^2 - P_i\sigma_{in}^2)(\eta_n P_m\sigma_{mn}^2 + P_n\sigma_{nn}^2)} e^{-\frac{\eta_n N_0}{P_n\sigma_{nn}^2}}, \tag{44}$$

where $\eta_n = 2^{\frac{R_n}{B}} - 1$ and R_n is the threshold rate of D2D pair n.

The stable throughput constraint requires that for each connection n $(n \in \{0, 1, 2, \ldots, N\})$, the average service rate of the data queue is larger than its packet arrival rate, i.e., $\mu_n > \lambda_n$. Thus, to obtain $\{\mu_0, \mu_1, \ldots, \mu_N\}$, we have to solve the following equations:

$$\begin{cases} \mu_0 = \sum\limits_{k=1}^{2^N} \prod\limits_{i=1}^{N} \left|1 - v_{k,i}^{(0)} - \frac{\lambda_i}{\mu_i}\right| \cdot \left(1 - \rho_{\mathbf{v}_k^{(0)}}\right) \\ \mu_1 = \sum\limits_{k=1}^{2^N} \prod\limits_{\substack{i=0,\\ i\neq 1}}^{N} \left|1 - v_{k,i}^{(1)} - \frac{\lambda_i}{\mu_i}\right| \cdot \left(1 - \rho_{\mathbf{v}_k^{(1)}}\right) \\ \vdots \\ \mu_n = \sum\limits_{k=1}^{2^N} \prod\limits_{i=0, i\neq n}^{N} \left|1 - v_{k,i}^{(n)} - \frac{\lambda_i}{\mu_i}\right| \cdot \left(1 - \rho_{\mathbf{v}_k^{(n)}}\right) \\ \vdots \\ \mu_N = \sum\limits_{k=1}^{2^N} \prod\limits_{i=0}^{N-1} \left|1 - v_{k,i}^{(N)} - \frac{\lambda_i}{\mu_i}\right| \cdot \left(1 - \rho_{\mathbf{v}_k^{(N)}}\right) \end{cases}. \tag{45}$$

We cannot obtain the closed-form packet service rates and throughput region based on the above equations. It is also known that it is very difficult to obtain the exact characterization of the stability region of the network with multiple interacting queues [32], [41]. The objective of deducing stable throughput region is to determine whether those wireless connections can share the same resource with each other. Thus, we propose the following algorithm to examine whether the transmissions of the cellular link and N D2D pairs can satisfy the QoS requirements, i.e., supporting packet arrival rates $(\lambda_0, \lambda_1, \ldots, \lambda_N)$, when reusing the same spectrum.

Algorithm 1. Decision process on the stability of the multiple D2D pairs scenario

---

Input: $(\lambda_0, \lambda_1, \ldots, \lambda_N)$, $(P_0, P_1, \ldots, P_N)$, and $(R_0, R_1, \ldots, R_N)$;

Initialization: set precision ϵ;

$(\mu_0^{(1)}, \mu_1^{(1)}, \ldots, \mu_N^{(1)}) = (1 - \rho_{\mathbf{v}_{\hat{k}}^{(0)}}, 1 - \rho_{\mathbf{v}_{\hat{k}}^{(1)}}, \ldots, 1 - \rho_{\mathbf{v}_{\hat{k}}^{(N)}})$, where $\mathbf{v}_{\hat{k}}^{(0)} = \mathbf{v}_{\hat{k}}^{(1)} = \cdots = \mathbf{v}_{\hat{k}}^{(N)} = (0, 0, \ldots, 0, v_{\hat{k},N+1} = 1, 1, \ldots, 1)$.

$j = 1$

repeat

  $j = j + 1$;

  for $n = 0$ to N **do**

$$\mu_n^{(j)} = \sum_{k=1}^{2^N} \prod_{\substack{i=0,\\ i\neq n}}^{N} \left|1 - v_{k,i}^{(n)} - \frac{\lambda_i}{\mu_i^{(j-1+\lfloor \frac{i}{j} \rfloor)}}\right| \cdot (1 - \rho_{\mathbf{v}_k^{(n)}});$$

  end for

  $\epsilon_{max} = \max\{\mu_0^{(j)} - \mu_0^{(j-1)}, \ldots, \mu_N^{(j)} - \mu_N^{(j-1)}\}$;

until $\epsilon_{max} < \epsilon$ or $\mu_n^j < \lambda_n\ \exists n$

If $\mu_n^j > \lambda_j\ \forall n$, $(\lambda_0, \lambda_1, \ldots, \lambda_N)$ belongs to the stable throughput region, i.e., the N D2D pairs can share the same spectrum with the cellular link.

