D2D Cooperative Communications for Disaster Management

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***Abstract*—In this paper, we investigate a disaster management system using D2D cooperative communications. Specifically, we consider two D2D cells, one is in healthy area and the other is in disaster area, where a user equipment (UE) in 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, a cellular base station (BS) shares the spectrum with the UE even though they may belong to different service providers. In return, this UE will have to provide some incentives to the BS by paying prices for causing interference and for trading energy. We formulate these processes as two *Stackelberg* games, *interference pricing* and *energy trading*, where their *Stackelberg* equilibriums are derived in closed-form solutions. Finally, numerical results are provided to validate our proposed schemes. It is shown that the energy trading scheme outperforms the interference pricing scheme in terms of assistance efficiency for the disaster area.**

I. Introduction

In recent years, device-to-device (D2D) communication has extracted increasing attention and been standardized into the 3GPP Release 12 [1], [2]. The key feature of D2D communication is that two communicating devices in close proximity reuse better links to communicate directly rather than through the base station (BS) in cellular networks. The D2D communication based mobile proximity services target the potential requirement for an service operator to integrate D2D communication in a cellular network, which is to build new mobile service opportunities and reduce traffic load on the network. The idea behind D2D communication is that an underlay direct communication among user equipments (UEs) using the same licensed radio resource can establish a direct local link and bypass the BS or access point (AP) [3]. D2D communications can help off-loading traffic of the cellular network, enhancing spectral efficiency, shortening time delay and reducing power consumption to keep up with the "greener trend, as well as to serve well in some urgent and extreme scenarios (e.g., earthquakes, flooding, avalanches) for providing public safety and disaster relief services [4], [5].

Wireless powered communication networks (WPCNs), where wireless devices can be remotely powered by radio frequency (RF) wireless energy transfer (WET) technology [6], have received increasing interests. A "*harvest-then-transmit*" protocol was proposed for WPCNs in [7]–[9], where the wireless users harvest power from the RF signals broadcast by a hybrid AP in the down-link (DL), and then send information to the AP in the up-link (UL) by employing the harvested energy. In addition, cooperative relaying was considered to employ the harvested power to forward the information received from the transmitter [10]–[12]. Different cooperative protocols, amplify-and-forward (AF) and decode-and-forward (DF), are investigated to obtain the power allocation for cooperative energy harvesting (EH) relaying systems [11], [12].

In an underlay D2D network, an underlay UE imposes interference to the cellular network. One potential solution is that the cellular network can accept a payment from the underlay D2D network, which is considered as an incentive to share the spectrum with the D2D UE devices. For this scenario, a *Stackelberg* game was proved to be a suitable candidate to formulate the decision making in the interference pricing process [13]. On the other hand, it is not practical to assume that the UE always has enough power to transmit its own information. Thus, it needs to harvest power for future operations (i.e., wireless information transfer). For this scenario, the UE is also willing to pay a certain price to the BS for an energy service. Again, a *Stackelberg* game can be considered a good tool to exploit the hierarchical energy interaction between the cellular and D2D networks. Both scenarios motivate our work in this paper.

In this paper, we investigate a disaster management system utilizing D2D cooperative communications. We consider a two-cell scenario where one cell is healthy and the other is affected by a disaster. In the healthy area, the cellular network can normally establish a connection with the D2D network, including WET. In the disaster area, it is assumed that the cellular network fails to connect with the D2D network, leading to disconnection between D2D pair due to the impact of disaster and power outage. We propose a recovery process of the D2D communication in disaster area via the connection between two cells. It is assumed that the BS and the UE in the healthy area belong to different service providers. Thus, this UE needs to pay prices for two services: i) being allowed to cause interference to the main cellular network and ii) purchasing energy. These 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* and *energy trading*, which can be formulated as two *Stackelberg* games and their *Stackelberg* equilibrium's will be derived to find the decisions for interference pricing and energy trading.

