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Distributed Transmit Power Optimization for Device-to-Device Communications Underlying Cellular Networks

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ABSTRACT In this paper, we propose four transmit power control strategies for the underlay device-to-device (D2D) communications, in which the spectral efficiency (SE) of the D2D communications is maximized while the amount of interference caused to a base station (BS) is kept less than a predefined threshold. To this end, we first propose a centralized power control strategy based on instantaneous and global channel state information (CSI) by formulating a convex optimization problem. Then, three distributed power control strategies are taken into account in which each D2D pair adjusts its transmit power in a distributed manner based on interference price and its local CSI, which significantly reduces the signaling overhead. In the distributed strategies, the interference price can be determined based on 1) the instantaneous local CSI; 2) the statistics of the local CSI (average power); and 3) the number of the D2D pairs without any CSI knowledge. Through extensive computer simulations, we show that the performances of the proposed strategies optimally adjust the transmit power of the D2D communications. Especially, we find that the distributed power control strategies can achieve almost the same SE with the centralized strategy with much lower signaling and control overhead.

INDEX TERMS D2D communications, distributed transmit power control, interference management, cellular networks.

I. INTRODUCTION

A. BACKGROUND

Currently, mobile communication systems are suffering from exponentially increasing mobile traffic caused by ever more extensive use of wireless services [1]. Even worse, it is expected that the amount of the mobile traffic will keep increasing exponentially over the coming years. It is therefore of the utmost importance to find ways to increase the capacity of mobile communication systems. Consequently, innovative wireless technologies are being developed for this purpose. Device-to-device (D2D) communication is one promising technology that can be used to solve the problem of explosive traffic increase, by providing the offload of cellular traffic to direct communication between D2D users [2]–[5]. More specifically, D2D communication allows users to transfer data through direct links among them such that communication resource of cellular base stations (BSs) can be saved and hence more traffic can be handled without increasing radio resource. In addition, the resource allocated to D2D links can be spatially reused, which possibly improves the overall capacity of mobile communication systems. Furthermore, it is expected that through D2D communication, new mobile services related to social networks can be provided to users and existing mobile services can be operated more efficiently.[1] For that reason, many service providers have recently shown a tremendous interest in D2D communication [6]. Along these lines, D2D communication

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[1] For example, Nearby Friends of Facebook can be provided to users with much lower power consumption and higher accuracy through the use of D2D communication.

has been taken into account in newly released LTE standards,[2] i.e., Rel. 12 [6], [7].

In D2D communication, nearby users can communicate with each other using a direct link between them without passing through a BS [2], [4], [8]–[10]. Therefore, D2D pairing to search for nearby users capable of communicating with the user in question and resource allocation schemes to determine radio resource to be used for D2D communication, are the two major considerations in D2D communication which should be addressed carefully to achieve high system performance. As can be seen from previous works in D2D pairing [2], [4], [8]–[11], nearby users can be found with high accuracy and low power consumption using the state-of-the-art schemes, e.g., FlashLinQ by Qualcomm. Therefore, we focus on resource allocation, specifically, transmit power control schemes for underlay D2D communication in which D2D communication share the same radio resources with legacy cellular communication.

For underlay D2D communication, non-orthogonal resource sharing with cellular system is applied in order to save radio resources, i.e., underlay D2D communication uses the same radio resource with cellular communication. In most cases, resources for uplink transmission is reused for underlay D2D communication such that uplink transmission of cellular system and D2D transmission take place simultaneously. As a result, underlay D2D transmissions inevitably deteriorate the uplink quality by causing excessive interference, which possibly diminishes the benefits of D2D communication. Therefore, a proper control of transmit power of D2D users to protect the uplink cellular user from the potentially severe interference caused by the D2D communications, is necessary.

B. RELATED WORK

In the light of its necessity, many works have been done on transmit power control of D2D users by taking into account interference to cellular users [12]–[18]. In [12], the authors considered the power control scheme based on the Signal-to-Interference-and-Noise Ratio (SINR) distribution of cellular user. The optimal power control scheme was taken into account in [13], [14] by considering the coexistence of single D2D pair with the cellular system. The effect of availability of channel state information (CSI) on power control for D2D communication was considered in [15]. A truncated channel inversion-based power control along with mode selection was taken into account in [16] where stochastic geometry is used to analyze the performance of D2D communication. Moreover, in [17], transmit power control strategies for D2D communication were derived using stochastic geometry, and the transmit power control and resource allocation were jointly taken into account by the authors of [18], in order to maximize energy efficiency.

Although the transmit power control can be executed in the centralized manner where the BS determines the transmit power of each D2D user based on the complete CSI of users [13]–[15], this centralized approach can require huge signaling and control overhead, especially when a large number of D2D transmissions can take place at the same time. Moreover, the centralized scheme is poorer than the distributed scheme in view of real-time operation because the collection of CSI and the notification of proper transmit power requires significant amount of time. Therefore, distributed power control scheme is adequate for underlay D2D communication. As a consequence, distributed power control schemes where the transmit power of D2D users is determined by themselves in the distributed manner based on local CSI, are extensively studied in many D2D related researches. Although the performance of distributed scheme can be deteriorated than that of centralized scheme, it is more appropriate for practical use.

In [19], a distributed power control scheme that iteratively determines the SINR target in order to minimize overall power consumption while guaranteeing the minimum sum rate of D2D user, was considered. Moreover, in [20], coalition formation game based on merge-and-split rule to improve energy efficiency in D2D communication was taken into account. Furthermore, the authors of [21] considered a distributed interference-aware resource allocation algorithm to maximize each user's energy efficiency subject to target quality of service and the maximum transmit power constraints in iterative manner.

Interference pricing is an efficient way to control the interference in a distributed manner by charging additional cost to user according to the amount of interference that it generates [22]–[27]. Accordingly, user will reduce its transmit power when the amount of the interference is significant. In the interference pricing, Stackelberg game is often used for mathematical formulation in which a BS and D2D users act as a leader and followers of the game, respectively, such that the BS determines the proper interference price by predicting the overall interference caused by D2D users for given interference price [22], [24]. In [23], untruthful reporting of CSI by D2D users was considered where a contract-based mechanism with the linear search algorithm was proposed.

It is worth noting that by using distributed power control schemes based on interference pricing, the interference caused by D2D transmissions can be controlled properly, however, global CSI or certain number of iterations is needed to determine the interference price. Therefore, the signaling and control overhead of those distributed power control schemes can be still considerably high since the number of D2D users can be large and channel conditions change over time. Moreover, the interference price is based on instantaneous CSI such that the price should be updated when channel changes. Furthermore, the price should be also modified when the set of D2D users which are transmitting is changed. Accordingly, more efficient algorithm needs to be devised which minimizes signaling and control overhead.

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[2] D2D communication in LTE standards is also known as proximity service (ProSe) [2].

C. OUR CONTRIBUTIONS

In this paper, we propose four transmit power control strategies for underlay D2D communications by taking into account interference caused to uplink cellular user. The main contributions of our work are summarized as follows:

1) We propose four novel transmit power control strategies whose objective is to maximize the spectral efficiency (SE) of underlay D2D communications while guaranteeing the interference caused to cellular communication being less than the predefined threshold. To this end, we formulate and solve a convex optimization problem from which a centralized transmit power allocation strategy is found. Then, in order to reduce the signaling overhead of centralized strategy caused by collecting CSI, we propose a distributed transmit power control algorithm in which the transmit power is adjusted based on their own CSI and interference price which imposes a penalty on causing interference to cellular communication. In our proposed scheme, interference price can be determined in an iterative manner using instantaneous CSI. Then, we propose two alternative ways[3] to determine the interference price without iterations, which can further reduce the signaling overhead of transmit power control.
2) We evaluate the performance of proposed schemes through extensive computer simulations. The results show that by using our proposed schemes, the amount of interference caused by the D2D communications can be maintained less than a predefined threshold while improving overall SE of the D2D communications. Moreover, we find that the performance of distributed scheme without global CSI almost coincides with that of centralized optimal scheme with global CSI such that the transmit power of D2D pairs can be adjusted almost optimally without any exchange of channel information, i.e., negligible signaling and control overhead, which validates the applicability of our proposed scheme in practice.

D. ORGANIZATION

The remainder of the paper is organized as follows. In Section II, we give a detailed explanation of system model considered in this paper. Both centralized and distributed power control strategies using interference price based on instantaneous CSI are proposed in Section III. In Section IV, the determination of interference price based on averaged CSI and without CSI are taken into account. Simulation results are shown in Section V. Finally, conclusion is drawn in Section VI.

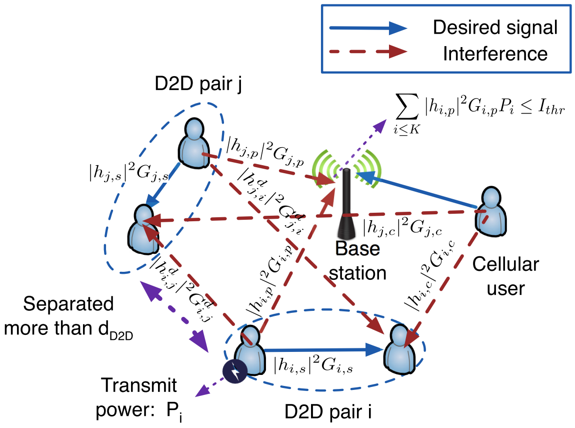

FIGURE 1. System model considered in transmit power control.

II. SYSTEM MODEL

In this section, we describe the system model considered in this work which is depicted in Fig. 1. The nomenclature used throughout this paper is provided in Table 1. We consider a single cell case[4] in which one BS is located at the center of the cell and multiple users are uniformly distributed in the cell. Two types of users are considered; cellular user and D2D user. Given that D2D users directly communicate with each other, they are in pairs, each consisting of one transmitter and one receiver, where the total number of D2D pairs is K. Moreover, we assume that D2D users transmit data during uplink phase of cellular system such that cellular users and D2D users transmit data simultaneously.