Within the first iteration of the proposed algorithm, we let

$$\left(\mu_0^{(1)}, \mu_1^{(1)}, \ldots, \mu_N^{(1)}\right) = \left(1 - \rho_{\mathbf{v}_{\hat{k}}^{(0)}}, 1 - \rho_{\mathbf{v}_{\hat{k}}^{(1)}}, \ldots, 1 - \rho_{\mathbf{v}_{\hat{k}}^{(N)}}\right), \tag{46}$$

where $\mathbf{v}_{\hat{k}}^{(0)} = \mathbf{v}_{\hat{k}}^{(1)} = \cdots = \mathbf{v}_{\hat{k}}^{(N)} = (0, 0, \ldots, 0, v_{k,N+1} = 1, 1, \ldots, 1)$. This is corresponding to the ideal case that each link is only affected by the inter-cell interference and free from intra-cell interference. Then, based on $(\mu_0^{(1)}, \mu_1^{(1)}, \ldots, \mu_N^{(1)})$, we can calculate $\mu_0^{(2)}$ according to (45). Then, based on $(\mu_0^{(2)}, \mu_1^{(1)}, \ldots, \mu_N^{(1)})$, we obtain $\mu_1^{(2)} \cdots$. After one iteration, we have the updated service rates as $(\mu_0^{(2)}, \mu_1^{(2)}, \ldots, \mu_N^{(2)})$. It is obvious that $\mu_n^{(2)} < \mu_n^{(1)}, \forall n$.

Within the jth iteration, $\mu_0^{(j+1)}$ is obtained based on $(\mu_0^{(j)}, \mu_1^{(j)}, \ldots, \mu_N^{(j)})$. $\mu_n^{(j+1)}$ is calculated according to $(\mu_0^{(j+1)}, \ldots, \mu_{n-1}^{(j+1)}, \mu_{n+1}^{(j)}, \ldots, \mu_N^{(j)})$. At the end of each iteration, we compare $(\mu_0^{(j+1)}, \mu_1^{(j+1)}, \ldots, \mu_N^{(j+1)})$ with $(\mu_0^{(j)}, \mu_1^{(j)}, \ldots, \mu_N^{(j)})$. If for each n, we have $\mu_n^{(j+1)} - \mu_n^{(j)} \leq \epsilon$, where ϵ is the pre-defined precision, the iterations end. Finally, if and only if $\mu_n > \lambda_n$, $\forall n$, we conclude that $(\lambda_0, \lambda_1, \ldots, \lambda_N)$ belongs to the stable throughput region. The overall algorithm is presented in **Algorithm 1**.

For the multiple D2D pairs scenario, the *transmission probabilities* can also be configured through (21) with $r_n = \frac{\lambda_n}{\mu_n}$.

B. Admission Control

We assume that there already exist $N-1$ ($N>1$) D2D pairs coexisting with one CUE by sharing the same spectrum band. Then, a new D2D pair requests to access the same spectrum. However, since we cannot obtain the closed-form expressions on the service rate of each link and the stable throughput region as well, it is difficult to analytically adjust the transmission powers to obtain the maximum acceptable packet arrival rate for the incoming D2D pair. The exhaustive search on transmission powers results in a computational complexity of $O(M_{po}^{N+1})$. The number of D2D pairs is assumed to be smaller than that of CUEs since two users in the same cell communicate with each other will not often happen [12], [42], [43]. Under most circumstances, owing to small $N=2,3$, the exhaustive search can be deployed in real networks.

With the increase of N, to reduce the computations, we do not reconfigure the transmission powers of the existing cellular and D2D connections when assigning power to the incoming D2D request, i.e., $\{P_0, P_1, P_2, \ldots, P_{N-1}\}$ are prior knowledge and fixed. We only need to determine the transmission power for the incoming D2D pair. The computational complexity is reduced to be $O(M_{po})$. If there exist multiple transmission powers of the Nth D2D pair ($P_{N,1}, P_{N,2}, \ldots$), which can satisfy the stable throughput constraint, we select the power based on minimizing the energy consumptions. Lower energy consumptions not only achieve energy efficiency, but also represent lower interference from the D2D link to the cellular connection and vice versa. As a result, more future D2D requests have access to the cellular spectrum. Mathematically, the power allocation strategy is formulated as

$$P_N^* = \arg\min_{P_{N,i}\in\mathcal{R}} P_{N,i}\frac{\lambda_N}{\mu_{N,i}}, \tag{47}$$

where $\mathcal{R}$ is the stable throughput region and $\mu_{N,i}$ is the packet service rate when adopting the transmission power $P_{N,i}$.