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II. System Model

We consider a system model 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, there are one EH relay[1], 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 the 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, '*harvest-then-transmit*' 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 time period of θT $(0 < \theta < 1)$, the BS of the healthy area provides energy to $\mathcal{U}_H$ to support the connection with the disaster area. In the second time period $(1-\theta)T$, $\mathcal{U}_H$ establishes the communications with $\mathcal{U}_D$ via the EH relay, which also cause the interference to the BS. In addition, we split the time period $(1-\theta)T$ into two sub-phases: in the first period $(1-\theta)T/2$, $\mathcal{U}_H$ transmits information and power to the EH relay $\mathcal{R}$, and then, the EH relay decode the information and forward to $\mathcal{U}_D$ by using harvested power in the remaining time period. We assume that 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

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

where $P_{\mathcal{B}}$ is the transmit power at the BS, and $\eta \in (0, 1]$ denotes the EH efficiency of $\mathcal{U}_H$. Without loss of generality, it is assumed that $\eta = 1$. This harvested energy E_s is consumed during the time period $(1-\theta)/2$. 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 at EH relay's antenna. 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

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

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

$$R_{sr} = \frac{1-\theta}{2} \log\left(1 + \frac{\rho P_s |h_{sr}|^2}{\rho\sigma_{ra}^2 + \sigma_{rp}^2}\right). \tag{5}$$

The harvested power at the EH relay is expressed as

$$P_r = \xi P_s |h_{sr}|^2 (1-\rho), \tag{6}$$

[1]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.

where $\xi \in (0, 1]$ denotes the energy conversion efficiency of the EH relay. Without loss of generality, it is assumed that $\xi = 1$. 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

$$y_d = \sqrt{P_r} h_{rd} \bar{x} + n_d, \tag{7}$$

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

$$R_{rd} = \frac{1-\theta}{2} \log\left(1 + \frac{\xi P_s |h_{sr}|^2 |h_{rd}|^2 (1-\rho)}{\sigma_d^2}\right). \tag{8}$$

From (5) and (8), the achievable rate at $\mathcal{U}_D$ can be written as

$$R = \min\{R_{sr}, R_{rd}\}. \tag{9}$$

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

$$I_{\mathcal{B}} = P_s|h|^2. \tag{10}$$

III. Disaster Management for D2D Cooperative 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 which results in a fact that $\mathcal{U}_H$ will pay two prices to support the wireless energy transfer and for interference introduced to the BS. The two processes, *energy trading* and *interference pricing* are formulated as a *Stackelberg* game, where their *Stackelberg* equilibrium will be derived in closed-form solutions.

A. Stackelberg *Game Formulation*

Let us consider two games:

1) 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 allocation and the optimal PS ratio to maximize its own utility. In the following, we formulate the utility functions of the leader and the follower:

1) **Leader Level**: The BS announces a price for the interference 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

$$\begin{aligned} &\max_{\lambda_2 \geq 0} \; U_{\mathcal{B},2}(\lambda_2) = \lambda_2(1-\theta)P_s|h|^2, \\ &s.t. \; P_s|h|^2 \leq I_{th}. \end{aligned} \tag{11}$$

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

$$\begin{aligned} &\max_{\rho, P_s} \; U_{\mathcal{U}_H}^{(2)}(\rho, P_s) = \mu R - \lambda_2(1-\theta)I_{\mathcal{B}}, \\ &s.t. \; 0 \leq \rho \leq 1, \; 0 \leq P_s \leq P_T. \end{aligned} \tag{12}$$

The *Stackelberg* game for the interference pricing are formulated by combining both problems (11) and (12).

2) Energy trading game: In this game, we formulate $\mathcal{U}_H$ as the leader who pays a price λ_1 on per unit of energy harvested from the RF signals radiated by the BS, referred as to 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 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

$$\max_{\theta,\rho,\lambda_1,P_s} U_{\mathcal{U}_H}^{(1)}(\theta,\rho,\lambda_1,P_s)=\mu R-\lambda_1\theta P_{\mathcal{B}}|g|^2,$$
$$s.t.\ 0\le\theta\le 1,\ 0\le\rho\le 1,\ \lambda\ge 0,\ 0\le P_s\le P_T. \tag{13}$$

2) **Follower Level**: The BS acts as the follower role who sells its energy service to $\mathcal{U}_H$ to support the connection between the healthy area and the disaster area, which 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

$$\max_{P_{\mathcal{B}}\ge 0} U_{\mathcal{B},1}(P_{\mathcal{B}},\lambda_1,\theta)=\theta(\lambda_1 P_{\mathcal{B}}|g|^2-\mathcal{F}(P_{\mathcal{B}})), \tag{14}$$

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[2] for the cost function of the PBs.

