

# A Stackelberg-Game Approach for Disaster-Recovery Communications Utilizing Cooperative D2D

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**Abstract**—In this paper, we investigate disaster-recovery 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 may belong to different service providers. Thus, the UE pays an amount of price as incentive to the BS as part of two processes: *energy trading* and *interference pricing*. We formulate these two processes as two *Stackelberg* games, where their equilibrium is derived as closed-form solutions. The results help provide a sustainable framework for disaster recovery when the involving parties juggle between energy trading, interference compromise and payment incentives in establishing communications during the recovery process.

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

## I. INTRODUCTION

In recent years, device-to-device (D2D) communication has attracted increasing 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 base station (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 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.

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, re-

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source 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 and costs 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 sufficient 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-recovery communications adopting cooperative D2D communications. Specially, we investigate a two-cell-framework scenario, i.e., one is in a healthy area,<sup>1</sup> while the other is in a disaster area.<sup>2</sup> 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. Although the disaster-recovery task would often be considered as a social corporate responsibility, making it fair and sustainable in economic terms is important for involving parties. It cannot be considered solely a charity process. For this purpose, it fits very well to employ game theory in certain disaster situations. In particular, we consider two key processes to support the recovery: *interference pricing decision* and *energy trading*, which can be formulated as two *Stackelberg* games. Accordingly, in these formulated games, while establishing disaster-recovery communications the UE needs to pay prices for two services to: i) be allowed to cause interference to the main cellular network and ii) trade for energy. These prices/payments can be considered as incentives to exploit the hierarchical interactions between the BS and the UE. In the following, we highlight the key designs and contributions of our proposed work as:

- Firstly, the *energy interaction* between the BS and the UE in the healthy area is exploited, which can be formulated as a *Stackelberg* game. In this game, the UE acts as a leader purchasing the energy service from the BS to recover the D2D connection in disaster area. The leader role in this process reflects the fact that the customers dictate the market, decide how much energy they would buy, and at what price they are willing to pay. Thus,

<sup>1</sup>In the healthy area, the cellular network can normally establish a connection with the D2D network, including WET.

<sup>2</sup>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.

the UE will aim 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 determining its optimal transmit power based on the released energy price (announced by the UE in the 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.

- Secondly, the *interference interaction* between the cellular and D2D network is modeled to capture the fact that the 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 also be formulated as a *Stackelberg* game, where the BS plays the leader role. The change of the leader role in this second process is because of the fact that the BS is the one that should decide the tolerance interference level as a result of the transmission of the UE in the healthy area. In other words, this BS sells interference acceptance service to maximize its utility function defined as the total payment received from the UE in the healthy area. Meanwhile, the UE in the healthy area is considered as the 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.
- Finally, closed-form solutions to the associated *Stackelberg* equilibrium of the aforementioned games are then derived and analyzed.

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

## II. SYSTEM MODEL

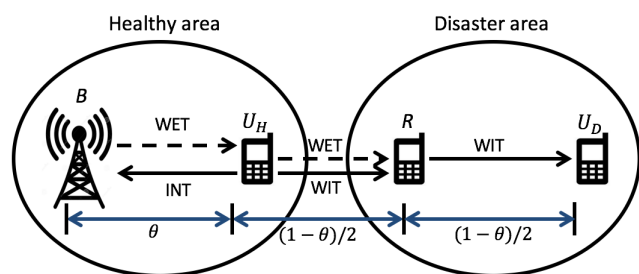


Fig. 1: System model.

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,<sup>3</sup> 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 energy 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.,  $\theta T$  ( $0 < \theta < 1$ ) 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 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

$$E_s = \eta \theta T P_B |g|^2, \quad (1)$$

where  $P_B$  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

$$P_T = \frac{2\theta}{1 - \theta} P_B |g|^2. \quad (2)$$

The received signal at the EH relay can be expressed as

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

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  $\sigma_{ra}^2$  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

$$y_r^{ID} = \sqrt{\rho} (\sqrt{P_s} h_{sr} x + n_{ra}) + n_{rp}, \quad (4)$$

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

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

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

<sup>3</sup>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.