We consider single channel case in which D2D pairs share the same radio resource with cellular user such that D2D links cause interference to data transmission of cellular user, i.e., the quality of cellular transmission in uplink is affected by the D2D transmissions. The cellular transmission can also cause interference to D2D links. In the analysis, we assume that the transmission of D2D pairs is scheduled in a way that D2D pairs which transmit simultaneously, are separated more than d_{D2D}. Note that this scheduling can be accomplished by adopting the scheduling based on carrier sense multiple access (CSMA) where nearby users are scheduled not to transmit at the same time. Moreover, as can be seen from our simulation results, our proposed schemes show sufficiently high performance even with small d_{D2D} such that this assumption is reasonable.

We use $G_{i,p}$ and $h_{i,p}$ to denote distance-related channel gain and multipath fading between the transmitter of D2D link i and the BS, respectively. Moreover, we use $G_{i,c}$ and $h_{i,c}$ to denote distance-related channel gain and multipath fading between the receiver of D2D link i and the cellular user, respectively. Furthermore, we use $G^d_{i,j}$ and $h^d_{i,j}$ to denote distance-related channel gain and multipath fading between the transmitter of D2D link i and the receiver of D2D link j, respectively, where $i \neq j$. Finally, we use $G_{i,s}$ and $h_{i,s}$

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[3] Although our centralized algorithm is similar to previous approaches, however, our distributed algorithms have sufficient novelty because they can be operated in distributed manner only based on the statistical information of CSI or even without any CSI, while they achieve similar performance with the centralized scheme.

[4] The consideration of multi-cell environment is left as a future work.

TABLE 1. List of nomenclature.

K	Number of D2D pairs
d_{D2D}	Minimum distance between D2D pairs
$G_{i,p}$	Distance-related channel gain between the transmitter of D2D link i and the BS
$h_{i,p}$	Multipath fading between the transmitter of D2D link i and the BS
$G_{i,c}$	Distance-related channel gain between the receiver of D2D link i and the cellular user
$h_{i,c}$	Multipath fading between the receiver of D2D link i and the cellular user
$G^{d}_{i,c}$	Distance-related interference channel gain between the receiver of D2D link i and the transmitter of D2D link j
$h^{d}_{i,c}$	Multipath fading between the receiver of D2D link i and the transmitter of D2D link j
$G_{i,s}$	Distance-related channel gain of D2D link i
$h_{i,s}$	Multipath fading of D2D link i
$P_{\max}$	Maximum transmit power
P_i	Transmit power of D2D link i
N_0W	Noise power
$I_{\text{D2D},i}$	Accumulated interference on D2D link i caused by other D2D pairs
$\acute{I}_{\text{D2D}}$	Approximated interference on D2D link
I_{thr}	Interference threshold
$\eta, \boldsymbol{\lambda}, \boldsymbol{\mu}$	Lagrange multiplier
$L(\cdot)$	Lagrangian function
$\mathbf{K_{max}}$	Set of D2D pairs utilize the maximum transmit power
$\mathbf{K_0}$	Set of D2D pairs which do not transmit
U_i	Utility of D2D pair i
δ	Interference price update constant for distributed transmit power control
c, c_{sto}, c_{avg}	Normalized price of interference

to denote distance-related channel gain and multipath fading of D2D link i, respectively, cf. Fig. 1. Herein, we assume that $h_{i,s}$, $h_{i,c}$, $h^{d}_{i,j}$, and $h_{i,p}$ are modeled as independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian (CSCG) random variable whose mean is zero and variance is one.[5]

In our power control schemes, the transmit power of D2D pair i, which we denote as P_i, is adjusted to maximize the sum of SE of D2D pairs, where P_i should be in the range $0 \leq P_i \leq P_{\max}$. The transmit power of cellular user is assumed to be fixed to $P_{\max}$. Although the joint optimization of transmit power for D2D pairs and cellular user is also possible, we assume that legacy cellular user has higher priority compared to D2D pairs. Accordingly, the cellular user always transmits with the maximum transmit power in order to maximize its SE, and the D2D pairs adjust their transmit power to improve their SE while not causing harmful interference to cellular user. However, given that the joint optimization of transmit power for D2D pairs and cellular user can be beneficial for the case when D2D communication is used for critical application, we have left this consideration as future work. It should be noted that our proposed scheme can also be used for the case when the transmit power of cellular user changes by adjusting the transmit power of cellular user accordingly.

Then, the sum of SE of D2D pairs can be formulated as follows

$$\sum_{i=1}^{K} \log\left(1 + \frac{|h_{i,s}|^2 G_{i,s} P_i}{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + I_{\text{D2D},i}}\right), \tag{1}$$

where N_0 is the noise spectral density, W is the bandwidth, $\log(\cdot)$ is used instead of $\log_2(\cdot)$ to simplify the derivation, and $I_{\text{D2D},i}$, which denotes the accumulated interference caused by other D2D pairs, can be written as $I_{\text{D2D},i} = \sum_{j \neq i} |h^{d}_{j,i}|^2 G^{d}_{j,i} P_j$.

Given that D2D pairs cause interference to a BS which deteriorates the QoS of cellular user, we assume that the total amount of interference generated from D2D pairs should be less than a predefined threshold [24], [28], which we denote as I_{thr}, cf. Fig. 1. Specifically, the following inequality should hold.

$$\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_i \leq I_{\text{thr}}. \tag{2}$$

When the QoS requirement of cellular user changes, the value of I_{thr} can be adjusted accordingly where the transmit power of D2D pairs has to be recalculated. Moreover, (2) can be used for the case when the cellular user has the minimum SE requirement.

Accordingly, the goal of transmit power control scheme should be maximizing (1) while not violating (2) by adjusting P_i. In the following, we will describe different power control schemes according to the availability of channel information and ways to find proper level of transmit power, i.e., centralized or distributed manner.

III. TRANSMIT POWER CONTROL STRATEGIES BASED ON INSTANTANEOUS CSI

In this section, we propose transmit power control schemes based on instantaneous channel information, i.e., $h_{i,s}$, and $h_{i,p}$ are used in determining transmit power level. First, we will consider a centralized transmit power control scheme in which the complete CSI are known to a BS such that the BS can decide the optimal P_i in a centralized manner.

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[5] The distribution of magnitude of our multipath fading model follows Rayleigh distribution, which is most popular for non-line-of-sight (NLOS) channel. The consideration of other channel models, e.g., Rician fading, has been left as future work.

Then, we will describe a distributed transmit power control scheme in which optimal power allocation is achieved in a distributed manner through iterative transmit power update of D2D pairs. In order to simplify the analysis, we have taken into account the approximated value[6] of $I_{\text{D2D},i}$, which we denote as $\hat{I}_{\text{D2D},i}$, where $\hat{I}_{\text{D2D},i} = \sum_{j \neq i} |h^d_{j,i}|^2 G^d_{j,i} P_{\max}$. Accordingly, the interference among D2D pairs will be higher in the analysis compared with its actual value, i.e., the worst case interference is taken into account. However, as can be seen from our performance evaluation, our transmit power control achieves sufficiently high performance which validates our approximation.

A. CENTRALIZED TRANSMIT POWER CONTROL

In a centralized transmit power control scheme, a BS determines the proper transmit power of each D2D pair based on instantaneous CSI which should be reported by D2D pairs beforehand. The optimal transmit power, i.e., P_i, can be found by solving the following optimization problem.

$$\begin{aligned} &\underset{P_i}{\text{maximize}} \sum_{i=1}^{K} \log\left(1 + \frac{|h_{i,s}|^2 G_{i,s} P_i}{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\text{D2D},i}}\right) \\ &\text{s.t.} \sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_i \le I_{\text{thr}} \\ &\quad 0 \le P_i \le P_{\max}. \end{aligned} \tag{3}$$

Note that the formulated problem is a convex optimization problem because all the constraints are linear functions of P_i and the Hessian of objective function is Positive Definite. Therefore, the optimal solution can be found using Karush-Kuhn-Tucker (KKT) condition [29]. To this end, we derive the Lagrangian function of the problem, $L(\mathbf{P}, \eta, \boldsymbol{\lambda}, \boldsymbol{\mu})$, as follows.

$$\begin{aligned} &L(\mathbf{P}, \eta, \boldsymbol{\lambda}, \boldsymbol{\mu}) \\ &\quad = -\sum_{i=1}^{K} \log\left(1 + \frac{|h_{i,s}|^2 G_{i,s} P_i}{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\text{D2D},i}}\right) \\ &\qquad + \eta\left(\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_i - I_{\text{thr}}\right) \\ &\qquad + \sum_{i=1}^{K} \left(-\lambda_i P_i + \mu_i (P_i - P_{\max})\right), \end{aligned} \tag{4}$$

where η, $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ are Lagrange multipliers.

Let $\hat{\mathbf{P}}$ be the optimal solution of problem (3), where $\hat{\mathbf{P}} = [\hat{P}_1, \cdots, \hat{P}_i, \cdots \hat{P}_K]$. Then, the $\hat{\mathbf{P}}$ should satisfy the following KKT condition.

$$\begin{aligned} 0 = &-\frac{|h_{i,s}|^2 G_{i,s}}{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\text{D2D},i} + |h_{i,s}|^2 G_{i,s} \hat{P}_i} \\ &+ \eta |h_{i,p}|^2 G_{i,p} - \lambda_i + \mu_i \end{aligned} \tag{5a}$$

$$0 = \eta\left(\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} \hat{P}_i - I_{\text{thr}}\right) \tag{5b}$$

$$0 = \lambda_i \hat{P}_i \tag{5c}$$

$$0 = \mu_i (\hat{P}_i - P_{\max}) \tag{5d}$$

$$0 \le \eta \tag{5e}$$

$$0 \le \lambda_i \tag{5f}$$

$$0 \le \mu_i \tag{5g}$$

where (5b)-(5d) correspond to the complementary slackness condition.

