Optimal Pricing for Interference Control in Time-reversal Device-to-Device Uplinks

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***Abstract*—The Device-to-Device (D2D) communication is a promising technique to empower local wireless communications. However, without proper management it may generate interference to the existing network and degrade the overall performance. By treating each multipath as a virtual antenna, time-reversal (TR) signal transmission in a rich-scattering environment produces a spatial-temporal resonance which efficiently suppresses the inter-user interference (IUI) while boosting the signal power at the target receiver. In this work, we design a TR-based D2D hybrid network, where both primary users (PUs) and D2D pairs share the same time-frequency resources and use TR focusing effect to combat interference. With the purpose of enhancing D2D performance while providing a performance protection to PUs, an efficient optimal pricing algorithm is proposed to dynamically control interference through TR focusing strength control.**

***Index Terms*—Time reversal, Device-to-Device communication, power control, optimal pricing, QoS protection.**

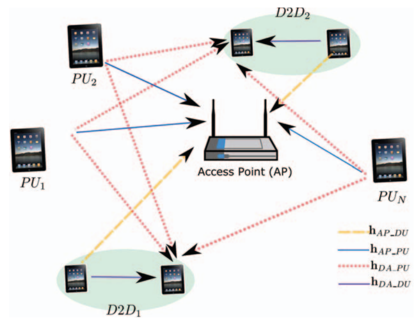

Fig. 1: The TR-based D2D hybrid uplink network.

I. Introduction

To meet the growing demand for higher data rate wireless access, Device-to-Device (D2D) communication as a new reliable, scalable and green paradigm has been proposed. Aiming to revolutionize the conventional communication method, D2D communication is defined as the direct communication between two devices without or with limited access point (AP) involvement, and operates as an underlay in the traditional network [1]–[3].

By utilizing proximity, D2D communication becomes a promising technique in that it brings in advantages such as higher network spectral efficiency, energy efficiency and flexibility. However, it may also introduce interference to the existing network and significantly degrade its performance without proper interference management. As a part of resource control, power control is a essential method to tackle interference in D2D networks. Power control over D2D links was firstly proposed to increase the network throughput in [3], [4] by considering the distance between users in a D2D pair and introducing a fixed booster factor and a backoff factor. Aiming at improving the performance of D2D pairs while maintaining a desired performance of network, an interference-aware resource allocation scheme was designed using the power measurement feedback from D2D pairs during uplink [5]. In [6], the resource allocation was considered under the assumption that the cellular base stations are capable of selecting the best resource allocation scheme among non-orthogonal sharing, orthogonal sharing and relaying mode for both PUs and D2D connections. Moreover, a sequential second price auction game was designed in [7] to allocate each spectrum resources to improve D2D performance in downlinks. A scheme that reuses the underutilized uplink spectrums and avoids near-far interference to D2D transmissions was proposed in [8]. Recently, a distributed resource allocation algorithm to improve the D2D throughput in an OFDM system was proposed in [9].

The time reversal (TR) based signal transmission technique treats each path of a multi-path channel in a rich scattering environment as a distributed virtual antenna. It creates a high-resolution spatial-temporal resonance, commonly known as focusing effect, via simply transmitting back a time-reversed conjugate version of the channel impulse response (CIR) [10]–[13]. As a result, TR effectively eliminates the inter-user interference (IUI) in a single-carrier multiuser communication networks. Meanwhile the signal-to-noise ratio (SNR) of the received signal is boosted due to the inherent nature of TR that fully collects energy of multi-path propagation.

In the aforementioned analysis of D2D communication networks, the existing models were built upon a multi-carrier system where primary users in the existing network are assigned with orthogonal channels shared with at most one D2D pair. Inspired by the study in [10]–[13], we propose a novel D2D communication framework incorporating the TR technique, where all D2D pairs and PUs transmit within the same frequency band and time slot. Together with the rich-scattering environment, TR technique generates a unique spatial-temporal resonance, which is a natural way that suppresses the IUIs and inter-tier interference (ITI) between D2D pairs and PUs (or access points (APs)). In the proposed TR-based hybrid D2D networks, the interference is managed by the means of TR focusing strength control.

The rest of this paper is organized as follows. The system model for TR-based D2D hybrid network is introduced in Section II, and in Section III the focusing strength optimization problem is analyzed. In Section IV, an optimal pricing algorithm is designed to simplify and solve the D2D optimization problem. The system performance is evaluated in Section V with conclusions in Section VI.