The harvested power at the EH relay is expressed as

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

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

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

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

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

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

$$R = \min\{R_{sr}, R_{rd}\}. \quad (10)$$

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

$$I_B = P_s |h|^2. \quad (11)$$

### III. DISASTER-RECOVERY COMMUNICATIONS UTILIZING COOPERATIVE D2D COMMUNICATIONS

In the downlink phase of the BS, i.e., the first time period,  $\mathcal{U}_H$  purchases energy from  $\mathcal{B}$  for its future 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 the two following games:

1) *Energy Trading Game*: In this game, we formulate  $\mathcal{U}_H$  as the leader who pays a price  $\lambda_1$  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 the 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 that 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

$$\begin{aligned} \max_{\theta, \rho, \lambda_1, P_s} U_{\mathcal{U}_H}^{(1)}(\theta, \rho, \lambda_1, P_s) &= \mu R - \lambda_1 \theta P_B |g|^2, \\ \text{s.t. } 0 &\leq \theta \leq 1, \quad 0 \leq \rho \leq 1, \quad \lambda \geq 0, \quad 0 \leq P_s \leq P_T. \end{aligned} \quad (12)$$

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

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

where  $\mathcal{F}(P_B)$  is used to model the cost of the BS per unit time for wirelessly charging. In this paper, we consider the following quadratic model<sup>4</sup> for the cost function of the PBs.

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

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).

2) **Interference Pricing Game:** In this game, the BS is considered as the leader who announces an interference price  $\lambda_2$  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

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

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

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

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.

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

1) **Solution to Energy Trading Game:** First, we consider the energy trading game, and derive the optimal power allocation of the BS  $P_B$ . For given  $\lambda_1$  and  $\theta$ , the utility  $U_{B,1}$  in (13) is obviously quadratic function with respect to  $P_B$  and the constraint is linear, which indicates that (13) is a convex optimization problem. Thus, the optimal solution to  $P_B$  can be achieved by the following *theorem*:

*Theorem 1:* For given  $\lambda_1$  and  $\theta$ , the optimal solution to the problem (13) can be achieved as

$$P_B^{\text{opt}} = \left[ \frac{\lambda_1 |g|^2 - B}{2A} \right]^+, \quad (17)$$

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  $P_B$ . Taking the first derivatives of (13) and equalling it to zero, one can have

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

Thus, we have proved *Theorem 1*. ■

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

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

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

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

where

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

To proceed, we need to solve the problem (21), however, it is not easy to find the optimal solutions for  $\lambda_1$  and  $\theta$  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  $\lambda_1$  for a given  $\theta$ , then, the optimal solution for  $\theta$  can be achieved by employing one-dimensional (1D) search. Thus, the following *theorem* is required to obtain the optimal energy price  $\lambda_1^{\text{opt}}$  for fixed  $\theta$ .

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

*Theorem 2:* The optimal solution of the energy price, denoted by  $\lambda_1^{\text{opt}}$  can be given by

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

*Proof:* We first fix  $\theta$  to take the first derivative of the objective function in (21) and equal it to zero as

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

By solving (23), we have

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

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

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

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

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

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  $\lambda_1$ , its second-order derivative 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  $\lambda_1^{\text{opt}}$  is the stationary point  $\lambda_1^{(2)}$ . ■

We have already achieved the optimal energy price  $\lambda_1^{\text{opt}}$  for a given  $\theta$ . Substituting  $\lambda_1^{\text{opt}}$  into the problem (21), we have the following optimization problem with respect to  $\theta$ :

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

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

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

This has completed the derivation of the *Stackelberg* equilibrium  $(P_B^{\text{opt}}, \rho^{\text{opt}}, \lambda_1^{\text{opt}}, \theta^{\text{opt}})$  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  $\rho^{\text{opt}}$  as follows:

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

where

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

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 equalling the first derivative of  $U_{\mathcal{U}_H}^{(2)}$  to zero as follows:

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

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

Now we focus on the interference pricing decision for (15). Particularly, the optimal interference price  $\lambda_2$  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  $\lambda_2$ :

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

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

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

*Proof:* First, it is easily verified that *property 1* always holds. Then, we provide the proof to show *properties 2* and *3*. Both of  $\lambda_2^{\text{low}}$  and  $\lambda_2^{\text{up}}$  shown in (31) can be achieved by letting  $P_s = 0$  and  $P_s = P_T$ , respectively. If

$$\lambda_2 \geq \lambda_2^{\text{up}} \triangleq \frac{aD}{E}, \quad (32)$$

which indicates

$$\frac{a}{\lambda_2 E} \leq \frac{1}{D}. \quad (33)$$

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

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

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

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

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

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

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

*Remark 1:* The optimal interference price  $\lambda_2$  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 too high.

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

- 1) When  $0 \leq \lambda_2 \leq \lambda_2^{\text{low}}$ ,  $\mathcal{U}_H$  transmits with its maximum power, while the interference at the BS is upper bounded. Additionally, the associated payment  $U_{B,2}$  to the BS is linear with respect to  $\lambda_2$ . 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  $\lambda_2 \geq \lambda_2^{\text{low}}$ ,  $\mathcal{U}_H$  reduces its transmit power with increased price  $\lambda_2$  released by the BS. In addition,  $\mathcal{U}_H$  transmitted power is decreasing due to  $\lambda_2$ .
- 3) When  $\lambda_2 \geq \lambda_2^{\text{up}}$ , the BS's profits for interference disappears, since  $U_{B,2}(\lambda_2) = 0$ .