When $\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} \hat{P}_i < I_{\text{thr}}$, the transmit power of all D2D pairs has to be $P_{\max}$, i.e., $\hat{P}_i = P_{\max}, \forall i$. Otherwise, if $\hat{P}_i < P_{\max}$ for some i, the sum of SE of D2D pairs, i.e., the objective of optimization problem in (3), can be improved by increasing $\hat{P}_i$ marginally without violating the constraint on interference, i.e., (2), which contradicts with our assumption that $\hat{P}_i$ is the optimal solution of (3). Accordingly, we can check whether $\hat{P}_i = P_{\max}, \forall i$ is the optimal solution by confirming that $\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_{\max} < I_{\text{thr}}$ is satisfied, and otherwise the optimal $\hat{P}_i$ can be derived by letting $\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} \hat{P}_i = I_{\text{thr}}$. In the following, we only consider the non-trivial case when $\hat{P}_i \neq P_{\max}$ for some i.

Let $\mathbf{K_{max}}$ be the set of D2D pairs which utilize the maximum transmit power, i.e., $P_i = P_{\max}, \forall i \in \mathbf{K_{max}}$, and $\mathbf{K_0}$ be the set of D2D pairs which utilize zero transmit power, i.e., $P_j = 0, \forall j \in \mathbf{K_0}$. Then, we can derive the following lemma.

Lemma 1: $\eta = 0$ *if and only if* $\mathbf{K_{max}} = \mathbf{K}$.

Proof: Please refer to Appendix A. ☐

From Lemma 1, we can find that when $\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_{\max} > I_{\text{thr}}$, i.e., $\mathbf{K_{max}}$ and $\mathbf{K}$ cannot be the same, η is positive. Therefore, in this case, $\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} \hat{P}_i = I_{\text{thr}}$ and KKT condition in (5a)-(5g) can be rewritten as shown in (6a)-(6d) at the top of the next page, where last two inequalities come from the fact that $\lambda_i, \mu_i \ge 0$.

For D2D pair $i \in \mathbf{K} \setminus (\mathbf{K_{max}} \cup \mathbf{K_0})$, the values of λ_i and μ_i become zero and as a consequence, $\hat{P}_i$ can be calculated as

$$\hat{P}_i = \begin{cases} P_{\max}, & \textit{for } i \in \mathbf{K_{max}} \\ 0, & \textit{for } i \in \mathbf{K_0} \\ \dfrac{1}{\eta |h_{i,p}|^2 G_{i,p}} \\ \quad - \dfrac{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\text{D2D},i}}{|h_{i,s}|^2 G_{i,s}}, & \textit{otherwise}. \end{cases} \tag{8}$$

From (6c) and (6d), we can obtain following inequalities.

$$\begin{aligned} P_{\max} \le \frac{1}{\eta |h_{i,p}|^2 G_{i,p}} - \frac{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\text{D2D},i}}{|h_{i,s}|^2 G_{i,s}}, \\ \forall i \in \mathbf{K_{max}} \end{aligned}$$

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[6] Without this approximation, the adjustment of transmit power of D2D pairs results in the change of $I_{\text{D2D},i}$ such that it requires large number of iterations to determine the transmit power which possibly hinders the real-time operation.

$$0 = -\frac{|h_{i,s}|^2 G_{i,s}}{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\mathrm{D2D},i} + |h_{i,s}|^2 G_{i,s} \hat{P}_i} + \eta |h_{i,p}|^2 G_{i,p}, \ \forall i \in \mathbf{K} \setminus (\mathbf{K_{max}} \cup \mathbf{K_0}) \tag{6a}$$

$$0 < \eta \tag{6b}$$

$$0 \leq -\frac{|h_{i,s}|^2 G_{i,s}}{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\mathrm{D2D},i}} + \eta |h_{i,p}|^2 G_{i,p}, \ \forall i \in \mathbf{K_0} \tag{6c}$$

$$0 \leq \frac{|h_{i,s}|^2 G_{i,s}}{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\mathrm{D2D},i} + |h_{i,s}|^2 G_{i,s} P_{\max}} - \eta |h_{i,p}|^2 G_{i,p}, \ \forall i \in \mathbf{K_{max}} \tag{6d}$$

$$\eta = \frac{|\mathbf{K}| - |\mathbf{K_0}| - |\mathbf{K_{max}}|}{I_{\mathrm{thr}} + \sum\limits_{i \in \mathbf{K} \setminus (\mathbf{K_{max}} \cup \mathbf{K_0})} \frac{(N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\mathrm{D2D},i}) |h_{i,p}|^2 G_{i,p}}{|h_{i,s}|^2 G_{i,s}} - \sum\limits_{i \in \mathbf{K_{max}}} P_{\max} |h_{i,p}|^2 G_{i,p}}. \tag{7}$$

$$0 \geq \frac{1}{\eta |h_{i,p}|^2 G_{i,p}} - \frac{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\mathrm{D2D},i}}{|h_{i,s}|^2 G_{i,s}}, \quad \forall i \in \mathbf{K_0}. \tag{9}$$

By using (9), $\hat{P}_i$ can be simplified as follows

$$\hat{P}_i = \min\left(\left[\frac{1}{\eta |h_{i,p}|^2 G_{i,p}} - \frac{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\mathrm{D2D},i}}{|h_{i,s}|^2 G_{i,s}}\right]^+, P_{\max}\right), \tag{10}$$

where $[\cdot]^+ = \max(0, \cdot)$.

It is worth noting that $\hat{P}_i$ is inversely proportional to the channel gain between a D2D transmitter and a BS, and it is proportional to the channel gain between the transmitter and receiver of D2D pair (i.e., $|h_{i,s}|^2 G_{i,s}$), which coincides with our intuition. Finally, by using the fact that $\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} \hat{P}_i = I_{\mathrm{thr}}$, we can derive η as (7), as shown at the top of this page.

Algorithm 1 can be used in order to find the proper values of η and $\hat{P}_i$. Unlike $\hat{P}_i$ which can be derived by each D2D pair using η and its local CSI, η can be calculated only when the complete CSI of all D2D pairs is available. Accordingly, each D2D pair must send its local CSI to the BS such that η can be calculated, and the centralized transmit power control will have huge signaling overhead caused by this CSI reporting, especially when the number of D2D pairs is large.

Algorithm 1 Algorithm to Find η and $\hat{P}_i$

```
$\mathbf{K_0} \leftarrow \emptyset$
$\mathbf{K_{max}} \leftarrow \emptyset$
Find $\eta$ by using (6e)
Find $\hat{P}_i$ by using (10)
while Inequalities in (6b)-(6d) are not satisfied do
    $\mathbf{K_0} \leftarrow$ {D2D links whose $\hat{P}_i = 0$}
    $\mathbf{K_{max}} \leftarrow$ {D2D links whose $\hat{P}_i = P_{\max}$}
    Find $\eta$ by using (6e)
    Find $\hat{P}_i$ by using (10)
```

B. DISTRIBUTED TRANSMIT POWER CONTROL

To resolve excessive signaling and control overhead problem of centralized transmit power control scheme, we propose a distributed transmit power control scheme which does not require reporting of channel information. In the distributed scheme, the optimal transmit power can be allocated through iterative transmit power update of individual D2D pairs using interference cost.

In the distributed transmit power control, we define the utility of D2D pair i, which we denote as U_i, as follows.

$$U_i = \underbrace{\log\left(1 + \frac{|h_{i,s}|^2 G_{i,s} P_i}{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\mathrm{D2D},i}}\right)}_{\text{SE of D2D pair } i} - \underbrace{c |h_{i,p}|^2 G_{i,p} P_i}_{\text{Interference cost}}, \tag{11}$$

where c is the normalized price of interference generated at the BS.

As we can see from (11), the utility of D2D pair increases with the SE and decreases with the amount of interference generated to the BS. Accordingly, the total amount of interference caused by D2D transmissions imposed on uplink transmission of cellular system can be managed by properly setting interference price, i.e., c. In the distributed transmit power control, the BS determines c based on the measured interference from D2D transmissions.

The transmit power of D2D pairs is adjusted by each D2D pair in a distributed manner. More specifically, D2D pair i changes its transmit power to maximize its utility. Let $\tilde{P}_i(t+1)$ be the transmit power chosen by the D2D pair i at time $t + 1$. Then, by using derivative of U_i with respect to P_i, $\tilde{P}_i(t + 1)$ can be derived as follows

$$\tilde{P}_i(t+1) = \min\left(\left[\frac{1}{c(t) |h_{i,p}|^2 G_{i,p}} - \frac{N_0 W + |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\mathrm{D2D},i}}{|h_{i,s}|^2 G_{i,s}}\right]^+, P_{\max}\right). \tag{12}$$

In (12), D2D pair i can determine its transmit power using local CSI and $c(t)$ which is notified by the BS at time t, i.e., exchange of CSI is not needed.

Note that (12) coincides with the power allocation in centralized power control in (10) if $\eta = c(t)$. Therefore, by making $c(t) = \eta$, the transmit power of D2D pairs in distributed transmit power control can be the same with that in centralized transmit power control, i.e., $\tilde{P}_i = \hat{P}_i$ such that the optimal performance can be achieved in the distributed scheme. In this paper, we assume that the BS updates the value of $c(t)$ by using the following equation.

$$c(t+1) = \left[c(t) - \delta \left(I_{\mathrm{thr}} - \sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_i(t) \right) \right]^{+}, \quad (13)$$

where δ denotes the price update constant which determines the convergence speed of interference price. It should be noted that the value of δ can be determined through exhaustive search by examining the speed of convergence, i.e., the variation of $c(t+1)$ over time. For example, if the update of $c(t+1)$ is slow, then the value of δ can be raised to increase the speed of convergence.

The update of $c(t+1)$ can be executed until the level of price update becomes smaller than predefined threshold, γ. The procedure of distributed transmit power control is summarized in Algorithm 2.

Algorithm 2 Algorithm for distributed transmit power control

```
$t \leftarrow 0$
Initialize $c(t)$
Find $\tilde{P}_i$ by using (12)
Find $c(t+1)$ by using (13)
while $|c(t+1) - c(t)| \geq \gamma$ do
    $t \leftarrow t+1$
    Find $\tilde{P}_i$ by using (12)
    Find $c(t+1)$ by using (13)
```

From (13), we can find that when sum interference caused at BS is less than predefined threshold, i.e., $I_{\mathrm{thr}} > \sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_i(t)$, the value of $c(t)$ decreases which results in the increase of transmit power. Otherwise, if the sum interference is larger than the threshold, $c(t)$ increases which results in the decrease of transmit power. Accordingly, the value of $c(t)$ will converge when the sum interference caused at BS is equal or less than predefined threshold, which guarantees the first constraint in (3) to be satisfied. In extreme case when $c = 0$, all the D2D pairs will use their maximum transmit power, i.e., $P_{\max}$.

