Transmit Power Control for D2D-Underlaid Cellular Networks Based on Statistical Features

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***Abstract*—By allowing two nearby mobile devices to communicate via a direct link between them, device-to-device (D2D) communications can efficiently increase the capacity of D2D-underlaid cellular networks, in which D2D and cellular communications share the same frequency band. However, the coexistence of D2D and cellular communications in the same frequency band will cause interference between the D2D and cellular users, thus degrading their performance. One may control the transmit power based on the real-time channel-state information (CSI) to mitigate this interference, but it is difficult to acquire the real-time CSI between D2D/cellular transmitters and D2D receivers. To overcome this difficulty, we propose novel statistical-feature-based power control (SFPC), which determines the transmit power based on statistical (instead of real-time) CSI. The proposed SFPC combines the power control—that is aware of D2D success likelihood—with opportunistic access control to 1) reduce the interference caused by D2D communications and 2) maximize the area spectral efficiency of D2D communications. Specifically, it aims to minimize the D2D transmit power and optimize the selection of access threshold. Our simulation results show that SFPC can increase both the cellular communication success probability and the energy efficiency of D2D communications, as well as reduce the average D2D transmit power.**

***Index Terms*—Cellular networks, device-to-device (D2D) communications, opportunistic access control, Poisson point process (PPP), power control.**

I. Introduction

DEVICE-TO-DEVICE (D2D) communications have been studied extensively to meet the increasing demand for wireless communication between nearby devices/users/applications, e.g., social networks or media sharing [1]–[5]. By allowing direct communications between nearby devices (without directing all communications through the BSs), D2D communications offer several potential benefits, such as reduction of mobile devices' energy consumption, improvement of spectrum utilization, and capacity.

In spite of these potential benefits, the coexistence of D2D and cellular communications in the same frequency band is challenging due to the difficulty of interference management. This is because 1) cellular users experience cross-tier interference from the D2D transmitters, and 2) D2D receivers experience both inter-D2D interference and cross-tier interferences from cellular users.

Transmit power control exploits real-time channel-state information (CSI) between communicating entities to mitigate the interference in wireless networks. However, due to dynamically changing communication environments and inaccurate channel estimation at the receivers, it is difficult to obtain the accurate real-time CSI [6]–[8], especially in D2D-underlaid cellular networks. That is, CSI frequently changes due to the high mobility of cellular and D2D users, and D2D receivers cannot accurately estimate the time-varying channel state between multiple D2D/cellular transmitters and D2D receivers within the channel's coherence time. If outdated CSI is used to determine the transmit power, wireless users may experience severe performance degradation and/or outage. To overcome this problem, we propose SFPC, which can determine the transmit power based on the statistical (instead of the real-time) CSI. The statistical CSI accounts for the effects of mobility and time-varying channel and, thus, is estimated based on the PDF of user locations and fadings. The proposed SFPC combines the power control that is aware of the D2D success probability with opportunistic access control to reduce the interference caused by D2D communications and maximize the area spectral efficiency of D2D communications.

A. Related Work and Motivation

There has been extensive research on dynamic power control for D2D-underlaid cellular networks to mitigate the interference caused by D2D communications. A dynamic power control method was proposed in [9], focusing on the protection of existing cellular links by limiting the D2D transmission power. A D2D power allocation scheme was proposed in [10] to maximize throughput for deterministic networks. Doppler *et al.* [1] reduced the interference from D2D transmitters to cellular users by restricting the D2D transmit power and the distance between D2D pairs. The fixed booster and backoff factors were proposed in [2] to control D2D transmit power and mitigate the interference caused by D2D communications.

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Most existing schemes for D2D power control are based on the real-time CSI to mitigate interference [2], [9]–[11]. However, the communication environment is complex and dynamic in D2D-underlaid cellular networks, making it difficult to obtain the accurate real-time CSI between multiple D2D/cellular transmitters and D2D receivers within the channel's coherence time.

The statistical features of CSI were also used in [12] and [13] for interference management. However, these schemes only involve two transmit powers: zero or peak power. To further decrease the interference and improve the energy efficiency of D2D communications, we propose SFPC that determines D2D transmit power within the range from zero to peak power.

Moreover, SFPC is different from the power control schemes in a cognitive radio cellular network, in which cognitive devices/users intelligently sense and opportunistically access spectrum holes left unused by cellular users to avoid interference. The power control algorithm utilizes the information gathered from sensing to limit the interference from cognitive radio users to cellular users [14]–[16], with no BS assistance. In contrast, the D2D transmit power is controlled by the cellular network. Specifically, SFPC utilizes the CSI statistical features provided by the BS for power control and opportunistic access control.

B. Advantages

The proposed SFPC has the following four main advantages.

1) *Reduced latency*: A shorter reaction time of power control reduces latency. SFPC achieves this based on the CSI statistical features provided by the BS without complex interactions to manage interference.
2) *Resilience to users' movements*: Users' movements cause CSI to vary. To cope with this problem, SFPC utilizes the statistical CSI (instead of the CSI in a particular deployment) and is thus robust to users' movements.
3) *Improved link reliability*: The D2D success probability is used as a control threshold to ensure the D2D communication reliability.
4) *Low overhead*: There is no signaling overhead for sharing the real-time CSI or location information.

This paper is organized as follows. We present the model for D2D-underlaid cellular networks in Section II. D2D success probability-aware power control and SFPC are presented in Sections III and IV, respectively. The proposed approaches are evaluated in Section V, and the paper concludes with Section VI.