Now, we describe the monotonicity for utility function  $U_{B,2}$  in 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 in the interval  $[\lambda_2^{\text{low}}, \lambda_2^{\text{up}}]$  in **Algorithm 1**.

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*Algorithm 1:* Interference pricing algorithm

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

---

Note that when the problem (15) achieves its optimality in 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:

$$\lambda_2^{\text{opt}} = \frac{a}{\left(\frac{I_{th}}{|h|^2} + \frac{1}{D}\right)E}. \quad (37)$$

*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

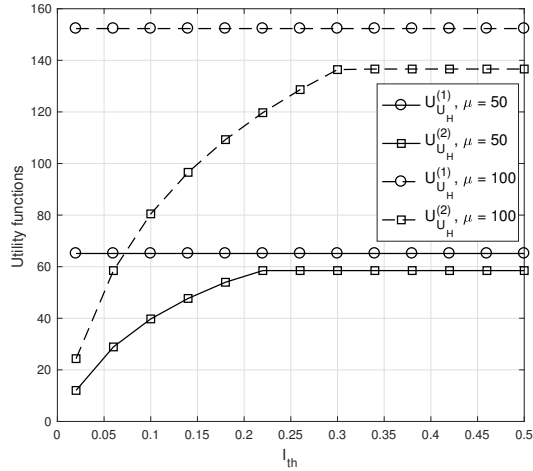
$$\lambda_2^{\text{opt}} = \frac{a}{(\min\{P_T, \frac{I_{th}}{|h|^2}\} + \frac{1}{D})E}. \quad (38)$$

#### IV. SIMULATION RESULTS

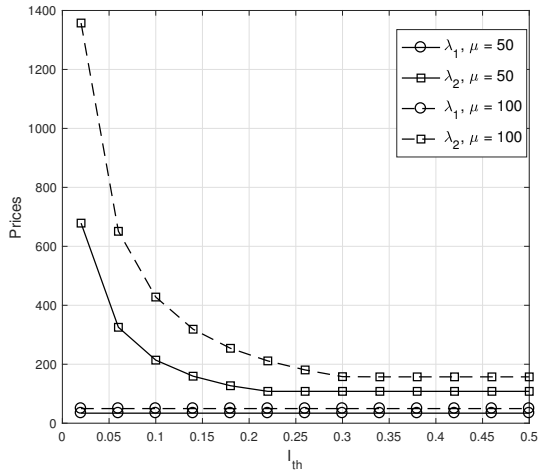
In this section, we provide simulation results to evaluate the performance of our proposed algorithms for interference management and energy trading in D2D disaster cellular networks shown in Section II. We assume that the fading channels are modelled as  $Cd^{-\alpha}$ , where  $C$  is the small-scale 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 otherwise specified.

First, we evaluate the profits performances, i.e., utility function and the price, of two proposed games versus the target interference  $I_{th}$  in Figure 2. From this results, it is observed that the utility function  $U_{\mathcal{U}_H}^{(1)}$  and the energy price  $\lambda_1$  are constants as the target interference  $I_{th}$  increases. In Figure 2(a), the utility function  $U_{\mathcal{U}_H}^{(2)}$  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  $\lambda_2$  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  $\xi$ . In Figure 3, one can observe that the utility functions, i.e.,  $U_{\mathcal{U}_H}^{(1)}$  and  $U_{\mathcal{U}_H}^{(2)}$ , and the prices, i.e.,  $\lambda_1$  and  $\lambda_2$ , get increased as  $\xi$  increases. Also, in Figure 3(a), the energy trading game has a better performance than the



(a) Utility versus  $I_{th}$ .

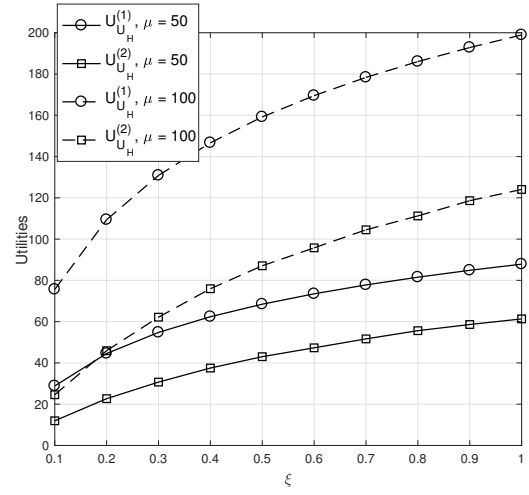


(b) Prices versus  $I_{th}$ .