In simulations, we will provide the results for both exhaustive search and the above discussed one-dimensional search -based power allocation schemes.

V. Numerical Results

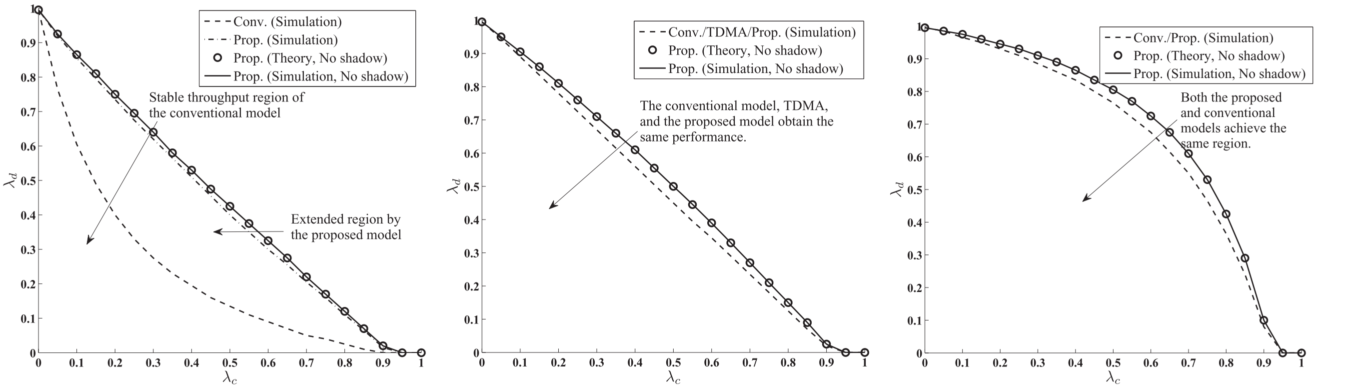
This section investigates the performance of the proposed model through Monte Carlo simulations to verify the significant improvement of proposed model. The channel model are presented in Table II, according to 3GPP evaluation guideline [44]. In addition, due to short-distance communications of D2D pairs, we set the path-loss exponent for a D2D link to be 3 [45] and the path-loss exponent for other links to be 4. The cell radius is 250m and the inter-cell interference is based on the stochastic geometry model in [19]. According to Friis formula, in 2GHz carrier, additional 38dB path loss is considered. We assume 1000 slots in one second and the packet size is 1000bits. The distance between each D2D transmitter and D2D receiver is 20m. We compare the proposed model with the common conventional model, where whether the D2D pair can be admitted or not is determined based on calculated SINRs which only characterize the scenario that inter-user interference always exists [10]–[19].

TABLE II
SIMULATION PARAMETERS

Parameters	Value
Carrier	2GHz
Bandwidth	180KHz
Shadowing	Log-normal distribution with deviation of 10dB
Small Scale Fading	Rayleigh fading
CUE Power Constraint	23dBm
D2D Power Constraint	17dBm
Noise Power	-174 dBm/Hz