II. System Model

Fig. 1 shows the system model of an uplink D2D-underlaid cellular network, in which an uplink cellular user communicates with the BS, while multiple D2D links are using the same spectrum. This D2D-underlaid cellular network model is commonly used in the literature [12], [13]. The uplink D2D-underlaid cellular network consists of cellular and D2D tiers. The BS and its associated cellular user form the cellular tier, where the circular disk $\mathcal{C}$ of radius R represents the coverage region of the BS located at the center. A cellular uplink user is located randomly within the cell according to a uniform distribution. The D2D transmitters and their intended receivers form the D2D tier. The D2D transmitters are randomly distributed in the network coverage area and represented as a homogeneous PPP, i.e., Φ, with density λ. We assume that the intended D2D receivers are uniformly and independently located within the distance R_d of their associated D2D transmitters, where R_d is the D2D communication range. The PDF of the communication distance, which is defined as the direct link distance between a D2D transmitter and its corresponding D2D receiver, is

$$f_d(x) = \frac{2x}{(R_d)^2}, \qquad 0 \le x \le R_d. \tag{1}$$

Let K be the number of D2D transmitters in $\mathcal{C}$, which is a Possion random variable with mean $\mathbb{E}[K] = \lambda \pi R^2$ according to the above model.

Given a particular realization of the PPP Φ, the received signals at the BS and D2D receiver k are

$$y_0 = h_{0,0} d_{0,0}^{-\alpha/2} s_0 + \sum_{i=1}^{K} h_{i,0} d_{i,0}^{-\alpha/2} s_i + n_0 \tag{2}$$

$$y_k = h_{k,k} d_{k,k}^{-\alpha/2} s_k + \sum_{i=0, i \neq k}^{K} h_{i,k} d_{i,k}^{-\alpha/2} s_i + n_k \tag{3}$$

where

1) y_0 and y_k represent the received signals at the BS and D2D receiver k, respectively;
2) s_0 and s_k are the signals sent by the uplink cellular user and D2D transmitter k, respectively;
3) n_0 and n_k are the additive noises at the BS and D2D receiver k, which are known to have complex normal distributions $\mathcal{CN}(0, \sigma^2)$ [12].

We assume that all links experience Rayleigh fading while ignoring the effect of slow fading [12], [13], [17]. Let $h_{0,0}$, $h_{i,0}$, $h_{0,k}$, and $h_{i,k}$ be small-scale fading from the cellular user to the BS, from D2D transmitter i to the BS, from the cellular user to the D2D receiver k, and from D2D transmitter i to the D2D receiver k, which are independently distributed as $\mathcal{CN}(0, 1)$ [12], [13]. A large-scale attenuation is assumed as the standard path-loss propagation $d_{A,B}^{-\alpha}$, where $d_{A,B}$ is the distance from A to B and α is the path-loss exponent. Let $d_{0,0}$, $d_{i,0}$, $d_{0,k}$, and $d_{i,k}$ denote the distance from the cellular user to the BS, from D2D transmitter i to the BS, from the cellular user to D2D receiver k, and from D2D transmitter i to D2D receiver k.

SINR is a commonly used metric for the evaluation of communication quality in cellular networks. User communications are successful if and only if their corresponding receivers' SINR are higher than the target SINR threshold. The SINR at the BS and D2D transmitter k is

$$\mathrm{SINR}_0(\mathbf{p}) = \frac{|h_{0,0}|^2 d_{0,0}^{-\alpha} p_0}{I_0^d + \sigma^2} \tag{4}$$

$$\mathrm{SINR}_k(\mathbf{p}) = \frac{|h_{k,k}|^2 d_{k,k}^{-\alpha} p_k}{I_k^c + I_k^d + \sigma^2} \tag{5}$$

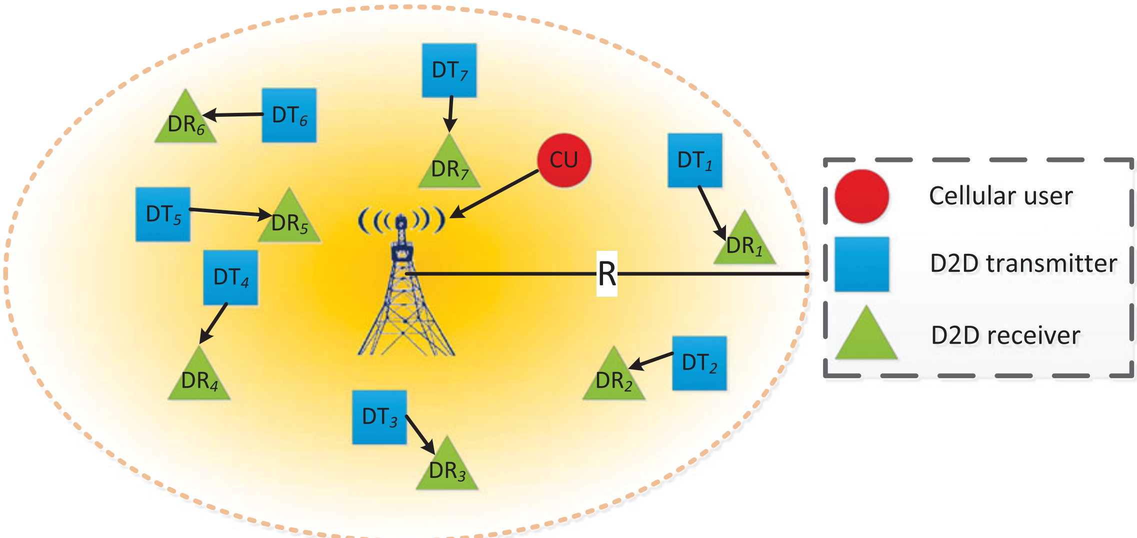

Fig. 1. System model of D2D-underlaid cellular networks.

where

$$I_0^d = \sum_{i=1}^{K} |h_{i,0}|^2 d_{i,0}^{-\alpha} p_i$$

$$I_k^d = \sum_{i=1, i\neq k}^{K} |h_{i,k}|^2 d_{i,k}^{-\alpha} p_i$$

$$I_k^c = |h_{0,k}|^2 d_{0,k}^{-\alpha/2} p_0$$

and $\mathbf{p} = [p_0, p_1, \ldots, p_K]^T$ is the transmit power vector, with p_0 being the power of the cellular user and $p_i (i \neq 0)$ being the power of D2D transmitter i; and I_0^d, I_k^d, and I_k^c are the interferences from D2D transmitters to BS, from other D2D pairs to D2D receiver k, and from the cellular user to D2D receiver k, respectively.

