A Stackelberg-Game Approach for Disaster-Assisted Communications Utilizing Cooperative D2D

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***Abstract*—In this paper, we investigate disaster-assisted communications utilizing two-cell cooperative D2D communications. Specifically, one cell is in a healthy area while the other is in a disaster area. A user equipment (UE) in the healthy area aims to assist a UE in the disaster area to recover wireless information transfer (WIT) via an energy harvesting (EH) relay. In the healthy area, the cellular BS shares the spectrum with the UE, however, both of them belong to different service providers, thus, the UE pays an amount of price as incentive to the BS for two processes: energy trading and interference. We formulate these two processes as two Stackelberg games, i.e., energy trading and interference pricing games. The Stackelberg equilibriums for both formulated games are derived as closed-form solutions. Numerical results indicate that the energy trading game outperforms the interference pricing game in terms of providing higher utility function with lower price for the communication of the D2D network.**

***Index Terms*—D2D communications, disaster-assisted communications, RF energy harvesting, energy trading, interference pricing, *Stackelberg* game.**

I. Introduction

In recent years, device-to-device (D2D) communication has extracted an increasing number of attentions and has been standardized into the 3GPP release 12 [1], [2]. The key feature of D2D communication is that two communicating devices in a close proximity reuse better links to communicate directly rather than through the BS in cellular network. The mobile proximity services target the potential requirement for service operator to integrate D2D communication in a cellular network, which is to build new mobile service opportunities and to reduce traffic load on the network. The idea behind D2D communication is an underlay direct communication among user equipments (UEs) that use the same licensed radio resource can establish locally direct D2D link and bypass the base station (BS) or access point (AP) [3]. D2D communications introduce several advantages, i.e., relieving the burden of the cellular network, enhancing spectral efficiency, shortening time delay and reducing power consumption to keep up with greener trend. In addition, D2D transmission is also adopted in secure communications and wireless powered communication networks (WPCNs) [4], [5]. In [4], D2D communication is employed to improve the security issue of the cellular network. In [5], a WPCN based secure D2D transmission is proposed, where the Stackelberg game is considered to analyse the D2D utility of secrecy throughput subject to the outage probability of the secrecy rate constraint.

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Natural disasters, e.g., flood, earthquakes and hurricanes, normally lead to the malfunction or failure of crucial infrastructures such as power grids and telecommunication networks [6], [7]. On the other hand, after the occurrence of a natural disaster, telecommunications play an important role in relief efforts and any phases of post-disaster management. Lacking power supply and/or suffering from damaged network infrastructure, i.e., base stations, D2D communication is considered as a candidate to serve well in some urgent scenarios in the extreme environment for providing public safety and disaster relief services [8], [9].

Radio frequency (RF) energy harvesting (EH) and wireless power transfer (WPT) are considered as important techniques to prolong the battery lifetime of wireless devices (WDs) without physical connections [10]–[12]. As a recent application of RF-EH and WPT techniques, WPCNs, where WDs can be remotely powered by wireless energy transfer (WET), have become a novel technology in wireless networking and have attracted more and more attention [13]. A "*harvest-then-transmit*" protocol was proposed for WPCNs in [14], where wireless users harvest power from the RF signals broadcast by a hybrid access-point (AP) in the downlink (DL), and then use the harvested energy to send information to the AP in the uplink (UL). State-of-art cooperative protocols for WPCNs are proposed in [15]–[17]. In [15], user cooperation for WPCN was proposed to jointly optimize the transmit power and time allocations in order to maximize the throughput. In [16], [17], two 'harvest-and-cooperate' protocols, i.e., *energy cooperation* and *dual cooperation*, were proposed to maximize the system throughput. In addition, cooperative relaying is considered for using the harvested power to forward the information received from the transmitter [18]–[20]. Different cooperative protocols, such as, amplify-and-forward (AF) and decode-and-forward (DF) are investigated to obtain the power allocation for cooperative EH relaying system [19], [20].

Due to the looseness architecture of D2D networks, resource allocation for D2D communications is challenging. Fortunately, game theory offers a set of mathematical tools to study complex interactions among rational players and to adapt their choices of strategies [3]. Therefore, game theory is a suitable tool to model and analyze the resource allocation problems for D2D networks. In addition, prices have economic interpretations but are actually system parameters designed in resource allocation schemes. In underlay D2D communications, due to sharing the same resource, UEs cause interference to the users of cellular networks. Thus, the UEs of the D2D network have to pay a price for their interference imposed on the cellular network as the result of utilizing the spectrum owned by the cellular network. For this case, Stackelberg game is adopted to formulate interference pricing decision [21]. On the other hand, it is not practical to assume that the UE always has enough power to transmit its information, thus, it needs to harvest power, i.e., via RF-EH, for its future operation, i.e., wireless information transfer. In such case, the UE will pay a price for the energy service provided by the BS, where the Stackelberg game is considered to exploit the hierarchical energy interaction between the cellular and D2D networks. Both cases motivate our paper.