Firstly, we consider the single D2D pair scenario, where uplink resources are reused. The stable throughput regions in different scenarios are given in Fig. 3. The distance between the BS and the CUE (L_{cc}) is fixed as 100m, and the location coordinate (in m) of each node is configured in Table III. Thus, the distance between the cellular transmitter to the D2D receiver (L_{cd}), and the distance between the D2D transmitter to the cellular receiver (L_{dc}) in Fig. 3(a) are $L_{cd}=L_{dc}\approx 65m$. Likewise, we have $L_{cd}=L_{dc}\approx 80m$ in Fig. 3(b) and $L_{cd}=L_{dc}\approx 95m$ in Fig. 3(c). Throughout the entire region of λ_c, we calculated the maximum achievable λ_d and obtain the curves of the stable throughout region. For the proposed model, the notation "Theory" stands for the results calculated through the theoretical analysis in Sec.III-B while "Simulation" denotes the results from exhaustive search on transmission powers. The TDMA region with two-user case is known as a straight line $\lambda_c+\lambda_d\approx 1$ and will not change with different location configurations. Thus, for simplification, we do not plot its curve in Fig. 3(a) and 3(c). The dotted lines are the simulation results which take shadow fading into considerations. Small distance leads to severe interference, which requires more accurate characterizations on the interference scenario. Thus, when the distance between the two links is small, the proposed model significantly enlarges the stable throughput region of the conventional one. With the increase of the distance between the two links, the conventional region approaches the proposed one and all of them achieve the same boundary when the conventional one reaches the TDMA region, as depicted in Fig. 3(b). After that, when the distance between the two links continues increasing, where the inter-link interference is too small to affect each other's transmissions, both the conventional region and the proposed one outperform that of TDMA, as shown in Fig. 3(c). In addition, the solid lines are based on the scenarios which only include path loss and Rayleigh fading. It is obvious that the simulation results match the theoretical calculations, which validates the analysis.

Moreover, detailed test on throughput behaviors of the proposed model, based on different locations of D2D pairs, is given in Fig. 4. The following results are obtained from the theoretical computations. For simplification, we still let $L_{cd}=L_{dc}$. The notation "Distance" represents the distance between the D2D pair and the cellular link $L_{cd}(L_{dc})$. When the D2D pair is close to the cellular link, the interactions between each other are strong and accurate interference model is especially necessary to provide insights on transmissions. Meanwhile, with small packet arrival rates, the collision rarely occurs. Thus, the performance of the proposed model approaches that



(a) $L_{cd} = L_{dc} \approx 70m$ (b) $L_{cd} = L_{dc} \approx 85m$ (c) $L_{cd} = L_{dc} \approx 100m$

Fig. 3. The stable throughput regions of single D2D pair scenarios.

TABLE III
LOCATION COORDINATES (IN M) IN SIMULATION SCENARIOS, TX:TRANSMITTER, RX:RECEIVER

	Fig. 3(a)	Fig. 3(b)	Fig. 3(c)	Fig. 7
BS	(0,0)	(0,0)	(0,0)	(0,0)
CUE	(100,0)	(100,0)	(100,0)	(100,0)
$D2D_1$ Tx.	(40,51)	(40,70)	(40,86)	(40,100)
$D2D_1$ Rx.	(60,51)	(60,70)	(60,86)	(60,100)
$D2D_2$ Tx.	–	–	–	(40,-60)
$D2D_2$ Rx.	–	–	–	(60,-60)

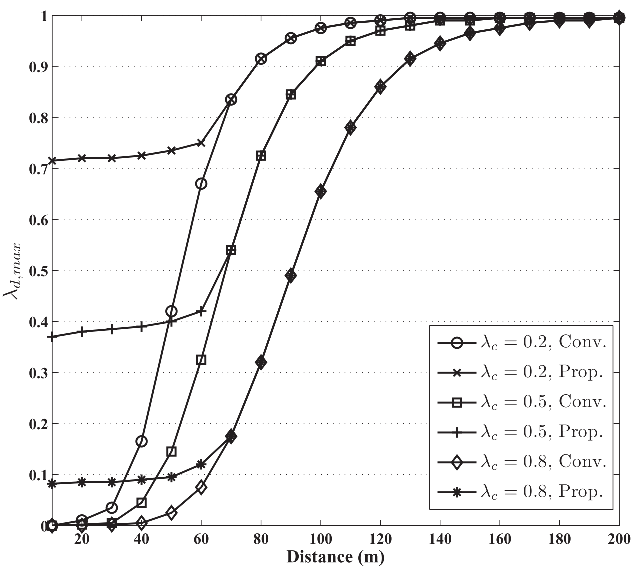


Fig. 4. Throughput behaviors with different distances between the D2D pair and CUE. Single D2D pair scenario. $L_{cc} = 100m$.

of TDMA transmissions. Then, with the increase of the distance, the mutual interferences become weak. According to **Property 1**, the underlay transmissions achieve the best behavior. Under these circumstances, the maximum accessible packet rates computed via the proposed model are the same as those of the conventional one. Finally, with sufficiently large distance, all the curves approach $(1 - \rho_d) \approx 1$. Based on the above experiments, the proposed model can always obtain the best performance in different kinds of scenarios. Especially with underlaying networks, our results demonstrate the potential to explore the possibility of reusing the cellular resources near the D2D pairs, admitting more D2D pairs to the limited cellular resources.