Area spectral efficiency is a measure of the number of users that can be simultaneously supported by a limited radio frequency bandwidth per unit area [18]–[20]. In D2D-underlaid cellular networks, area spectral efficiency of D2D communications can be expressed as [13]

$$\mathcal{T}(\gamma) = \widetilde{\lambda} \mathbb{P}\left(\mathrm{SINR}(\mathbf{p}) > \gamma\right) \log_2(1+\gamma) \tag{6}$$

where γ denotes the target SINR threshold, $\mathbb{P}\left(\mathrm{SINR}(\mathbf{p}) > \gamma\right)$ is the mean of the D2D success probability, $\widetilde{\lambda} = P_t \lambda$ denotes the effective D2D link density without any inactive D2D link, and P_t is the mean of the access probability. The abbreviations and notations used throughout this paper are summarized in Tables I and II for the ease of reference.

TABLE I
ABBREVIATIONS DEFINITION

Abbreviations	Meaning
D2D	Device-to-Device
BS	Base Station
PPP	Poisson Point Process
PDF	Probability Density Function
SINR	Signal to Interference plus Noise Ratio
CSI	Channel State Information
SFPC	Statistical-Feature-based Power Control

TABLE II
NOTATIONS DEFINITION

Symbol	Meaning
R	Cell radius
R_d	D2D communication range
$h_{A,B}$	Fading from A to B
$d_{A,B}$	Distance from A to B
λ	D2D link density
a	Path-loss exponent
γ	Target SINR threshold
p_0	Transmit power of cellular user
p_k	Transmit power of D2D transmitter k
$p_k^\star$	Minimum transmit power of D2D transmitter k
$P_{t,k}$	Access probability of D2D transmitter k
$P_{t,k}^\star$	Optimal access probability of D2D transmitter k
$G_k^\star$	Optimal access threshold of D2D transmitter k

III. Device-to-Device Success Probability-Aware Power Control

This section presents D2D success probability-aware power control, a key component of SFPC. The proposed algorithm significantly decreases the cross-tier interference from D2D communications to cellular communications by minimizing the D2D transmit power, while satisfying the target SINR requirements of D2D communications. For D2D transmitter k ($k \in \{1, 2, \ldots, K\}$), the minimum transmit power is obtained by solving the following optimization problem:

$$\begin{aligned} \min \quad & p_k \\ \text{s.t.} \quad & \frac{|h_{k,k}|^2 d_{k,k}^{-\alpha} p_k}{|h_{0,k}|^2 d_{0,k}^{-\alpha} p_0 + \sum_{i=1, i\neq k}^{K} |h_{i,k}|^2 d_{i,k}^{-\alpha} p_i + \sigma^2} \geqslant \gamma \\ & p_i \leqslant p_{\max,d}, \qquad i \in \{1, 2, \ldots, K\} \\ & p_0 \leqslant p_{\max,c} \end{aligned} \tag{7}$$

where $p_{\max,d}$ and $p_{\max,c}$ are the maximum transmit power of D2D and cellular communications, respectively.

Clearly, one D2D transmitter can lower its transmit power if the corresponding D2D receiver's SINR is higher than γ, reducing both the inter-D2D interference and cross-tier interference while satisfying the requirements of D2D communications. However, because the communication environment is complex and dynamic in D2D-underlaid cellular networks, it is difficult to get accurate real-time CSI to estimate the SINR in real wireless networks, especially in D2D-underlaid cellular networks. This is because 1) CSI frequently changes due to the high mobility of cellular and D2D users, and 2) D2D receivers may not accurately estimate the time-varying channel between multiple D2D transmitters (cellular user) and D2D receivers within the channel's coherence time. If outdated CSI is used to determine the transmit power, users will experience severe performance loss and/or outage. Therefore, we estimate the D2D success probability—the SINR complementary cumulative distribution function [21]—based on the statistical CSI and, then, use the D2D success probability to determine the minimum D2D transmit power.

We estimate the D2D success probability as follows. For any given p_k, the SINR at D2D receiver k is defined as in (4), and the D2D success probability of D2D receiver k can then be expressed as

$$\mathbb{P}\left(\text{SINR}_k(\mathbf{p}) > \gamma | p_k\right) = e^{-a_1 p_k^{-1} - a_2 p_k^{-\frac{2}{a}}} \cdot g_1\left(p_k^{-\frac{2}{a}}\right) \tag{8}$$

where

$$a_1 = \sigma^2 \gamma d_{k,k}^a$$
$$a_2 = \frac{\pi\lambda}{\text{sinc}\left(\frac{2}{a}\right)} \mathbb{E}\left[(p_i)^{\frac{2}{a}}\right] \gamma^{\frac{2}{a}} d_{k,k}^2$$
$$g(x) = \frac{1}{1 + x\left(\gamma d_{k,k}^a p_0\right)^{\frac{2}{a}} \cdot \left(\frac{128R}{45\pi}\right)^{-2}}.$$

Proof: See Appendix A. ∎

We also compute a lower bound of D2D success probability to ensure the D2D success probability to be always higher than the operator-specified threshold even in the presence of the maximum interference. The lower bound of D2D success probability is computed by setting $p_i = p_{\max,d}$ in a_2 to maximize the inter-D2D interference, which can be expressed as

$$\mathbb{P}_{\text{low}}\left(\text{SINR}_k(\mathbf{p}) > \gamma | p_k\right) = e^{-a_1 p_k^{-1} - a_3 p_k^{-\frac{2}{a}}} \cdot g\left(p_k^{-\frac{2}{a}}\right) \tag{9}$$

where

$$a_3 = \frac{\pi\lambda}{\text{sinc}\left(\frac{2}{a}\right)} (p_{\max,d})^{\frac{2}{a}} \gamma^{\frac{2}{a}} d_{k,k}^2,$$

and $\mathbb{P}_{\text{low}}\left(\text{SINR}_k(\mathbf{p}) > \gamma | p_k\right)$ denotes the lower bound of the D2D success probability.