$$\mathcal{F}(x)=Ax^2+Bx \tag{15}$$

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

The *Stackelberg* game for the energy trading are formulated by combining both problems (13) and (14). 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* equilibriums 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 $P_{\mathcal{B}}$. It is observed that for given λ_1 and θ, the utility (14) is obviously a quadratic function with respect to $P_{\mathcal{B}}$ and the constraint is linear, which indicates that (14) 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 (14) can be achieved as

$$P_{\mathcal{B}}^{\text{opt}}=\left[\frac{\lambda_1|g|^2-B}{2A}\right]^+, \tag{16}$$

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

Proof: The proof of this *theorem* can be derived by taking into consideration a fact that the objective function to the problem (14) is a concave function with respect to $P_{\mathcal{B}}$. By equalling the first derivatives of (14) to zero, one can arrive at (16). ∎

Next, we derive the optimal solution of the PS ratio ρ, which can be achieved from (9). The first term of (9) is a monotonically increasing function in terms of ρ, whereas the second term of (9) is a monotonically decreasing over ρ. Hence, in order to obtain the optimal solution ρ^{opt}, both terms satisfy the following equation

$$\frac{\rho P_s|h_{sr}|^2}{\rho\sigma_{ra}^2+\sigma_{rp}^2}=\frac{\xi P_s|h_{sr}|^2|h_{rd}|^2(1-\rho)}{\sigma_d^2}. \tag{17}$$

Thus, the optimal PS ratio ρ^{opt} can be written as (18) on the top of next page.

Thus, we rewrite the (13) by substituting ρ^{opt} and $P_s^{\text{opt}}=P_T$ as

$$\max_{\theta,\lambda_1} U_{\mathcal{U}_H}^{(1)}(\theta,\lambda_1)=a\log\left[1+C\left(\lambda_1 X-2Y\right)\right]$$
$$-\lambda_1^2X+2\lambda_1 Y,$$
$$s.t.\ 0<\theta<1,\ \lambda_1\ge 0, \tag{19}$$

where

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

To proceed, we need to solve the problem (19), 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

$$\lambda_1^{\text{opt}}=\frac{-2(1-3CY)+\sqrt{4(1-CY)^2+8aC^2X}}{4CX}. \tag{20}$$

Proof: The proof of this *theorem* is omitted here due to space limitation. ∎

We have already achieved the optimal energy price λ_1^{opt} for a given θ. Substituting λ_1^{opt} into the problem (19), we have the following optimization problem with respect to θ:

$$\max_{\theta}\ U_{\mathcal{U}_H}^{(1)}(\theta,\lambda_1^{\text{opt}}),\ s.t.\ 0<\theta<1. \tag{21}$$

The problem (21) can be efficiently solved via 1D search. The optimal solution to (21), denoted by θ^{opt}, can be achieved by

$$\theta^{\text{opt}}=\arg\max_{\theta\in(0,1)}\ U_{\mathcal{U}_H}^{(1)}(\theta,\lambda_1^{\text{opt}}). \tag{22}$$

This has completed the derivation of the *Stackelberg* equilibrium $(P_{\mathcal{B}}^{\text{opt}},\lambda_1^{\text{opt}},\theta^{\text{opt}})$ for the formulated energy trading based *Stackelberg* game, which have been shown in (16), (20) and (22).

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 (12) with ρ^{opt} as follows:

$$\max_{P_s} U_{\mathcal{U}_H}^{(2)}(P_s)=a\log(1+DP_s)-\lambda_2 EP_s,$$
$$s.t.\ 0\le P_s\le P_T. \tag{23}$$

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 (23) is a convex optimization problem with respect to P_s. Thus, the optimal solution to (23) can be achieved by taking its first derivatives and equalling to zero

[2]Note that the quadratic function shown in (15) has been applied in the energy market to model the energy cost [14].

$$\rho^{\text{opt}} = \frac{-[\sigma_d^2 - \xi|h_{rd}|^2(\sigma_{rp}^2 - \sigma_{ra}^2)] + \sqrt{[\sigma_d^2 - \xi|h_{rd}|^2(\sigma_{rp}^2 - \sigma_{ra}^2)]^2 + 4\xi^2|h_{rd}|^4\sigma_{ra}^2\sigma_{rp}^2}}{2\xi|h_{rd}|^2\sigma_{ra}^2} \tag{18}$$

as follows:

$$\frac{\partial U_{\mathcal{U}_H}^{(2)}}{\partial P_s} = \frac{aD}{1+DP_s} - \lambda_2 E = 0, \quad \Rightarrow P_s = \left[\frac{a}{\lambda_2 E} - \frac{1}{D}\right]_0^{P_T}, \tag{24}$$