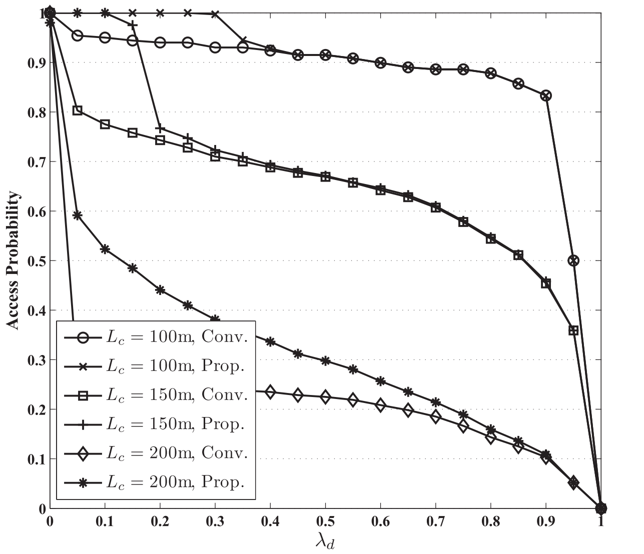


Fig. 5. Admission behaviors with different locations of CUE. Single D2D pair scenario. $\lambda_c = 0.5$.

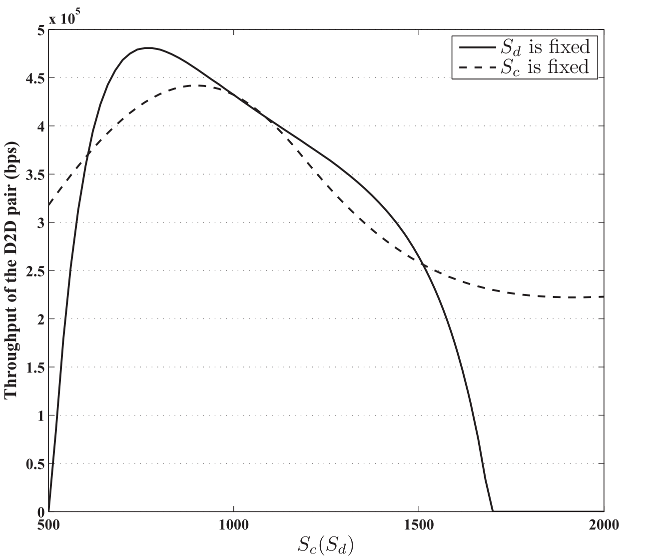
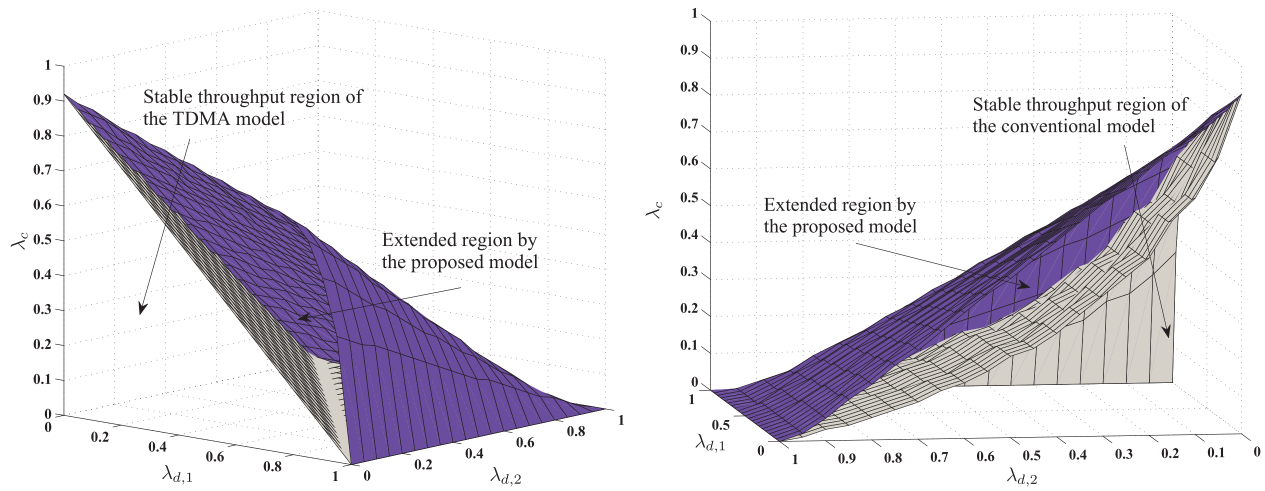


Fig. 6. Throughput behaviors when adjusting packet sizes. Single D2D pair scenario.

