Resource Management for Device-to-Device Communication: A Physical Layer Security Perspective

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***Abstract*— As a promising technology for 5G networks, device-to-device (D2D) communication can improve spectrum utilization by sharing the resources of cellular users (CUs). However, this is at the cost of generating interference to the CUs. While most existing works focused on eliminating or suppressing the interference between the D2D links and the CUs, such interference could in fact be beneficial for improving the security of cellular communication. Specifically, D2D links may, in return for reusing cellular resources to achieve high spectral efficiency, act as friendly jammers and help the CUs against malicious wiretapping. To reach this win-win situation, D2D resource management has to be designed from a physical layer security perspective. In this paper, we consider the joint optimization of power allocation and channel assignment of the D2D links and the CUs with the aim to provide security to the CUs and improve the spectral efficiency of the D2D links simultaneously. We focus on the challenging downlink resource sharing problem and investigate both single-channel and multi-channel D2D communications. The resulting resource management design problems turn out to be difficult nonlinear mixed integer problems. Nevertheless, by exploiting the inherent properties of the formulated optimization problems, we are able to analytically characterize the optimal power allocation of the CUs and D2D links, and develop efficient methods for joint optimization of their channel assignments. Simulation results show that the proposed resource management policies outperform several baseline schemes and can indeed achieve the desired twofold objective.**

***Index Terms*— Device-to-device communication, physical layer security, resource management.**

I. Introduction

RECENTLY, device-to-device (D2D) communication has emerged as a promising technology for addressing the ever increasing demand for wireless traffic [1]. By allowing two physically close users to establish a direct communication link, instead of being relayed by a base station (BS), D2D communication can better utilize cellular resources and achieve higher spectral efficiency with lower power consumption [2]. Therefore, the concept of D2D communication has been incorporated into the current cellular network, e.g., the Long Term Evolution (LTE) system [1], and will be an important component of 5G cellular networks [3].

D2D communication relies on resource sharing between underlay D2D links and cellular users (CUs) [3], [4]. D2D links can reuse either downlink or uplink cellular resources in an orthogonal or nonorthogonal manner [5]. In orthogonal resource sharing, dedicated channels are allocated to D2D links, while in nonorthogonal resource sharing, the D2D links and the CUs use the same channels. Orthogonal sharing, though simple in implementation, cannot exploit the full potential of D2D communication. Hence, nonorthogonal sharing has received more attention due to its higher spectral efficiency [4], but also has the disadvantage of generating interference. In particular, in the downlink case, the transmissions of the BS are interfered by the D2D links, while in the uplink case, the transmissions of the CUs are interfered. Consequently, the mutual interference jeopardizes both the quality-of-service (QoS) of cellular communication and the spectral efficiency of D2D communication.

In the literature, there are numerous works that advocate suppressing this mutual interference for resource sharing between D2D links and CUs. Specifically, the authors of [5] first studied resource sharing of one CU and one D2D link with the aim to maximize the sum rate. This work was later generalized to multiple CUs and D2D links in [6] which considered single-channel communication, i.e., each D2D link could only reuse one CU channel. Multi-channel D2D communication, where a D2D link was allowed to reuse multiple cellular channels, was studied in [7] and [8] and an improved spectral efficiency over single-channel D2D communication was demonstrated. The more complicated case, where a CU channel is allowed to be shared by multiple D2D links, was investigated in [9]. Moreover, [10] and [11] studied resource allocation in D2D networks from a game theoretic perspective to coordinate the mutual interference between the CUs and the D2D links. Besides, improving energy efficiency of underlay D2D links in cellular networks was also investigated in several works, e.g., [12]–[14].

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The common objective of most existing works on resource management for D2D communication, including [5]–[13], was to eliminate or suppress the interference between the CUs and the D2D links. In other words, interference has been viewed as harmful. Nevertheless, from a physical layer security perspective, such interference could be beneficial as it can be used to jam malicious eavesdroppers [15]–[18]. Therefore, while pursuing high spectral efficiency, D2D links can, in return for being allowed to share the cellular resources, help CUs to improve security and prevent wiretapping, which eventually leads to a win-win situation for both the CUs and the D2D links. To achieve this favorable solution, however, the resource management for D2D communication has to be redesigned from the physical layer security perspective, which is the goal of this paper.

There are only a few works that investigated security-orientated D2D communication. In particular, the authors of [19] and [20] studied the security of D2D communication but did not consider the potential of D2D links to improve cellular security, which is the focus of this paper. The possibility of achieving security improvement by having D2D links act as friendly jammers was analyzed in [21] and [22], but the authors did not consider resource management. In [23]–[25], the authors considered secure resource sharing for a single CU-D2D pair, and security-orientated channel assignment of CUs and D2D links was studied in [26] and [27]. The twofold benefit of improving security and spectral efficiency critically depends on the joint management of all resources of the CUs and D2D links, including their powers and channels. However, the existing works studied only separate optimization of the power allocation [23], [24] or the channel assignment [26], [27], but not joint resource management. More importantly, these works focused on relatively simple uplink resource sharing and/or single-channel D2D communication problems (possibly only for one D2D-CU pair) [23]–[27], whereas the much more challenging downlink resource sharing and multi-channel D2D communication problems have not been investigated yet. Hence, in this paper, we will address these open problems.

Specifically, this paper focuses on resource management for D2D communication underlaying cellular networks with the aim to achieve a win-win situation in providing security for the CUs and improving spectral efficiency for the D2D links. The proposed joint resource management framework has the following characteristics: 1) the considered downlink resource sharing includes uplink resource sharing as a special case; 2) both single-channel and multi-channel D2D communications are considered; 3) the power allocation and channel assignment of the D2D links and the CUs are jointly optimized. The formulated secure resource sharing problems are, however, difficult nonlinear mixed integer programs with coupled constraints. We propose efficient methods to solve them and show that the desired twofold goal is indeed achieved. The main technical contributions of this paper can be summarized as follows:

- We utilize downlink resource sharing to provide security for the CUs and to improve the spectral efficiency of the D2D links via single-channel and multi-channel D2D communications. The resource management is formulated as a joint power allocation and channel assignment optimization problem, aiming to maximize the sum rate of the D2D links under security QoS constraints for the CUs.
- For single-channel D2D communication, we analytically characterize the optimal power allocation of each CU and D2D link and find the jointly optimal channel assignment under given individual CU power budgets. We prove the differentiability of the optimized D2D data rate with respect to the individual CU power budgets, and based on this result, we propose an efficient method for optimizing the individual CU power budgets to achieve further security and spectral efficiency improvements.
- For multi-channel D2D communication, we show the hidden convexity of the resource optimization problem for given D2D signal-to-interference-plus-noise ratios (SINRs) and analytically characterize the optimal power allocation and channel assignment. Then, efficient methods are proposed to jointly optimize the power allocation, channel assignment, and D2D SINR levels with convergence and performance guarantees.
- The performance of the proposed secure resource management schemes is investigated via simulations. We show that security of cellular communication and spectral efficiency of D2D communication can be improved simultaneously.

This paper is organized as follows. Section II introduces the system model and the proposed D2D resource management problem formulation based on a physical layer security perspective. Subsequently, we investigate joint power allocation and channel assignment optimization for single-channel and multi-channel D2D communications in Sections III and IV, respectively. Numerical results are provided Section V, and conclusions are drawn in Section VI.

II. Problem Statement

A. System Model

Consider the downlink[1] of a cellular system, which includes a BS and C CUs indexed by $c = 1, \ldots, C$. In general, each CU is served by a dedicated channel, which could be a time slot, frequency band, or resource block. Hence, there are C cellular channels also indexed by $c = 1, \ldots, C$. In the considered system, there exists an eavesdropper who tries to overhear the CUs' transmissions. Meanwhile, the cellular channels can be shared by D D2D links, indexed by $d = 1, \ldots, D$, to improve spectral efficiency.

Let x_c and $x_{d,c}$ be the transmitted signals of CU c and D2D link d on channel c with powers $p_c = E[|x_c|^2]$ and $p_{d,c} = E[|x_{d,c}|^2]$, respectively, where $E[\cdot]$ denotes the expectation operation. Then, the signals received by CU c and D2D link d on channel c are given respectively by

$$y_c = h_c x_c + h^I_{d,c} x_{d,c} + z_c \tag{1}$$

$$y_{d,c} = h_{d,c} x_{d,c} + h^I_{c,d} x_c + z_{d,c}. \tag{2}$$

[1]Mathematically, downlink resource sharing includes uplink resource sharing as a special case and thus the methods proposed in this paper can be readily applied or simplified to the uplink, see Remarks 5 and 9 for details.

Wherein, h_c and $h_{d,c}$ denote the channel coefficients from the BS to CU c and from D2D link d's transmitter (TX) to its receiver (RX) on channel c, respectively; $h^I_{c,d}$ and $h^I_{d,c}$ denote the cross channel coefficients from the BS to D2D link d's RX and from D2D link d's TX to CU c on channel c, respectively; and z_c and $z_{d,c}$ denote zero-mean white Gaussian noises with variances σ_c^2 and $\sigma_{d,c}^2$, respectively. Meanwhile, the eavesdropper also receives the CU and D2D signals. Specifically, the signal received by the eavesdropper on channel c is given by

$$y_{e,c} = h^I_{c,e} x_c + h^I_{d,e} x_{d,c} + z_{e,c} \tag{3}$$

where $h^I_{c,e}$ and $h^I_{d,e}$ denote the channel coefficients from the BS and D2D link d's TX to the eavesdropper on channel c, respectively, and $z_{e,c}$ is zero-mean white Gaussian noise with variance $\sigma^2_{e,c}$. For notational simplicity, we introduce the following normalized gains: $g_c \triangleq |h_c|^2/\sigma_c^2$, $g_{d,c} \triangleq |h_{d,c}|^2/\sigma^2_{d,c}$, $g^I_{c,d} \triangleq |h^I_{c,d}|^2/\sigma^2_{d,c}$, $g^I_{d,c} \triangleq |h^I_{d,c}|^2/\sigma^2_c$, $g^I_{d,e} \triangleq |h^I_{d,e}|^2/\sigma^2_{e,c}$, and $g^I_{c,e} \triangleq |h^I_{c,e}|^2/\sigma^2_{e,c}$.

We let $\omega_{d,c} = 1$ indicate that D2D link d reuses channel c, otherwise $\omega_{d,c} = 0$. For operational and billing simplicity, it is often assumed [5]–[8], [11], [12] that each CU channel can be reused by at most one D2D link, which can be modelled as $\sum_{d=1}^{D} \omega_{d,c} \le 1$, $\forall c$. On the other hand, a D2D link may reuse a single CU channel or multiple CU channels, which is referred to as single-channel and multi-channel D2D communications [6]–[8], respectively. Apparently, multi-channel D2D communication can better utilize the cellular resources, but leads to more challenging resource management problems.

B. Problem Formulation

If channel c is reused by D2D link d, i.e., $\omega_{d,c} = 1$, then the data rate of D2D link d on channel c is[2]

$$R_{d,c}(p_c, p_{d,c}) \triangleq \log_2\left(1 + \frac{p_{d,c} g_{d,c}}{1 + p_c g^I_{c,d}}\right). \tag{4}$$

The aggregate rate achieved by D2D link d over multiple channels (i.e., for multi-channel D2D communication) is $R_d \triangleq \sum_{c=1}^{C} \omega_{d,c} R_{d,c}$. Meanwhile, if channel c is reused by D2D link d with $\omega_{d,c} = 1$, CU c can achieve the following the secrecy rate [15], [16]:

$$R^1_c(p_c, p_{d,c}) \triangleq \left[\log_2\left(1 + \frac{p_c g_c}{1 + p_{d,c} g^I_{d,c}}\right) - \log_2\left(1 + \frac{p_c g^I_{c,e}}{1 + p_{d,c} g^I_{d,e}}\right)\right]_+ \tag{5}$$

where $[\cdot]_+ = \max\{\cdot, 0\}$. If channel c is not shared by any D2D link, i.e., $\omega_{d,c} = 0$, the secrecy rate of CU c is

$$R^0_c(p_c) \triangleq \left[\log_2(1 + p_c g_c) - \log_2\left(1 + p_c g^I_{c,e}\right)\right]_+. \tag{6}$$

[2]In this paper, x_c and $x_{d,c}$ are assumed to be Gaussian signals.