II. System Model

According to the TR uplink diagram in [13], the received signal at the AP side is the combination of all signals coming from both PUs and D2D users (DUs) that can be written as

$$\mathbf{s}^{AP}=\sum_{k=1}^{N}\sqrt{P_{PU}^{(k)}}\mathbf{H}_{AP\_PU}^{(k)}\mathbf{x}_{PU}^{(k)}+\sum_{m=1}^{M}\sqrt{P_{DU}^{(m)}}\mathbf{H}_{AP\_DU}^{(m)}\mathbf{x}_{DU}^{(m)}+\mathbf{n}, \quad (1)$$

where N is the number of primary users (PUs), M is the number of D2D pairs, $P_{PU}^{(k)}$ is the transmit power of the k^{th} PU with

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transmitted symbol $\mathbf{x}_{PU}^{(k)}$, $P_{DU}^{(m)}$ is the transmit power of the m^{th} D2D transmitter, and $\mathbf{n}$ represents the white Gaussian noise at the AP with zero mean and variance σ^2. Moreover, $\mathbf{H}_{AP\_PU}^{(k)}$ is the Toeplitz matrix formed by the channel from the k^{th} PU to the AP, similar to $\mathbf{H}_{AP\_DU}^{(m)}$.

The received signal $\mathbf{s}^{AP}$ in (1) will pass through a TR filter bank $\{\mathbf{g}_{PU_i},\ \forall\ i\}$ to extract information and suppress interference. Here, the TR signature is defined as $g_{PU_i}[k] = h_{AP\_PU}^{(i)*}[L-1-k]/\sqrt{\sum_{l=0}^{L-1}|h_{AP\_PU}^{(i)}[l]|^2}$, where $*$ denotes the conjugate, $h_{AP\_PU}^{(i)}$ is the channel delay profile with length L. The received signal at the m^{th} D2D receiver is similar to that one at AP, and due to the limited space details are omitted.

III. Problem Formulation

Based upon the analysis, the system uplink SINR for the i^{th} PU and the m^{th} D2D pair are given in (2) and (3). In (2), $\mathbf{R}_{AP\_PU_j} = \mathbf{H}_{AP\_PU}^{(j)H}\mathbf{H}_{AP\_PU}^{(j)}$, $\mathbf{R}_{AP\_PU_i}^{(0)} = \mathbf{H}_{AP\_PU_L}^{(i)H}\mathbf{H}_{AP\_PU_L}^{(i)}$ with upscript H denoting Hermitian and $\mathbf{H}_{AP\_PU_L}^{(i)}$ being the L^{th} row of toeplitz matrix $\mathbf{H}_{AP\_PU}^{(i)}$, $\hat{\mathbf{R}}_{AP\_PU_i} = \mathbf{H}_{AP\_PU}^{(i)H}\mathbf{H}_{AP\_PU}^{(i)} - \mathbf{R}_{AP\_PU_i}^{(0)}$. Other channel correlation matrices $\mathbf{R}_{AP\_DU_k}$ etc. are defined similarly. Moreover, $P_{PU}^{(i)}\mathbf{g}_{PU_i}^H\hat{\mathbf{R}}_{AP\_PU_i}\mathbf{g}_{PU_i}$, $\sum_{j\neq i}P_{PU}^{(j)}\mathbf{g}_{PU_j}^H\mathbf{R}_{AP\_PU_j}\mathbf{g}_{PU_j}$ and $\sum P_{DU}^{(k)}\mathbf{g}_{DU_k}^H\mathbf{R}_{AP\_DU_k}\mathbf{g}_{DU_k}$, represent ISI, IUI and ITI respectively. For simplicity, we assume the variances of channel noise are all the same at different receivers.