It should be noted that the BS can calculate $c(t)$ without knowing complete CSI. Instead, it only needs to know the accumulated interference at the BS caused by D2D transmission, which is much easier to obtain compared with the individual channel gain, e.g., $h_{i,p}$ and $G_{i,p}$. Accordingly, unlike the centralized scheme in which D2D users have to report their local channel information to the BS, only the notification of interference price, $c(t)$, is required which can significantly reduce the overall signaling overhead.

IV. TRANSMIT POWER CONTROL STRATEGIES BASED ON CSI STATISTICS

In previous section, we assume that the transmit power of D2D pairs is adjusted according to instantaneous channel condition. Therefore, the transmit power allocated to each D2D pair has to be varied according to the change of channel condition which possibly results in huge signaling and control overhead due to frequent channel information exchange or update of interference price. Moreover, although distributed transmit power control may relieve the overhead, iterative price update is still needed, which might constitute huge overhead and time for convergence.

To solve the problem of transmit power control schemes based on instantaneous CSI, we have proposed the schemes with average channel information which are based on distributed transmit power control scheme explained in previous section. Therefore, each D2D pair adjusts its transmit power according to interference price notified by the BS. Moreover, we have further simplified the analysis by assuming[7] that $\acute{I}_{\mathrm{D2D}} \approx |h_{i,c}|^2 G_{i,c} P_{\max} + \hat{I}_{\mathrm{D2D},i}$ such that the amount of interference caused to D2D transmission which is generated from other D2D pair and a cellular user is $\acute{I}_{\mathrm{D2D}}$. In this case, when the interference price notified by the BS is $\hat{c}$, the transmit power of D2D pair i can be determined as

$$\min \left(\left[\frac{1}{\hat{c}|h_{i,p}|^2 G_{i,p}} - \frac{N_0 W + \acute{I}_{\mathrm{D2D}}}{|h_{i,s}|^2 G_{i,s}} \right]^{+}, P_{\max} \right). \quad (14)$$

Unlike transmit power control schemes proposed in previous section where the interference price changes with time-varying channel conditions, the interference price in (14) will remain the same even when the channel changes due to multipath fading. Accordingly, the signaling overhead can be greatly reduced because the notification of interference price can be performed less frequently. However, the original constraint on uplink interference, i.e., $\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_i \leq I_{\mathrm{thr}}$, cannot be satisfied for specific time instant. Therefore, in this section, we have taken into account the expected interference constraint,[8] in which the expected value of interference on the BS is less than a predefined threshold, i.e., $\mathbb{E}\left[\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_i \right] \leq I_{\mathrm{thr}}$, where $\mathbb{E}[\cdot]$ is the expectation.

---

[7] Although we have made an approximation on interference, as can be seen from the performance evaluation, the performance of the proposed scheme achieves sufficiently high performance which justifies the validity of this approximation.

[8] In order to evaluate the effect of this expected interference constraint, in our performance evaluation, we have examined the probability of interference constraint being violated, i.e., outage probability.

$$\mathbb{E}_{\mathbf{H_p},\mathbf{H_s}}\left[\sum_{i=1}^{K}|h_{i,p}|^2G_{i,p}\min\left(\left[\frac{1}{\hat{c}_{sto}|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}\right]^+,P_{\max}\right)\right]=I_{\text{thr}}. \tag{15}$$

$$\begin{aligned}&\mathbb{E}_{\mathbf{H_p},\mathbf{H_s}}\left[\sum_{i=1}^{K}|h_{i,p}|^2G_{i,p}\min\left(\left[\frac{1}{\hat{c}_{sto}|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}\right]^+,P_{\max}\right)\right]\\&=\sum_{i=1}^{K}\mathbb{E}_{\mathbf{H_p},\mathbf{H_s}}\left[|h_{i,p}|^2G_{i,p}\min\left(\left[\frac{1}{\hat{c}_{sto}|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}\right]^+,P_{\max}\right)\right]\\&=\sum_{i=1}^{K}\mathbb{E}_{\mathbf{H_p},\mathbf{H_s}}\left[\frac{1}{\hat{c}_{sto}}-\frac{|h_{i,p}|^2G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}{|h_{i,s}|^2G_{i,s}}\;\middle|\;0<\frac{1}{\hat{c}_{sto}|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}<P_{\max}\right]\\&\quad+\sum_{i=1}^{K}\mathbb{E}_{\mathbf{H_p},\mathbf{H_s}}\left[|h_{i,p}|^2G_{i,p}P_{\max}\;\middle|\;P_{\max}\le\frac{1}{\hat{c}_{sto}|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}\right].\end{aligned} \tag{16}$$

A. TRANSMIT POWER CONTROL WITH EXPECTATION

In the following, we propose a transmit power control scheme based on expectation in which the average SE of D2D pairs is maximized while guaranteeing the average amount of interference caused to uplink being less than I_{thr}. As we have stated previously, the transmit power of D2D pair can be determined using (14). Therefore, our goal is to choose proper value of interference price, which we denote as c_{sto}. The proper value of c_{sto} can be found by solving the following optimization problem.

$$\begin{aligned}&\underset{c_{sto}}{\text{maximize}}\ \mathbb{E}_{\mathbf{H_p},\mathbf{H_s}}\left[\sum_{i=1}^{K}\log\left(1+\frac{|h_{i,s}|^2G_{i,s}P_i}{N_0W+\acute{I}_{\text{D2D}}}\right)\right]\\&\text{s.t. }\mathbb{E}_{\mathbf{H_p},\mathbf{H_s}}\left[\sum_{i=1}^{K}|h_{i,p}|^2G_{i,p}P_i\right]\le I_{\text{thr}}\\&\min\left(\left[\frac{1}{c_{sto}|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}\right]^+,P_{\max}\right)\\&\quad=P_i,\end{aligned} \tag{17}$$

where $\mathbf{H_p}$ and $\mathbf{H_s}$ are the vectors of $h_{i,p}$ and $h_{i,s}$, respectively, i.e., $\mathbf{H_p}=[h_{1,p},\cdots,h_{i,p},\cdots h_{K,p}]$ and $\mathbf{H_s}=[h_{1,s},\cdots,h_{i,s},\cdots h_{K,s}]$.

Given that $\mathbb{E}_{\mathbf{H_p},\mathbf{H_s}}\left[\sum_{i=1}^{K}|h_{i,p}|^2G_{i,p}P_i\right]$ and $\mathbb{E}_{\mathbf{H_p},\mathbf{H_s}}\left[\sum_{i=1}^{K}\log\left(1+\frac{|h_{i,s}|^2G_{i,s}P_i}{N_0W+\acute{I}_{\text{D2D}}}\right)\right]$ are decreasing functions of c_{sto}, the optimal c_{sto}, which we denote as $\hat{c}_{sto}$, can be found by solving (15), as shown at the top of this page, where the left side of the equation can be summarized as (16), as shown at the top of this page.

In (16), the condition $0<\frac{1}{\hat{c}_{sto}|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}<P_{\max}$ can be reorganized as follows:

$$\begin{aligned}&\frac{|h_{i,s}|^2G_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})+\hat{c}_{sto}P_{\max}|h_{i,s}|^2G_{i,s}G_{i,p}}\\&\quad<|h_{i,p}|^2\\&\quad<\frac{|h_{i,s}|^2G_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}.\end{aligned} \tag{18}$$

Similarly, $P_{\max}\le\frac{1}{\hat{c}_{sto}|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}$ can be reorganized as

$$|h_{i,p}|^2\le\frac{|h_{i,s}|^2G_{i,s}}{\hat{c}_{sto}G_{i,p}\left(N_0W+\acute{I}_{\text{D2D}}\right)+\hat{c}_{sto}P_{\max}|h_{i,s}|^2G_{i,s}G_{i,p}}. \tag{19}$$

By using (18) and (19), the first and the second term in (16) can be rewritten as (20) and (21), as shown at the top of the next page, respectively. Therefore, the optimal $\hat{c}_{sto}$ can be found using (15), (20) and (21). Although (20) and (21) seem complicated to solve, given that they are related to one-dimensional integral, they can be easily calculated through numerical integration. Moreover, given that the values of $G_{i,s}$ and $G_{i,p}$ have to be known to derive the optimal $\hat{c}_{sto}$, D2D pairs should send this CSI to the BS, however this CSI reporting will be less frequent compared to that for the centralized transmit power control.

B. BLIND TRANSMIT POWER CONTROL

In this section, we propose much simpler transmit power control scheme in order to obtain meaningful insights[9] regarding transmit power control where the effect of multipath fading is neglected by letting $h_{i,p}, h_{i,s}=1$. The interference price under this assumption, which we denote as c_{avg}, can be found by solving the following problem.

$$\begin{aligned}&\underset{c_{avg}}{\text{maximize}}\ \sum_{i=1}^{K}\log\left(1+\frac{G_{i,s}P_i}{N_0W+\acute{I}_{\text{D2D}}}\right)\\&\text{s.t. }\sum_{i=1}^{K}G_{i,p}P_i\le I_{\text{thr}}\end{aligned}$$

---

[9] Although the value of $\hat{c}_{sto}$ can be found numerically using (15), (20) and (21), it is hard to get any meaningful insight from these equations.