Hence, the secrecy rate of CU c can be compactly expressed as

$$SR_c(p_c, p_{d,c}) \triangleq \left(1 - \sum_{d=1}^{D} \omega_{d,c}\right) R^0_c(p_c) + \sum_{d=1}^{D} \omega_{d,c} R^1_c(p_c, p_{d,c}). \tag{7}$$

In general, cellular communication has a higher priority than D2D communication and shall be protected. However, the high transmit power of the BS makes it susceptible to wiretapping.[3] According to (5)-(7), the secrecy rates of the CUs are determined by the power allocation and channel assignment of the CUs and the D2D links. Thus, to ensure security for each CU, we adopt the following security QoS constraints: $SR_c(p_c, p_{d,c}) \ge \theta_c$ for $c = 1, \ldots, C$, where $\theta_c \ge 0$ is the minimum secrecy rate for CU c. On the other hand, D2D communication is introduced as a supplement of cellular communication, mainly for improving spectral efficiency. Therefore, a win-win situation can be reached by formulating the network design in form of the following secure resource management problem:

$$\begin{aligned}
\underset{\{p_c, p_{d,c}, \omega_{d,c}\}}{\text{maximize}} \quad & \sum_{d=1}^{D}\sum_{c=1}^{C} \omega_{d,c} R_{d,c}(p_c, p_{d,c}) \\
\text{subject to} \quad & SR_c(p_c, p_{d,c}) \ge \theta_c, \quad \forall c \\
& \sum_{d=1}^{D} \omega_{d,c} \le 1, \quad \forall c; \ \omega_{d,c} \in \{0,1\}, \ \forall d, c \\
& \sum_{c=1}^{C} \omega_{d,c} p_{d,c} \le P_d, \quad \forall d; \ p_{d,c} \ge 0, \ \forall d, c \\
& \sum_{c=1}^{C} p_c \le P_{BS}; \quad p_c \ge 0, \ \forall c
\end{aligned} \tag{8}$$

which provides a security guarantee for each CU and maximizes the spectral efficiency of the D2D links simultaneously. In (8), P_d and P_{BS} are the power budget of D2D link d and the total power budget of the BS, respectively.

For underlay D2D communication, resource sharing between CUs and D2D links is coordinated by the cellular network. Hence, we assume that the BS has full knowledge of all channel gains via channel estimation or/and feedback [5]–[13]. Note that both the CUs and the D2D links can estimate their transmit channels and cross channels via pilots. If the eavesdropper is a legitimate user of the cellular system, one can reasonably assume that its instantaneous channel gains (i.e., $g^I_{c,e}$ and $g^I_{d,e}$) are known at the BS [24], [26], [27]. On the other hand, if instantaneous channel state information (CSI) of the eavesdropper is not available but only its statistical CSI is known at the BS, one can replace the channel gains $g^I_{c,e}$ and $g^I_{d,e}$ by their means [16], [18].[4]

[3]We note that, compared with CUs, D2D links are less likely to be overheard because of the low transmit power of the D2D TX [21]. Therefore, we focus on enhancing the security of the CUs.

[4]If channel c is reused by D2D link d, i.e., $\omega_{d,c} = 1$, then $SR_c(p_c, p_{d,c}) \ge \theta_c$ can be expressed as $\Gamma(1 + p_{d,c} g^I_{d,e}) \ge 1 + p_c g^I_{c,e} + p_{d,c} g^I_{d,e}$, where $\Gamma \triangleq 2^{-\theta_c}\left(1 + \frac{p_c g_c}{1 + p_{d,c} g^I_{d,c}}\right)$. In the case that only the means of $g^I_{c,e}$ and $g^I_{d,e}$ are known, the constraint can be written to $\Gamma(1 + p_{d,c} E[g^I_{d,e}]) \ge 1 + p_c E[g^I_{c,e}] + p_{d,c} E[g^I_{d,e}]$.

Problem (8) requires the joint optimization of the power allocation and channel assignment of all CUs and D2D links, which corresponds, however, to a difficult mixed integer problem. Indeed, even if variables $\{\omega_{d,c}\}$ are fixed, neither the objective function nor the security QoS constraints are jointly concave in $\{p_{d,c}, p_c\}$. Moreover, the mixture of the reuse and non-reuse patterns in the security QoS constraints and the power constraints inevitably couple the power allocation and channel assignment. In the following, we will investigate several important properties of the considered problem and propose efficient methods to solve it.

III. Single-Channel D2D

In this section, we first consider single-channel D2D communication, i.e., each D2D link is allowed to reuse at most one CU channel. Although a special case of multi-channel D2D communication, single-channel D2D communication has received much attention due to its relative simplicity and straightforward management [3]–[6]. The corresponding resource management problem is given by

$$\begin{aligned}
\underset{\{p_c, p_{d,c}, \omega_{d,c}\}}{\text{maximize}} \; & \sum_{d=1}^{D}\sum_{c=1}^{C} \omega_{d,c} R_{d,c}(p_c, p_{d,c}) \\
\text{subject to } & SR_c(p_c, p_{d,c}) \geq \theta_c, \quad \forall c \\
& \sum_{c=1}^{C} \omega_{d,c} \leq 1, \quad \forall d; \;\; \sum_{d=1}^{D} \omega_{d,c} \leq 1, \;\forall c \\
& \omega_{d,c} \in \{0,1\}, \quad \forall d, c \\
& \sum_{c=1}^{C} \omega_{d,c} p_{d,c} \leq P_d, \quad \forall d; \;\; p_{d,c} \geq 0, \;\forall d, c \\
& \sum_{c=1}^{C} p_c \leq P_{BS}; \quad p_c \geq 0, \;\forall c
\end{aligned} \tag{9}$$

which is a more restricted version of (8) with the additional constraints $\sum_{c=1}^{C} \omega_{d,c} \leq 1$, $\forall d$. Before solving (9), we first investigate the feasibility of this problem.

Lemma 1: Let $\alpha_c = 2^{\theta_c}$. When channel c is not reused by any D2D link, then $SR_c(p_c, p_{d,c}) \geq \theta_c$ can be achieved only if

$$g_c - \alpha_c g_{c,e}^I \geq 0. \tag{10}$$

When channel c is reused by D2D link d, then $SR_c(p_c, p_{d,c}) \geq \theta_c$ can be achieved only if

$$g_c - \alpha_c g_{c,e}^I + p_{d,c}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I) \geq 0. \tag{11}$$

Proof: See Appendix A. □

Remark 1: Lemma 1 provides the necessary condition[5] for the feasibility of problem (9). If there is no D2D communication, CU c will fail to meet the security requirement if $g_c - \alpha_c g_{c,e}^I < 0$. The situation can be improved, if channel c is shared by D2D link d. In this case, even if $g_c - \alpha_c g_{c,e}^I < 0$, the security QoS constraint may still be satisfied if the more relaxed condition (11) is met. In fact, the sign of the term $g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I$ determines whether D2D link d can improve the security of CU c. Specifically, if $g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I > 0$, then D2D link d is able to improve CU c's security; if $g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I \leq 0$, then D2D link d may degrade the secrecy performance of CU c. In the latter case, CU c sacrifices its security to improve the spectral efficiency of D2D link d, which may be tolerated if $g_c - \alpha_c g_{c,e}^I > 0$.

[5]This condition is only necessary in the downlink case but is sufficient and necessary in the uplink case.

A. Resource Optimization under Individual Power Budgets

Now, we tackle the single-channel D2D resource management problem in (9). Since each D2D link can only share one CU channel, the D2D power constraints $\sum_{c=1}^{C} \omega_{d,c} p_{d,c} \leq P_d$, $\forall d$, actually decouple into $p_{d,c} \leq P_d$, $\forall d, c$, which makes problem (9) easier to solve than problem (8). However, problem (9) is still difficult to solve due to its mixed integer nature as well as the coupled power constraint $\sum_{c=1}^{C} p_c \leq P_{BS}$ at the BS. To address the latter difficulty, one simple approach is to replace the total power budget P_{BS} by a set of individual power budgets $\{t_c\}$ for each CU c such that $\sum_{c=1}^{C} t_c = P_{BS}$. Then, problem (9) can be simplified to

$$\begin{aligned}
\underset{\{p_c, p_{d,c}, \omega_{d,c}\}}{\text{maximize}} \; & \sum_{d=1}^{D}\sum_{c=1}^{C} \omega_{d,c} R_{d,c}(p_c, p_{d,c}) \\
\text{subject to } & SR_c(p_c, p_{d,c}) \geq \theta_c, \quad \forall c \\
& \sum_{c=1}^{C} \omega_{d,c} \leq 1, \quad \forall d; \;\; \sum_{d=1}^{D} \omega_{d,c} \leq 1, \;\forall c \\
& \omega_{d,c} \in \{0,1\}, \quad \forall d, c \\
& 0 \leq p_{d,c} \leq P_d, \quad \forall d, c \\
& 0 \leq p_c \leq t_c, \quad \forall c.
\end{aligned} \tag{12}$$

For given individual power budgets $\{t_c\}$, the power constraints in (12) are all decoupled. We will show in Section III-B that the solution to (12) can be used to solve (9).

The simplified problem in (12) is, however, still a difficult mixed integer program. Nevertheless, in the following, we show that the optimal solution to (12) can be efficiently found. For this purpose, we assume for the moment that the channel assignment is given, i.e., variables $\{\omega_{d,c}\}$ are fixed. Then, (12) becomes a pure power allocation problem. If channel c is not shared by any D2D link, i.e., $\omega_{d,c} = 0$ for $d = 1, \ldots, D$, then the optimal choice is apparently $p_{d,c}^\star = 0$ for $d = 1, \ldots, D$. In this case, CU c has to satisfy the security QoS constraint $SR_c(p_c, p_{d,c}) = R_c^0(p_c) \geq \theta_c$ by itself, and the minimum power to meet this constraint is

$$p_c^\star = \frac{\alpha_c - 1}{g_c - \alpha_c g_{c,e}^I}. \tag{13}$$

On the other hand, for the channels reused by a D2D link, since the objective function and the power constraints are decoupled, the power allocation problem (with fixed $\{\omega_{d,c}\}$) decomposes into a number of subproblems:

$$\begin{aligned}
\underset{p_c, p_{d,c}}{\text{maximize}} \; & R_{d,c}(p_c, p_{d,c}) \\
\text{subject to } & R_c^1(p_c, p_{d,c}) \geq \theta_c \\
& 0 \leq p_{d,c} \leq P_d, \quad 0 \leq p_c \leq t_c \\
& g_c - \alpha_c g_{c,e}^I + p_{d,c}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I) \geq 0
\end{aligned} \tag{14}$$

for each pair (c, d) such that $\omega_{d,c} = 1$. The last constraint in (14) is the feasibility condition in (11) for channel c to be shared by D2D link d. The optimal solution to subproblem (14) is provided in the following theorem.

Theorem 1: The optimal solution to (14) *is given by*

$$p_c^\star = \frac{(\alpha_c - 1)(1 + p_{d,c}^\star g_{d,c}^I)(1 + p_{d,c}^\star g_{d,e}^I)}{g_c - \alpha_c g_{c,e}^I + p_{d,c}^\star (g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I)} \tag{15}$$

and $p_{d,c}^\star \in \{x_{d,c}^1, x_{d,c}^2, L_{d,c}, U_{d,c}\}$, *where* $x_{d,c}^1$ *and* $x_{d,c}^2$ *are the roots of the quadratic equation* $\bar{A}x^2 + \bar{B}x + \bar{C} = 0$ *with* $\bar{A} \triangleq (\alpha_c g_{c,e}^I g_{d,c}^I - g_c g_{d,e}^I)^2 + (\alpha_c - 1)g_{c,d}^I \left[g_c (g_{d,e}^I)^2 - \alpha_c g_{c,e}^I (g_{d,c}^I)^2\right]$, $\bar{B} \triangleq 2\alpha_c g_{c,e}^I(\alpha_c g_{d,c}^I g_{c,e}^I - g_c g_{d,c}^I - g_c g_{d,e}^I) + 2(\alpha_c - 1)g_{c,d}^I(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I) + 2g_c^2 g_{d,e}^I$, $\bar{C} \triangleq (g_c - \alpha_c g_{c,e}^I)^2 + (\alpha_c - 1)g_{c,d}^I(g_c - \alpha_c g_{c,e}^I)$, *and*

$$L_{d,c} \triangleq \begin{cases} \max\{0, \delta_c/\xi_{d,c}, y_{d,c}^1\}, & \xi_{d,c} > 0 \\ \max\{0, y_{d,c}^1\}, & \xi_{d,c} \le 0 \end{cases}$$

$$U_{d,c} \triangleq \begin{cases} \min\{P_d, y_{d,c}^2\}, & \xi_{d,c} > 0 \\ \min\{P_d, \delta_c/\xi_{d,c}, y_{d,c}^2\}, & \xi_{d,c} \le 0 \end{cases}$$

where $\delta_c \triangleq \alpha_c g_{c,e}^I - g_c$, $\xi_{d,c} \triangleq g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I$, *and*

$$y_{d,c}^1 \triangleq \frac{-\bar{b} - \sqrt{\bar{b}^2 - 4\bar{a}\bar{c}}}{2\bar{a}}, \quad y_{d,c}^2 \triangleq \frac{-\bar{b} + \sqrt{\bar{b}^2 - 4\bar{a}\bar{c}}}{2\bar{a}}$$

with $\bar{a} \triangleq (\alpha_c - 1)g_{d,e}^I g_{d,c}^I$, $\bar{b} \triangleq (\alpha_c - 1)(g_{d,e}^I + g_{d,c}^I) - t_c(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I)$, *and* $\bar{c} \triangleq \alpha_c - 1 + t_c(\alpha_c g_{c,e}^I - g_c)$.