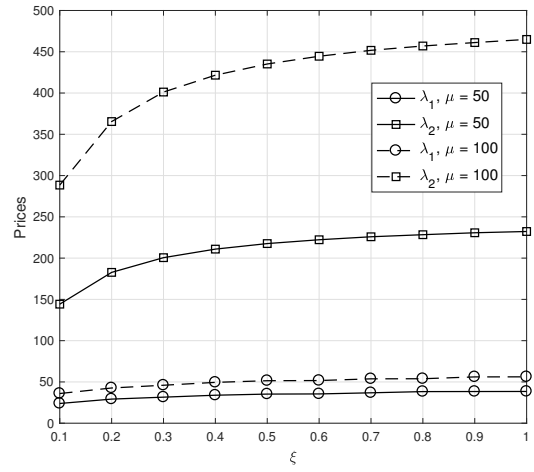
Fig. 2: The comparison between energy trading and interference pricing with the interference  $I_{th}$ .

interference pricing game in terms of the utility function, which means that  $\mathcal{U}_H$  can achieve more profits by employing energy trading interaction with the BS than employing the interference pricing decision. Whereas, in Figure 3(b),  $\mathcal{U}_H$  will pay more price for the interference than the energy service, which highlights the financial efficiency for the energy trading.

Then, we exploit the impact of the performance 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  $U_{\mathcal{U}_H}^{(1)}$  decreases with the increasing of  $d_1$ , whereas  $U_{\mathcal{U}_H}^{(2)}$  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.,  $\lambda_2$ , is located in the range of  $[\lambda_2^{low}, \lambda_2^{up}]$ , which may lead to the increasing of  $U_{\mathcal{U}_H}^{(1)}$ . On the other side,



(a) Utility versus  $\xi$ .



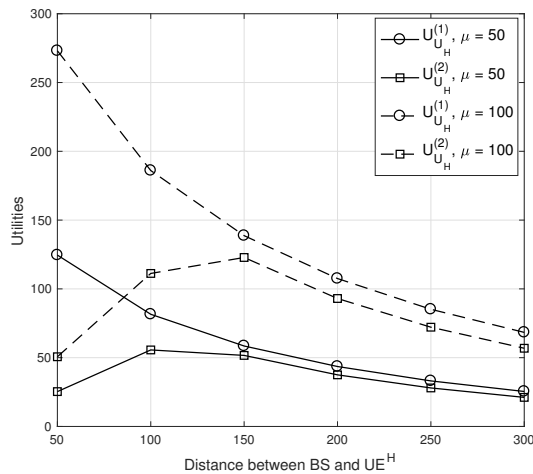
(b) Prices versus  $\xi$ .

Fig. 3: The comparison between energy trading and interference pricing with EH efficiency  $\xi$ .

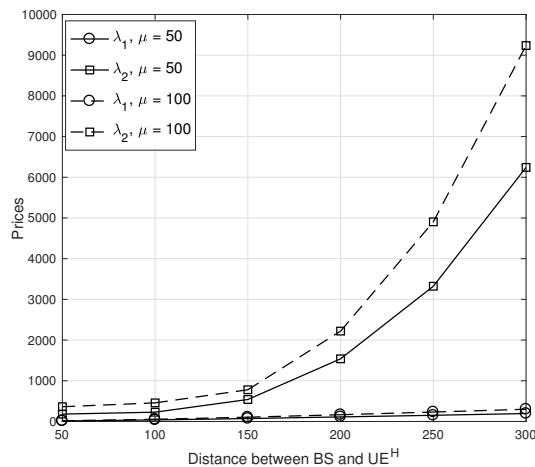
as  $d_1$  increases,  $\mathcal{U}_H$  transmit power is up to its harvested power such that this interference price  $\lambda_2$  falls in the range of  $(0, \lambda_2^{low}]$ , which means that  $U_{\mathcal{U}_H}^{(2)}$  will decrease as  $d_1$  increases. In addition,  $U_{\mathcal{U}_H}^{(1)}$  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 the healthy area aims to assist the connection with the UE in disaster area via an EH relay. In the healthy area, we considered a practical scenario that both BS and UE belong to 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



(a) Utility versus distance between BS and  $U_H$ .



(b) Prices versus distance between BS and  $U_H$ .

Fig. 4: The comparison between energy trading and interference pricing with distance between BS and  $U_H$ .

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, during the energy trading phase than that during the interference pricing phase. This is due to the fact that 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. This work has provided a sustainable and fair framework to assist communications in disaster recovery where multiple parties are involved and compromised to some extent in resources.

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