$$\begin{aligned}
&\int_{y=0}^{\infty}\int_{x=\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})+\hat{c}_{sto}P_{\max}yG_{i,s}G_{i,p}}}^{\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}}\left(\frac{1}{\hat{c}_{sto}}-\frac{xG_{i,p}(N_0W+\acute{I}_{\text{D2D}})}{yG_{i,s}}\right)e^{-x}e^{-y}\mathrm{d}x\mathrm{d}y\\
&\quad=\int_{y=0}^{\infty}\frac{1}{\hat{c}_{sto}}\left(e^{-\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})+\hat{c}_{sto}P_{\max}yG_{i,s}G_{i,p}}}-e^{-\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}}\right)-\frac{G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}{yG_{i,s}}\\
&\quad\quad\times\left(e^{-\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})+\hat{c}_{sto}P_{\max}yG_{i,s}G_{i,p}}}\left(\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})+\hat{c}_{sto}P_{\max}yG_{i,s}G_{i,p}}+1\right)\right.\\
&\quad\quad\left.-e^{-\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}}\left(\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}+1\right)\right)\mathrm{d}y.
\end{aligned}\tag{20}$$

$$\begin{aligned}
&\int_{y=0}^{\infty}\int_{x=0}^{\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})+\hat{c}_{sto}P_{\max}yG_{i,s}G_{i,p}}}xG_{i,p}P_{\max}e^{-x}e^{-y}\mathrm{d}x\mathrm{d}y\\
&\quad=G_{i,p}P_{\max}\int_{y=0}^{\infty}\left(1-\left(1+\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})+\hat{c}_{sto}P_{\max}yG_{i,s}G_{i,p}}\right)e^{-\frac{yG_{i,s}}{\hat{c}_{sto}G_{i,p}(N_0W+\acute{I}_{\text{D2D}})+\hat{c}_{sto}P_{\max}yG_{i,s}G_{i,p}}}\right)e^{-y}\mathrm{d}y.
\end{aligned}\tag{21}$$

$$\min\left(\left[\frac{1}{c_{avg}G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{G_{i,s}}\right]^+,P_{\max}\right)=P_i. \tag{22}$$

Same as problem (17), the optimal solution of problem (22), which we denote as $\hat{c}_{avg}$, can be found by solving the following equation.

$$\sum_{i=1}^{K}\min\left(\left[\frac{1}{\hat{c}_{avg}}-\frac{G_{i,p}\left(N_0W+\acute{I}_{\text{D2D}}\right)}{G_{i,s}}\right]^+,G_{i,p}P_{\max}\right)=I_{\text{thr}}. \tag{23}$$

Although (23) is much simpler compared to (15), it is unknown whether the average interference caused to the BS is less than I_{thr} when $\hat{c}_{avg}$ is used. Consequently, in the following theorem, we prove that the solution of problem (17) and problem (22) are indeed the same, i.e., $\hat{c}_{avg}=\hat{c}_{sto}$ when $P_{\max}$ is sufficiently large and $\hat{c}_{avg}\ll\frac{G_{i,s}}{G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}$, $\forall i$. Furthermore, we prove that the interference price can be expressed in a simple form, i.e., $\frac{K}{I_{\text{thr}}}$.

Theorem 1: When $P_{max}\gg 0$ and $\hat{c}_{avg}\ll\frac{G_{i,s}}{G_{i,p}(N_0W+\acute{I}_{D2D})}$, $\forall i$, $\hat{c}_{avg}=\hat{c}_{sto}\approx\frac{K}{I_{thr}}$.

Proof: Please refer to Appendix B. □

Remark 1: The first condition for Theorem 1, which is $P_{\max}\gg 0$, will be satisfied when D2D pairs do not utilize the maximum transmit power, $P_i<P_{\max}$. This condition is likely to meet when the interference among D2D pairs is large, i.e., the D2D pairs are densely populated. The second condition, $\hat{c}_{avg}\ll\frac{G_{i,s}}{G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}$, $\forall i$ is likely to be satisfied when $G_{i,s}\gg G_{i,p}$ and $I_{\text{thr}}\gg N_0W+\acute{I}_{\text{D2D}}$. In practical D2D environment, $G_{i,s}\gg G_{i,p}$ is likely to hold because the transmitter and receiver within the same D2D pair are likely to be much closely located compared with D2D user and BS. Moreover, $I_{\text{thr}}\gg N_0W+\acute{I}_{\text{D2D}}$ is likely to be satisfied for the cellular system which has sufficiently large interference margin for D2D communication. Although we do not show analytically, through simulations, we have found that $\hat{c}_{avg},\hat{c}_{sto}\approx\frac{K}{I_{\text{thr}}}$ for most of the typical environments for D2D communications which validates the Theorem 1.

It is worth noting that the interference price can be represented in a much simpler form, i.e., $\hat{c}_{avg}=\hat{c}_{sto}\approx\frac{K}{I_{\text{thr}}}$, such that it can be calculated without knowing any information on channel gain, unlike previous works which considered interference pricing [22]–[25]. In other words, the interference price can be calculated solely based on the number of D2D pairs, where the transmit power of D2D pair i can be calculated as

$$P_i=\min\left(\left[\frac{I_{\text{thr}}}{K|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}\right]^+,P_{\max}\right). \tag{24}$$

Therefore, if K and I_{thr} are known, each D2D pair can adjust its transmit power in fully distributed manner based on its local channel information only and the single notification of the number of D2D pairs, K, is sufficient for the operation of our proposed scheme. Moreover, unlike previous works on D2D transmit power control which considered interference pricing, the interference price in our proposed scheme does not need to be changed according to the D2D pairs which transmit data as long as the number of active D2D pairs is unchanged. Finally, using the following equation, it can be shown that the total amount of interference caused to a BS is always smaller than I_{thr}, i.e., the interference constraint of cellular BS is not violated for all time instants, when (24) is used for the transmit power control.

$$\begin{aligned}
&\sum_{i=1}^{K}|h_{i,p}|^2G_{i,p}P_i\\
&\quad=\sum_{i=1}^{K}|h_{i,p}|^2G_{i,p}\\
&\quad\quad\times\min\left(\left[\frac{I_{\text{thr}}}{K|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\text{D2D}}}{|h_{i,s}|^2G_{i,s}}\right]^+,P_{\max}\right)
\end{aligned}$$

$$
\begin{aligned}
&\leq \sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} \left[\frac{I_{\mathrm{thr}}}{K|h_{i,p}|^2 G_{i,p}} - \frac{N_0 W + \acute{I}_{\mathrm{D2D}}}{|h_{i,s}|^2 G_{i,s}} \right] \\
&\leq \sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} \left[\frac{I_{\mathrm{thr}}}{K|h_{i,p}|^2 G_{i,p}} \right] \\
&= I_{\mathrm{thr}}. \qquad (25)
\end{aligned}
$$

V. NUMERICAL RESULTS

In this section, the performance of the proposed D2D power control strategies is evaluated via computer simulations based on Matlab. We place a BS at the center and place K D2D pairs and cellular user uniformly around the BS. We assume that the cell radius is 500 m and the maximum and minimum distance between two D2D users in the same D2D pair are set to 10 m and 3 m, respectively. Moreover, we assume that the minimum distance between two D2D pairs, i.e., d_{D2D}, is 50 m and let $I_{\mathrm{D2D},i} = -101$ dBm for all proposed schemes. Furthermore, we assume that the maximum transmit power of D2D pair, $P_{\max}$, is equal to 23 dBm, K is equal to 10, $N_0 = -174$ dBm/Hz, $W = 10$ MHz, and I_{thr} is equal to $N_0 W$. In addition, multipath fading, i.e., $h_{i,s}$, $h_{i,c}$, $h^d_{i,c}$ and $h_{i,p}$, are generated using i.i.d. CSCG random variable with mean of zero and variance of one. For distance-related channel gain, $G_{i,p}$, $G_{i,c}$ and $G^d_{i,j}$ follow Cost 231 HATA model [30] and $G_{i,s}$ follows the LoS model in ITU-1411 with antenna heights of 1.5 m same as in [31]. For each simulation, 3000 channel realizations are generated and the performance for each channel realization is averaged to obtain numerical result. It should be noted that the actual value of interference between D2D pairs and the interference caused by the cellular user are properly taken into account in the simulation although these interference are approximated in the analysis.

A. SPECTRAL EFFICIENCY AND INTERFERENCE TO CELLULAR UPLINK

First, we evaluate the SE of individual D2D pair and the amount of interference caused to a BS from D2D communications with various power control strategies including proposed ones. For comparison, we consider three conventional power control schemes,[10] which are Maximum Power (MP), Equally Reduced Power (ERP) and Equal Interference (EI) [15]. In a MP scheme, each D2D pair utilizes the maximum transmit power, i.e., $P_i = P_{\max}$, without considering interference caused to the BS. Accordingly, high SE can be achieved while interference caused to the BS is likely to be higher than allowable interference threshold, I_{thr}. On the other hand, in an ERP scheme, the transmit power of all D2D pairs is equally reduced to meet interference constraint such that the transmit power of D2D pair is adjusted as follows.

$$
P_i = \min\left(\frac{I_{\mathrm{thr}}}{\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p}}, P_{\max} \right). \qquad (26)
$$

Finally, in an EI scheme, the transmit power of active D2D pairs is adjusted such that the amount of interference caused by each active D2D pair on cellular BS is the same, where the number of active D2D pairs is optimally chosen through the exhaustive search, i.e., the achievable SE is compared for all possible combinations of D2D pairs. Let K_A be the number of active D2D pairs, then the transmit power of active D2D pair is determined as follows.

$$
P_i = \min\left(\frac{I_{\mathrm{thr}}}{K_A |h_{i,p}|^2 G_{i,p}}, P_{\max} \right). \qquad (27)
$$

In the EI scheme, the complete channel information of D2D pairs has to be known in order to decide the active set of D2D pairs, which inevitably incurs huge signaling overhead. Moreover, given that the optimal value of K_A, which can be different from K, has to be determined through exhaustive search, the computational complexity will be also high compared to other conventional schemes. However, unlike previous two conventional schemes whose operation is straightforward, the optimal set of D2D pairs is found through an exhaustive search in the EI scheme such that it will provide better performance, as can be confirmed in the following simulation results.

In the performance evaluation, we also consider four proposed transmit power control schemes. First, we consider a centralized transmit power control scheme based on instantaneous CSI which we denote as Cent. scheme. We also examine three distributed transmit power control schemes according to availability of CSI in the determination of interference price. Dist. scheme (Ins. Ch.) corresponds to the case when interference price is determined based on (12), which requires instantaneous CSI. Moreover, we also consider Dist. scheme (Avg. Ch.) and Dist. scheme (No Ch.) in which interference price are determined using (22) or as $\frac{K}{I_{\mathrm{thr}}}$, respectively. Note that in Dist. scheme (Avg. Ch.), interference price changes according to distance-related channel gain while in Dist. scheme (No Ch.), interference price is invariant to channel gain.