We introduce matrix $\mathbf{D}$ as a nonnegative diagonal matrix with $[\mathbf{D}]_{ii} = 1/\mathbf{g}_{PU_i}^H\mathbf{R}_{AP\_PU_i}^{(0)}\mathbf{g}_{PU_i}$. The inter-tier interference matrix $\mathbf{A}$ representing the interference caused by D2D users is defined as $[\mathbf{A}]_{ij} = \mathbf{g}_{PU_j}^H\mathbf{R}_{AP\_DU_i}\mathbf{g}_{PU_j}$. The crosstalk matrix $\mathbf{\Phi}$ for the uplink primary users whose elements correspond to the ISI and IUI terms as $[\mathbf{\Phi}]_{ij} = \mathbf{g}_{PU_j}^H\mathbf{R}_{AP\_PU_i}\mathbf{g}_{PU_j}$ if $i \neq j$ and $\mathbf{g}_{PU_j}^H\hat{\mathbf{R}}_{AP\_PU_j}\mathbf{g}_{PU_j}$, otherwise. Then the uplink SINR for PU i in (2) can be rewritten as

$$\gamma_i^{PU} = SINR_{PU_i}^{UL} = \frac{P_{PU}^{(i)}}{\mathbf{D}_{ii}(\mathbf{\Phi}_i^T\mathbf{P}_{PU} + \mathbf{A}_i^T\mathbf{P}_{DU} + \sigma^2)}. \quad (4)$$

Similarly, for each D2D pair we can define $\tilde{\mathbf{D}}$ as $\left[\tilde{\mathbf{D}}\right]_{ii} = 1/\mathbf{g}_{DU_i}^H\mathbf{R}_{DA_i\_DU_i}^{(0)}\mathbf{g}_{DU_i}$, inter-tier interference matrix $\tilde{\mathbf{A}}$ as $\left[\tilde{\mathbf{A}}\right]_{ij} = \mathbf{g}_{DU_j}^H\mathbf{R}_{DA_j\_PU_i}\mathbf{g}_{DU_j}$, and crosstalk matrix $\tilde{\mathbf{\Phi}}$ as $[\tilde{\mathbf{\Phi}}]_{ij} = \mathbf{g}_{PU_j}^H\mathbf{R}_{DA_j\_DU_i}\mathbf{g}_{PU_j}$ if $i \neq j$ and $[\tilde{\mathbf{\Phi}}]_{ij} = \mathbf{g}_{PU_j}^H\hat{\mathbf{R}}_{DA_j\_DU_j}\mathbf{g}_{PU_j}$, otherwise. The uplink SINR for the m^{th} D2D pair in (3) can be rewritten as

$$\gamma_m^{DU} = SINR_{DU_m}^{UL} = \frac{P_{DU}^{(m)}}{\tilde{\mathbf{D}}_{mm}(\tilde{\mathbf{\Phi}}_m^T\mathbf{P}_{DU} + \tilde{\mathbf{A}}_m^T\mathbf{P}_{PU} + \sigma_m^2)}. \quad (5)$$

In order to jointly optimize the resources utilized by PUs and DUs, we formulate our problem as a D2D throughput maximization problem with a service protection to the PUs. Given the individual PU power constraints $\mathbf{P}_{max}^{PU}$, D2D power constraints $\mathbf{P}_{max}^{DU}$ and SINR threshold for PUs γ_{PU}^{th}, the maximization problem can be written as

$$\begin{aligned} \max_{\mathbf{P}_{PU},\ \mathbf{P}_{DU}} \quad & \sum_{m=1}^{M}\alpha_m log_2(1+\gamma_m^{DU}) \\ \text{s.t.} \quad & \mathbf{P}_{PU} \succeq \mathbf{0}, \quad \mathbf{P}_{PU} \preceq \mathbf{P}_{max}^{PU}, \quad \gamma_i^{PU} \succeq \gamma_{PU}^{th}, \forall i \\ & \mathbf{P}_{DU} \succeq \mathbf{0}, \quad \mathbf{P}_{DU} \preceq \mathbf{P}_{max}^{DU}. \end{aligned} \quad (6)$$

where $\{\alpha_m\}_{m=1}^M$ denotes the weighted factor in sum rate.