In this paper, we study disaster-assisted communications adopting cooperative D2D communications. Specially, we investigate a two-cell-framework scenario, i.e., one is in a healthy area,[1] while the other is in a disaster area.[2] For this scenario, we consider the recovery of the D2D communication in the disaster area via the connection between two cells. It is assumed that both BS and UE in the healthy area belong to different service providers. Thus, this UE needs to pay prices for two services: i) be allowed to cause interference to the main cellular network and ii) to trade for energy. These prices/payments can be considered as incentives to exploit the hierarchical interactions between the BS and the UE. We refer these two processes as interference pricing decision and energy trading, which can be formulated as two Stackelberg games. In the following, we highlight our contributions as:

- We first model the interference interaction between the cellular and D2D network, where a BS in the cellular network provides services and the transmission of the D2D network is controlled by the BS for interference management. This interaction can be formulated as a Stackelberg game. In this game, the BS plays a leader role who sells interference service to maximize its utility function defined as the total payment received from the UE in healthy area, while, the UE in healthy area is considered as a follower paying for its interference, imposed on the BS, to maximize its utility function defined as the difference between the achievable throughput and the total payment to the BS.
- The energy interaction between the BS and the UE in healthy area is exploited, which can be also formulated as a Stackelberg game. In this game, the UE acts a leader role purchasing the energy service from the BS to recover the D2D connection in disaster area. The UE aims to optimize its energy price and energy transfer time allocation to maximize its utility function which is defined as the difference between the achievable throughput and the energy payment to the BS. On the other hand, the BS is considered as a follower, where it determines its optimal transmit power based on the released energy price, announced by the UE in healthy area, to maximize its own utility function. The utility function of the BS is defined as the difference between the payment received from the UE and its energy cost.
- Closed-form solutions to the associated Stackelberg equilibrium of the aforementioned games are derived.

The rest of of the paper is organized as follows. Section II presents the system model of disaster-assisted communications adopting cooperative D2D communications. Section III proposes two game theoretical schemes for this disaster-assisted communication system. Numerical results are provided to validate our proposed schemes in Section IV. Finally, Section V concludes the paper.

[1]In the healthy area, the cellular network can normally establish a connection with the D2D network, including WET.

[2]In the disaster area, the cellular network fails to connect with D2D network due to natural disaster, e.g., earthquake, leading to disconnection between D2D pair who also suffers from insufficient transmit power.

II. System Model

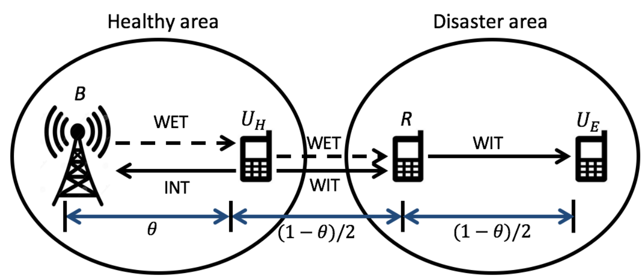

Fig. 1: System model.

We consider a system model shown in Fig. 1 that includes one BS, denoted by $\mathcal{B}$, and one UE, denoted by $\mathcal{U}_H$, in the healthy area, where $\mathcal{B}$ provides power to $\mathcal{U}_H$ to facilitate its future information transfer. In the disaster area, it consists of one EH relay,[3] denoted by $\mathcal{R}$, and one UE, denoted by $\mathcal{U}_D$. In case of a disaster, $\mathcal{U}_H$ has to recover communication with $\mathcal{U}_D$ in disaster area via relay $\mathcal{R}$ due to long distance. Due to energy limitation of the UE and the EH relay, it is assumed that there is no sufficient power supply for information transfer. Therefore, a '*harvest-then-transmit*' approach is employed at $\mathcal{U}_H$ who harvests power from the BS and then transmits the information to $\mathcal{U}_D$ via the EH relay. Note that a *power splitting* (PS) scheme is considered at the EH relay who also harvests power to support information forwarding. The whole transmission is performed during the time period T.

In the first period of T, i.e., θT $(0 < \theta < 1)$ which is the downlink phase of the BS, the BS of the healthy area provides energy to $\mathcal{U}_H$ to support the connection with the disaster area. In the second period of T, i.e., $(1-\theta)T$ which is the uplink phase of the BS, $\mathcal{U}_H$ establishes the communications with $\mathcal{U}_D$ via the EH relay. The transmission of $\mathcal{U}_H$ in the second period causes interference to the BS. In addition, we split the time period $(1-\theta)T$ into two equal slots. In the first slot $(1-\theta)T/2$, $\mathcal{U}_H$ transmits information and power to the EH relay $\mathcal{R}$. Then, the EH relay decodes the information and forward to $\mathcal{U}_D$ by using harvested power in the remaining time slot. The channel coefficients between $\mathcal{B}$ and $\mathcal{U}_H$, $\mathcal{U}_H$ and $\mathcal{R}$, $\mathcal{R}$ and $\mathcal{U}_D$, as well

[3]The EH relay can be considered a special UE which can harvest energy to forward the information from the healthy area. Generally, this EH relay is located close to the healthy area to facilitate the communications with $\mathcal{U}_H$ in the healthy area.

as $\mathcal{U}_H$ and $\mathcal{B}$ are denoted as g, h_{sr}, h_{rd} and h, respectively. First, the BS of the healthy area provides power to $\mathcal{U}_H$, which can be expressed as

$$E_s = \eta\theta T P_{\mathcal{B}}|g|^2, \tag{1}$$

where $P_{\mathcal{B}}$ is the transmit power at the BS, and $\eta \in (0, 1]$ denotes the EH efficiency of $\mathcal{U}_H$. For convenience and without loss of generality, it is assumed that $\eta = 1$ in this paper. This harvested energy E_s is consumed during the time slot $(1-\theta)T/2$. Thus, the maximum transmit power at $\mathcal{U}_H$ can be written as

$$P_T = \frac{2\theta}{1-\theta} P_{\mathcal{B}}|g|^2. \tag{2}$$

The received signal at the EH relay can be expressed as

$$y_r = \sqrt{P_s} h_{sr} x + n_{ra}, \tag{3}$$

where P_s is the transmit power of $\mathcal{U}_H$, satisfying $P_s \leq P_T$, n_{ra} represents the additive white Gaussian noise (AWGN) with zero mean and variance σ_{ra}^2 from the antenna at EH relay. The EH relay employs a PS scheme to split the received signal into two parts, i.e., information decoding (ID) and energy harvesting (EH). Thus, both parts can be given by

$$y_r^{ID} = \sqrt{\rho}(\sqrt{P_s} h_{sr} x + n_{ra}) + n_{rp}, \tag{4}$$
$$y_r^{EH} = \sqrt{1-\rho}(\sqrt{P_s} h_{sr} x + n_{ra}), \tag{5}$$

where $\rho \in (0, 1)$ is the PS ratio, and n_{rp} denotes the AWGN with zero mean and variance σ_{rp}^2 from signal processing at EH relay. The information rate at the EH relay is written as

$$R_{sr} = \frac{1-\theta}{2} \log\left(1 + \frac{\rho P_s |h_{sr}|^2}{\rho\sigma_{ra}^2 + \sigma_{rp}^2}\right). \tag{6}$$