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

Now we focus on the interference pricing decision for (11), particularly, the optimal interference price λ_2 can be achieved via one-dimensional (1D) search. In order to illustrate more insights into the interference interaction between the BS and $\mathcal{U}_H$, we consider the following the equations regarding the lower and upper bound of λ_2:

$$\lambda_2^{\text{up}} = \frac{aD}{E}, \ \lambda_2^{\text{low}} = \frac{a}{(P_T + \frac{1}{D})E}. \tag{25}$$

It is easily verified that (25) holds when either $P_s = 0$ or P_T. Now, the optimal solution to interference price λ_2 is considered, 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. Formally, we summarize this interference pricing algorithm at the interval $[\lambda_2^{\text{low}} \ \lambda_2^{\text{up}}]$ in **Algorithm** 1.

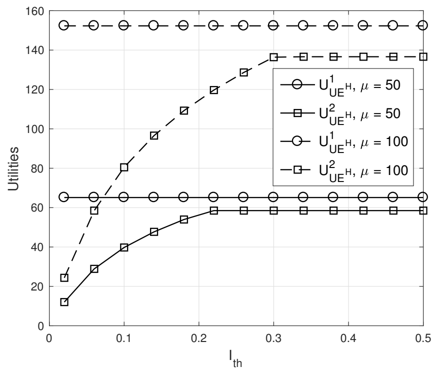
Algorithm 1: Interference pricing algorithm

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 $P_{\mathcal{B}}$ 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** $\lambda_2^{\text{opt}} \leftarrow \arg\max_{\lambda_2} U_{\mathcal{B},2}(\lambda_2)$.

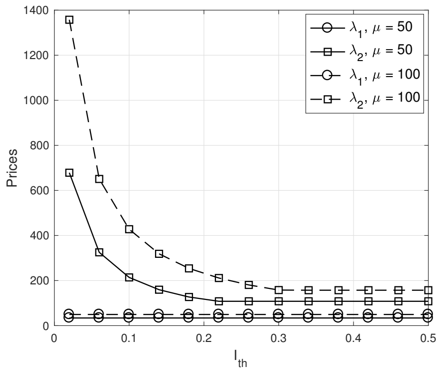
For the interference pricing game, we have the following descriptions:

1) When $0 \le \lambda_2 \le \lambda_2^{\text{low}}$, $\mathcal{U}_H$ transmits its maximum transmit 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 disappear, since $U_{\mathcal{B},2}(\lambda_2) = 0$.

Remark 1: When $P_s = P_T$, in order to satisfy the maximum utility function in (13), the interference constraint should be satisfied as well, thus, the closed-form interference price can



(a) Utility versus target interference I_{th}.



(b) Prices versus target interference I_{th}.

Fig. 1: The comparison between energy trading and interference pricing with target interference I_{th}.

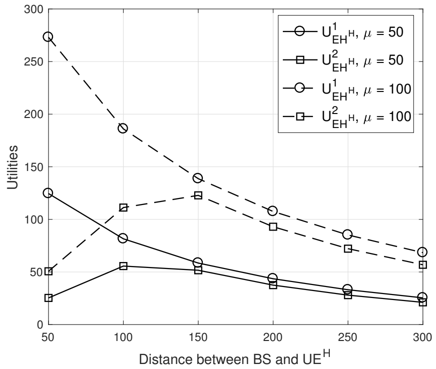
be expressed as follows

$$\lambda_2^{\text{opt}} = \frac{a}{(\min\{P_T, \frac{I_{th}h}{|h|^2}\} + \frac{1}{D})E}. \tag{26}$$