A. Two-stage Optimization I: Primary Feasibility Problem

The optimization problem in (6) can be decomposed into a two stage problem. The first subproblems is a feasibility problem for PUs in uplink where we want to maximize the minimum among all the received SINR γ_i^{PU}, i.e.,

$$\begin{aligned} \max_{\mathbf{P}_{PU}} \quad & \min_{i=1,\cdots,N} \quad \gamma_i^{PU} \\ \text{s.t.} \quad & \mathbf{P}_{PU} \succeq \mathbf{0}, \quad \mathbf{P}_{PU} \preceq \mathbf{P}_{max}^{PU}, \end{aligned} \quad (7)$$

Let us denote the γ_{PU}^* as the optimal value towards the problem in (7) with optimal variable $\mathbf{P}_{PU}^*$. Then if $\gamma_{PU}^* \leq \gamma_{PU}^{th}$, the optimal value of problem in (6) is 0 and the ultimate optimal powers are $\mathbf{P}_{PU}^*$ and $\mathbf{P}_{DU}^* = \mathbf{0}$. Otherwise, the threshold SINR for PUs is achievable, and the first subproblem is feasible. It is easy to show that in the solution to (7) all users will have the same SINRs. Based on (4) and supposing $\mathbf{P}_{DU}$ is known and fixed, the corresponding feasible PU power allocation vector that achieves γ_{PU}^{th} for all PUs is a function of $\mathbf{P}_{DU}$ as $\mathbf{P}_{PU} = \gamma_{PU}^{th}(\mathbf{I} - \gamma_{PU}^{th}\mathbf{D\Phi}^T)^{-1}\mathbf{D}(\mathbf{A}^T\mathbf{P}_{DU} + \boldsymbol{\sigma})$.

Let $\mathbf{P}_o$ denote the power vector for PUs to achieve γ_{PU}^{th} without considering D2D pairs, then $\mathbf{P}_o = \gamma_{PU}^{th}(\mathbf{I} - \gamma_{PU}^{th}\mathbf{D\Phi}^T)^{-1}\mathbf{D}\boldsymbol{\sigma}$. Matrix $\mathbf{F}$ represents the power-boost matrix introduced by the interference of D2D pairs, $\mathbf{F} = \gamma_{PU}^{th}(\mathbf{I} - \gamma_{PU}^{th}\mathbf{D\Phi}^T)^{-1}\mathbf{DA}^T$. Hence, the optimal power assignment for PUs in (6) is decoupled into two parts as $\mathbf{P}_{PU}^* = \mathbf{P}_o + \mathbf{F}\mathbf{P}_{DU}^*$.

B. Two-stage Optimization II: D2D Throughput Maximization

Once the first subproblems is feasible, we can obtain a meaningful pair of $\mathbf{P}_o$ and $\mathbf{F}$ to address the second-stage problem that is defined a D2D throughput maximization as

$$\begin{aligned} \max_{\mathbf{P}_{DU}} \quad & \sum_{m=1}^{M}\alpha_m log_2(1+\gamma_m^{DU}) \\ \text{s.t.} \quad & \mathbf{P}_{DU} \succeq \mathbf{0}, \quad \mathbf{P}_{DU} \preceq \mathbf{P}_{max}^{DU}, \\ & \mathbf{P}_o + \mathbf{F}\mathbf{P}_{DU} \succeq \mathbf{0}, \quad \mathbf{P}_o + \mathbf{F}\mathbf{P}_{DU} \preceq \mathbf{P}_{max}^{PU}. \end{aligned} \quad (8)$$

In (8), the objective function is not concave with many inequality constraints which make the searching space for optimal $\mathbf{P}_{DU}$ too complicated. To address the nonconvexity, we convert the problem in (8) into an equivalent D2D SINR allocation problem. An efficient algorithm is proposed in Section IV that borrows the principle of the stackelberg game to relax the problem into an optimal pricing problem.

IV. Optimal Pricing for Joint Power Control in Heterogeneous Uplinks

In the proposed algorithm, the AP acts as the leader that decides the price. Each D2D pair independently chooses a best response that maximizes their utilities with the price from AP. The mathematical formulation is described as follows.

In the leader's problem, AP wants to find a price c that maximizes his utility, which is the revenue from followers that depends on both AP's price and D2D users' choices:

$$\begin{aligned} \max_{c} \quad & u^{AP}(c,\ \boldsymbol{\gamma}^{DU}) = c\sum_{k=1}^{M}\gamma_k^{DU} \\ \text{s.t.} \quad & \rho(diag\{\boldsymbol{\gamma}^{DU}\}\tilde{\mathbf{D}}\hat{\tilde{\mathbf{\Phi}}}^T) < 1, \quad \mathbf{P}_o + \mathbf{F}\mathbf{P}_{DU}(\boldsymbol{\gamma}^{DU}) \succeq \mathbf{0}, \\ & \mathbf{P}_{DU}(\boldsymbol{\gamma}^{DU}) \preceq \mathbf{P}_{max}^{DU}, \quad \mathbf{P}_o + \mathbf{F}\mathbf{P}_{DU}(\boldsymbol{\gamma}^{DU}) \preceq \mathbf{P}_{max}^{PU}, \end{aligned} \quad (9)$$