The harvested power at the EH relay is expressed as

$$P_r = \xi P_s |h_{sr}|^2 (1-\rho), \tag{7}$$

where $\xi \in (0, 1]$ denotes the energy conversion efficiency of the EH relay. For convenience and without loss of generality, it is assumed that $\xi = 1$ in this paper. The EH relay decodes the information and forward to $\mathcal{U}_D$ by using the harvested power. Thus, the received signal at $\mathcal{U}_D$ can be given by

$$y_d = \sqrt{P_r} h_{rd} \bar{x} + n_d, \tag{8}$$

where $\bar{x}$ denotes the decoded signal by the EH relay. The information rate at $\mathcal{U}_D$ is written as

$$R_{rd} = \frac{1-\theta}{2} \log\left(1 + \frac{\xi P_s |h_{sr}|^2 |h_{rd}|^2 (1-\rho)}{\sigma_d^2}\right). \tag{9}$$

From (6) and (9), the achievable rate at $\mathcal{U}_D$ can be written as

$$R = \min\{R_{sr}, R_{rd}\}. \tag{10}$$

On the other hand, the interference is introduced by $\mathcal{U}_H$ to BS per time unit is given by

$$I_{\mathcal{B}} = P_s |h|^2. \tag{11}$$

III. Disaster-Assisted Communications Utilizing Cooperative D2D Communications

In this section, we consider a practical scenario that $\mathcal{B}$, $\mathcal{U}_H$ and $\mathcal{U}_D$ belong to the different service providers. In the downlink phase of the BS, i.e., the first time period, $\mathcal{U}_H$ purchases energy from $\mathcal{B}$ for its furture transmission. This process is referred to as *energy trading*. In the uplink phase of the BS, i.e., the second time period, $\mathcal{U}_H$ utilizes the frequency owned by the BS to transmit its information to $\mathcal{U}_E$ with the help of the relay $\mathcal{R}$. As the result of using the BS's frequency resource, $\mathcal{U}_H$ pays a price for the interference imposed on the BS. This process is referred to as *interference pricing*. In the sequel, the two processes, i.e., *energy trading* and *interference pricing*, are formulated as two Stackelberg games, where their Stackelberg equilibrium will be derived in closed-form solutions.

A. Stackelberg Game Formulations

Let us consider two following games:

1) Energy trading game: In this game, we formulate $\mathcal{U}_H$ as a leader who pays a price λ_1 per unit of energy harvested from the RF signals radiated by the BS, referred to as the energy price, whereas the BS is formulated as a follower who optimizes its transmit power based on the released energy price to maximize its profits. Now, we write this energy trading game as follows:

1) **Leader Level**: $\mathcal{U}_H$ is considered as the leader role which pays a price to purchase the energy service from the BS to recover the connection with the disaster area. It aims to maximize its utility function defined as the difference between the achievable throughput and the total energy payment to the BS. The leader level optimization problem is given by

$$\max_{\theta,\rho,\lambda_1,P_s} U_{\mathcal{U}_H}^{(1)}(\theta, \rho, \lambda_1, P_s) = \mu R - \lambda_1 \theta P_{\mathcal{B}}|g|^2,$$
$$s.t.\ 0 \leq \theta \leq 1,\ 0 \leq \rho \leq 1,\ \lambda \geq 0,\ 0 \leq P_s \leq P_T. \tag{12}$$

2) **Follower Level**: The BS acts as the follower who sells its energy service to $\mathcal{U}_H$ to support the connection between the healthy area and the disaster area. The BS aims to maximize its utility function defined as the difference between the energy payment from $\mathcal{U}_H$ and the energy cost. Thus, the follower level optimization problem can be expressed as

$$\max_{P_{\mathcal{B}} \geq 0} U_{\mathcal{B},1}(P_{\mathcal{B}}, \lambda_1, \theta) = \theta(\lambda_1 P_{\mathcal{B}}|g|^2 - \mathcal{F}(P_{\mathcal{B}})), \tag{13}$$

where $\mathcal{F}(P_{\mathcal{B}})$ is used to model the cost of the BS per unit time for wirelessly charging. In this paper, we consider the following quadratic model[4] for the cost function of the PBs.

$$\mathcal{F}(x) = Ax^2 + Bx \tag{14}$$

where $A > 0$ and $B > 0$ are the constants.

The Stackelberg game for the energy trading are formulated by combining both problems (12) and (13).

[4]Note that the quadratic function shown in (14) has been applied in the energy market to model the energy cost [22].