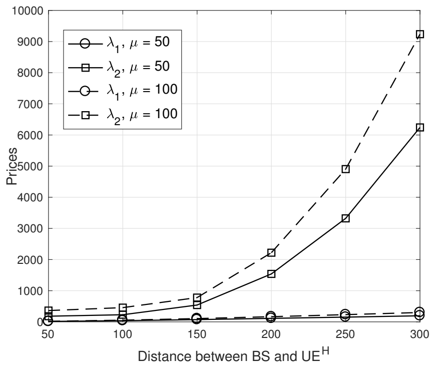
IV. Simulation Results

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 EH relay, and EH relay 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 of two proposed games (i.e., utility function and the price) versus the target interference I_{th} in Figure 1. From this results, it is observed that the utility function $U_{\mathcal{U}_H}^{(1)}$ and the energy price λ_1 are constant as the target interference I_{th} increases. In Figure 1(a),



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



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

Fig. 2: The comparison between energy trading and interference pricing with distance between BS and $\mathcal{U}_H$.

the utility function $U^{(2)}_{\mathcal{U}_H}$ increases with I_{th} at the beginning of interference regimes, and levels off after a certain value of I_{th}. Whereas in Figure 1(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 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 2 shows that the utility function and the price against the distance between the BS and $\mathcal{U}_H$ (i.e., d_1). From Figure 2(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 2(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 $[\lambda_2^{\text{low}}\ \lambda_2^{\text{up}}]$, 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 located at $(0\ \lambda_2^{\text{low}}]$, which means that $U^{(2)}_{\mathcal{U}_H}$ will decrease as d_1 increases. In addition, $U^{(1)}_{\mathcal{U}_H}$ has better profit performance gains than $U^{(2)}_{\mathcal{U}_H}$, and the energy trading scheme has more financial saving than the interference pricing scheme.

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, the UE needs to pay prices to the BS as incentives for two reasons: causing interference and energy transfer service. These two processes can be formulated as two *Stackelberg* games: interference pricing and energy trading games. We derived the *Stackelberg* equilibriums for both proposed games in terms of closed-form solutions. Finally, numerical results have been provided to validate our proposed schemes, where the energy trading scheme has a better performance than the interference pricing scheme in terms of assistance efficiency for disaster area.

VI. Acknowledgement

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References

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

[2] X. Lin, J. G. Andrews, A. Ghosh, and R. Ratasuk, "An overview of 3GPP device-to-device proximity services," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 40–48, Apr. 2014.

[3] 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.

[4] K. Ali, H. X. Nguyen, Q. T. Vien, and P. Shah, "Disaster management communication networks: Challenges and architecture design," in *in Proc. Pervasive Computing and Communication Workshops (PerCom Workshops)*, pp. 537–542, Mar. 2015.

[5] K. Ali, H. X. Nguyen, P. Shah, Q. T. Vien, and N. Bhuvanasundaram, "Architecture for public safety network using D2D communication," in *in Proc. IEEE WCNC, Doha, Qatar*, pp. 1–6, Apr. 2016.

[6] S. Bi, Y. Zeng, and R. Zhang, "Wireless powered communication networks: an overview," *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 10–18, Apr. 2016.

[7] H. Ju and R. Zhang, "Throughput maximization in wireless powered communication networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 418–428, Jan. 2014.

[8] H. Chen, X. Zhou, Y. Li, P. Wang, and B. Vucetic, "Wireless-powered cooperative communications via a hybrid relay," in *Proc. IEEE Information Theory Workshop (ITW)*, pp. 666–670, Nov. 2014.

[9] H. Chen, Y. Li, J. L. Rebelatto, B. F. Ucha-Filho, and B. Vucetic, "Harvest-then-cooperate: Wireless-powered cooperative communications," *IEEE Trans. Signal Process.*, vol. 63, no. 7, pp. 1700–1711, Apr. 2015.

[10] Z. Ding, S. M. Perlaza, I. Esnaola, and H. V. Poor, "Power allocation strategies in energy harvesting wireless cooperative networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 846–860, Feb. 2014.

[11] L. Hu, C. Zhang, and Z. Ding, "Dynamic power splitting policies for af relay networks with wireless energy harvesting," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, pp. 2035–2039, June 2015.

[12] Z. Chu, M. Johnston, and S. L. Goff, "SWIPT for wireless cooperative networks," *Electron. Lett.*, vol. 51, no. 6, pp. 536–538, 2015.

[13] Y. Liu, R. Wang, and Z. Han, "Interference-constrained pricing for D2D networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 1, pp. 475–486, Jan. 2017.

[14] A. H. Mohsenian-Rad, V. W. S. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid," *IEEE Trans. Smart Grid*, vol. 1, no. 3, pp. 320–331, Dec. 2010.