Let P_{th} be the operator-specified D2D success probability threshold. Thus, the problem in (7) can be transformed to

$$\begin{aligned} \min \quad & p_k \\ \text{s.t.} \quad & \mathbb{P}_{\text{low}}\left(\text{SINR}_k(\mathbf{p}) > \gamma | p_k\right) \geqslant P_{\text{th}} \\ & p_i \leqslant p_{\max,d}, \qquad i \in \{1, 2, \ldots, K\} \\ & p_0 \leqslant p_{\max,c} \end{aligned} \tag{10}$$

and then by solving

$$e^{-a_1 \cdot p_k^{-1} - a_3 \cdot p_k^{-\frac{2}{a}}} \cdot g\left(p_k^{-\frac{2}{a}}\right) - P_{\text{th}} = 0 \tag{11}$$

we can determine the minimum D2D transmit power $p_k^\star$ for D2D transmitter k. Unsurprisingly, it is challenging to find a closed-form solution for $p_k^\star$ in (11). For simplicity, we ignore the noise by assuming $\sigma^2 = 0$ in a_1. This is reasonable because the interference is much stronger than the noise in (especially dense) D2D-underlaid cellular networks. This simplification also transforms (11) to a homogeneous equation, which is solvable. Thus, the minimum D2D transmit power can be expressed as

$$\begin{aligned} p_k^\star &= \min\left(\left(\frac{a_3 a_4}{a_4 W\left(\frac{a_3}{a_4} e^{\frac{a_3 P_{th}}{a_4}}\right) - a_3 P_{\text{th}}}\right)^{\frac{a}{2}}, p_{\max,d}\right) \\ &= \min\left(\left(\frac{a_5 a_6 d_{k,k}^2}{a_6 W\left(\frac{a_5}{a_6} e^{\frac{a_5 P_{\text{th}}}{a_6}}\right) - a_5 P_{\text{th}}}\right)^{\frac{a}{2}}, p_{\max,d}\right) \\ &= \min\left(\frac{\mu}{d_{k,k}^{-a}}, p_{\max,d}\right) \qquad (12) \\ &= f(d_{k,k}) \qquad (13) \end{aligned}$$

where

$$a_4 = P_{\text{th}}(\gamma d_{k,k}^a p_0)^{\frac{2}{a}} \left(\frac{128R}{45\pi}\right)^{-2}$$
$$a_5 = \frac{\pi\lambda}{\text{sinc}\left(\frac{2}{a}\right)} (p_{\max,d})^{\frac{2}{a}} \gamma^{\frac{2}{a}}$$
$$a_6 = P_{\text{th}}(\gamma p_0)^{\frac{2}{a}} \left(\frac{128R}{45\pi}\right)^{-2}$$
$$\mu = \left(\frac{a_5 a_6}{a_6 W\left(\frac{a_5}{a_6} e^{\frac{a_5 P_{\text{th}}}{a_6}}\right) - a_5 P_{\text{th}}}\right)^{\frac{a}{2}} \tag{14}$$

and W denotes the Lambert W function. In addition, $\mathbf{p}^\star = [p_0, p_1^\star, \ldots, p_K^\star]^T$ denotes the minimum transmit power vector, with $p_i^\star (i \neq 0)$ being the minimum transmit power of D2D transmitter i.

Proof: See Appendix B. ∎

Note that $p_k^\star$ depends on $d_{k,k}$ in (13). This is because for a specific PPP realization, each D2D link experiences different SINRs and, thus, has different transmit power levels, depending

Algorithm 1: D2D Success Probability-Aware Power Control.

1: BS computes μ according to (14);
2: BS broadcasts μ to D2D transmitters;
3: **for** each D2D transmitter **do**
4: Estimate communication distance;
5: Compute the minimum transmit power in (13);
6: Set the transmit power being the minimum transmit power;
7: **end for**

on its location and surrounding environments, i.e., the distance between a D2D transmitter and its intended receiver. In other words, a D2D transmitter with short communication distance has lower transmit power than a D2D transmitter with a larger communication distance, as it has potentially higher SINR.

The proposed power control is based on the statistical CSI, which does not require the real-time CSI. The statistical CSI is estimated based on the PDF of users' locations and fadings. Therefore, the signaling for sharing CSI and location information is not needed. A D2D transmitter selects the transmit power based solely on the knowledge of the communication distance and μ.

Remark 1: To realize the proposed power control algorithm, each D2D transmitter needs to know 1) the communication distance and 2) the value of μ. Each D2D transmitter can obtain the communication distance through the feedback from the corresponding D2D receiver. For instance, in a multicarrier system, a D2D receiver can reliably estimate the distance-based path loss using pilot signals sent on a control channel by averaging the effects of fadings over multiple resource blocks and sends it back to the D2D transmitter via a feedback channel [12]. As shown in (14), each D2D transmitter has the same μ, because the PDF of inter-D2D interference and the cross-tier interference are the same for different D2D receivers. Therefore, the value of μ can be broadcast by the BS. In order to obtain the value of μ, the BS needs to know the D2D link density, the target SINR threshold, the transmit power constraints, the cell radius, and the D2D success probability threshold. The D2D link density is estimated by the BS during the process of establishing the D2D link [3], [4], [12], [22], and the other information is set by the operator. Therefore, the BS can obtain the value of μ and broadcast it to D2D transmitters via a downlink control channel. Finally, each D2D transmitter can determine its minimum transmit power, depending on the communication distance and μ. The D2D success probability-aware power control method is summarized in Algorithm 1.

IV. Statistical-Feature-Based Power Control

The inter-D2D interference would be very high in the case of dense D2D link deployment. As a result, the D2D success probability threshold may not be satisfied, even when the maximum power $p_{\max,d}$ is adopted by the D2D transmitter, especially when the target SINR threshold is high.