In Figs. 2 and 3, the SE of individual D2D pair and overall interference caused on BS due to D2D transmission are depicted. In these figures, we assume that the number of D2D pairs, K, is 10 and I_{thr} is varied. As can be seen from Fig. 3, all considered power control schemes except conventional MP scheme in which all D2D pairs use the maximum transmit power, show almost the same interference level which coincides with I_{thr}. In other words, the constraint on the maximum allowable interference on the BS is satisfied. On the other hand, the conventional MP scheme shows considerably high interference level since it does not take into

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[10] Although there exists other works which considered the transmit power control in D2D transmission, we were unable to compare the performance of these schemes with that of ours because the considered system model is different. For example, in [13], [14], single D2D pair has been considered while in our system model, the number of active D2D pairs can be more than one.

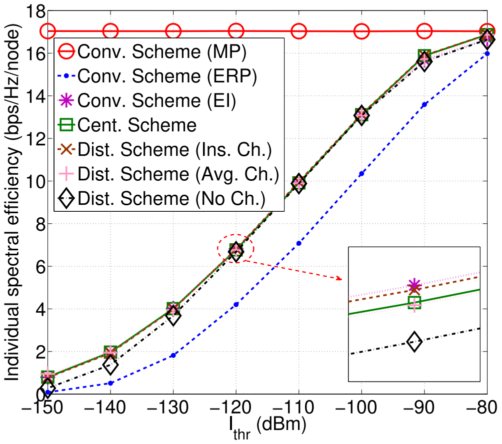

FIGURE 2. Individual spectral efficiency vs. I_{thr} when $K = 10$.

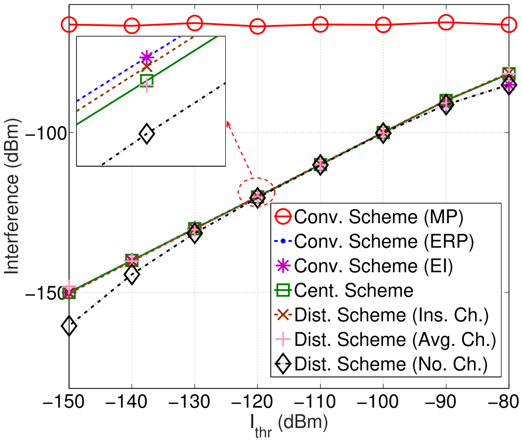

FIGURE 3. Interference to BS vs. I_{thr} when $K = 10$.

account interference on the BS. We can also observe that the interference level of Dist. scheme (No Ch.) is slightly smaller than other schemes. It should be noted that in transmit power control schemes without instantaneous CSI, i.e., Dist. scheme (Avg. Ch.) and Dist. scheme (No Ch.), interference caused to BS can be larger than I_{thr} occasionally, however, the averaged interference does not exceed the interference constraint.

When I_{thr} is small, e.g., $I_{\text{thr}} = -150$ dBm, the SE of D2D transmission becomes very small in all schemes except conventional MP scheme, because the transmit power of D2D pair decreases according to I_{thr} in order not to violate interference constraint. On the other hand, in conventional MP scheme, SE is invariant since the transmit power does not change with I_{thr}. In Fig. 2, we can find that our proposed power control schemes achieve higher SE compared to conventional ERP scheme which reveals the benefit of all our propose schemes. We can also find that the SE of all proposed power control schemes and EI scheme is almost the same each other, such that the globally optimal performance can be achieved in a fully distributed scheme, i.e., Dist. scheme (No Ch.), where the transmit power is controlled in a distributed manner solely based on local channel information. For example, when $I_{\text{thr}} = -110$ dBm, the difference between the SE of Cent. scheme and that of Dist. scheme (No Ch.) is 0.3%. Although the SE of conventional EI scheme is the same with our proposed scheme, the signaling overhead will be much higher in the EI scheme and it justifies the benefit of our proposed scheme.

Note that the SE of the fully distributed scheme deteriorates slightly when I_{thr} is small since in this case, the interference price increases to reduce the interference to the BS such that our assumption in Theorem 1, i.e., $\hat{c}_{avg} \ll \frac{G_{i,s}}{G_{i,p}(N_0W+\acute{I}_{\text{D2D}})}$, $\forall i$, becomes invalid. However, in most of the cases, the SE of the fully distributed scheme coincides with that of other schemes.

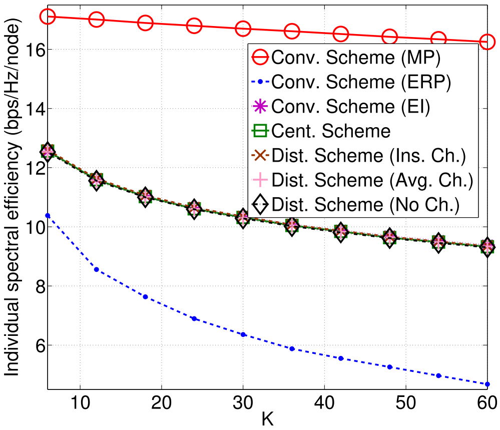

FIGURE 4. Individual spectral efficiency vs. K when $I_{\text{thr}} = N_0W$.

In Figs. 4 and 5, the individual SE and overall interference caused to BS as a function of the number of D2D pairs, K, when $I_{\text{thr}} = N_0W$, are depicted. From Fig. 5, we can find that the interference of all considered transmit power control schemes except conventional MP scheme, coincides with I_{thr}, which is -104 dBm, such that the interference constraint is satisfied. Note that even when the number of D2D pairs increases, the interference caused by D2D transmission in our proposed power control schemes is kept below the threshold. Same with previous simulation results, the SE is the same for all proposed schemes and EI scheme and is higher than that of conventional ERP scheme, as can be seen from Fig. 4. Note that as K increases, the individual SE of all schemes decreases because 1) transmit power of D2D pairs decreases to meet interference constraint and 2) interference between D2D pairs increases. However, the sum of SE of D2D pairs which can be obtained by multiplying individual SE by K, will increase as K increases.

In order to verify the effect of d_{D2D} on the performance of considered schemes, we show the individual SE and overall interference caused to BS as a function of d_{D2D} when $K = 10$ and $I_{\text{thr}} = N_0W$, in Figs. 6 and 7, respectively. From the results, we can find that the interference of all considered schemes except conventional MP scheme, coincides with I_{thr} while the SE decreases slightly as d_{D2D} decreases because of increased interference among D2D pairs. However, the level

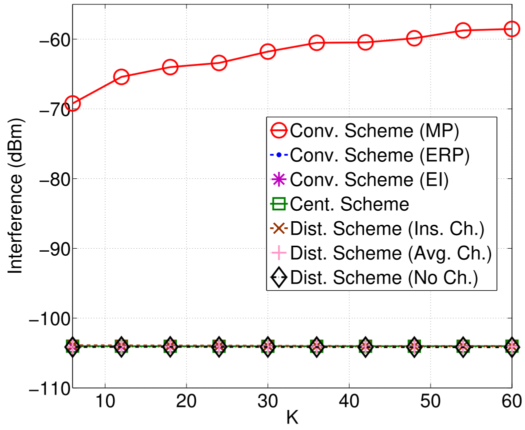

FIGURE 5. Interference to BS vs. K when $I_{\mathrm{thr}} = N_0W$.

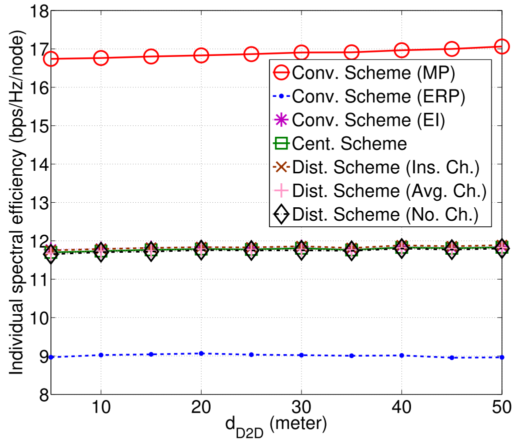

FIGURE 6. Individual spectral efficiency vs. d_{D2D} when $K = 10$ and $I_{\mathrm{thr}} = N_0W$.

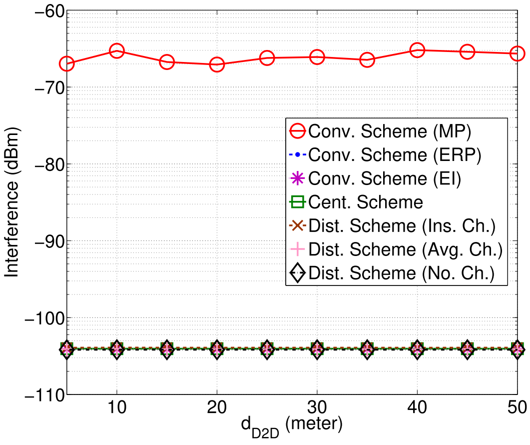

FIGURE 7. Interference to BS vs. d_{D2D} when $K = 10$ and $I_{\mathrm{thr}} = N_0W$.

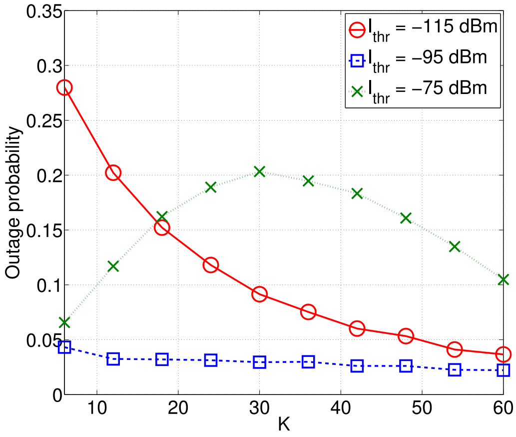

FIGURE 8. Outage probability of cellular user for Dist. Scheme (Avg. Ch.) vs. K.

of reduction in SE is minor, because the increase of interference among D2D pairs is not large, cf. Fig. 12. More specifically, small d_{D2D} does not always imply that the distance between D2D pairs is small, however, it is more likely to indicate high probability that D2D pairs can be closely located since the D2D pairs are distributed randomly. Accordingly, the case when the distance between two D2D pairs is close to d_{D2D} rarely happens such that the change of d_{D2D} does not significantly change the performance of considered schemes.