Proof: See Appendix B. □

Remark 2: According to Theorem 1, if channel c is reused by D2D link d, the optimal power allocated to CU c is given by (15), which indicates that the security QoS constraint in (14) will be satisfied with equality. The optimal power of D2D link d on channel c is from the set $\{x_{d,c}^1, x_{d,c}^2, L_{d,c}, U_{d,c}\}$. Therefore, by comparing the objective values of $R_{d,c}(p_c, p_{d,c})$ for the four possible $p_{d,c} \in \{x_{d,c}^1, x_{d,c}^2, L_{d,c}, U_{d,c}\}$, one can easily determine the optimal $p_{d,c}^\star$ and $p_c^\star$. Consequently, we have analytically characterized the optimal power allocation of CU c and D2D link d for both the case where channel c is allocated to a D2D link d and the case where channel c is not shared by any D2D link.

Next, we investigate how to determine the optimal channel assignment, i.e., $\{\omega_{d,c}\}$, in (12). Thanks to the optimal power allocation obtained above, given any $\omega_{d,c} = 1$, we are able to determine the corresponding maximum value $R_{d,c}(p_c^\star, p_{d,c}^\star)$ (if $\omega_{d,c} = 0$, then obviously $R_{d,c}(p_c, p_{d,c}) = 0$). Therefore, the mixed integer problem in (12) reduces to a pure combinatorial problem as follows:

$$\begin{aligned} &\underset{\{\omega_{d,c}\}}{\text{maximize}} \ \sum_{d=1}^{D}\sum_{c=1}^{C} \omega_{d,c} R_{d,c}(p_c^\star, p_{d,c}^\star) \\ &\text{subject to} \ \sum_{c=1}^{C} \omega_{d,c} \le 1, \quad \forall d; \ \sum_{d=1}^{D} \omega_{d,c} \le 1, \ \forall c \\ &\qquad\qquad \omega_{d,c} \in \{0, 1\}, \quad \forall d, c \end{aligned} \tag{16}$$

which, although involving binary variables, can be efficiently solved. Indeed, (16) belongs to the class of one-to-one assignment problems [28], whose optimal solutions can be found in polynomial time by different methods, e.g., the well-known Hungarian algorithm [29].

Remark 3: Another convenient way to solve (16) is to relax each binary variable $\omega_{d,c} \in \{0, 1\}$ into a continuous variable $\omega_{d,c} \in [0, 1]$. Then, (16) becomes a linear program that can be efficiently solved by many algorithms and software tools. Interestingly, the solution of the relaxed linear problem still exhibits the binary property. In other words, by relaxing (16) into a linear problem, we do not loose optimality. Such a favorable result can be proved by using the so-called totally unimodular property [28, Th. 4.2]. Consequently, we are able to efficiently find the jointly optimal channel assignment and power allocation for problem (12) by using Theorem 1 and solving the one-to-one assignment problem in (16).

B. Optimization of Individual Power Budgets

Although we have obtained the optimal solution to problem (12), it is a simplified version of the original problem (9) as we have replaced the total power constraint $\sum_{c=1}^{C} p_c \le P_{BS}$ with the individual power constraints $p_c \le t_c, \forall c$. Hence, one may naturally wonder how to choose the individual power budgets $\{t_c\}$. A simple way is to use equal individual power budgets

$$t_c = \frac{P_{BS}}{C}, \quad c = 1, \ldots, C \tag{17}$$

which is, however, a heuristic and in general suboptimal choice. A more intelligent way is to further optimize $\{t_c\}$.

For given individual power budgets, if the optimal assignment of channel c is $\omega_{d,c}^\star = 1$, then $p_c^\star(t_c)$ and $p_{d,c}^\star(t_c)$ are related to t_c via Theorem 1. If channel c is not assigned to any D2D link, i.e., $\omega_{d,c}^\star = 0, \forall d$, then $p_c^\star$ is given by (13) and $p_{d,c}^\star = 0, \forall d$. Since each CU channel is only assigned to at most one D2D link, we can express the optimal objective value of the simplified problem (12) in terms of $\boldsymbol{t} \triangleq [t_1, \ldots, t_C]^T$ as $f(\boldsymbol{t}) \triangleq \sum_{c=1}^{C} f_c(t_c)$, where $f_c(t_c) = R_{d,c}(p_c^\star(t_c), p_{d,c}^\star(t_c))$ denotes the optimal objective value of subproblem (14). Then, the individual power budgets can be optimized in the following manner:

$$\begin{aligned} &\underset{\boldsymbol{t}}{\text{maximize}} \ f(\boldsymbol{t}) \triangleq \sum_{c=1}^{C} f_c(t_c) \\ &\text{subject to} \ \sum_{c=1}^{C} t_c \le P_{BS}; \quad t_c \ge 0, \ \forall c. \end{aligned} \tag{18}$$

Note that, however, the optimal value function $f_c(t_c)$ does not admit an explicit expression, making it hard to optimize $\{t_c\}$. To overcome this difficulty, we prove the following property of $f_c(t_c)$.

Theorem 2: Suppose that $\omega_{d,c}^\star = 1$ *and let* $(p_c^\star, p_{d,c}^\star)$ *be the optimal solution to problem* (12) *for given* t_c. *Then,* $f_c(t_c)$ *is differentiable and its derivative is given in* (19) *at the bottom of the next page, where*

$$l_{d,c} \triangleq \begin{cases} \max\{0, \delta_c/\xi_{d,c},\}, & \xi_{d,c} > 0 \\ 0, & \xi_{d,c} \le 0 \end{cases}$$

$$u_{d,c} \triangleq \begin{cases} P_d, & \xi_{d,c} > 0 \\ \min\{P_d, \delta_c/\xi_{d,c}\}, & \xi_{d,c} \le 0 \end{cases}$$

and $p'_c(p_{d,c})$ is the derivative of p_c in (15) with respect to $p_{d,c}$ and given by

$$p'_c(p_{d,c}) = (\alpha_c - 1)\left[\frac{g^I_{d,c}\left(1+g^I_{d,e}p_{d,c}\right)+g^I_{d,e}\left(1+g^I_{d,c}p_{d,c}\right)}{g_c\left(1+g^I_{d,e}p_{d,c}\right)-\alpha_c g^I_{c,e}\left(1+g^I_{d,c}p_{d,c}\right)} - \frac{\left(1+g^I_{d,e}p_{d,c}\right)\left(1+g^I_{d,c}p_{d,c}\right)\left(g_c g^I_{d,e}-\alpha_c g^I_{c,e}g^I_{d,c}\right)}{\left[g_c\left(1+g^I_{d,e}p_{d,c}\right)-\alpha_c g^I_{c,e}\left(1+g^I_{d,c}p_{d,c}\right)\right]^2}\right]. \tag{20}$$

Proof: See Appendix C. □

From Theorem 2, for a given individual power budget t_c, if channel c is allocated to D2D link d (i.e., $\omega^\star_{d,c}=1$) with the optimal power allocation $(p^\star_c, p^\star_{d,c})$, then the optimal value function $f_c(t_c) = R_{d,c}(p^\star_c(t_c), p^\star_{d,c}(t_c))$ is not only continuous but also differentiable. Though an explicit expression of $f_c(t_c)$ is unknown, we are able to calculate the derivative of $f_c(t_c)$ via (19). Consequently, we can obtain the gradient of $f(\boldsymbol{t})$ as $\boldsymbol{s_t} \triangleq [f'_1(t_1), \ldots, f'_C(t_C)]^T$, which makes it possible to exploit gradient-based methods to solve the individual power budget optimization problem in (18).

Given the gradient $\boldsymbol{s_t}$, a convenient method to solve (18) is the gradient projection method. Specifically, we define the constraint set of (18) as

$$\mathcal{T} \triangleq \left\{\boldsymbol{t} : \sum_{c=1}^{C} t_c \le P_{BS};\ t_c \ge 0, \quad \forall c\right\}. \tag{21}$$

Then, the individual power budgets $\boldsymbol{t}$ are updated as follows

$$\boldsymbol{t}(n+1) = \left[\boldsymbol{t}(n) + \kappa_n \boldsymbol{s}_{\boldsymbol{t}(n)}\right]_{\mathcal{T}} \tag{22}$$

where κ_n is the step size at iteration n, and $[\cdot]_{\mathcal{T}}$ stands for the projection onto set $\mathcal{T}$. The adaptation in (22) starts from an initial point $\boldsymbol{t}(0)$, which could be any feasible point in $\mathcal{T}$, for example the equal power budgets in (17). In each iteration, one shall calculate the projection $[\cdot]_{\mathcal{T}}$, which, fortunately, can be expressed in a waterfilling fashion upon the fact that $\mathcal{T}$ is a simplex.

Lemma 2: ([30]) Let $\boldsymbol{t} = [\boldsymbol{u}]_{\mathcal{T}}$. Then, $t_c = [u_c - \rho]_+$ for $c = 1, \ldots, C$, where ρ is the minimum value such that $\sum_{c=1}^{C} t_c \le P_{BS}$.

The proposed secure resource management method for single-channel D2D communication is summarized in Algorithm 1. With a properly chosen step size,[6] Algorithm 1 is guaranteed to converge to a KKT point (i.e., stationary point) of (18).

[6]For example, one can use a diminishing step size $\kappa_n = \kappa_0(1+\eta)/(n+\eta)$, where $\kappa_0 \in (0,1]$ is the initial step size and $\eta \ge 0$ is a constant.

Algorithm 1 : Secure Single-Channel D2D Resource Management

1: Choose an initial point $\boldsymbol{t}(0)$ and precision ϵ and set $n=0$;
2: Obtain $(p^\star_c, p^\star_{d,c})$ for all possible channel assignments from Theorem 1;
3: Solve the one-to-one assignment problem in (16);
4: Obtain the derivative of $f_c(t_c)$ and gradient $\boldsymbol{s}_{\boldsymbol{t}(n)}$ from Theorem 2;
5: Update $\boldsymbol{t}$ as $\boldsymbol{t}(n+1) = \left[\boldsymbol{t}(n) + \kappa_n \boldsymbol{s}_{\boldsymbol{t}(n)}\right]_{\mathcal{T}}$ and $n = n+1$
6: If $\|\boldsymbol{t}(n) - \boldsymbol{t}(n-1)\| \le \epsilon$ stop, otherwise go to step 2.

Remark 4: The resource management problem in (9) can be equivalently transformed into a two-level problem. In the upper level, the individual power budget optimization problem in (18) with variables $\boldsymbol{t}$ is solved by Algorithm 1, and in the lower level, the simplified problem in (12) with given $\boldsymbol{t}$ is optimally solved by solving the subproblems in (14) and the one-to-one assignment problem in (16). Therefore, Algorithm 1 provides a stationary solution to (9), which is typically the best possible solution one can achieve in polynomial time for NP-hard mixed integer problems.

Remark 5: In the uplink case, one can formulate a secure resource management problem similar to (9) with properly defined channel gains. The only difference is that the downlink total power constraint $\sum_{c=1}^{C} p_c \le P_{BS}$ has to be replaced by uplink individual power constraints $p_c \le P_c$, $\forall c$. In this case, the proposed method can be applied as well. Indeed, the uplink resource management problem is a simplified version of the downlink problem in (9) and has the same structure as the simplified problem in (12) after replacing t_c by P_c. Therefore, the globally optimal power allocation and channel assignment for uplink resource sharing can be found by using Theorem 1 and solving the assignment problem in (16).