Targeting the case of strong inter-D2D interference, we propose SFPC which extends D2D success probability-aware power control by integrating it with opportunistic access control to maximize the area spectral efficiency of D2D communications while decreasing both inter-D2D and cross-tier interferences. Instead of allowing all D2D transmitters to access the channels, a part of D2D pairs cannot access the network to decrease interferences in the proposed SFPC. Selecting a proper access probability and access threshold play an important role in our algorithm. Choosing a small access probability (a large access threshold) reduces interferences at the cost of a smaller number of active D2D transmitters in the cell. Therefore, it is important to find an optimal access probability and access threshold to maximize the area spectral efficiency of D2D communications. In what follows, we determine an optimal access probability and access threshold.

We maximize area spectral efficiency of D2D communications $\mathcal{T}(\gamma)$ by optimizing the mean of the access probability P_t, which can be expressed as

$$\begin{aligned} \max_{P_t} \quad & \mathcal{T}(\gamma) \\ \text{s.t.} \quad & 0 < P_t \leqslant 1 \end{aligned} \tag{15}$$

where $\mathcal{T}(\gamma)$ is defined in (6). Note that P_t is the average access probability. For a specific PPP realization, each D2D link experiences a different SINR and, thus, has different access probabilities depending on the communication distance. That is, a D2D transmitter with a short communication distance has a higher access probability than a D2D transmitter with a larger communication distance, because it has a potentially higher SINR. Since the analysis performed for a typical link indicates the spatially averaged performance of the network by Slivnyak's theorem [23], [24], the means of the D2D success and access probabilities can be expressed as

$$\begin{aligned} \mathbb{P}\left(\mathrm{SINR}(\mathbf{p}^\star) > \gamma\right) &= \frac{\sum_{k=1}^{K} \mathbb{E}[\mathbb{P}(\mathrm{SINR}_k(\mathbf{p}^\star) > \gamma)]}{K} \\ &= \frac{K\mathbb{E}[\mathbb{P}(\mathrm{SINR}_k(\mathbf{p}^\star) > \gamma)]}{K} \\ &= \mathbb{E}[\mathbb{P}(\mathrm{SINR}_k(\mathbf{p}^\star) > \gamma)|d_{k,k}] \end{aligned}$$

and

$$\begin{aligned} P_t &= \frac{\sum_{k=1}^{K} \mathbb{E}[P_{t,k}]}{K} \\ &= \mathbb{E}[P_{t,k}|d_{k,k}] \end{aligned} \tag{16}$$

where $P_{t,k}$ denotes the access probability for D2D transmitter k. Therefore, for any given $d_{k,k}$, the problem in (15) can be transformed to

$$\begin{aligned} \max_{P_{t,k}} \quad & P_{t,k}\lambda\mathbb{P}(\mathrm{SINR}_k(\mathbf{p}^\star) > \gamma)\log_2(1+\gamma) \\ \text{s.t.} \quad & 0 < P_{t,k} \leqslant 1. \end{aligned} \tag{17}$$

Based on (8), the above objective function can be transformed further to

$$\max_{P_{t,k}} \quad P_{t,k}\mathbb{P}(\text{SINR}_k(\mathbf{p}^\star) > \gamma)$$

$$\Rightarrow \max_{P_{t,k}} \quad P_{t,k}\cdot e^{-a_1(p_k^\star)^{-1}-P_{t,k}b_1 d_{k,k}^2 (p_k^\star)^{-\frac{2}{a}}}\cdot g((p_k^\star)^{-\frac{2}{a}})$$

where

$$b_1 = \frac{\pi\lambda}{\text{sinc}\left(\frac{2}{a}\right)}\mathbb{E}\left[(p_i^\star)^{\frac{2}{a}}\right]\gamma^{\frac{2}{a}} \tag{18}$$

and $p_i^\star$ is the minimum D2D transmit power of D2D transmitter i identified by D2D success probability-aware power control, which can be expressed as

$$\mathbb{E}\left[(p_i^\star)^{\frac{2}{a}}\right] = \int_0^{R_d}(f(x))^{\frac{2}{a}}\frac{2x}{(R_d)^2}dx \tag{19}$$

where R_d is the D2D communication range, and $f(x)$ is defined in (13).

The transformed problem can be solved by

$$\frac{d\{P_{t,k}\cdot e^{-a_1(p_k^\star)^{-1}-b_1 d_{k,k}^2 P_{t,k}(p_k^\star)^{-\frac{2}{a}}}\cdot g_3((p_k^\star)^{-\frac{2}{a}})\}}{dP_{t,k}} = 0$$

and thus

$$b_1 d_{k,k}^2 P_{t,k}(p_k^\star)^{-\frac{2}{a}} = 1. \tag{20}$$

Subsequently, the optimal access probability for D2D transmitter k, denoted by $P_{t,k}^\star$, can be expressed as

$$P_{t,k}^\star = \min\left\{\frac{(p_k^\star)^{\frac{2}{a}}}{b_1 d_{k,k}^2}, 1\right\} = \min\left\{\frac{(f(d_{k,k}))^{\frac{2}{a}}}{b_1 d_{k,k}^2}, 1\right\}. \tag{21}$$

Then, the optimal access threshold is designed according to the optimal access probability; D2D transmitter k is active whenever its channel gain $|h_{k,k}|^2 d_{k,k}^{-a}$ is above its optimal access threshold. Since $P_{t,k}^\star = \mathbb{P}(|h_{k,k}|^2 d_{k,k}^{-a} > G_k^\star)$, the optimal access threshold can be obtained as

$$G_k^\star = \frac{-\ln(P_{t,k}^\star)}{d_{k,k}^\alpha} \tag{22}$$

where $G_k^\star$ denotes the optimal access threshold for D2D transmitter k. A D2D transmitter selects the transmit power based solely on the knowledge of its communication distance, channel gain, μ, and the optimal access threshold. As shown in Fig. 2, it can be observed that the SFPC improves the area spectral efficiency of D2D communications over D2D success probability-aware power control and the performance gain increases as λ and γ increase. The SFPC is summarized in Algorithm 2.