2) Interference pricing game: In this game, the BS is considered as the leader who announces an interference price λ_2 to maximize its own utility, and $\mathcal{U}_H$ is formulated as the follower to obtain the optimal transmit power maximizing its own utility. In the following, we formulate the optimizations of the leader and the follower:

1) **Leader Level**: The BS announces a price for the interference caused by the $\mathcal{U}_H$ to maximize its own profit, which is defined as the total payment from $\mathcal{U}_H$. Thus, the leader level optimization problem can be written as

$$\begin{aligned} \max_{\lambda_2 \geq 0} \ & U_{\mathcal{B},2}(\lambda_2) = \lambda_2(1-\theta)P_s|h|^2, \\ s.t. \ & P_s|h|^2 \leq I_{th}. \end{aligned} \tag{15}$$

2) **Follower Level**: $\mathcal{U}_H$ pays a price for the interference to maximize its utility function defined as the difference between the achievable throughput and the total payment to the BS. Thus, the follower level optimization problem is given by

$$\begin{aligned} \max_{P_s} \ & U^{(2)}_{\mathcal{U}_H}(P_s) = \mu R - \lambda_2(1-\theta)I_{\mathcal{B}}, \\ s.t. \ & 0 \leq P_s \leq P_T. \end{aligned} \tag{16}$$

The Stackelberg game for the interference pricing are formulated by combining both problems (15) and (16).

In the following, we derive the Stackelberg equilibrium for both formulated games, and analyze the connection between both proposed games.

B. Solution to Proposed Stackelberg Games

In this subsection, we derive closed-form Stackelberg equilibrium for both formulated games by analyzing the optimal strategies for the BS and $\mathcal{U}_H$ to maximize their own utilities.

1) Solution to Energy Trading Game: First, we consider the energy trading game, and derive the optimal power allocation of the BS $P_{\mathcal{B}}$. For given λ_1 and θ, the utility $U_{\mathcal{B},1}$ in (13) is obviously quadratic function with respect to $P_{\mathcal{B}}$ and the constraint is linear, which indicates that (13) is a convex optimization problem. Thus, the optimal solution to $P_{\mathcal{B}}$ can be achieved by the following *theorem*:

Theorem 1: For given λ_1 and θ, the optimal solution to the problem (13) can be achieved as

$$P_{\mathcal{B}}^{\text{opt}} = \left[\frac{\lambda_1|g|^2 - B}{2A}\right]^+, \tag{17}$$

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

Proof: It is easily observed that the objective function to the problem (13) is a concave function with respect to $P_{\mathcal{B}}$, and take the first derivatives equals to zero.

$$\begin{aligned} &\frac{\partial U_{\mathcal{B},1}}{\partial P_{\mathcal{B}}} = \theta(\lambda_1|g|^2 - 2AP_{\mathcal{B}} - B) = 0, \\ &\Rightarrow P_{\mathcal{B}}^{\text{opt}} = \begin{cases} \frac{\lambda_1|g|^2-B}{2A}, & \text{for } \lambda_1|g|^2 - B > 0, \\ 0, & \text{for } \lambda_1|g|^2 - B \leq 0. \end{cases} \end{aligned} \tag{18}$$

Thus, we have proved *Theorem* 1. ■

Next, we derive the optimal solution of the PS ratio ρ, which can be achieved by taking (10). The first term of (10), i.e., R_{sr}, is a monotonically increasing function in terms of ρ, whereas the second term of (10), i.e., R_{rd}, is a monotonically decreasing over ρ. Hence, in order to obtain the optimal solution ρ^{opt}, both terms satisfy the following equation

$$\frac{\rho P_s|h_{sr}|^2}{\rho\sigma_{ra}^2 + \sigma_{rp}^2} = \frac{\xi P_s|h_{sr}|^2|h_{rd}|^2(1-\rho)}{\sigma_d^2}. \tag{19}$$

Therefore, the optimal PS ratio, i.e., ρ^{opt}, can be written as (20) on the top of next page. Thus, we rewrite the (12) by substituting ρ^{opt} and $P_s^{\text{opt}} = P_T$ as

$$\begin{aligned} \max_{\theta,\lambda_1} \ & U^{(1)}_{\mathcal{U}_H}(\theta, \lambda_1) = a \log\left[1 + C\Big(\lambda_1 X - 2Y\Big)\right] \\ & \quad - \lambda_1^2 X + 2\lambda_1 Y, \\ s.t. \ & 0 < \theta < 1, \ \lambda_1 \geq 0, \end{aligned} \tag{21}$$

where

$$\begin{aligned} &a = \frac{\mu(1-\theta)}{2}, \ C = \frac{2\rho^{\text{opt}}|h_{sr}|^2}{(1-\theta)(\rho^{\text{opt}}\sigma_{ra}^2 + \sigma_{rp}^2)}, \\ &X = \frac{\theta|g|^4}{2A}, Y = \frac{B\theta|g|^2}{4A}. \end{aligned}$$

To proceed, we need to solve the problem (21), however, it is not easy to find the optimal solutions for λ_1 and θ simultaneously due to the complexity of its objective function. In order to circumvent this issue, we consider a two-step approach. Particularly, we first find the closed-form solution for λ_1 for a given θ, then, the optimal solution for θ can be achieved by employing one-dimensional (1D) search. Thus, the following *theorem* is required to obtain the optimal energy price λ_1^{opt} for fixed θ.