IV. Multi-Channel D2D

In this section, we consider multi-channel D2D communication that allows each D2D link to share multiple CU channels. Apparently, multi-channel D2D communication can better utilize the cellular resources and achieve higher spectral efficiency than single-channel D2D communication. On the other hand, however, multi-channel D2D communication also results in the more complicated secure resource management problem in (8), which includes the single-channel problem in (9) as a special case. Therefore, in general the methods proposed in the previous section cannot be applied for solving (8), and we have to devise a new method for multi-channel D2D resource management.

$$f'_c(t_c) = \begin{cases} 0, & \text{if } p^\star_c \ne t_c \\ \frac{1}{\ln 2}\frac{g_{d,c}\left(1+g^I_{c,d}t_c - g^I_{c,d}p^\star_{d,c}p'_c(p^\star_{d,c})\right)}{(1+p^\star_{d,c}g_{d,c}+t_c g^I_{c,d})(1+t_c g^I_{c,d})p'_c(p^\star_{d,c})}, & \text{if } p^\star_c = t_c \text{ and } p^\star_{d,c} \in (l_{d,c}, u_{d,c}) \\ \frac{1}{\ln 2}\frac{-l_{d,c}g_{d,c}g^I_{c,d}}{(1+t_c g^I_{c,d}+l_{d,c}g_{d,c})(1+t_c g^I_{c,d})}, & \text{if } p^\star_c = t_c \text{ and } p^\star_{d,c} = l_{d,c} \\ \frac{1}{\ln 2}\frac{-u_{d,c}g_{d,c}g^I_{c,d}}{(1+t_c g^I_{c,d}+u_{d,c}g_{d,c})(1+t_c g^I_{c,d})}, & \text{if } p^\star_c = t_c \text{ and } p^\star_{d,c} = u_{d,c} \end{cases} \tag{19}$$

A. Equivalent Transformation and Hidden Convexity

The feasibility condition of problem (8) is provided in Lemma 1. Specifically, channel c can be reused by D2D link d only if $g_c - \alpha_c g^I_{c,e} + p_{d,c}(g_c g^I_{d,e} - \alpha_c g^I_{c,e} g^I_{d,c}) \geq 0$, which in fact presents an additional constraint in (8) and makes it more complicated. Indeed, problem (8) is intractable in its original form. Therefore, we first transform it into a more favorable form by determining the optimal power of each CU.

Lemma 3: If channel c is not reused by any D2D link, i.e., $\omega_{d,c} = 0$, $\forall d$, then the optimal power of CU c is

$$p^\star_c = \frac{\alpha_c - 1}{g_c - \alpha_c g^I_{c,e}}. \tag{23}$$

If channel c is reused by D2D link d, i.e., $\omega_{d,c} = 1$, then

$$p^\star_c = \frac{(\alpha_c - 1)(1 + p_{d,c} g^I_{d,c})(1 + p_{d,c} g^I_{d,e})}{g_c - \alpha_c g^I_{c,e} + p_{d,c}(g_c g^I_{d,e} - \alpha_c g^I_{c,e} g^I_{d,c})}. \tag{24}$$

Proof: The proof follows directly from that of Theorem 1. □

Lemma 3 implies that the security QoS constraint can be eliminated by expressing the optimal power $p^\star_c$ of CU c, if its channel is shared by D2D link d, as a function of $p_{d,c}$. We can exploit this relation to simplify problem (8). In particular, the total power constraint $\sum_{c=1}^{C} p_c \leq P_{BS}$ at the BS can be rewritten as

$$\sum_{c=1}^{C} \left[\sum_{d=1}^{D} \omega_{d,c} \frac{(\alpha_c - 1)(1 + p_{d,c} g^I_{d,c})(1 + p_{d,c} g^I_{d,e})}{g_c - \alpha_c g^I_{c,e} + p_{d,c}(g_c g^I_{d,e} - \alpha_c g^I_{c,e} g^I_{d,c})} + \left(1 - \sum_{d=1}^{D} \omega_{d,c}\right) \frac{\alpha_c - 1}{g_c - \alpha_c g^I_{c,e}} \right] \leq P_{BS} \tag{25}$$

which includes both the non-reuse case (23) and the reuse case (24). Moreover, substituting (24) into $R_{d,c}(p_c, p_{d,c})$, we obtain

$$R_{d,c}(p_{d,c}) = \log_2 \left(1 + \frac{p_{d,c} g_{d,c}}{1 + \frac{(\alpha_c - 1)(1 + p_{d,c} g^I_{d,c})(1 + p_{d,c} g^I_{d,e}) g^I_{c,d}}{g_c - \alpha_c g^I_{c,e} + p_{d,c}(g_c g^I_{d,e} - \alpha_c g^I_{c,e} g^I_{d,c})}} \right). \tag{26}$$

Note that if $\omega_{d,c} = 0$, the corresponding $R_{d,c}$ will vanish in the objective function. Therefore, problem (8) can be equivalently transformed into the following form:

$$\begin{aligned} \underset{\{p_{d,c}, \omega_{d,c}\}}{\text{maximize}} \quad & \sum_{d=1}^{D} \sum_{c=1}^{C} \omega_{d,c} R_{d,c}(p_{d,c}) \\ \text{subject to} \quad & \sum_{d=1}^{D} \omega_{d,c} \leq 1, \quad \forall c; \; 0 \leq \omega_{d,c} \leq 1, \; \forall d, c \\ & \sum_{c=1}^{C} \omega_{d,c} p_{d,c} \leq P_d, \quad \forall d; \; p_{d,c} \geq 0, \; \forall d, c \\ & g_c - \alpha_c g^I_{c,e} + p_{d,c}(g_c g^I_{d,e} - \alpha_c g^I_{c,e} g^I_{d,c}) \geq 0, \\ & \forall d, c \\ & (26) \end{aligned} \tag{27}$$

where $R_{d,c}(p_{d,c})$ is given in (26).

So far, we have eliminated the security QoS constraints and reduced the variable space from $\{p_c, p_{d,c}, \omega_{d,c}\}$ to $\{p_{d,c}, \omega_{d,c}\}$, which leads to the equivalent problem in (27). On the other hand, however, the objective function and the constraints in (27) are even more complicated than those in the original problem in (8). In addition, because of its mixed integer structure, (27) is still intractable. To find a tractable solution, we introduce the following two steps. First, we relax the binary variables $\omega_{d,c} \in \{0, 1\}$, $\forall d, c$ into continuous variables $\omega_{d,c} \in [0, 1]$, $\forall d, c$. Second, we introduce auxiliary variable $\gamma_{d,c}$, which represents the SINR in $R_{d,c}$ for $\forall d, c$. Then, mixed integer problem (27) is transformed into the following continuous problem:

$$\begin{aligned} \underset{\{p_{d,c}, \omega_{d,c}, \gamma_{d,c}\}}{\text{maximize}} \quad & \sum_{d=1}^{D} \sum_{c=1}^{C} \omega_{d,c} \log_2(1 + \gamma_{d,c}) \\ \text{subject to} \quad & \frac{p_{d,c} g_{d,c}}{1 + \frac{(\alpha_c - 1)(1 + p_{d,c} g^I_{d,c})(1 + p_{d,c} g^I_{d,e}) g^I_{c,d}}{g_c - \alpha_c g^I_{c,e} + p_{d,c}(g_c g^I_{d,e} - \alpha_c g^I_{c,e} g^I_{d,c})}} \geq \gamma_{d,c}, \\ & \forall d, c \\ & \sum_{d=1}^{D} \omega_{d,c} \leq 1, \; \forall c; \; \omega_{d,c} \geq 0, \; \forall d, c \\ & \sum_{c=1}^{C} \omega_{d,c} p_{d,c} \leq P_d, \; \forall d; \; p_{d,c} \geq 0, \; \forall d, c \\ & g_c - \alpha_c g^I_{c,e} + p_{d,c}(g_c g^I_{d,e} - \alpha_c g^I_{c,e} g^I_{d,c}) \geq 0, \\ & \forall d, c \\ & (26). \end{aligned} \tag{28}$$

Unfortunately, this problem is still difficult to solve due to the nonconvexity of both the objective function and the constraints. Nevertheless, we are able to reveal a hidden convexity in (28) if auxiliary variables $\{\gamma_{d,c}\}$ are fixed.

For this purpose, we need to transform (28) into an equivalent form. Specifically, we introduce variable $q_{d,c} = \omega_{d,c} p_{d,c}$, $\forall d, c$. Then, (28) is equivalent to the problem in (29) at the bottom of the next page. At first glance, the equivalent problem in (29) seems to be more complicated than (28). However, (29) possesses the following favorable property.

Theorem 3: Suppose that $\{\gamma_{d,c}\}$ are fixed. Then, problem (29) *is a convex optimization problem.*

Proof: See Appendix D. □

Remark 6: Theorem 3 reveals that, for fixed SINRs (i.e., $\{\gamma_{d,c}\}$), (29) (or equivalently (28)) is actually a convex optimization problem. Therefore, the jointly optimal power allocation and (relaxed) channel assignment can be efficiently found by exploiting one of the numerous available convex optimization methods, e.g., the interior method [31]. Furthermore, given the structure and convexity of (29), we are able to analytically characterize the optimal power allocation and channel assignment in the dual domain.

B. Analytical Characterization and Algorithms

To find the optimal power allocation and channel assignment, we rewrite (29) into the following compact form:

$$\begin{aligned}
&\underset{\{q_{d,c},\omega_{d,c},\gamma_{d,c}\}}{\text{maximize}} \ \sum_{d=1}^{D}\sum_{c=1}^{C}\omega_{d,c}\log_2(1+\gamma_{d,c}) \\
&\text{subject to} \ \sum_{d=1}^{D}\omega_{d,c}\le 1,\ \forall c;\ \omega_{d,c}\ge 0,\ \forall d,c \\
&\qquad \gamma_{d,c}\omega_{d,c}+\gamma_{d,c}g_{c,d}^{I}\varphi(q_{d,c},\omega_{d,c})\le q_{d,c}g_{d,c}, \\
&\qquad \forall d,c \\
&\qquad \sum_{c=1}^{C}q_{d,c}\le P_d,\quad \forall d \\
&\qquad q_{d,c}\ge 0,\quad q_{d,c}\xi_{d,c}\ge\omega_{d,c}\delta_c,\ \forall d,c \\
&\qquad \sum_{c=1}^{C}\sum_{d=1}^{D}\varphi(q_{d,c},\omega_{d,c})-\sum_{c=1}^{C}\sum_{d=1}^{D}\omega_{d,c}\tau_c \\
&\qquad +\sum_{c=1}^{C}\tau_c\le P_{BS}
\end{aligned} \tag{30}$$

where δ_c and $\xi_{d,c}$ are defined in Theorem 1,

$$\varphi(q_{d,c},\omega_{d,c})\triangleq\omega_{d,c}p_c\left(\frac{q_{d,c}}{\omega_{d,c}}\right) \text{ and } \tau_c\triangleq\frac{\alpha_c-1}{g_c-\alpha_c g_{c,e}^{I}},$$

and function $p_c(p_{d,c})$ is given in (24). Then, the (partial) Lagrangian of (30) (or (29)) is given by

$$\begin{aligned}
&L(\boldsymbol{q},\boldsymbol{\omega},\boldsymbol{\lambda},\boldsymbol{\mu},\eta) \\
&=\sum_{d=1}^{D}\sum_{c=1}^{C}\omega_{d,c}\log_2(1+\gamma_{d,c})+\sum_{d=1}^{D}\mu_d\left(P_d-\sum_{c=1}^{C}q_{d,c}\right) \\
&\quad+\sum_{d=1}^{D}\sum_{c=1}^{C}\lambda_{d,c}\left(q_{d,c}g_{d,c}-\gamma_{d,c}\omega_{d,c}-\gamma_{d,c}g_{c,d}^{I}\varphi(q_{d,c},\omega_{d,c})\right) \\
&\quad+S\eta\left(P_{BS}-\sum_{c=1}^{C}\sum_{d=1}^{D}\varphi(q_{d,c},\omega_{d,c})+\sum_{c=1}^{C}\sum_{d=1}^{D}\omega_{d,c}\tau_c-\sum_{c=1}^{C}\tau_c\right)
\end{aligned} \tag{31}$$

where $\boldsymbol{\omega}\triangleq\{\omega_{d,c}\}$, $\boldsymbol{\lambda}\triangleq\{\lambda_{d,c}\}$, $\boldsymbol{\mu}\triangleq\{\mu_d\}$ are sets of Lagrange multipliers and $\boldsymbol{q}\triangleq\{q_{d,c}\}$. The optimal power allocation of each D2D link is provided in the following proposition.