V. Simulation

We now use simulation to evaluate the performance of SFPC algorithm for D2D-underlaid cellular networks in terms of cellular communication success probability, average D2D transmit power, energy efficiency of D2D communications, and D2D success probability. The performance of the proposed SFPC is compared with three other strategies:

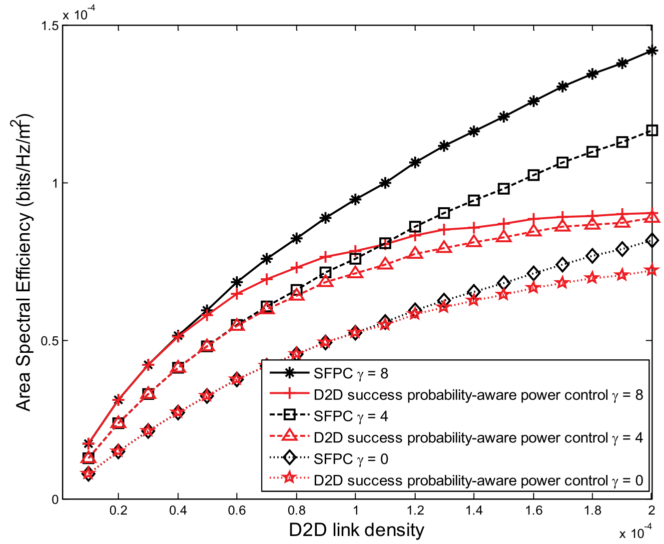

Fig. 2. Area spectral efficiency of D2D communications according to different D2D target SINR thresholds with a set of parameters $p_0 = 100$ mW, $p_k = 0.1$ mW, $R = 500$ m, $R_d = 50$ m, and $P_{\text{th}} = 85\%$.

Algorithm 2: Statistical-Feature-Based Power Control.

BS computes μ and b_1 according to (14) and (18);
BS broadcasts the values to D2D transmitters;
for Each D2D transmitter **do**
  Estimate its communication distance and channel gain;
  Compute the optimal access threshold according to (22);
  if The channel gain is above the optimal access threshold
    Carry out Algorithm 1 and set the transmit power being the minimum transmit power according to (13);
  else
    Set the transmit power being 0;
  end if
end for

1) conditional SIR-aware access control (Conditional SIR-aware AC) [13];
2) ON–OFF power control (ON–OFF PC) [12];
3) no PC: all D2D transmitters use $p_{\max,d}$.

The default simulation settings are summarized in Table III, unless otherwise specified, which are set based on the results in [12] and [13]. The BS is located at the center, and the cellular user is uniformly located in the cell of radius R. D2D transmitters are distributed in the cell according to a PPP with density λ. Given the D2D communication range R_d, each intended D2D receiver is uniformly and independently located within R_d of its associated D2D transmitter in the isotropic direction. We obtain the following results by averaging 2000 simulation runs.

Fig. 3 shows the cellular communication success probability as a function of the D2D link density. From Fig. 3, one can notice that the proposed algorithm greatly improves the

TABLE III
DEFAULT SIMULATION SETTINGS

Parameter	Value
Cell radius (R)	500 (m)
D2D communication range (R_d)	20 (m)
D2D link density on a subchannel (λ)	from 0.00003 to 0.00010
Path-loss exponent (α)	4
The transmit power of the cellular user	$p_0 =$ 100 mW
The maximum D2D transmit power	$p_{\max,d} =$ 0.1 mW
D2D success probability threshold ($P_{\rm th}$)	75%, 85%
BS target SINR threshold	−3 (dB)
D2D target SINR threshold	4 (dB)
Noise variance (σ^2) for 1-MHz bandwidth	−143.97 (dBm)
The number of realizations	2000 geometry drop

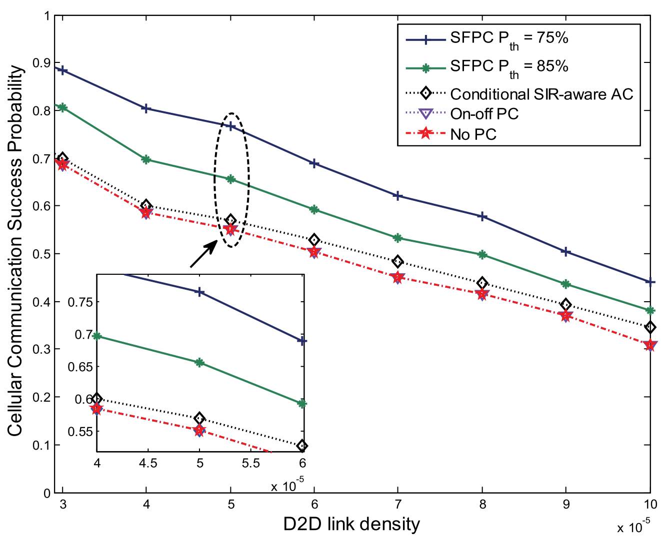

Fig. 3. Cellular communication success probability.

cellular communication success probability, implying the proposed algorithm's efficiency in mitigating the interference caused by D2D communications via power control. For example, when the D2D link density is 0.00005 ($\mathbb{E}[K] = 39.2$), SFPC improves the cellular communication success probability from 55.2% (ON–OFF PC, No PC) and 57% (conditional SIR-aware AC) to 65.6% (SFPC $P_{\rm th} = 85\%$) and 76.6% (SFPC $P_{\rm th} = 75\%$), respectively. Note that the ON–OFF power control yields the same performance as the case of no power control because the access probability is 1. The cellular communication success probability decreases as the D2D success probability threshold increases because the D2D transmit power increases monotonically as the D2D success probability threshold increases, thus increasing the interference from D2D communications.