Theorem 2: The optimal solution of the energy price, denoted by λ_1^{opt} can be given by

$$\lambda_1^{\text{opt}} = \frac{-2(1-3CY) + \sqrt{4(1-CY)^2 + 8aC^2X}}{4CX}. \tag{22}$$

Proof: We first fix θ to take the first derivatives of the objective function in (21) equal to zero as

$$\begin{aligned} &\frac{\partial U^{(1)}_{\mathcal{U}_H}}{\partial \lambda_1} = \frac{aCX}{1 + C[(\lambda_1 X - Y) - Y]} - 2(\lambda_1 X - Y) = 0, \\ &\Rightarrow 2C(\lambda_1 X - Y)^2 + 2(1-CY)(\lambda_1 X - Y) - aCX = 0. \end{aligned} \tag{23}$$

By solving (23), we have

$$\begin{cases} \lambda_1^{(1)} = \frac{-2(1-3CY) - \sqrt{4(1-CY)^2 + 8aC^2X}}{4CX}, \\ \lambda_1^{(2)} = \frac{-2(1-3CY) + \sqrt{4(1-CY)^2 + 8aC^2X}}{4CX}. \end{cases} \tag{24}$$

Now, let us verify the validity of both solutions shown in (24). The objective function in (21) includes the logarithm term, where the term inside the logarithm function should be non-negative. Thus, we substitute these solutions shown in (24)

$$\rho^{\text{opt}} = \frac{-[\sigma_d^2 - \xi|h_{rd}|^2(\sigma_{rp}^2 - \sigma_{ra}^2)] + \sqrt{[\sigma_d^2 - \xi|h_{rd}|^2(\sigma_{rp}^2 - \sigma_{ra}^2)]^2 + 4\xi^2|h_{rd}|^4\sigma_{ra}^2\sigma_{rp}^2}}{2\xi|h_{rd}|^2\sigma_{ra}^2}. \tag{20}$$

into the logarithm term of (21), respectively. We first check $\lambda_1^{(1)}$ as follows:

$$\begin{aligned} &1 + C\bigg(\frac{-2(1-3CY) - \sqrt{4(1-CY)^2 + 8aC^2X}}{4C} - 2Y\bigg)\bigg] \\ &= 1 + C\bigg(\frac{-2(1-CY) - \sqrt{4(1-CY)^2 + 8aC^2X}}{4C}\bigg) \\ &< 1 + C\bigg(\frac{-2(1-CY) - |2(1-CY)|}{4C}\bigg) \leq 1. \end{aligned} \tag{25}$$

Similarly, we check $\lambda_1^{(2)}$ as

$$\begin{aligned} &1 + C\bigg(\frac{-2(1-3CY) + \sqrt{4(1-CY)^2 + 8aC^2X}}{4C} - 2Y\bigg)\bigg] \\ &= 1 + C\bigg(\frac{-2(1-CY) + \sqrt{4(1-CY)^2 + 8aC^2X}}{4C}\bigg) \\ &> 1 + C\bigg(\frac{-2(1-CY) - |2(1-CY)|}{4C}\bigg) \geq 1. \end{aligned} \tag{26}$$

From the above analyzes, one can observe that $\lambda_1^{(2)}$ is the valid stationary point. Due to the concavity of the objective function in (21) in terms of λ_1, its second-order derivatives is less than zero, which indicates that its maximum value is the stationary point $\lambda_1^{(2)}$. Also, it is easily verified that $\lambda_1^{(2)} > 0$, which satisfies the constraint in (21). Thus, the optimal solution to (21), denote by λ_1^{opt} is the stationary point $\lambda_1^{(2)}$. ■

We have already achieved the optimal energy price λ_1^{opt} for a given θ. Substituting λ_1^{opt} into the problem (21), we have the following optimization problem with respect to θ:

$$\max_{\theta} \ U_{\mathcal{U}_H}^{(1)}(\theta, \lambda_1^{\text{opt}}), \ s.t. \ 0 < \theta < 1. \tag{27}$$

The problem (27) can be efficiently solved via 1D search. The optimal solution to (27), denoted by θ^{opt}, can ba achieved by

$$\theta^{\text{opt}} = \arg\max_{\theta \in (0,1)} \ U_{\mathcal{U}_H}^{(1)}(\theta, \lambda_1^{\text{opt}}). \tag{28}$$

This has completed the derivation of the Stackelberg equilibrium $(P_{\mathcal{B}}^{\text{opt}}, \rho^{\text{opt}}, \lambda_1^{\text{opt}}, \theta^{\text{opt}})$ for the formulated energy trading based Stackelberg game, which have been shown in (17), (20), (22) and (28).

2) Solution to Interference Pricing Game: In this subsection, we derive the Stackelberg equilibrium for the interference pricing game. First, we consider the optimization problem (16) with ρ^{opt} as follows:

$$\begin{aligned} &\max_{P_s} U_{\mathcal{U}_H}^{(2)}(P_s) = a\log(1 + DP_s) - \lambda_2 E P_s, \\ &s.t. \ 0 \leq P_s \leq P_T. \end{aligned} \tag{29}$$

where

$$D = \frac{\rho^{\text{opt}}|h_{sr}|^2}{\rho^{\text{opt}}\sigma_{ra}^2 + \sigma_{rp}^2}, E = (1-\theta)|h|^2.$$

It is easily verified that (29) is a convex optimization problem in terms of P_s. Thus, the optimal solution to (29) can be achieved by taking the first derivatives of $U_{\mathcal{U}_H}^{(2)}$ equal to zero as follows:

$$\begin{aligned} &\frac{\partial U_{\mathcal{U}_H}^{(2)}}{\partial P_s} = \frac{aD}{1 + DP_s} - \lambda_2 E = 0, \\ &\Rightarrow P_s = \left[\frac{a}{\lambda_2 E} - \frac{1}{D}\right]_0^{P_T}, \end{aligned} \tag{30}$$

where $[x]_a^b := \max\{\min\{x, b\}, a\}$.

Now we focus on the interference pricing decision for (15). Particularly, the optimal interference price λ_2 can be achieved via 1D search. In order to illustrate more insights into the interference interaction between the BS and the D2D transmitter, we consider the following the equations regarding the lower and upper bound of λ_2:

$$\lambda_2^{\text{up}} = \frac{aD}{E}, \ \lambda_2^{\text{low}} = \frac{a}{(P_T + \frac{1}{D})E}. \tag{31}$$

It is easily verified that (31) holds when either $P_s = 0$ or P_T. From (31), we have the following *properties*:

1) $0 \leq U_{\mathcal{B},2}(\lambda_2) < \infty$;
2) $U_{\mathcal{B},2}(\lambda_2) = 0$ if $\lambda_2 = 0$ or $\lambda_2 \geq \lambda_2^{\text{up}}$;
3) $U_{\mathcal{B},2}(\lambda_2) = \lambda_2(1-\theta)P_T|h|^2$ if $0 \leq \lambda_2 \leq \lambda_2^{\text{low}}$.