Proposition 1: Given the Lagrange multipliers $(\boldsymbol{\lambda},\boldsymbol{\mu},\eta)$, the optimal power of D2D link d on channel c in (29) is given by

$$p_{d,c}^{\star}=\begin{cases}0, & \xi_{d,c}\le 0 \ \textit{and}\ \frac{\lambda_{d,c}g_{d,c}-\mu_d}{\lambda_{d,c}\gamma_{d,c}g_{c,d}^{I}+\eta}\le p_c'(0)\\ u_{d,c}, & \xi_{d,c}\le 0 \ \textit{and}\ \frac{\lambda_{d,c}g_{d,c}-\mu_d}{\lambda_{d,c}\gamma_{d,c}g_{c,d}^{I}+\eta}\ge p_c'(u_{d,c})\\ l_{d,c}, & \xi_{d,c}> 0 \ \textit{and}\ \frac{\lambda_{d,c}g_{d,c}-\mu_d}{\lambda_{d,c}\gamma_{d,c}g_{c,d}^{I}+\eta}\le p_c'(l_{d,c})\\ \bar{p}_{d,c}, & \textit{otherwise}\end{cases} \tag{32}$$

where $u_{d,c}$ and $l_{d,c}$ are defined in Theorem 2, and $\bar{p}_{d,c}$ is the root of the following equation:

$$p_c'(p_{d,c})=\frac{\lambda_{d,c}g_{d,c}-\mu_d}{\lambda_{d,c}\gamma_{d,c}g_{c,d}^{I}+\eta} \tag{33}$$

where $p_c'(p_{d,c})$ is given in (20).

Proof: See Appendix E. □

Moreover, the optimal channel assignment can be found as follows.

Proposition 2: Given the Lagrange multipliers $(\boldsymbol{\lambda},\boldsymbol{\mu},\eta)$ and power allocation $\{p_{d,c}\}$, for each channel c the optimal $\{\omega_{d,c}\}$ are given by

$$\omega_{d,c}^{\star}=\begin{cases}1, & d=\arg\max_{d'}\{\Gamma_{d',c}\}\\ 0, & \text{otherwise}\end{cases} \tag{34}$$

where

$$\begin{aligned}
\Gamma_{d,c}\triangleq{}&\log_2(1+\gamma_{d,c})-\mu_d p_{d,c} \\
&+\lambda_{d,c}\left(p_{d,c}g_{d,c}-\gamma_{d,c}-\gamma_{d,c}g_{c,d}^{I}p_c(p_{d,c})\right) \\
&+\eta\left(\tau_c-p_c(p_{d,c})\right).
\end{aligned} \tag{35}$$

Proof: See Appendix E. □

Remark 7: Propositions 1 and 2 analytically characterize the optimal D2D power allocation and channel assignment. Interestingly, according to Proposition 2, although we have relaxed $\omega_{d,c}\in\{0,1\}$ to $\omega_{d,c}\in[0,1]$, the obtained solution is still binary. Such an relaxation may cause a problem when there are multiple $d=\arg\max_{d'}\{\Gamma_{d',c}\}$, i.e., $\Gamma_{d,c}$ is equal for some D2D links. Note, however, that $\Gamma_{d,c}$ depends on the channel gains $g_{d,c}$, $g_{c,d}^{I}$, g_c, and $g_{c,e}^{I}$, which are all continuous and random. Therefore, the probability that multiple $\Gamma_{d,c}$ are

$$\begin{aligned}
&\underset{\{q_{d,c},\omega_{d,c},\gamma_{d,c}\}}{\text{maximize}} \ \sum_{d=1}^{D}\sum_{c=1}^{C}\omega_{d,c}\log_2(1+\gamma_{d,c}) \\
&\text{subject to} \ \frac{\frac{q_{d,c}}{\omega_{d,c}}g_{d,c}}{1+\frac{(\alpha_c-1)(1+\frac{q_{d,c}}{\omega_{d,c}}g_{d,c}^{I})(1+\frac{q_{d,c}}{\omega_{d,c}}g_{d,e}^{I})g_{c,d}^{I}}{g_c-\alpha_c g_{c,e}^{I}+\frac{q_{d,c}}{\omega_{d,c}}(g_c g_{d,e}^{I}-\alpha_c g_{c,e}^{I}g_{d,c}^{I})}}\ge\gamma_{d,c},\ \forall d,c \\
&\qquad \sum_{d=1}^{D}\omega_{d,c}\le 1,\quad \forall c;\ \omega_{d,c}\ge 0,\ \forall d,c;\ \sum_{c=1}^{C}q_{d,c}\le P_d,\ \forall d;\ q_{d,c}\ge 0,\ \forall d,c \\
&\qquad \omega_{d,c}(g_c-\alpha_c g_{c,e}^{I})+q_{d,c}(g_c g_{d,e}^{I}-\alpha_c g_{c,e}^{I}g_{d,c}^{I})\ge 0,\ \forall d,c \\
&\qquad \sum_{c=1}^{C}\left[\sum_{d=1}^{D}\omega_{d,c}\frac{(\alpha_c-1)(1+\frac{q_{d,c}}{\omega_{d,c}}g_{d,c}^{I})(1+\frac{q_{d,c}}{\omega_{d,c}}g_{d,e}^{I})}{g_c-\alpha_c g_{c,e}^{I}+\frac{q_{d,c}}{\omega_{d,c}}(g_c g_{d,e}^{I}-\alpha_c g_{c,e}^{I}g_{d,c}^{I})}+\left(1-\sum_{d=1}^{D}\omega_{d,c}\right)\frac{\alpha_c-1}{g_c-\alpha_c g_{c,e}^{I}}\right]\le P_{BS}
\end{aligned} \tag{29}$$

Algorithm 2 : Optimal Power Allocation and Channel Assignment for Given SINRs

1: Choose initial $\boldsymbol{\lambda}(0)$, $\boldsymbol{\mu}(0)$, $\eta(0)$ and precision ϵ and set $k=0$;
2: Obtain $\{p^\star_{d,c}\}$ from Proposition 1;
3: Obtain $\{\omega^\star_{d,c}\}$ from Proposition 2;
4: Update $\boldsymbol{\upsilon}=(\boldsymbol{\lambda},\boldsymbol{\mu},\eta)$ as $\boldsymbol{\upsilon}(k+1)=\left[\boldsymbol{\upsilon}(k)+\kappa_k \boldsymbol{s}_{\boldsymbol{\upsilon}(k)}\right]_+$ and $k=k+1$
5: If $\|\boldsymbol{\upsilon}(k)-\boldsymbol{\upsilon}(k-1)\|\le\epsilon$ stop, otherwise go to step 2.

equal is zero and the relaxation does not cause a loss of optimality in practice.

Meanwhile, Propositions 1 and 2 also suggest a convenient way to compute the optimal power allocation and channel assignment. In particular, given $(\boldsymbol{\lambda},\boldsymbol{\mu},\eta)$, one can first determine the optimal $\{p_{d,c}\}$ based on (32), and then determine the optimal $\{\omega_{d,c}\}$ based on (34). To find the optimal Lagrange multipliers, the subgradient projection method can be adopted. In particular, the subgradients of $\lambda_{d,c}$, μ_d, and η are given respectively by [32]

$$s_{\lambda_{d,c}} \triangleq \omega_{d,c}\left[p_{d,c}g_{d,c}-\gamma_{d,c}-\gamma_{d,c}g^I_{c,d}p_c(p_{d,c})\right]$$

$$s_{\mu_d} \triangleq P_d-\sum_{c=1}^{C}\omega_{d,c}p_{d,c}$$

$$s_\eta \triangleq P_{BS}-\sum_{c=1}^{C}\sum_{d=1}^{D}\omega_{d,c}p_c(p_{d,c})-\sum_{c=1}^{C}\left(1-\sum_{d=1}^{D}\omega_{d,c}\right)\tau_c.$$

Define $\boldsymbol{\upsilon}\triangleq(\boldsymbol{\lambda},\boldsymbol{\mu},\eta)$, $\boldsymbol{s}_{\boldsymbol{\lambda}}\triangleq\{s_{\lambda_{d,c}}\}$, $\boldsymbol{s}_{\boldsymbol{\mu}}\triangleq\{s_{\mu_d}\}$, and $\boldsymbol{s}_{\boldsymbol{\upsilon}}\triangleq(\boldsymbol{s}_{\boldsymbol{\lambda}},\boldsymbol{s}_{\boldsymbol{\mu}},s_\eta)$. We summarize the method for searching the optimal power allocation and channel assignment for given SINRs $\{\gamma_{d,c}\}$ in Algorithm 2, where κ_k is the step size in iteration k.

The results so far we obtained are for given SINRs, i.e., fixed auxiliary variables $\{\gamma_{d,c}\}$. Now, we investigate how to optimize $\{\gamma_{d,c}\}$. A natural way is to optimize $\{\gamma_{d,c}\}$ and $\{p_{d,c},\omega_{d,c}\}$ in an alternating manner. From problem (28), given $\{p_{d,c},\omega_{d,c}\}$, the objective is increasing in $\gamma_{d,c}$ for $\forall d,c$ and thus the first constraint is always satisfied at equality. Therefore, given $\{p_{d,c},\omega_{d,c}\}$, the optimal $\{\gamma_{d,c}\}$ are given by

$$\begin{aligned}\gamma^\star_{d,c}&=\frac{p_{d,c}g_{d,c}}{1+p_c(p_{d,c})g^I_{c,d}}\\&=\frac{p_{d,c}g_{d,c}}{1+\frac{(\alpha_c-1)(1+p_{d,c}g^I_{d,c})(1+p_{d,c}g^I_{d,e})g^I_{c,d}}{g_c-\alpha_c g^I_{c,e}+p_{d,c}(g_c g^I_{d,e}-\alpha_c g^I_{c,e}g^I_{d,c})}},\ \forall d,c. \quad (36)\end{aligned}$$

This leads to a simple but efficient method for joint optimization of $\boldsymbol{\gamma}\triangleq\{\gamma_{d,c}\}$ and $\{p_{d,c},\omega_{d,c}\}$, which is stated in Algorithm 3, whose convergence properties are stated in Proposition 3.

Proposition 3: The sequence $\{p_{d,c},\omega_{d,c},\gamma_{d,c}\}$ generated by Algorithm 3 converges to a stationary solution of problem (28).

Proof: See Appendix F. □

Remark 8: From Proposition 3, Algorithm 3 is guaranteed to converge to a stationary solution of problem (28). Note that (28) is a relaxed version of (27) or equivalently the original problem in (8), where binary variables $\{\omega_{d,c}\}$ are relaxed to continuous ones. Nevertheless, from Proposition 2, Algorithm 3 will yield binary $\{\omega_{d,c}\}$ in general. Therefore, the obtained solution will also be a stationary solution of (27) or (8) in practice.

Algorithm 3 : Secure Multi-Channel D2D Resource Management

1: Choose initial $\boldsymbol{\gamma}(0)$ and precision ϵ and set $n=0$;
2: Compute $\{p^\star_{d,c},\omega^\star_{d,c}\}$ using Algorithm 2;
3: Update $\boldsymbol{\gamma}(n+1)$ according to (36) and $n=n+1$
4: If $\|\boldsymbol{\gamma}(n)-\boldsymbol{\gamma}(n-1)\|\le\epsilon$ stop, otherwise go to step 2.

Remark 9: In the uplink case, a similar multi-channel D2D resource management problem can be formulated with the total power constraint $\sum_{c=1}^{C}p_c\le P_{BS}$ in (8) replaced by individual power constraints $p_c\le P_c$, $\forall c$. In this case, Lemma 3 still holds and thus we can still eliminate the security QoS constraints by using the relation in (24). Furthermore, the constraints $p_c\le P_c$, $\forall c$, are equivalent to

$$\sum_{d=1}^{D}\omega_{d,c}\frac{(\alpha_c-1)(1+p_{d,c}g^I_{d,c})(1+p_{d,c}g^I_{d,e})}{g_c-\alpha_c g^I_{c,e}+p_{d,c}(g_c g^I_{d,e}-\alpha_c g^I_{c,e}g^I_{d,c})} + \left(1-\sum_{d=1}^{D}\omega_{d,c}\right)\frac{\alpha_c-1}{g_c-\alpha_c g^I_{c,e}}\le P_c,\quad\forall c. \quad (37)$$

Then, following the same steps as above, one can characterize the optimal power allocation and channel assignment in analytical form similar to (32) and (34). Therefore, with slight modifications, Algorithm 3 can also be used for uplink resource sharing.