Fig. 4 plots the average D2D transmit power versus the D2D link density. SFPC can reduce the transmit power significantly compared to other schemes, especially when the D2D link density is low. For example, at $\lambda = 0.00003$ ($\mathbb{E}[K] = 23.5$), the average D2D transmit power is 0.1 (ON–OFF PC, No PC), 0.091 (conditional SIR-aware AC), 0.042 (SFPC $P_{\rm th} = 85\%$), and 0.013 (SFPC $P_{\rm th} = 75\%$), respectively. The average D2D transmit power monotonically increases as the D2D success

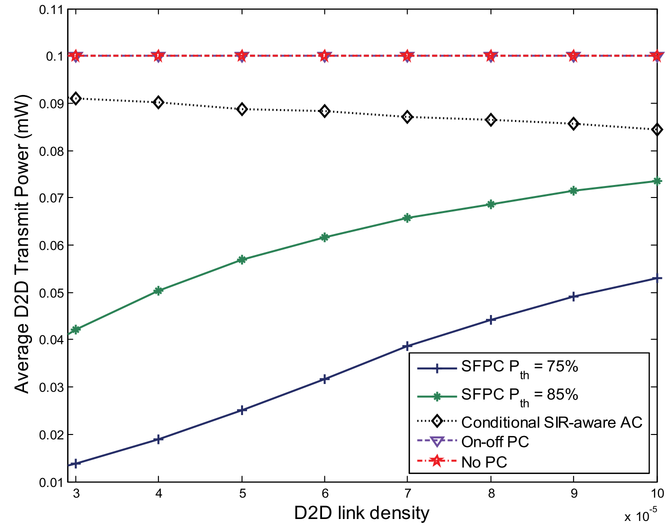

Fig. 4. Average D2D transmit power.

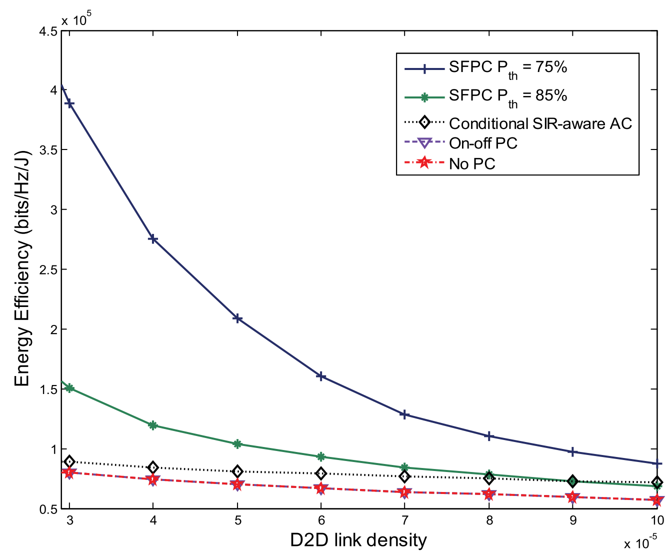

Fig. 5. Energy efficiency of D2D communications.

probability threshold increases. This is because D2D transmitters have to increase their transmit power to improve D2D receivers' SINR in order to satisfy the higher D2D success probability threshold. Since a dense D2D link deployment causes a strong inter-D2D interference, D2D transmitters increase their transmit power to meet the D2D success probability threshold, and thus, the average D2D transmit power monotonically increases as the D2D link density increases.

Next, we evaluate the energy efficiency of D2D communications, which is defined as the information-bits per unit of transmit energy and very important for technological advances in current and emerging cellular networks. Clearly, our proposed scheme enhances the energy-efficiency of D2D communications, as shown in Fig. 5, due to its reduction of inter-D2D interference with power control. Energy-efficiency of D2D communications decreases monotonically as D2D link density increases as dense D2D link deployment accompanies

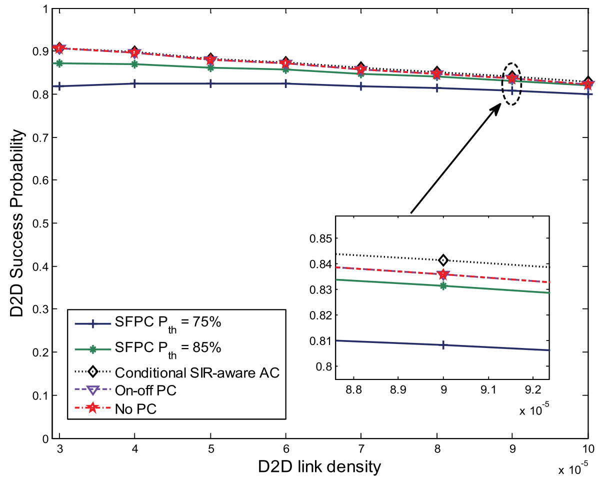

Fig. 6. D2D success probability.

strong inter-D2D interference, forcing D2D transmitters to raise their transmit power to maintain the same SINR.

Fig. 6 shows the D2D success probability versus the D2D link density. The figure shows that SFPC can ensure the D2D success probability to be higher than the given threshold whenever possible. We can observe that the D2D success probability is higher than the D2D success probability threshold under SFPC with $P_{\rm th} = 75\%$. For example, at $\lambda = 0.00009$ ($\mathbb{E}[K] = 70.6$), the D2D success probability is 0.836 (ON–OFF PC, No PC), 0.841 (conditional SIR-aware AC), 0.832 (SFPC $P_{\rm th} = 85\%$), and 0.808 (SFPC $P_{\rm th} = 75\%$), respectively. However, when $P_{\rm th} = 85\%$ and $\lambda \geq 0.00007$, the D2D success probability achieved by SFPC cannot satisfy the D2D success probability threshold due to the strong inter-D2D interference and the transmit power constraints. In this case, the D2D success probability achieved by SFPC is close to that of other schemes. In addition, the D2D success probability increases as the D2D success probability threshold increases by SFPC algorithm.