B. OUTAGE PROBABILITY OF CELLULAR USER

In our Dist. scheme (Avg. Ch.), the amount of interference caused to the cellular BS can be larger than I_{thr} according to multipath fading because the interference price is determined based on distance-related channel gain.[11] In order to better assess this effect, we have examined the probability that the total amount of interference caused to the BS is larger than threshold, which we denote as outage probability. The outage probability of our Dist. scheme (Avg. Ch.) can be formulated as follows.

$$\Pr\left\{\sum_{i=1}^{K} G_{i,p}\min\left(\left[\frac{1}{\hat{c}_{avg}G_{i,p}} - \frac{N_0W+\acute{I}_{\mathrm{D2D}}}{G_{i,s}}\right]^+, P_{\max}\right) > I_{\mathrm{thr}}\right\}. \tag{28}$$

In Fig. 8, we have depicted the outage probability of cellular user for Dist. scheme (Avg. Ch.)[12] by varying K and I_{thr}. As we can see from the results, the outage probability decreases as K increases, when $K \geq 30$ because the effect of multipath fading diminishes. When the number of D2D pairs is sufficiently large, i.e., 50, the outage probability is less than 5% when I_{thr} = -95 dBm and -115 dBm. Therefore, we can conclude that the adverse effect of our proposed scheme will be minor in view of outage.

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[11] However, as we showed in Theorem 1, the average amount of interference caused to the BS will not be larger than I_{thr}.

[12] We do not consider the outage probability of Dist. scheme (No Ch.) because we have shown that the amount of interference is always smaller than I_{thr} in (25).

C. EFFECT OF INACCURATE INFORMATION ON NUMBER OF ACTIVE D2D PAIRS

In our fully distributed scheme, i.e., Dist. scheme (No Ch.), the transmit power is adjusted by each D2D pairs based on local CSI and the interference price which is proportional to the number of active D2D pairs. Given that the number of active D2D pairs can change over time, a BS may use inaccurate K in determining the interference price which possibly deteriorates the performance of our fully distributed scheme.

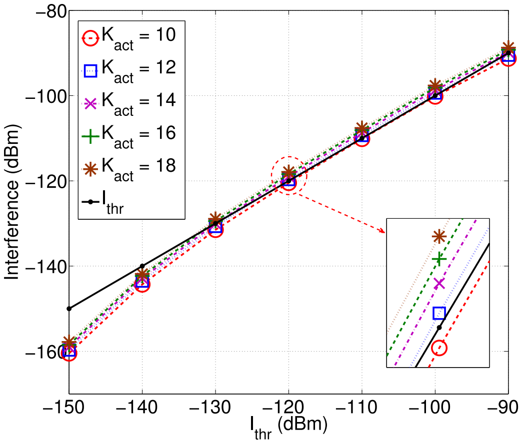

FIGURE 9. **Interference to BS vs. I_{thr} with inaccurate K.**

In Fig. 9, the overall interference[13] caused on BS due to the D2D transmission is depicted for Dist. scheme (No Ch.) when inaccurate K is used, to investigate the robustness of our proposed scheme. In the simulation, we assume that the interference price is determined by assuming $K = 10$, and the actual number of D2D pairs is K_{act}. We also depict I_{thr} for the comparison. As we can see from Fig. 9, the amount of interference increases as K_{act} increases, because the actual number of D2D pairs is larger than predicted. However, the level of violation of interference constraint is only minor, even when $K_{act} = 18$. Therefore, we can conclude that our fully distributed scheme is robust to inaccurate information on the number of D2D pairs in view of interference.

D. INTERFERENCE PRICE AND INTERFERENCE AMONG D2D PAIRS

In this section, we investigate the interference price of our proposed schemes and interference among D2D pairs. First, in Fig. 10, we show $\mathbb{E}[\eta]$ in (6e), $\mathbb{E}[c]$ in (13), $\mathbb{E}[\hat{c}_{avg}]$ in (22), and $\frac{K}{I_{\mathrm{thr}}}$, which correspond to interference price, by varying I_{thr} and K. Note that the expectation is used since the interference price can vary according to channel conditions.

As we can see from Fig. 10, interference price increases as I_{thr} decreases in order to reduce the interference caused to a BS. For the same reason, the interference price is higher when the number of D2D pairs is large. We can also find that in most of the cases, all interference prices coincide such that the simplest way to obtain interference price, i.e., $\frac{K}{I_{\mathrm{thr}}}$, will be sufficient to obtain interference price. Note that $\frac{K}{I_{\mathrm{thr}}}$ slightly diverges from other prices when its value is large since the condition in Theorem 1 does not hold when the interference price is large.

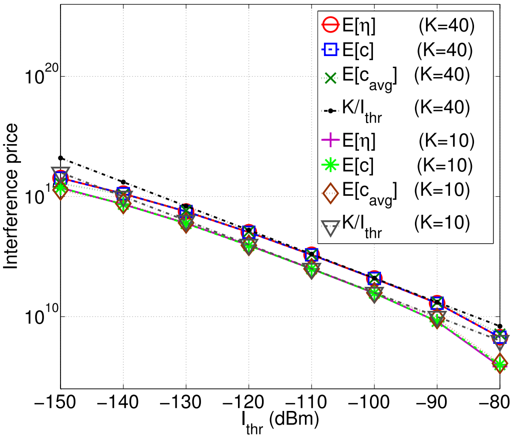

FIGURE 10. **Interference price vs. I_{thr} when $K = 10$ and 40.**

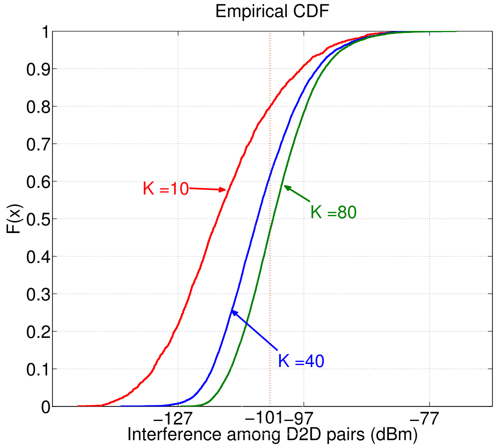

FIGURE 11. **CDF of interference among D2D pairs when $K = 10$, 40 and 80.**

In Fig. 11, we show the cumulative density function (CDF) of interference caused among D2D pairs by varying K to justify our assumption that interference among D2D pairs is fixed to $\acute{I}_{\mathrm{D2D}}$. As we can see from Fig. 11, the interference among D2D pairs is somewhat dispersed when K is small, however, as K increases,[14] the interference is concentrated around $I_{\mathrm{D2D},i}$, i.e., -101 dBm, such that our assumption on interference among D2D pairs becomes valid.

In order to verify the effect of d_{D2D} on interference among D2D pairs, in Fig. 12, we show the CDF of interference among D2D pairs by varying d_{D2D} when $K = 80$. As we can see from the result, the interference among D2D pairs

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[13] We do not show the SE because we want to focus on negative effect of inaccurate information on legacy cellular user.

[14] In practical wireless communication system, the number of D2D pairs is likely to be high because the use of wireless communication becomes more popular due to Internet of Things (IoT) technology.

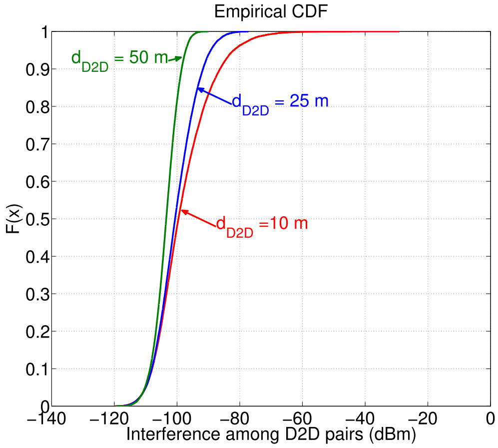

FIGURE 12. **CDF of interference among D2D pairs when d_{D2D} = 10 m, 25 m and 50 m.**

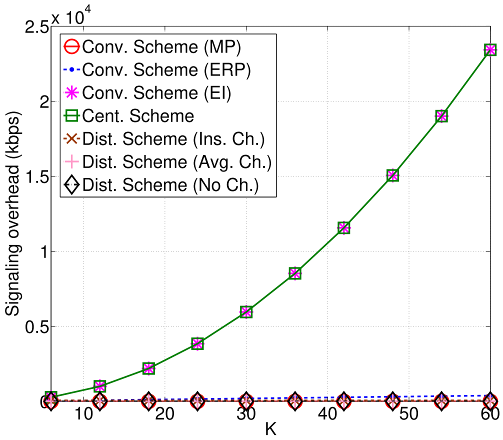

FIGURE 13. **Signaling overhead of considered schemes vs. K when $I_{\text{thr}} = N_0W$.**

increases as d_{D2D} decreases because D2D pairs can be located more densely. However, we can find that the interference is concentrated around −100 dBm, which is close to $I_{\text{D2D},i}$. More specifically, the median of interference is −99.6 dBm, −100.6 dBm, and −103.4 dBm for d_{D2D} = 10 m, 25 m and 50 m, respectively, which justifies our assumption on interference among D2D users.

E. SIGNALING OVERHEAD

Finally, in Fig. 13, we show the signaling overhead of considered schemes as a function of the number of D2D pairs, K, when $I_{\text{thr}} = N_0W$. In this simulation, we assume that 64-bit floating-point operation is used such that the CSI reporting and the notification of cost in distributed schemes require 64 bits of signaling overhead. Moreover, we assume that the period of CSI reporting for instantaneous channel is 10 milliseconds. As can be seen from Fig. 13, the signaling overhead of schemes which requires complete channel information, i.e., conventional EI scheme and Cent. scheme, increases exponentially as K increases. On the other hand, the signaling overhead of distributed schemes does not increase significantly according to K, which confirms the benefits of distributed operations with respect to signaling overhead.