$$SINR_{PU_i}^{UL} = \frac{P_{PU}^{(i)}\mathbf{g}_{PU_i}^H\mathbf{R}_{AP\_PU_i}^{(0)}\mathbf{g}_{PU_i}}{P_{PU}^{(i)}\mathbf{g}_{PU_i}^H\hat{\mathbf{R}}_{AP\_PU_i}\mathbf{g}_{PU_i} + \sum_{j\neq i} P_{PU}^{(j)}\mathbf{g}_{PU_j}^H\mathbf{R}_{AP\_PU_j}\mathbf{g}_{PU_j} + \sum_{k=1}^{M} P_{DU}^{(k)}\mathbf{g}_{DU_k}^H\mathbf{R}_{AP\_DU_k}\mathbf{g}_{DU_k} + \sigma^2}, \quad (2)$$

$$SINR_{DU_m}^{UL} = \frac{P_{DU}^{(m)}\mathbf{g}_{DU_m}^H\mathbf{R}_{DA_m\_DU_m}^{(0)}\mathbf{g}_{DU_m}}{P_{DU}^{(m)}\mathbf{g}_{DU_m}^H\hat{\mathbf{R}}_{DA_m\_DU_m}\mathbf{g}_{DU_m} + \sum_{k\neq m} P_{DU}^{(k)}\mathbf{g}_{DU_k}^H\mathbf{R}_{DA_m\_DU_k}\mathbf{g}_{DU_k} + \sum_{i=1}^{N} P_{PU}^{(i)}\mathbf{g}_{PU_i}^H\mathbf{R}_{DA_m\_PU_i}\mathbf{g}_{PU_i} + \sigma^2}. \quad (3)$$

where $\rho(\cdot)$ denotes the spectral radius. The feasibility condition $\mathbf{P}_{DU} \succeq \mathbf{0}$ in (8) is equivalent to $\rho(diag\{\boldsymbol{\gamma}^{DU}\}\tilde{\mathbf{D}}\hat{\boldsymbol{\Phi}}^T) < 1$.

With the price c from AP, each D2D pair forms a noncooperative best response problem as

$$\max_{\gamma_k^{DU}} \ u_k^{D2D}(\gamma_k^{DU}) = \alpha_k log_2(1+\gamma_k^{DU}) - c\gamma_k^{DU} \quad \text{s.t.} \ \gamma_k^{DU} \geq 0. \quad (10)$$

In this price optimization problem, the total gain is obtained as $U_{gain}(c,\ \boldsymbol{\gamma}^{DU}) = \sum_{m=1}^{M} \alpha_m log_2(1+\gamma_m^{DU})$. Even though the optimal pricing problem has the same objective as the one in (8), due to reduction of the dimension of searching space by utilizing a scalar price c as the variable, the optimal value of the total throughput is lower than the optimum obtained in (8) in some cases.

A. Best Strategies for D2D Users in the Followers Game

In order to find the best strategy for both AP and D2D users, we apply the backward induction approach in game theory to our problem. Given the price AP select, each D2D pair independently chooses their best response $\gamma_m^{DU^*}(c)$ that maximizes his utility in (10). Because of the convexity of (10), the optimal point can be easily obtained through KKT conditions as

$$\gamma_m^{DU^*}(c) = \left(\frac{\alpha_m}{c \times ln2} - 1\right)^+, \quad (11)$$

where $(X)^+ = max\{0, X\}$. The (11) is a typical waterfilling solution. When $c < \frac{\alpha_m}{ln2}$, $\gamma_m^{DU^*}(c)$ is a decreasing and convex function in c, and $\gamma_m^{DU^*}(c) = 0$ for any $c \geq \frac{\alpha_m}{ln2}$.