All in all, the proposed SFPC increases the cellular communication reliability and energy efficiency. There is a reciprocal relationship between the cellular communication success probability and D2D success probability. Therefore, there is an inherent tradeoff between cellular communication success probability and D2D success probability. There are various services based on D2D communication such as vehicle-to-vehicle communications, context sharing, and local advertising. Some services are given higher priority than cellular communications, but others are not. The priority of D2D communications depends on the specific D2D service. The priority of D2D communications can be controlled by the operator by setting a proper D2D success probability threshold—a higher D2D success probability threshold indicates a higher D2D communication priority.

VI. Conclusion

In this paper, we have proposed SFPC for D2D-underlaid cellular networks that combines power control that is aware of D2D success probability with opportunistic access control to reduce the interference caused by D2D communications and maximize the area spectral efficiency of D2D communications. To overcome the difficulty in obtaining real-time CSI, SFPC utilizes statistical CSI, which is simple and incurs low overhead. The performance gain achieved by SFPC is evaluated in terms of cellular communication success probability, average D2D transmit power, and energy efficiency of D2D communications.

Appendix A

The D2D success probability of D2D receiver k can be expressed as

$$\begin{aligned}
&\mathbb{P}\left(\text{SINR}_k(\mathbf{p}) > \gamma | p_k\right) \\
&= \mathbb{P}\left(\frac{|h_{k,k}|^2 d_{k,k}^{-\alpha} p_k}{I_k^c + I_k^d + \sigma^2} > \gamma\right), \quad k \in \Phi \\
&= \mathbb{P}\left(|h_{k,k}|^2 > \frac{\gamma d_{k,k}^{\alpha}(I_k^c + I_k^d + \sigma^2)}{p_k}\right) \\
&\overset{(a)}{=} \mathbb{E}_{I_k^c, I_k^d}\left[\exp\left(-\frac{\gamma d_{k,k}^{\alpha}(I_k^c + I_k^d + \sigma^2)}{p_k}\right)\right] \\
&= e^{-s\sigma^2}\mathcal{L}_{I_k^c}(s)\mathcal{L}_{I_k^d}(s)
\end{aligned} \tag{23}$$

where $s = \frac{\gamma d_{k,k}^{\alpha}}{p_k}$, and $\mathcal{L}_{I_k^c}(s)$ ($\mathcal{L}_{I_k^d}(s)$) is the Laplace transform of random variable I_k^c (I_k^d). The equality (a) follows from $|h_{k,k}|^2 \sim \exp(1)$ [12]. $\mathcal{L}_{I_k^d}(s)$ can be derived further as in [24]

$$\begin{aligned}
\mathcal{L}_{I_k^d}(s) &= \mathbb{E}\left[\exp\left(-s\sum_{i\in\Phi\backslash k} p_i |h_{i,k}|^2 d_{i,k}^{-\alpha}\right)\right] \\
&= \exp\left(-2\pi\lambda\left[\int_0^{\infty}(1-\mathbb{E}[e^{-sp_i h/u^a}])\text{udu}\right]\right) \\
&= \exp\left(-\frac{\pi\lambda}{\text{sinc}(2/a)}\mathbb{E}\left[(p_i)^{\frac{2}{a}}\right](s)^{\frac{2}{a}}\right).
\end{aligned} \tag{24}$$

$\mathcal{L}_{I_k^c}(s)$ can be derived as

$$\begin{aligned}
\mathcal{L}_{I_k^c}(s) &= \mathbb{E}[\exp(-sp_0|h_{0,k}|^2 d_{0,k}^{-\alpha})] \\
&= \mathbb{E}_{d_{0,k}}\left[\frac{1}{1+sp_0 d_{0,k}^{-\alpha}}\right].
\end{aligned} \tag{25}$$

For simplicity, we approximate the expression $\mathcal{L}_{I_k^c}(s)$ by $\mathbb{E}_{d_{0,k}}[\frac{1}{1+\frac{k}{d_{0,k}^{a}}}] \simeq [\frac{1}{1+\frac{k^{2/a}}{\mathbb{E}[d_{0,k}]^2}}]$ for [12]. Furthermore, $\mathbb{E}[d_{0,k}] = \frac{128R}{45\pi}$ as shown in [25], and therefore, the Laplace transform of the random variable I_k^c can be expressed as

$$\begin{aligned}
\mathcal{L}_{I_k^c}(s) &= \frac{1}{1+\frac{(sp_0)^{2/a}}{\mathbb{E}[d_{0,k}]^2}} \\
&= \frac{1}{1+\frac{(sp_0)^{2/a}}{(128R/45\pi)^2}}.
\end{aligned} \tag{26}$$

Plugging (24) and (26) into (23), we can derive the D2D success probability as given in (8)

Appendix B

For any given D2D success probability threshold $P_{\rm th}$, we can find the relationship between minimum transmit power $p^{\star}_{d_k}$ and $d_{k,k}$, which can be expressed as

$$e^{-a_3 p_k^{-\frac{2}{a}}} = \frac{P_{\rm th}}{g\left(p_k^{-\frac{2}{a}}\right)} \quad (27)$$

$$= P_{\rm th}\left(1 + p_k^{-\frac{2}{a}}\left(\gamma_{\min} d_{k,k}^{a} p_{\max,c}\right)^{\frac{2}{a}}\left(\frac{45\pi}{128R}\right)^2\right).$$

For a general type of equation $e^{ax+b} = cx + d$, where x is the variable to be solved; a, b, c, d are constants; and $a, c \neq 0$, the solution by using Lambert W function is

$$x = -\frac{W\left(-\frac{a}{c}e^{b-\frac{ad}{c}}\right)}{a} - \frac{d}{c} \quad (28)$$

where W denotes Lambert W function. Using (28) as a typical solution for the type of (27), we can obtain (13).

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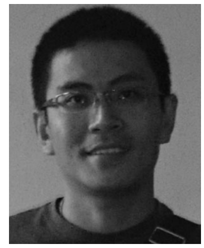

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