Proof: First, it is easily verified that *property* 1 always hold. Then, we provide the proof to show *properties* 2 and 3. Both of λ_2^{low} and λ_2^{up} shown in (31) can be achieved by letting $P_s = 0$ and $P_s = P_T$, respectively. If

$$\lambda_2 \geq \lambda_2^{\text{up}} \triangleq \frac{aD}{E}, \tag{32}$$

which indicates

$$\frac{a}{\lambda_2 E} \leq \frac{1}{D}. \tag{33}$$

According to (30), it is easily concluded that $P_s = 0$, and by substituting it into (15), we have $U_{\mathcal{B},2}(\lambda_2) = 0$. Additionally, $U_{\mathcal{B},2}(\lambda_2) = 0$ if $\lambda_2 = 0$ always hold. Similarly if,

$$\begin{aligned} &\lambda_2 \leq \lambda_2^{\text{low}} \triangleq \frac{a}{(P_T + \frac{1}{D})E}, \\ &\Rightarrow \frac{a}{\lambda_2 E} \geq P_T + \frac{1}{D}, \Rightarrow \frac{a}{\lambda_2 E} - \frac{1}{D} \geq P_T. \end{aligned} \tag{34}$$

According to (30), it is easily concluded that $P_s = P_T$, and replace it into (15), we have $U_{\mathcal{B},2}(\lambda_2) = \lambda_2(1-\theta)P_T|h|^2$. Moreover, we consider the case $U_{\mathcal{B},2}(\lambda_2)$ with $P_s = 0$, we have

$$\frac{a}{\lambda_2 E} - \frac{1}{D} \leq 0, \Rightarrow \lambda_2 \geq \frac{aD}{E} \triangleq \lambda_2^{\text{up}}. \tag{35}$$

Similarly, for the case $U_{\mathcal{B},2}(\lambda_2) = \lambda_2(1-\theta)P_T|h|^2$ with $P_s = P_T$, or

$$\frac{a}{\lambda_2 E} - \frac{1}{D} \geq P_T, \Rightarrow 0 \leq \lambda_2 \leq \frac{a}{(P_T + \frac{1}{D})E} \triangleq \lambda_2^{\text{low}} \tag{36}$$

Thus, *properties* 2 and 3 have been proved. ■

Remark 1: The optimal interference price λ_2 lies in a certain range, depending on numbers of factors such as the channel conditions, distance between the BS and $\mathcal{U}_H$, interference, BS transmit power, energy price and energy transfer time allocation. The interference utility function is always nonnegative, since the transmit power of $\mathcal{U}_H$ is nonnegative with energy harvesting from the BS. The maximum utility function is bounded with the maximum harvested power of $\mathcal{U}_H$, i.e., P_T, also, the revenue will disappear when the interference price is too low or two high.

It is easily verified that P_s is a strictly decreasing function with respect to λ_2 at the interval $[\lambda_2^{\text{low}}, \lambda_2^{\text{up}}]$. For the interference pricing game, we have the following descriptions:

1) When $0 \le \lambda_2 \le \lambda_2^{\text{low}}$, $\mathcal{U}_H$ transmits with its maximum power, while the interference at the BS is upper bounded. Additionally, the associated payment $U_{\mathcal{B},2}$ to the BS is linear with respect to λ_2. The straightforward explanation is that the BS announces a low enough price, in which $\mathcal{U}_H$ can afford this payment released by the BS and transmit its power at a high level.
2) When $\lambda_2 \ge \lambda_2^{\text{low}}$, $\mathcal{U}_H$ reduces its transmit power with increased price λ_2 released by the BS. In addition, $\mathcal{U}_H$ transmitted power is decreasing due to λ_2.
3) When $\lambda_2 \ge \lambda_2^{\text{up}}$, the BS's profits for interference disappears, since $U_{\mathcal{B},2}(\lambda_2) = 0$.

Now, we describe the monotonicity for utility function $U_{\mathcal{B},2}$ between the interval $[\lambda_2^{\text{low}}, \lambda_2^{\text{up}}]$. First, this price interval is divided into sufficient small intervals. Then, for each small interval, the BS optimize the interference price paid by $\mathcal{U}_H$ to maximize its utility function while maintaining the interference constraint. In the sequel, we summarize this interference pricing algorithm at the interval $[\lambda_2^{\text{low}}\ \lambda_2^{\text{up}}]$ in **Algorithm** 1.