B. Best Pricing Strategy in the Leader Game

Substituting the best response function in (11) into the utility function of AP in (9), we have our upper problem become

$$\max_{c} \ u^{AP}(c) = \sum_{k=1}^{M} \left(\frac{\alpha_k}{ln2} - c\right)^+ \quad \text{s.t.} \ \text{same constraints in}(9). \quad (12)$$

The task of AP is to find the optimal price c^* such that his utility in (12) is maximized w.r.t the constraints. Although the upper problem is still not a convex optimization problem, a low-complex and efficient algorithm can be applied to find the optimal c^*.

Proposition 1: The utility function $u^{AP}(c)$ is a piecewise affine, continuous and decreasing function in c.

Proposition 2: The D2D best response power allocation function $P_{DU_m}(\boldsymbol{\gamma}^{DU^*}(c))m$ and the best response SINR $\gamma_m^{DU^*}(c)$ are continuous and nonincreasing in c.

Proposition 3: The spectral radius $\rho(diag\{\boldsymbol{\gamma}^{DU^*}(c)\}\tilde{\mathbf{D}}\hat{\boldsymbol{\Phi}}^T)$ is a monotonically nonincreasing function in c.

Algorithm 1 Optimal Price Search

Step 1 Solve the feasibility problem in (7). Check if the solutions $\gamma_{max} \leq \gamma^{th}$, if so $\mathbf{P}_{PU}^* \leftarrow \mathbf{P}_{PU}$, $\mathbf{P}_{DU}^* \leftarrow \mathbf{0}$ and stop. Otherwise, go to Step 2.

Step 2 Calculate $\mathbf{P}_o$ and $\mathbf{F}$, set $count = 0$, and obtain the searching interval $[c_{min}, c_{max}]$ through the *Feasible Price Interval Search Algorithm*. Go to Step 3.

Step 3 Within the interval obtained in Step 2: set $c = \frac{c_{max}-c_{min}}{2}$, and check if c is feasible, namely $\rho(diag\{\boldsymbol{\gamma}^{DU^*}(c)\}\tilde{\mathbf{D}}\hat{\boldsymbol{\Phi}}^T) < 1$, $\mathbf{P}_{DU}(\boldsymbol{\gamma}^{DU^*}(c)) < \mathbf{P}_{max}^{DU}$ and $\mathbf{P}_{PU}^*(c) < \mathbf{P}_{max}^{PU}$. If so, $c_{max} \leftarrow c$, otherwise $c_{min} \leftarrow c$. Go to Step 4.

Step 4 If $c_{max} - c_{min} \geq \epsilon$ and $count \leq MaxIter$, repeat Step 3. Otherwise, $c^* \leftarrow c$.

Algorithm 2 Feasible Price Interval Search

Initial Define $v_m = \frac{\alpha_m}{ln2}$. $\mathbf{O} = [v^{(1)}, \ \cdots, \ v^{(\tilde{M})}]$ is a ascending permutation of $\{v_m\}_{m=1}^M$ with repeated value discarded and $\tilde{M} \leq M$. $I_{low} \leftarrow 1$, $I_{up} \leftarrow \tilde{M}$.

Step 1 Check if $\mathbf{O}(I_{low})$ is infeasible. If so, $c_{min} \leftarrow 0$, $c_{max} \leftarrow \mathbf{O}(I_{low})$, return. Otherwise, go to Step 2.

Step 2 Chek if $\mathbf{O}(I_{up})$ is infeasible. If so, $c_{min} \leftarrow \mathbf{O}(I_{up})$, $c_{max} \leftarrow \infty$ and return. Otherwise, go to Step 3.

Step 3 $I_{curr} \leftarrow \left\lfloor \frac{I_{low}+I_{up}}{2} \right\rfloor$, and $c \leftarrow \mathbf{O}(I_{curr})$. Check if c is feasible. If so, $I_{up} \leftarrow I_{curr}$, otherwise $I_{low} \leftarrow I_{curr}$. If $I_{low} = I_{up} - 1$, go to Step 4. Otherwise repeat Step 3.

Step 4 $c_{min} \leftarrow \mathbf{O}(I_{low})$, $c_{max} \leftarrow \mathbf{O}(I_{up})$, return.