V. Numerical Results

In this section, we demonstrate the performance of the proposed secure D2D resource management schemes through numerical simulations. Specifically, we consider a cellular system with a radius of 500m and the BS at the center. The CUs, D2D links, and eavesdropper are randomly and uniformly distributed within the cell. The distance between each D2D link's TX and RX is set to 20m. The path loss grows exponentially with the distance with an exponent of 3.5. The small-scale fading channel coefficients are independently and identically complex Gaussian distributed with zero mean and unit variance. Following [33], the total power budget of the BS is set to $P_{BS}=46$dBm and the power budget of each D2D link is set to $P_d=24$dBm for $d=1,\ldots,D$. The noise power spectral density is -174dBm/Hz and the bandwidth of each channel is 10MHz. For convenience, the proposed single-channel and multi-channel D2D resource sharing schemes are named SC-D2D and MC-D2D, respectively.

In Fig. 1, we investigate the convergence of Algorithms 1 and 3 for single-channel and multi-channel D2D communications, respectively. In the simulation, there are 4 CUs and 2 D2D links, and the minimum secrecy rate is set to $\theta_c=1$bps/Hz for each CU. We compare the proposed methods with the globally optimal solutions that are obtained via an exhaustive search over all possible channel assignments along with the optimal power allocation. One

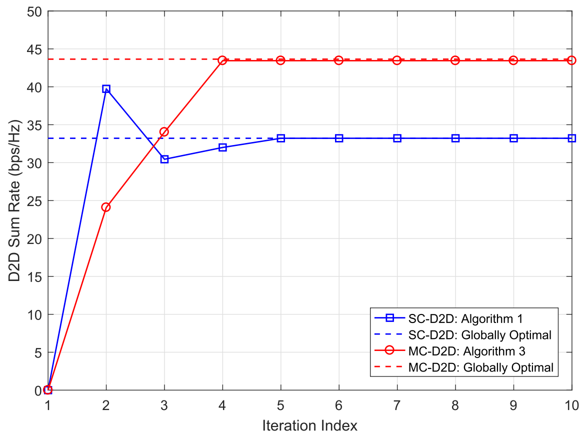

Fig. 1. Convergence behavior of Algorithm 1 for single-channel D2D and Algorithm 3 for multi-channel D2D.

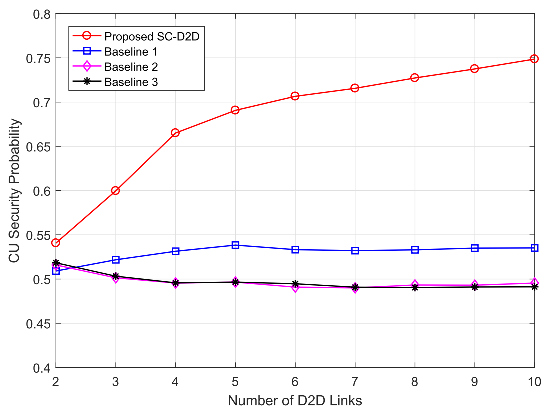

Fig. 2. The probability that a CU satisfies the security QoS constraint versus the number of D2D links.

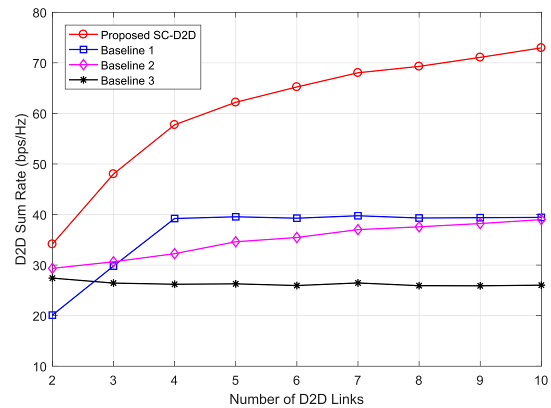

Fig. 3. The average sum rate of the D2D links versus the number of D2D links.

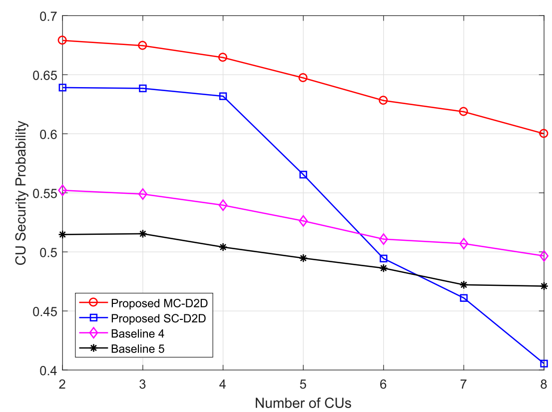

Fig. 4. The probability that a CU satisfies the security QoS constraint versus the number of CUs.

can observe that both Algorithms 1 and 3 converge rapidly. More importantly, Algorithm 1 converges exactly to the globally optimal solution for single-channel D2D, while the convergence point of Algorithm 3 closely approaches the globally optimal solution for multi-channel D2D. This indicates that Algorithms 1 and 3, though only guaranteed to converge to a stationary point, achieve optimal or near-optimal performance in practice.

In Figs. 2 and 3, we show the performance of different secure resource sharing schemes for single-channel D2D communication. There are 4 CUs with minimum secrecy rate $\theta_c = 1$bps/Hz for $c = 1, \ldots, 4$. The proposed SC-D2D scheme is compared with three baseline schemes. In Baseline 1, only the power allocation of the D2D links and the CUs is optimized [23], [24] but the channel assignment is randomly chosen. In Baseline 2, the channel assignment is optimized for fixed powers [26], [27], where each D2D TX transmits with the maximum power P_d and the power of each CU is obtained from (15) or (13). In Baseline 3, the fixed power allocation and random channel assignment are used. Fig. 2 shows the average probability that the security requirement of a CU is satisfied, which is referred to as the CU security probability in short, while Fig. 3 shows the sum rate of the D2D links averaged over random channels. One can observe that the proposed resource management policy with joint power allocation and channel assignment optimization significantly outperforms the baseline schemes in terms of both security and spectral efficiency. This indicates that separate optimization of power allocation and channel assignment cannot exploit the full potential of D2D communication. The proposed joint resource management can simultaneously and significantly improve the security of the CUs and the spectral efficiency of the D2D links as the number of D2D links increases.

In Figs. 4-7, we investigate the performance of the proposed secure resource sharing scheme for multi-channel D2D communication. The MC-D2D scheme is compared with the SC-D2D scheme as well as two baseline schemes. In Baseline 4, only the powers of the D2D links and CUs are optimized, while the cellular channels are randomly assigned to the D2D links. In Baseline 5, the channel assignment to the D2D links is optimized, but each D2D link d uses a fixed power $p_{d,c} = P_d/C$ on each channel c and the power of each CU is obtained from Lemma 3.

Figs. 4 and 5 show the CU security probability and D2D sum rate as functions of the number of CUs, respectively. There are 4 D2D links and the minimum secrecy rate is $\theta_c = 1$bps/Hz, $\forall c$. The proposed multi-channel resource

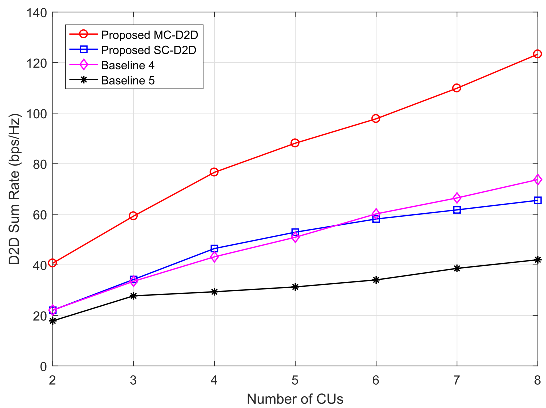

Fig. 5. The average sum rate of the D2D links versus versus the number of CUs.

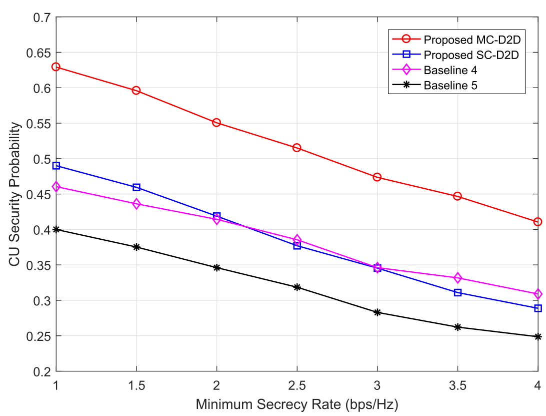

Fig. 6. The probability that a CU satisfies the security QoS constraint versus the minimum secrecy rate.

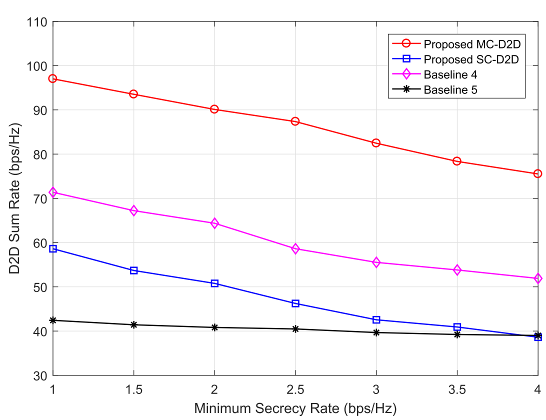

Fig. 7. The average sum rate of the D2D links versus the minimum secrecy rate.

management scheme outperforms the single-channel scheme as well as the two baseline schemes. From Figs. 4 and 5, one can observe that MC-D2D can provide better security for the CUs and also achieve higher spectral efficiency than SC-D2D. Noticeably, as the number of CUs increases, both the security performance and the data rate provided by SC-D2D drop and eventually SC-D2D is outperformed by Baseline 4 and even Baseline 5. This is because Baselines 4 and 5, though not jointly optimized, are multi-channel schemes. This clearly shows that multi-channel D2D communication can utilize the cellular resources more efficiently than single-channel D2D communication.

Figs. 6 and 7 show the CU security probability and the D2D sum rate versus the minimum secrecy rate θ_c for 6 CUs and 4 D2D links. As the minimum secrecy rate increases, both the CU security probability and the sum rate of the D2D links decrease. This is because the security QoS constraints become more stringent, which causes the objective value, i.e., the sum rate of the D2D links, to decrease and also makes it more difficult for the CUs to meet the higher security QoS thresholds. For all considered minimum secrecy rates, the proposed multi-channel D2D resource sharing scheme yields the best performance compared with the single-channel scheme and the two baseline schemes, which is consistent with Figs. 4 and 5.

VI. Conclusions

We considered downlink resource management for single-channel and multi-channel D2D communications from a physical layer security perspective. By letting D2D links act as friendly jammers, the CUs' security and the D2D links' spectral efficiency could be improve simultaneously. To realize the full potential of this win-win situation, the power allocation and channel assignment of the D2D links and CUs had to be jointly optimized, which led to difficult nonlinear mixed integer programs. By exploiting the inherent structure of the formulated secure resource sharing problems, we could characterize the optimal power allocation of the D2D links and the CUs, and developed efficient methods with guaranteed convergence for joint optimization of the power allocation and channel assignment. Numerical results confirmed the importance of joint resource management and showed remarkable performance gains of the proposed single-channel and multi-channel resource sharing schemes compared to several baseline schemes. In this paper, we considered a network with a single eavesdropper. An interesting topic for future research is the extension of the proposed secure D2D resource management schemes to scenarios with multiple eavesdroppers.

Appendix

A. Proof of Lemma 1

If channel c is not reused by any D2D link, $SR_c(p_c, p_{d,c}) \geq \theta_c$ reduces to $R_c^0(p_c) \geq \theta_c$, which can be rewritten as $p_c(g_c - \alpha_c g_{c,e}^I) \geq \alpha_c - 1$. Since $p_c \geq 0$ and $\alpha_c - 1 \geq 0$, $p_c(g_c - \alpha_c g_{c,e}^I) \geq \alpha_c - 1$ can hold only if $g_c - \alpha_c g_{c,e}^I \geq 0$. If channel c is reused by D2D link d, $SR_c(p_c, p_{d,c}) \geq \theta_c$ becomes $R_c^1(p_c) \geq \theta_c$, which can be rewritten as

$$p_c\left[g_c - \alpha_c g_{c,e}^I + p_{d,c}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I)\right] \\ \geq (\alpha_c - 1)(1 + p_{d,c} g_{d,c}^I)(1 + p_{d,c} g_{d,e}^I). \quad (38)$$

Since the right hand side of (38) is nonnegative and $p_c \geq 0$, (38) can hold only if $g_c - \alpha_c g_{c,e}^I + p_{d,c}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I) \geq 0$.