Since the objective of improving throughput region is to admit more D2D pairs, we use "Access Probability" in the following figures. The "Access Probability" represents the



(a) Comparisons between the proposed model and TDMA transmissions. (b) Comparisons between the proposed model and the conventional one.

Fig. 7. The stable throughput regions in a multiple D2D pair scenario. $N = 2$.

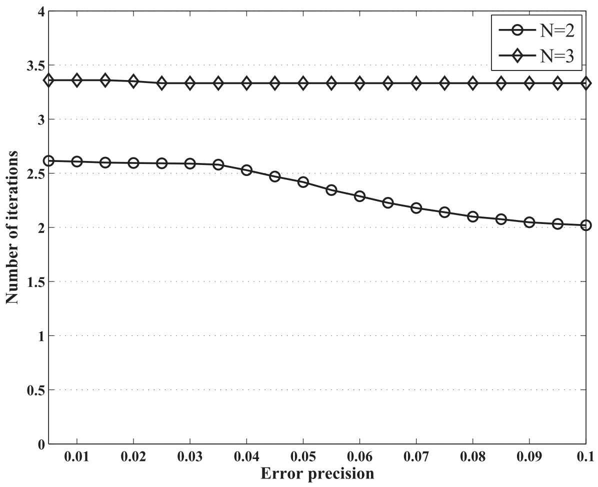


Fig. 8. Iteration behaviors of **Algorithm 1**.

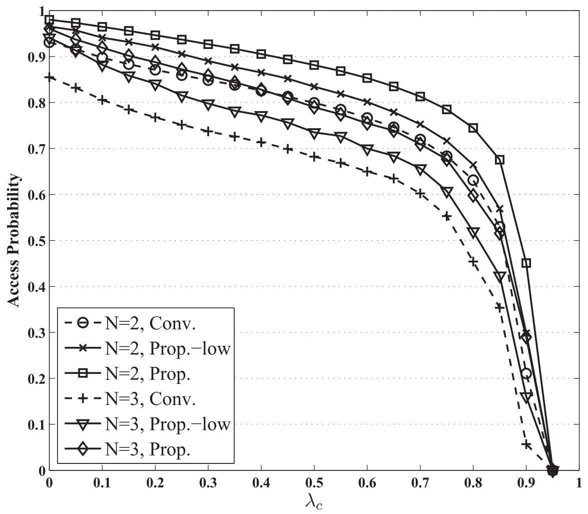


Fig. 9. Admission behaviors of multiple D2D pairs scenarios. $L_{cc} = 100m$.

possibility that the D2D pair can be admitted by specific cellular link in Monte Carlo simulations. We evaluate the system behaviors when changing the distance (L_{cc}) between the BS and CUE, as shown in Fig. 5. With the increase of L_{cc}, the access probabilities decrease. This is because that with the same requirement of data rate, longer distance requires larger transmit power, resulting in more interference. However, the curves still accord with the trends discussed above, showing the significant improvement of the proposed model. In addition, with large L_{cc}, i.e., the CUE is on the edge of the cell, the access probabilities significantly decrease due to inter-cell interference.

Fig. 6 presents the results when adjusting packet sizes S_c, S_d. The data arrival rate of the cellular link is fixed as 5×10^5bps. The transmission powers of both links are fixed. The horizontal axis of the solid line is S_c, where we change the packet size of the cellular link and the packet size of the D2D link is fixed as 1000bits. On the other hand, for the dotted line, we change the packet size of the D2D link while the packet size of the cellular link is fixed as 1000bits. It is obvious that the maximum achievable data rates can be further improved by carefully designing the packet sizes. Just as the discussions in Sec. III-B, we can separately calculate the results with different packet sizes and find the optimal coding and modulation strategies.