VI. CONCLUSION

In this paper, we proposed four transmit power control strategies for underlay D2D communications by taking into account the interference caused to the uplink transmission of cellular network. To this end, a convex optimization problem was first formulated, where the objective is to maximize sum SE of D2D pairs while limiting interference imposed on the BS. Based on the optimization problem, the optimal transmit power allocation was also proposed. In addition, we proposed three distributed transmit power control strategies in which transmit power of D2D pairs is adjusted by charging interference cost to D2D pairs whose amount is proportional to interference caused to the BS. The interference price can be determined based on instantaneous local CSI, statistics of local CSI (e.g., average value of the CSI), and the number of the D2D pairs without any knowledge on CSI. Through extensive computer simulations, we showed that the proposed transmit power control techniques for D2D pairs significantly reduce interference to the cellular uplink, while maximizing the sum SE of the D2D pairs even when the CSI is not available at all. Interesting topics for future work include the extension of our work to more advanced systems, i.e., fog of everything (FOE) network [32] and the joint optimization of transmit power allocation with channel allocation and D2D pairing.

APPENDIX

A. PROOF OF LEMMA 1

First, we can find that when $\mathbf{K_{max}}$ and $\mathbf{K}$ are the same, $\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} P_{\max} < I_{\text{thr}}$ and due to the complimentary slackness condition, η has to be zero. For the case when $\eta = 0$, we can show that all D2D pairs will utilize the maximum transmit power, i.e., $P_{\max}$, through contradiction. Let $\eta = 0$ and $\hat{P}_j < P_{\max}$ for some j. Given that $\eta = 0$, $\sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} \hat{P}_i < I_{\text{thr}}$ due to the complimentary slackness condition. Then, the overall SE of D2D pair can be increased without violating the constraints of the problem, by using new $\hat{P}'_j$ which can be calculated as

$$\hat{P}'_j = \max\left(P_{\max}, \hat{P}_j + \frac{I_{\text{thr}} - \sum_{i=1}^{K} |h_{i,p}|^2 G_{i,p} \hat{P}_i}{|h_{j,p}|^2 G_{j,p}}\right). \quad (29)$$

Therefore, $\hat{P}_j$ is not the optimal solution of the problem and hence all D2D pairs have to use the maximum transmit power.

$$\mathbb{E}_{\mathbf{H_p},\mathbf{H_S}}\left[\sum_{i=1}^{K}|h_{i,p}|^2G_{i,p}\min\left(\left[\frac{I_{\mathrm{thr}}}{K|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\mathrm{D2D}}}{|h_{i,s}|^2G_{i,s}}\right]^{+},P_{\max}\right)\right]=I_{\mathrm{thr}}. \tag{31}$$

$$\begin{aligned}
&\mathbb{E}_{\mathbf{H_p},\mathbf{H_S}}\left[\frac{I_{\mathrm{thr}}}{K}-\frac{|h_{i,p}|^2G_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}{|h_{i,s}|^2G_{i,s}}\Big|0<\frac{I_{\mathrm{thr}}}{K|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\mathrm{D2D}}}{|h_{i,s}|^2G_{i,s}}<P_{\max}\right]\\
&\quad+\mathbb{E}_{\mathbf{H_p},\mathbf{H_S}}\left[|h_{i,p}|^2G_{i,p}P_{\max}\Big|P_{\max}\le\frac{I_{\mathrm{thr}}}{K|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\mathrm{D2D}}}{|h_{i,s}|^2G_{i,s}}\right]\\
&\overset{(a)}{=}\mathbb{E}_{\mathbf{H_p},\mathbf{H_S}}\left[\frac{I_{\mathrm{thr}}}{K}-\frac{|h_{i,p}|^2G_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}{|h_{i,s}|^2G_{i,s}}\Big|0\le|h_{i,p}|^2<\frac{I_{\mathrm{thr}}|h_{i,s}|^2G_{i,s}}{KG_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}\right]\\
&\quad+\mathbb{E}_{\mathbf{H_p},\mathbf{H_S}}\left[|h_{i,p}|^2G_{i,p}P_{\max}\Big||h_{i,p}|^2\le\frac{I_{\mathrm{thr}}}{KP_{\max}G_{i,p}}\right].
\end{aligned} \tag{32}$$

$$\begin{aligned}
&\mathbb{E}_{\mathbf{H_p},\mathbf{H_S}}\left[\frac{I_{\mathrm{thr}}}{K}-\frac{|h_{i,p}|^2G_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}{|h_{i,s}|^2G_{i,s}}\Big|0\le|h_{i,p}|^2<\frac{I_{\mathrm{thr}}|h_{i,s}|^2G_{i,s}}{KG_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}\right]\\
&=\int_{y=0}^{\infty}\int_{x=0}^{\frac{I_{\mathrm{thr}}G_{i,s}}{KG_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}y}\left(\frac{I_{\mathrm{thr}}}{K}-\frac{xG_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}{yG_{i,s}}\right)e^{-x}e^{-y}\mathrm{d}x\mathrm{d}y\\
&=\frac{G_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}{G_{i,s}}\int_{y=0}^{\infty}\int_{x=0}^{\frac{I_{\mathrm{thr}}G_{i,s}}{KG_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}y}\left(\frac{G_{i,s}I_{\mathrm{thr}}}{KG_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}-\frac{x}{y}\right)e^{-x}e^{-y}\mathrm{d}x\mathrm{d}y\\
&=\frac{G_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}{G_{i,s}}\int_{y=0}^{\infty}\left(\frac{e^{-\frac{I_{\mathrm{thr}}G_{i,s}}{KG_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}y}}{y}-\frac{1}{y}+\frac{I_{\mathrm{thr}}G_{i,s}}{KG_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}\right)e^{-y}\mathrm{d}y\\
&=\frac{I_{\mathrm{thr}}}{K}\left(1+\int_{\bar{y}=0}^{\infty}\frac{1}{\bar{y}}e^{-\bar{y}}\mathrm{d}\bar{y}-\int_{y=0}^{\infty}\frac{1}{y}e^{-y}\mathrm{d}y\right)\\
&=\frac{I_{\mathrm{thr}}}{K}.
\end{aligned} \tag{33}$$

B. PROOF OF THEOREM 1

When $P_{\max}\gg 0$ and $\hat{c}_{avg}\ll\frac{G_{i,s}}{G_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}$, for all i, (23) can be rewritten as

$$\begin{aligned}
&\sum_{i=1}^{K}G_{i,p}\min\left(\left[\frac{1}{\hat{c}_{avg}G_{i,p}}-\frac{N_0W+\acute{I}_{\mathrm{D2D}}}{G_{i,s}}\right]^{+},P_{\max}\right)\\
&\quad=\sum_{i=1}^{K}G_{i,p}\frac{1}{\hat{c}_{avg}G_{i,p}}\\
&\quad=\frac{K}{\hat{c}_{avg}}\\
&\quad=I_{\mathrm{thr}}.
\end{aligned} \tag{30}$$

From (30), we can find that $\hat{c}_{avg}=\frac{K}{I_{\mathrm{thr}}}$. By showing that the equality in (31), as shown at the top of this page holds, the proof of the theorem can be completed. By referring (16), we can derive (32), as shown at the top of this page, where (a) in (32) comes from (18), (19), and our assumption that $P_{\max}\gg 0$.

Given that $|h_{i,p}|^2$ and $|h_{i,s}|^2$ follow exponential distribution, by using the probability of density function (PDF) of exponential distribution, $\mathbb{E}_{\mathbf{H_p},\mathbf{H_S}}\Big[|h_{i,p}|^2G_{i,p}P_{\max}\big||h_{i,p}|^2\le\frac{I_{\mathrm{thr}}}{KP_{\max}G_{i,p}}\Big]$ can be summarized as

$$\begin{aligned}
&\mathbb{E}_{\mathbf{H_p},\mathbf{H_S}}\left[|h_{i,p}|^2G_{i,p}P_{\max}\Big||h_{i,p}|^2\le\frac{I_{\mathrm{thr}}}{KP_{\max}G_{i,p}}\right]\\
&=\int_{y=0}^{\infty}\int_{x=0}^{\frac{I_{\mathrm{thr}}}{KP_{\max}G_{i,p}}}xG_{i,p}P_{\max}e^{-x}e^{-y}\mathrm{d}x\mathrm{d}y\\
&=G_{i,p}P_{\max}\int_{x=0}^{\frac{I_{\mathrm{thr}}}{KP_{\max}G_{i,p}}}xe^{-x}\mathrm{d}x\\
&=G_{i,p}P_{\max}\left(1-\left(1+\frac{I_{\mathrm{thr}}}{KP_{\max}G_{i,p}}\right)e^{-\frac{I_{\mathrm{thr}}}{KP_{\max}G_{i,p}}}\right)\\
&\overset{(b)}{=}0,
\end{aligned} \tag{34}$$

where (b) holds due to the fact that $P_{\max}\gg 0$. Moreover, we can derive (33), as shown at the top of this page, where $\bar{y}=\frac{I_{\mathrm{thr}}G_{i,s}}{KG_{i,p}(N_0W+\acute{I}_{\mathrm{D2D}})}y$.

From (33) and (34), we can derive the following equalities, which completes the proof of the theorem.

$$\begin{aligned}
&\mathbb{E}_{\mathbf{H_p},\mathbf{H_S}}\sum_{i=1}^{K}|h_{i,p}|^2G_{i,p}\\
&\qquad\times\min\left(\left[\frac{I_{\mathrm{thr}}}{K|h_{i,p}|^2G_{i,p}}-\frac{N_0W+\acute{I}_{\mathrm{D2D}}}{|h_{i,s}|^2G_{i,s}}\right]^{+},P_{\max}\right)\\
&\quad=\sum_{i=1}^{K}\frac{I_{\mathrm{thr}}}{K}\\
&\quad=I_{\mathrm{thr}}.
\end{aligned} \tag{35}$$

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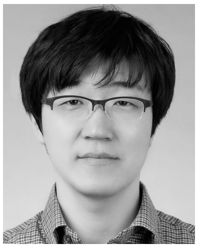

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