Algorithm 1: Interference pricing algorithm

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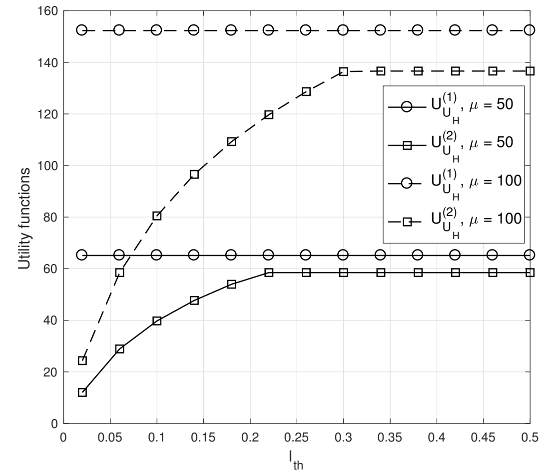
1) BS initializes the interference price λ_2 at the range $[\lambda_2^{\text{low}}\ \lambda_2^{\text{up}}]$.
2) Set η is a small positive value.
3) **For** count $= \lambda_2^{\text{low}} : \eta : \lambda_2^{\text{up}}$
   a) BS calculate the received interference $I_{\mathcal{B}}$ and its utility function $U_{\mathcal{B},2}$.
   b) **If** $I_{\mathcal{B}}(\lambda_2(\text{count})) \le I_{th}$, then, $U_{\mathcal{B},2} = \lambda_2(\text{count})(1-\theta)P_s|h|^2$;
   else $U_{\mathcal{B},2} = \lambda_2(\text{count})(1-\theta)I_{th}$.
4) **end**
5) **Output** $\lambda_2^{\text{opt}} \leftarrow \arg\max_{\lambda_2} U_{\mathcal{B},2}(\lambda_2)$.

Note that when the problem (15) achieves its optimality at the interval $[\lambda_2^{\text{low}}\ \lambda_2^{\text{up}}]$, it should satisfy $P_s = \frac{I_{th}}{|h|^2}$. Thus, we can obtain the optimal solution to the interference price in terms of closed-form solution as follows:

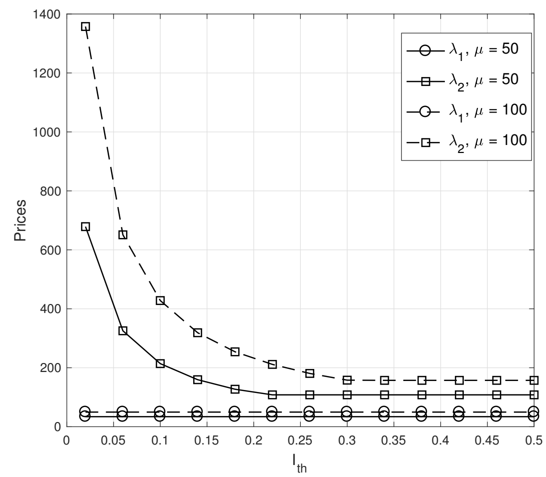
$$\lambda_2^{\text{opt}} = \frac{a}{(\frac{I_t h}{|h|^2} + \frac{1}{D})E}. \tag{37}$$

Remark 2: When $P_s = P_T$ to satisfy the maximum utility function in (12), also the interference constraint should be satisfied as well, thus, the closed-form interference price can be expressed as follows

$$\lambda_2^{\text{opt}} = \frac{a}{(\min\{P_T, \frac{I_t h}{|h|^2}\} + \frac{1}{D})E}. \tag{38}$$



(a) Utility versus I_{th}.



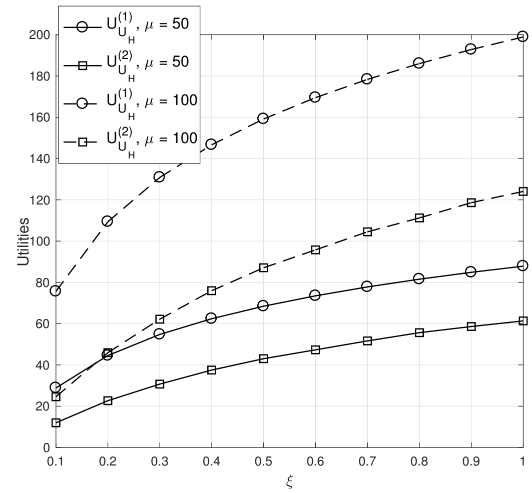
(b) Prices versus I_{th}.

Fig. 2: The comparison between energy trading and interference pricing with the interference I_{th}.

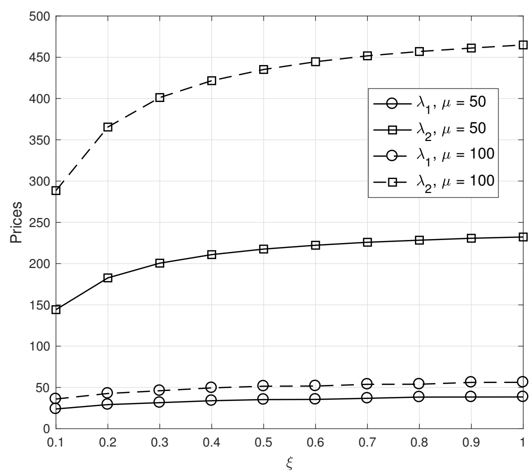
IV. Simulation Results

In this section, we provide the simulation results to evaluate the performance of our proposed algorithms for interference management and energy trading in D2D disaster cellular networks shown in Section II. We assume that the fading channels are modelled as $Cd^{-\alpha}$, where C is the small-scale fading factor which is modelled as Rayleigh fading process, d denotes as d_1, d_2 and d_3, which are the distance from $\mathcal{B}$ to $\mathcal{U}_H$, $\mathcal{U}_H$ to $\mathcal{R}$, and $\mathcal{R}$ to $\mathcal{U}_D$, respectively. The noise power is assumed to be $\sigma_{ra}^2 = \sigma_{rp}^2 = \sigma_d^2 = 10^{-4}$ mw. Also, we assume that $A = B = 1$ for quadratic energy cost model. Moreover, we set $\xi = 0.8$ and $I_{th} = 0.1$ unless specified.