B. Proof of Theorem 1

The security QoS constraint $R_c^1(p_c, p_{d,c}) \geq \theta_c$ in (14) can be rewritten as (38). Since $g_c - \alpha_c g_{c,e}^I + p_{d,c}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I) \geq 0$, (38) leads to

$$p_c \geq \frac{(\alpha_c - 1)(1 + p_{d,c} g_{d,c}^I)(1 + p_{d,c} g_{d,e}^I)}{g_c - \alpha_c g_{c,e}^I + p_{d,c}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I)}. \tag{39}$$

Since $R_{d,c}(p_c, p_{d,c})$ is monotonically decreasing in p_c, the optimal $p_c^\star$ shall take the lower bound, which leads to (15) in Theorem 1.

Substituting p_c in (15) into $R_{d,c}(p_c, p_{d,c})$, we obtain $R_{d,c}(p_c, p_{d,c}) = \log_2(1 + \phi(p_{d,c}))$, where $\phi(p_{d,c})$ is given in (40) at the bottom of this page. Thus, maximizing $R_{d,c}(p_c, p_{d,c})$ is equivalent to maximizing $\phi(p_{d,c})$, which, however, is a highly nonlinear function of $p_{d,c}$. Through some calculations, we are able to obtain that $\phi'(p_{d,c}) = 0$ is equivalent to $\bar{A}p_{d,c}^2 + \bar{B}p_{d,c} + \bar{C} = 0$, where parameters $\bar{A}$, $\bar{B}$, and $\bar{C}$ are defined in Theorem 1. Therefore, the stationary points of $\phi(p_{d,c})$ are given by the roots of the quadratic equation $\bar{A}p_{d,c}^2 + \bar{B}p_{d,c} + \bar{C} = 0$.

In addition to the stationary points, the maximizer of $\phi(p_{d,c})$ may also be at the boundary of $p_{d,c}$, which is directly constrained by $0 \leq p_{d,c} \leq P_d$ and $p_{d,c}\xi_{d,c} \geq \delta_c$, where $\xi_{d,c}$ and δ_c are defined in Theorem 1. If $\xi_{d,c} > 0$, then $p_{d,c} \geq \delta_c/\xi_{d,c}$; if $\xi_{d,c} \leq 0$, then $p_{d,c} \leq \delta_c/\xi_{d,c}$, which can be concisely expressed as $l_{d,c} \leq p_{d,c} \leq u_{d,c}$, where $l_{d,c}$ and $u_{d,c}$ are defined in Theorem 2.

Meanwhile, $p_{d,c}$ is also implicitly constrained by $p_c \leq t_c$. To see this, substituting p_c in (15) into $p_c \leq t_c$ results in

$$\begin{aligned}(\alpha_c - 1)&(1 + p_{d,c} g_{d,c}^I)(1 + p_{d,c} g_{d,e}^I) \\ &\leq t_c \left[g_c - \alpha_c g_{c,e}^I + p_{d,c}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I)\right]\end{aligned} \tag{41}$$

which can be rewritten as $\bar{a}p_{d,c}^2 + \bar{b}p_{d,c} + \bar{c} \leq 0$ with $\bar{a}$, $\bar{b}$, and $\bar{c}$ defined in Theorem 1. Hence, we have $y_{d,c}^1 \leq p_{d,c} \leq y_{d,c}^2$, where $y_{d,c}^1 = \frac{-\bar{b}-\sqrt{\bar{b}^2-4\bar{a}\bar{c}}}{2\bar{a}}$ and $y_{d,c}^2 = \frac{-\bar{b}+\sqrt{\bar{b}^2-4\bar{a}\bar{c}}}{2\bar{a}}$. Consequently, we have $\max\{l_{d,c}, y_{d,c}^1\} \leq p_{d,c} \leq \min\{u_{d,c}, y_{d,c}^2\}$, which corresponds to the lower and upper bounds $L_{d,c}$ and $U_{d,c}$ in Theorem 1. Consequently, the optimal $p_{d,c}^\star$ must be from the set of stationary points and lower and upper bounds.

C. Proof of Theorem 2

Suppose that the security QoS constraint in subproblem (14) is feasible. Then, for any given $t_c \geq 0$, the constraint set of (14) is a nonempty compact set. According to Theorem 1, there is a unique solution $(p_c^\star, p_{d,c}^\star)$ to (14). It then follows from [34, Corollary 4.4] that $f_c(t_c)$ is directionally differentiable. Since $f_c(t_c)$ is a one-dimensional function, the directional differentiability implies the differentiability of $f_c(t_c)$.

It follows from Theorem 1 that the security QoS constraint in (14) is satisfied with equality and the optimal p_c can be expressed as a function of $p_{d,c}$. Moreover, from Appendix VI-B, the constraints $0 \leq p_{d,c} \leq P_d$ and $p_{d,c}\xi_{d,c} \geq \delta_c$ can be equivalently expressed as $l_{d,c} \leq p_{d,c} \leq u_{d,c}$. Therefore, subproblem (14) is equivalent to

$$\begin{aligned}&\underset{p_{d,c}}{\text{maximize}}\ R_{d,c}(p_c(p_{d,c}), p_{d,c}) \\ &\text{subject to}\ l_{d,c} \leq p_{d,c} \leq u_{d,c},\ 0 \leq p_c(p_{d,c}) \leq t_c\end{aligned} \tag{42}$$

where function $p_c(p_{d,c})$ is given in (15). To find the derivative of $f_c(t_c)$, we need the following (partial) Lagrangian of (42):

$$L(p_{d,c}, \lambda, \mu, t_c) = R_{d,c}(p_c(p_{d,c}), p_{d,c}) - \lambda(p_c(p_{d,c}) - t_c) \tag{43}$$

where λ is the Lagrange multiplier associated with the constraint $p_c(p_{d,c}) \leq t_c$. Then, according to [34, Corollary 4.4], the derivative of $f_c(t_c)$ is given by

$$f_c'(t_c) = \frac{\partial L(p_{d,c}^\star, \lambda^\star, \mu^\star, t_c)}{\partial t_c} = \lambda^\star \tag{44}$$

where $\lambda^\star$ is the optimal Lagrange multiplier. Therefore, we shall find the optimal $\lambda^\star$.

To this end, we rely on the KKT conditions of (42). Although (42) is a nonconvex problem, its solution still satisfies the following necessary KKT conditions:

$$\text{C1}: \lambda^\star(p_c^\star - t_c) = 0; \quad \text{C2}: \frac{\partial L(p_{d,c}^\star, \lambda^\star, \mu^\star, t_c)}{\partial p_{d,c}} = 0 \tag{45}$$

where $p_c^\star = p_c(p_{d,c}^\star)$. Condition C1 indicates that $f_c'(t_c) = \lambda^\star = 0$ if $p_c^\star \neq t_c$. For $p_c^\star = t_c$ and $p_{d,c}^\star \in (l_{d,c}, u_{d,c})$, it follows from condition C2 that

$$\begin{aligned}\frac{\partial L(p_{d,c}^\star, \lambda^\star, \mu^\star, t_c)}{\partial p_{d,c}} &= \frac{dR_{d,c}(p_c(p_{d,c}^\star), p_{d,c}^\star)}{dp_{d,c}} \\ &\quad - \lambda^\star \frac{dp_c(p_{d,c}^\star)}{dp_{d,c}} = 0\end{aligned} \tag{46}$$

which leads to

$$\begin{aligned}f_c'(t_c) &= \lambda^\star = \frac{dR_{d,c}(p_c(p_{d,c}^\star), p_{d,c}^\star)}{dp_{d,c}} \frac{1}{p_c'(p_{d,c}^\star)} \\ &= \frac{1}{\ln 2} \frac{g_{d,c} + g_{c,d}^I(1 - p_{d,c}^\star g_{d,c}) p_c'(p_{d,c}^\star)}{(1 + p_{d,c}^\star g_{d,c} + p_c(p_{d,c}^\star) g_{c,d}^I)(1 + p_c(p_{d,c}^\star) g_{c,d}^I)} \frac{1}{p_c'(p_{d,c}^\star)} \\ &= \frac{1}{\ln 2} \frac{g_{d,c}(1 + g_{c,d}^I p_c(p_{d,c}^\star) - g_{c,d}^I p_{d,c}^\star p_c'(p_{d,c}^\star))}{(1 + p_{d,c}^\star g_{d,c} + t_c g_{c,d}^I)(1 + t_c g_{c,d}^I)} \frac{1}{p_c'(p_{d,c}^\star)},\end{aligned} \tag{47}$$

where $p_c'(p_{d,c}^\star) = dp_c(p_{d,c}^\star)/dp_{d,c}$. Finally, if $p_c^\star = t_c$ and $p_{d,c}^\star = l_{d,c}$, then we have

$$f_c(t_c) = R_{d,c}(t_c, l_{d,c}) = \log_2\left(1 + \frac{l_{d,c} g_{d,c}}{1 + t_c g_{c,d}^I}\right) \tag{48}$$

$$\phi(p_{d,c}) \triangleq \frac{g_d^c p_{d,c}[h_{c,B} - \alpha_c h_{c,E} + (h_{c,B} g_{d,E}^c - \alpha_c h_{c,E} g_{d,B}^c) p_{d,c}]}{h_{c,B} - \alpha_c h_{c,E} + (h_{c,B} g_{d,E}^c - \alpha_c h_{c,E} g_{d,B}^c) p_{d,c} + h_{c,d}(\alpha_c - 1)(1 + g_{d,E}^c p_{d,c})(1 + g_{d,B}^c p_{d,c})}. \tag{40}$$

and thus

$$f_c'(t_c) = \frac{1}{\ln 2} \frac{-l_{d,c} g_{d,c} g_{c,d}^I}{(1 + t_c g_{c,d}^I + l_{d,c} g_{d,c})(1 + t_c g_{c,d}^I)}. \quad (49)$$

For $p_c^\star = t_c$ and $p_{d,c}^\star = u_{d,c}$, $f_c'(t_c)$ can be obtained in a similar manner.

D. Proof of Theorem 3

For fixed $\{\gamma_{d,c}\}$, the objective function in (29) is linear in $\{\omega_{d,c}\}$ and thus concave. In the following, we shall show that the first and last constraints in (29) are convex. To this end, we first reveal an important property of $p_c^\star(p_{d,c})$ in (24), i.e., the optimal power of CU c as a function of $p_{d,c}$. Through some calculations, we obtain the second derivative of $p_c^\star(p_{d,c})$ as

$$\frac{d^2 p_c^\star(p_{d,c})}{dp_{d,c}^2} = \frac{(\alpha_c - 1)\alpha_c g_{c,e}^I g_c (g_{d,e}^I - g_{d,c}^I)^2}{\left[g_c - \alpha_c g_{c,e}^I + p_{d,c}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I)\right]^3} \geq 0 \quad (50)$$

where the nonnegativity is due to $g_c - \alpha_c g_{c,e}^I + p_{d,c}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I) \geq 0$ in (29). Thus, $p_c^\star(p_{d,c})$ is convex in $p_{d,c}$.

The first constraint in (29) can be rewritten as

$$\gamma_{d,c}\omega_{d,c}\left(1 + \frac{(\alpha_c - 1)(1 + \frac{q_{d,c}}{\omega_{d,c}} g_{d,c}^I)(1 + \frac{q_{d,c}}{\omega_{d,c}} g_{d,e}^I) g_{c,d}^I}{g_c - \alpha_c g_{c,e}^I + \frac{q_{d,c}}{\omega_{d,c}}(g_c g_{d,e}^I - \alpha_c g_{c,e}^I g_{d,c}^I)}\right) = \gamma_{d,c}\omega_{d,c}\left(1 + p_c^\star\left(\frac{q_{d,c}}{\omega_{d,c}}\right) g_{c,d}^I\right) \leq q_{d,c} g_{d,c}. \quad (51)$$

Since $1 + p_c^\star(p_{d,c}) g_{c,d}^I$ is convex in $p_{d,c}$, $\omega_{d,c}\left(1 + p_c^\star\left(\frac{q_{d,c}}{\omega_{d,c}}\right) g_{c,d}^I\right)$ is convex in $(q_{d,c}, \omega_{d,c})$ according to the perspective transformation [31]. Therefore, (51) is a convex constraint. Similarly, the last constraint in (29) can be expressed as

$$\sum_{c=1}^{C}\left[\sum_{d=1}^{D}\omega_{d,c} p_c^\star\left(\frac{q_{d,c}}{\omega_{d,c}}\right) + \left(1 - \sum_{d=1}^{D}\omega_{d,c}\right)\frac{\alpha_c - 1}{g_c - \alpha_c g_{c,e}^I}\right] \leq P_{BS}. \quad (52)$$

It follows from the convexity of $p_c^\star(p_{d,c})$ that $\omega_{d,c} p_c^\star\left(\frac{q_{d,c}}{\omega_{d,c}}\right)$ is convex in $(q_{d,c}, \omega_{d,c})$. Therefore, (52) is also a convex constraint. Consequently, (29) is a convex problem for fixed $\{\gamma_{d,c}\}$.