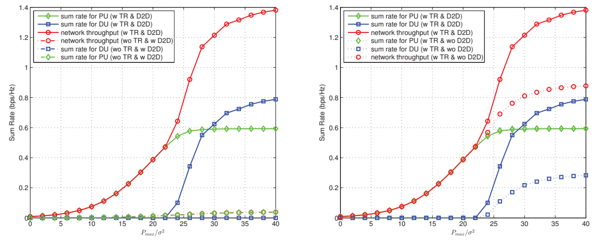
Based upon the Proposition 1, 2 and 3, we can have our following searching algorithm for optimal price c^*. The bisection method in Algorithm 1 ensures the convergence and the properties in the propositions guarantee that the limit is the optimum c^*. The Feasible Price Interval Search Algorithm is described in Algorithm 2.

V. Simulation Result

To evaluate the proposed framework, several experiments are conducted and the efficiency of the proposed optimal pricing algorithm is tested through price-of-anarcy (PoA) [14]. In the simulation, we set the pathloss factor $\gamma = 3$ and bandwidth to be 125 MHz. Moreover, each PUs are uniformly distributed in a circular indoor environment with radius to be 5 meters, whereas each D2D pairs uniformly locate in a concentric ring that is 1 meter away from the center.

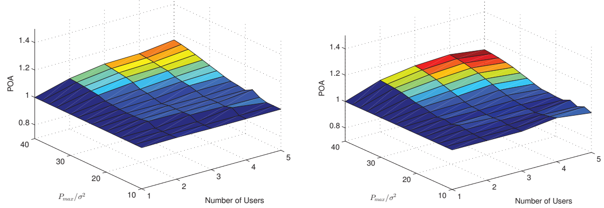
A. Performance Simulation

Here, we consider a uplink network with 3 PUs and 2 pairs of D2D transceivers. PUs transmit directly to AP with individual power



(a) TR v.s. direct transmission. (b) D2D v.s. conventional communication.

Fig. 2: Sum rate Comparison



(a) equal weight. (b) random weight.

Fig. 3: Price of Anarchy

constraints p_{max} and a higher QoS priority. In the D2D-scenario uplinks, D2D senders directly communicate to their receivers with a power constraint $0.2p_{max}$ and a lower priority. In the TR conventional uplinks, the D2D senders transmit to AP with a lower priority, power constraint p_{max} and TR signature. The uplink performance comparison between TR technique and direct transmission under D2D scenario is shown in Fig. 2a. While Fig. 2b demonstrates the performance comparison between conventional TR network and TR-based D2D network. The D2D network adopts the proposed optimal pricing algorithm for power control.

Indicated by the gap between solid curves and dashed curves in Fig. 2a, the rate performace for both PUs and DUs with TR signature improves a lot compared with the case without TR signature. The reason is that TR signature naturally boosts the signal strength and suppresses the interference due to its spatial-temporal resonance. Moreover, in Fig. 2b the two PU curves denoted as "$\diamond$" overlap due to the same QoS priority and constraints for PUs. However, as D2D communication takes advantages of proximity, by applying D2D mode to lower priority users, they can achieve a much higher sum rate with a lower power consumption as shown by the curves denoted as "$\square$". Consequently, the overall system performance of the TR-based D2D hybrid network outperforms others.

B. Price of Anarchy

The PoA is a measure of the inefficiency of equilibria in game theory, which is defined as the ratio between the worst objective function value of an equilibrium of the game and that of an optimal outcome. To evaluate the efficiency of the proposed optimal pricing algorithm, we evaluate the PoA in terms of throughput as $\eta = \mathbb{E}\left\{\frac{\text{Throughput}_{exhaustive}}{\text{Throughput}_{optimalprice}}\right\}$.

The results are shown in Fig. 3, and we can see that in both equal weight and random weight cases, the proposed optimal pricing algorithm could achieve almost the same result as the exhaustive search method when the number of D2D pairs is small and SNR is low. Even when the the number of D2D pairs and SNR increase, the POA value is upper bounded by 1.15. Hence we can conclude that the proposed optimal pricing algorithm reduce the computational complexity greatly without degrading much the optimal system performance.

VI. Conclusions

In this work, we propose a TR-based D2D hybrid network where PUs communicate through AP and D2D users communicate directly to their partners. Thanks to the sspatial-temporal resonances generated by the TR signal transmission in a rich-scattering environment, ITI and IUI will be alleviated in this single-carrier system. We design an efficient optimal pricing algorithm that works to improve the D2D throughput and guarantee a QoS protection for PUs. Simulations validate the performance improvement of the proposed scheme.

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