The above simulations are based on single D2D pair scenario. We extend our experiments to multiple D2D pairs. The stable throughput regions, when two D2D pairs ($N = 2$) share the same resources with one cellular link, are plotted in Fig. 7, with simulation scenario configured in Table III. The results are obtained based on **Algorithm 1** with error precision 0.01. As described in **Property 1**, the performance of the proposed model in single D2D pair scenario is equal to either TDMA transmissions or the conventional model. However, through Fig. 7, it can be easily observed that the stable throughput region of the proposed model can be larger than both TDMA transmissions and the conventional model at the same time. **Property 1** does not hold in multiple D2D pairs scenarios.

Before further experiments, we would like to examine the effectiveness of the proposed **Algorithm 1**. Thus, Fig. 8

provides the results of the iterations when $N = 2$ and $N = 3$. We adopt Monte Carlo simulations and obtain the average number of iterations for one "successful cycle", where one "successful cycle" is that the changes of the service rates do not exceed the error precision and the stable throughput constraints are also satisfied after certain times of iterations. Although the closed-form expressions on the stable throughput regions for multiple D2D pairs scenarios are unavailable, we can determine the stabilities after a small amount of calculation. In addition, due to the fast convergence, the configuration of the error precision will not significantly affect the system performance.

The further simulation results are presented Fig. 9. The D2D pairs are uniformly distributed in cellular and the average packet arrival rates of D2D pairs are uniformly distributed in [0,1]. According to the two admission strategies mentioned in Sec. IV-B, "Prop." denotes the exhaustive method, and "Prop.-low" stands for the scenario where the D2D pairs are admitted one by one and we only configure the transmission power of the incoming D2D pair. We can see from the figure that even the low-complexity strategy "Prop.-low" can achieve better performance than that of conventional model. With large N, the accuracy of actual interference model plays a more significant role in determining network performance. Thus our proposed model achieves more significant improvement with the increase of N.

VI. Conclusion and Future Work

In this paper, we introduce stable throughput analysis into D2D communications underlaying cellular networks, taking into consideration the packet arrival and service process at each transmitter. A new cross-layer model is established to characterize the actual inter-user interference scenarios between cellular connection and D2D link when they share the same resources. The stable throughput region is derived as a guideline for BS to determine whether two wireless connections can share the same resources. Subsequently, the model and theoretical analysis are extended to a generalized scenario where multiple D2D pairs reuse the same cellular resources. Furthermore, we introduce a low-complexity dynamic admission control scheme to deal with the admission process for the incoming D2D requests. As a consequence, the proposed model outperforms both TDMA and the conventional one, expanding the admission region for D2D pairs by accurately characterizing the interference scenarios. With the increase of the number of D2D pairs that reuse the same cellular resources, the improvement of the proposed model becomes more significant. Such significant improvement is verified through simulations under various scenes.

For the future work, we seek for the hybrid transmission strategy to further improve the throughput region since either orthogonal or non-orthogonal scheduling has its advantages under certain circumstances. To be specific, when multiple links share the same resources, we can let those links which cause severe interference to each other perform orthogonal transmissions and those links which are far away from each other form a random access system. The optimal mode selection and scheduling design need to be fully studied.

Appendix A
Proof of **Lemma 1**

The proof of (9) can be found in [46].

Then, setting $\tilde{t} = \sum_{n=1}^{N} t_n$, based on (9), we have

$$\begin{aligned}
\Pr\left\{\frac{t}{\sum\limits_{n=1}^{N} t_n + a} < b\right\} &= \mathbb{E}|_{\tilde{t}}\left\{\Pr\left\{t < b(\tilde{t}+a)|\tilde{t}\right\}\right\} \\
&= \int_0^{\infty} \sum_{n=1}^{N} \frac{\sigma_n^{2(N-2)}}{\prod\limits_{\substack{m=1,\\ m\neq n}}^{N} (\sigma_n^2 - \sigma_m^2)} e^{-\frac{\tilde{t}}{\sigma_n^2}} \left(1 - e^{\frac{b(\tilde{t}+a)}{\sigma^2}}\right) d\tilde{t} \\
&= 1 - \sum_{n=1}^{N} \frac{\sigma^2 \sigma_n^{2(N-1)}}{\prod\limits_{\substack{m=1,\\ m\neq n}}^{N} (\sigma_n^2 - \sigma_m^2)(b\sigma_n^2 + \sigma^2)} e^{-\frac{ab}{\sigma^2}}. \qquad (48)
\end{aligned}$$

Thus, (10) is also verified.