E. Proof of Propositions 1 and 2

Since (30) is a convex problem, its optimal solution is characterized by the KKT conditions. Hence, we have

$$\frac{\partial L}{\partial q_{d,c}} = \lambda_{d,c} g_{d,c} - \lambda_{d,c}\gamma_{d,c} g_{c,d}^I \frac{\partial \varphi(q_{d,c}, \omega_{d,c})}{\partial q_{d,c}} - \mu_d - \eta \frac{\partial \varphi(q_{d,c}, \omega_{d,c})}{\partial q_{d,c}} = 0. \quad (53)$$

It follows from the definition of $\varphi(q_{d,c}, \omega_{d,c})$ that

$$\frac{\partial \varphi(q_{d,c}, \omega_{d,c})}{\partial q_{d,c}} = p_c'\left(\frac{q_{d,c}}{\omega_{d,c}}\right) = p_c'(p_{d,c}) \quad (54)$$

where the second equality is due to $q_{d,c} = \omega_{d,c} p_{d,c}$ and $p_c'(p_{d,c})$ is the derivative of $p_c(p_{d,c})$ and given in (20). Therefore, we obtain

$$p_c'(p_{d,c}) = \frac{\lambda_{d,c} g_{d,c} - \mu_d}{\lambda_{d,c}\gamma_{d,c} g_{c,d}^I + \eta} \quad (55)$$

whose root, denoted by $\bar{p}_{d,c}$, is a stationary point.

Since $p_c(p_{d,c})$ is a convex function, $p_c'(p_{d,c})$ is monotonically increasing. For $p_{d,c}$, there are still two constraints, namely $p_{d,c} \geq 0$ and $p_{d,c}\xi_{d,c} \geq \delta_c$. If $\xi_{d,c} > 0$, then $p_{d,c} \geq l_{d,c} \triangleq \max\{0, \delta_c/\xi_{d,c}\}$. In this case, if $\frac{\lambda_{d,c} g_{d,c} - \mu_d}{\lambda_{d,c}\gamma_{d,c} g_{c,d}^I + \eta} \leq p_c'(l_{d,c})$, then $p_{d,c}^\star = l_{d,c}$, otherwise $p_{d,c}^\star = \bar{p}_{d,c}$. If $\xi_{d,c} \leq 0$, then $0 \leq p_{d,c} \leq u_{d,c} \triangleq \min\{P_d, \delta_c/\xi_{d,c}\}$. In this case, if $\frac{\lambda_{d,c} g_{d,c} - \mu_d}{\lambda_{d,c}\gamma_{d,c} g_{c,d}^I + \eta} \leq p_c'(0)$, then $p_{d,c}^\star = 0$; if $\frac{\lambda_{d,c} g_{d,c} - \mu_d}{\lambda_{d,c}\gamma_{d,c} g_{c,d}^I + \eta} \geq p_c'(u_{d,c})$, then $p_{d,c}^\star = u_{d,c}$; otherwise $p_{d,c}^\star = \bar{p}_{d,c}$. Proposition 1 is thus proved.

Given $(\boldsymbol{\lambda}, \boldsymbol{\mu}, \eta)$ and $p_{d,c} = q_{d,c}/\omega_{d,c}$, $\forall d, c$, the Lagrangian in (31) can be expressed in (56) at the bottom of this page, which is linear in $\{\omega_{d,c}\}$. The optimal $\{\omega_{d,c}\}$ are obtained by maximizing $L(\boldsymbol{q}, \boldsymbol{\omega}, \boldsymbol{\lambda}, \boldsymbol{\mu}, \eta)$ within $\{\omega_{d,c} : \sum_{d=1}^{D} \omega_{d,c} \leq 1, \forall c;\ \omega_{d,c} \geq 0, \forall d, c\}$. The solution is that, for each channel c, $\omega_{d^\star,c} = 1$ for $d^\star = \arg\max_d\{\Gamma_{d,c}\}$ and $\omega_{d,c} = 0$ for $d \neq d^\star$. Proposition 2 is thus proved.

F. Proof of Proposition 3

It is not difficult to see that, in Algorithm 3, each $\gamma_{d,c}$ is nondecreasing, so is the objective value of (28). Since all $\{\gamma_{d,c}\}$ are bounded from above, the convergence of Algorithm 3 is guaranteed. Furthermore, (28) is actually an optimization problem over a biconvex set [35]. Therefore, from [35, Corollary 4.10], the convergence point of Algorithm 3 is a stationary solution of (28).

$$L(\boldsymbol{q}, \boldsymbol{\omega}, \boldsymbol{\lambda}, \boldsymbol{\mu}, \eta) = \sum_{d=1}^{D}\sum_{c=1}^{C}\omega_{d,c}\underbrace{\left[\log_2(1 + \gamma_{d,c}) - \mu_d p_{d,c} + \lambda_{d,c}\left(p_{d,c} g_{d,c} - \gamma_{d,c} - \gamma_{d,c} g_{c,d}^I p_c(p_{d,c})\right) - \eta p_c(p_{d,c}) + \eta\tau_c\right]}_{\Gamma_{d,c}} + \sum_{d=1}^{D}\mu_d P_d + \eta P_{BS} - \eta\sum_{c=1}^{C}\tau_c. \quad (56)$$

REFERENCES

[1] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 42–49, Dec. 2009.

[2] G. Fodor *et al.*, "Design aspects of network assisted device-to-device communications," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 170–177, Mar. 2012.

[3] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu, "Device-to-device communication in 5G cellular networks: Challenges, solutions, and future directions," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 86–92, May 2014.

[4] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1801–1819, 4th Quart., 2014.

[5] C.-H. Yu, K. Doppler, C. B. Ribeiro, and O. Tirkkonen, "Resource sharing optimization for device-to-device communication underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2752–2763, Aug. 2011.

[6] D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, G. Feng, and S. Li, "Device-to-device communications underlaying cellular networks," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3541–3551, Aug. 2013.

[7] J. Wang, D. Zhu, C. Zhao, J. C. F. Li, and M. Lei, "Resource sharing of underlaying device-to-device and uplink cellular communications," *IEEE Commun. Lett.*, vol. 17, no. 6, pp. 1148–1151, Jun. 2013.

[8] D. Zhu, J. Wang, C. Zhao, and A. L. Swindlehurst, "Downlink resource reuse for device-to-device communications underlaying cellular networks," *IEEE Signal Process. Lett.*, vol. 21, no. 5, pp. 531–534, May 2014.

[9] W. Zhao and S. Wang, "Resource sharing scheme for device-to-device communication underlaying cellular networks," *IEEE Trans. Commun.*, vol. 63, no. 12, pp. 4838–4848, Oct. 2015.

[10] L. Song, D. Niyato, Z. Han, and E. Hossain, "Game-theoretic resource allocation methods for device-to-device communication," *IEEE Wireless Commun.*, vol. 21, no. 3, pp. 136–144, Jun. 2014.

[11] H. Dai, Y. Huang, and L. Yang, "Game theoretic Max-logit learning approaches for joint base station selection and resource allocation in heterogeneous networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 6, pp. 1068–1081, Jun. 2015.

[12] D. Wu, J. Wang, R. Q. Hu, Y. Cai, and L. Zhou, "Energy-efficient resource sharing for mobile device-to-device multimedia communications," *IEEE Trans. Veh. Technol.*, vol. 63, no. 5, pp. 2093–2103, Jun. 2014.

[13] K. Yang, S. Martin, C. Xing, J. Wu, and R. Fan, "Energy-efficient power control for device-to-device communications," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3208–3220, Dec. 2016.

[14] Y. Wu, J. Chen, L. P. Qian, J. Huang, and X. S. Shen, "Energy-aware cooperative traffic offloading via device-to-device cooperations: An analytical approach," *IEEE Trans. Mobile Comput.*, vol. 16, no. 1, pp. 97–114, Jan. 2017.

[15] A. D. Wyner, "The wire-tap channel," *Bell Syst. Tech. J.*, vol. 54, no. 8, pp. 1355–1387, 1975.

[16] A. Mukherjee, S. A. A. Fakoorian, J. Huang, and A. L. Swindlehurst, "Principles of physical layer security in multiuser wireless networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1550–1573, 3rd Quart., 2014.

[17] Y. Zou, J. Zhu, L. Yang, Y.-C. Liang, and Y.-D. Yao, "Securing physical-layer communications for cognitive radio networks," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 48–54, Sep. 2015.

[18] Y. Wu, R. Schober, D. W. K. Ng, C. Xiao, and G. Caire, "Secure massive MIMO transmission with an active eavesdropper," *IEEE Trans. Inf. Theory*, vol. 62, no. 7, pp. 3880–3900, Jul. 2016.

[19] L. Sun, Q. Du, P. Ren, and Y. Wang, "Two birds with one stone: Towards secure and interference-free D2D transmissions via constellation rotation," *IEEE Trans. Veh. Technol.*, vol. 65, no. 10, pp. 8767–8774, Oct. 2016.

[20] A. Zhang and X. Lin, "Security-aware and privacy-preserving D2D communications in 5G," *IEEE Netw.*, vol. 31, no. 4, pp. 70–77, Jul./Aug. 2017.

[21] D. Zhu, A. L. Swindlehurst, S. A. A. Fakoorian, W. Xu, and C. Zhao, "Device-to-device communications: The physical layer security advantage," in *Proc. IEEE ICASSP*, Florence, Italy, May 2014, pp. 1606–1610.

[22] C. Ma, J. Liu, X. Tian, H. Yu, Y. Cui, and X. Wang, "Interference exploitation in D2D-enabled cellular networks: A secrecy perspective," *IEEE Trans. Commun.*, vol. 63, no. 1, pp. 229–242, Jan. 2015.

[23] J. Yue, C. Ma, H. Yu, and W. Zhou, "Secrecy-based access control for device-to-device communication underlaying cellular networks," *IEEE Commun. Lett.*, vol. 17, no. 11, pp. 2068–2071, Nov. 2013.

[24] Y. Wang, Z. Chen, Y. Yao, M. Shen, and B. Xia, "Secure communications of cellular users in device-to-device communication underlaying cellular networks," in *Proc. 6th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2014, pp. 1–6.

[25] J. Wang, Q. Tang, C. Yang, R. Schober, and J. Li, "Security enhancement via device-to-device communication in cellular networks," *IEEE Signal Process. Lett.*, vol. 23, no. 11, pp. 1622–1626, Nov. 2016.

[26] H. Zhang, T. Wang, L. Song, and Z. Han, "Radio resource allocation for physical-layer security in D2D underlay communications," in *Proc. IEEE ICC*, Sydney, NSW, Australia, Jun. 2014, pp. 2319–2324.

[27] R. Zhang, X. Cheng, and L. Yang, "Cooperation via spectrum sharing for physical layer security in device-to-device communications underlaying cellular networks," *IEEE Trans. Wireless Commun*, vol. 15, no. 8, pp. 5651–5663, Aug. 2016.

[28] R. Burkard, M. Dell'Amico, and S. Martello, *Assignment Problems*. Philadelphia, PA, USA: SIAM, 2009.

[29] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to Algorithms*, 3rd ed. Cambridge, MA, USA: MIT Press, 2009.

[30] J. Wang and D. P. Palomar, "Robust MMSE precoding in MIMO channels with pre-fixed receivers," *IEEE Trans. Signal Process.*, vol. 58, no. 11, pp. 5802–5818, Nov. 2010.

[31] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[32] D. P. Palomar and M. Chiang, "A tutorial on decomposition methods for network utility maximization," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 8, pp. 1439–1451, Aug. 2006.

[33] *Further Advancements for E-UTRA Physical Layer Aspects, Release 9*, document TR 36.814, 3GPP, Mar. 2010.

[34] S. Dempe, *Foundations of Bilevel Programming*. New York, NY, USA: Kluwer, 2002.

[35] J. Gorski, F. Pfeuffer, and K. Klamroth, "Biconvex sets and optimization with biconvex functions: A survey and extensions," *Math. Methods Oper. Res.*, vol. 66, no. 3, pp. 373–407, Dec. 2007.

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