First, we evaluate the profits performances, i.e., utility function and the price, of two proposed games versus the target

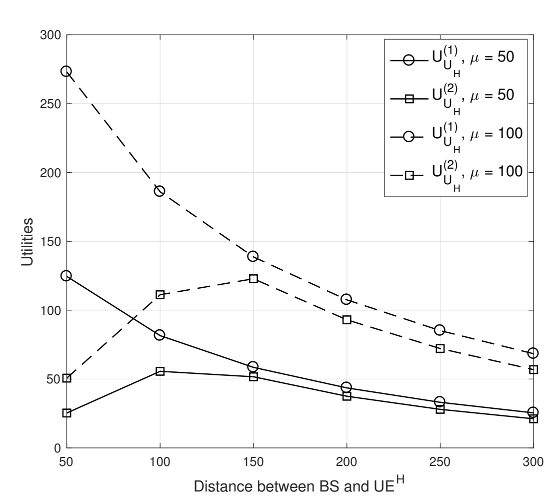


(a) Utility versus ξ.

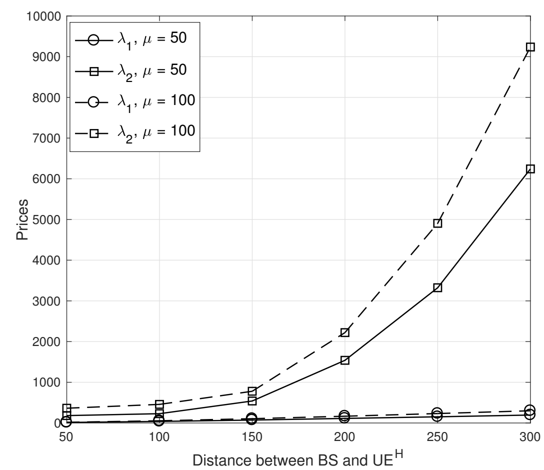


(b) Prices versus ξ.

Fig. 3: The comparison between energy trading and interference pricing with EH efficiency ξ.



(a) Utility versus distance between BS and $\mathcal{U}_H$.



(b) Prices versus distance between BS and $\mathcal{U}_H$.

Fig. 4: The comparison between energy trading and interference pricing with distance between BS and $\mathcal{U}_H$.

interference I_{th} in Figure 2. From this results, it is observed that the utility function $U^{(1)}_{\mathcal{U}_H}$ and the energy price λ_1 is a constant as the target interference I_{th} increases. In Figure 2(a), the utility function $U^{(2)}_{\mathcal{U}_H}$ increases with I_{th} at the beginning of interference regimes, and approximately achieves to a stable status with the increasing of I_{th}. Whereas in Figure 2(b), the price λ_2 decreases in the low interference regimes, and with the increasing of I_{th}, it approximately approaches to a constant level. This is because of the fact that once the achievable interference exceeds the target interference, $\mathcal{U}_H$ will not gain more revenue and the price paid by $\mathcal{U}_H$ for the interference pricing decision will not decrease.

Next, we evaluate the profit performances of two proposed games versus the EH efficiency ξ. In Figure 3, one can observe that the utility functions, i.e., $U^{(1)}_{\mathcal{U}_H}$ and $U^{(2)}_{\mathcal{U}_H}$, and the prices, i.e., λ_1 and λ_2, get increased as ξ increases. Also, in Figure 3(a), the energy trading game has a better performance than the interference pricing game in terms of the utility function,which means that $\mathcal{U}_H$ can achieve the more profits by employing energy trading interaction with the BS than the interference pricing decision. Whereas, in Figure 3(b), $\mathcal{U}_H$ will pay more price to purchase the interference than the energy service, which highlights the financial efficiency for the energy trading.

Then, we exploit the impact of the profit performances of these two proposed game-theoretical schemes versus the distance between the BS and $\mathcal{U}_H$, i.e., d_1. Figure 4 shows the utility function and the price against the distance between the BS and $\mathcal{U}_H$, i.e., d_1. From Figure 4(a), one can observe that $U^{(1)}_{\mathcal{U}_H}$ decreases with the increasing of d_1, whereas $U^{(2)}_{\mathcal{U}_H}$ increases at low distance regimes, and then declines at high distance regimes. In addition, it can be seen from Figure 4(b) that the prices are increasing as d_1 increases. This is due to the fact that, in the low distance regimes, $\mathcal{U}_H$ transmit power decreases with the increasing of d_1 when the interference price paid by $\mathcal{U}_H$, i.e., λ_2, is located in the range of $[\lambda_2^{\text{low}}\ \lambda_2^{\text{up}}]$, which may lead to the increasing of $U^{(1)}_{\mathcal{U}_H}$. On the other side, as d_1 increases, $\mathcal{U}_H$ transmit power is up to its harvested power such that this interference price λ_2 falls in the range of $(0\ \lambda_2^{\text{low}}]$, which means that $U_{\mathcal{U}_H}^{(2)}$ will decrease as d_1 increases. In addition, $U_{\mathcal{U}_H}^{(1)}$ has better profit performance gains than $U_{\mathcal{U}_H}^{(2)}$ does, and the energy trading scheme has more financial saving than the interference pricing scheme does.

V. Conclusion

In this paper, we studied the disaster management in two-cell D2D cooperative communications. Specifically, the UE in healthy area aims to assist the connection with the UE in disaster area via an EH relay. In healthy area, we considered a practical scenario that both BS and UE belong to the different service providers, thus UE needs to pay prices as incentives for two services: energy transfer and interference services. These two processes are formulated as two Stackelberg games, i.e., energy trading and interference pricing games. We derived the Stackelberg equilibriums for both proposed games in closed-form solutions. Finally, numerical results reveal that the D2D network obtains higher performance, i.e., higher utility and lower price, in the energy trading game than that of the interference pricing game. This is due to the two following facts. First, the transmitter of the D2D network is the leader in the former game while it is the follower in the latter game. Second, the energy harvesting operation of the D2D network is not limited in the downlink phase of the base station while the transmitting operation of the D2D network is restricted by the interference threshold in the uplink phase of the base station.

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