Appendix B
Proof of **Theorem 1**

According to (2), in order to obtain the stable throughput region, we are supposed to derive the expressions on μ_c and μ_d. Replacing μ_d in (3) with (4), we have

$$a_1\mu_c^2 + a_2\mu_c + a_3 = 0, \qquad (49)$$

where

$$a_1 = 1 - \rho_d, \qquad (50)$$

$$a_2 = \lambda_d(\rho_c^{(I)} - \rho_c) - (1-\rho_c)(1-\rho_d) - \lambda_c(\rho_d^{(I)} - \rho_d), \qquad (51)$$

and

$$a_3 = \lambda_c\left(\rho_d^{(I)} - \rho_d\right)(1-\rho_c). \qquad (52)$$

Let $f(\mu_c) = a_1\mu_c^2 + a_2\mu_c + a_3$, a quadratic function. First, we should prove the existence of solution in the interval $\mu_c \in (0, 1-\rho_c]$. Since ρ_c is the outage probability under non-interference circumstance, the largest achievable service rate is no more than $1-\rho_c$. It is easy to prove that $f(0) > 0$, $f(1-\rho_c) > 0$, $0 < -a_2/2a_1 < 1-\rho_c$. Thus, based on the properties of a quadratic function, the existence of solution is equivalent to $\Delta = a_2^2 - 4a_1a_3 \geq 0$, i.e.,

$$\begin{aligned}
&\left(\rho_d^{(I)}-\rho_d\right)^2\lambda_c^2 - 2\left(\rho_d^{(I)}-\rho_d\right)\Big[\lambda_d\left(\rho_c^{(I)}-\rho_c\right) \\
&+(1-\rho_c)(1-\rho_d)\Big]\lambda_c + \Big[\lambda_d\left(\rho_c^{(I)}-\rho_c\right) - (1-\rho_c)(1-\rho_d)\Big]^2 \geq 0, \qquad (53)
\end{aligned}$$

the solution of which is

$$\left\{ \begin{array}{l} \text{(a)}: \ \lambda_c \le \dfrac{\left(\sqrt{\lambda_d(\rho_c^{(I)}-\rho_c)}-\sqrt{(1-\rho_c)(1-\rho_d)}\right)^2}{\rho_d^{(I)}-\rho_d} \\ \text{or (b)}: \ \lambda_c \ge \dfrac{\left(\sqrt{\lambda_d(\rho_c^{(I)}-\rho_c)}+\sqrt{(1-\rho_c)(1-\rho_d)}\right)^2}{\rho_d^{(I)}-\rho_d} \end{array} \right\} \tag{54}$$

Since $\frac{\left(\sqrt{\lambda_d(\rho_c^{(I)}-\rho_c)}+\sqrt{(1-\rho_c)(1-\rho_d)}\right)^2}{\rho_d^{(I)}-\rho_d} > 1-\rho_c$, only (54).(a) needs to be satisfied. Then, according to $\lambda_c < \mu_c$, we have $\lambda_c < \frac{\sqrt{a_2^2-4a_1a_3}-a_2}{2a_1}$. The solution of $\lambda_c < \frac{\sqrt{a_2^2-4a_1a_3}-a_2}{2a_1}$ is expressed as

$$\left\{ \begin{array}{l} \text{(a)}: \lambda_c < (1-\rho_c)-\lambda_d \dfrac{\rho_c^{(I)}-\rho_c}{1-\rho_d^{(I)}} \\ \text{or (b)}: \lambda_c < \dfrac{(1-\rho_c)(1-\rho_d)-\lambda_d\left(\rho_c^{(I)}-\rho_c\right)}{2-\rho_d-\rho_d^{(I)}} \end{array} \right\} \tag{55}$$

Based on (54).(a) and (55).(a), it is easy to prove that $(1-\rho_c)-\lambda_d\frac{\rho_c^{(I)}-\rho_c)}{1-\rho_d^{(I)}} \le \frac{\left(\sqrt{\lambda_d(\rho_c^{(I)}-\rho_c)}-\sqrt{(1-\rho_c)(1-\rho_d)}\right)^2}{\rho_d^{(I)}-\rho_d}$. Thus, (18).(a) is verified. Likewise, we can obtain (18).(b) through $\lambda_d < \mu_d$. Meanwhile, (19) is based on (54).(a), (55).(b) and the corresponding expression on λ_d.

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