

Towards a Fair Spectrum Access Strategy in Device-to-Device Communications

N. Madani¹, P. Azmi²

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Abstract—Base station assisted device-to-device communications (D2D) lets cellular users communicate directly. As D2D connections can operate on a joint frequency band, interference management is essential to boost the spectral efficiency and users' quality of service. Two different approaches are proposed to tackle the interference in D2D networks. A power control scheme and a frequency-time scheduling are examined to achieve long-term fairness among D2D users. The power control maximizes weighted sum-rate of the users, where the weights indicate priority of the users. The second proposed strategy is to avoid interference when it is high. In this algorithm, the spectrum band is divided among users as interference coupling rises. A metric from the information theory literature has been adopted to measure the coupling. The proposed schemes are tested through multiple time slots and the average rate of a user and network sum-rate have been observed. The results demonstrate the superior performance of the proposed power control scheme.

Index Terms—Device-to-Device communications, interference management, power control, scheduling

I. INTRODUCTION

Device-to-Device communications (D2D) is a prominent technology which is expected to integrate into cellular systems. In D2D communications, two proximate cellular users exchange data via a direct link without routing their data through the base station [1], [2]. The proximity of transmitters and receivers let high data-rate and low-delay connections be established. D2D links can offload cellular traffic and provide a rich platform for context-aware services.

Incorporating D2D communications to cellular networks entails devising new resource allocation schemes. In underlay model, D2D users can transmit on the spectrum band of cellular users. As cellular users and D2D users operate on the same band, interference arises. To preserve users' quality of service (QoS) and achieve network objectives, interference should be properly managed. Many research studies have focused on underlay

model and proposed resource allocation algorithms in this framework [3], [4], [5].

Another strategy is to explicitly assign part of the cellular band to D2D users. This type of D2D communications can occur with little assistance or no assistance from the cellular network [2]. There is no interference between cellular and D2D tiers in this model. However, the interference among D2D users should be mitigated. FlashLinQ [6] is a distributed protocol for scheduling D2D links. A user is given the right to transmit with full power as it does not lower the signal-to-interference ratio (SIR) of the previously scheduled links below a predefined threshold. Moreover, the SIR of the current user at the receiver side should meet the threshold.

ITLinQ [7] is also a distributed scheduling algorithm which has been proposed for D2D networks. It is based on the concept of information theoretic independent set (ITIS). In an ITIS, concurrent transmission of the users with proper power levels can achieve the capacity region of the interfering links with a constant gap. ITLinQ detects the minimum number of ITISs within the available links. The users in each ITIS use the same spectrum band and transmit with constant power levels. ITLinQ targets system sum-rate whereas FlashLinQ aims QoS for users. Both FlashLinQ and ITLinQ lack power control scheme.

In this work, we consider interference management in a network composing of D2D pairs. Two different algorithms are employed in a time-slotted basis. We propose a power control scheme to maximize weighted sum-rate of D2D users. The weights are defined based on proportional fairness and indicate the priority of users in power control. We also propose a frequency-time scheduling algorithm. In power control scheme, the power levels vary in each time slot. However, the utilized spectrum band is the same for the users in all time slots. In second strategy, the power levels are fixed and different bandwidth portions are assigned to the users over the time slots. The performance of both algorithms are evaluated in terms of average link rate and system sum-rate over multiple time slots.

Sec. II includes the problem statement and the proposed scenarios. Sec. III presents the simulation results and Sec. IV concludes our work.

II. PROBLEM STATEMENT AND PROPOSED SCENARIOS

We consider a D2D system consisting of K transmitter-receiver pairs. A piece of cellular band is dedicated to D2D users. Therefore, there is no interference between cellular and D2D users. We assume a block composing of T time slots. While large scale

¹PhD student, Department of Electrical and Computer Engineering, Tarbiat Modares university, Iran, njmadani@gmail.com

²Corresponding author, Full professor, Department of Electrical Engineering, Ferdowsi Tarbiat Modares University, Iran, pazmi@modares.ac.ir

fading is constant throughout the block, the small scale fading varies through the time slots.

A. Spectrum Reusing and Power Control

In first model, the D2D users operate on the same frequency band. Therefore, each D2D receiver collects interference besides its intended signal. This interference is treated as noise and a power control strategy is employed in each time slot. The power control aims to maximize the weighted sum-rate of D2D users.

The signal-to-interference-plus-noise-ratio (SINR) and the rate of the k 'th D2D user are defined as follows:

$$\text{SINR}_k = \left(\frac{p_k h_{kk}}{\sigma^2 + \sum_{j=1, j \neq k}^K p_j h_{jk}} \right), \quad (1)$$

$$R_k = \log(1 + \text{SINR}_k).$$

In the above formulation, p denotes the transmit power level and h_{ij} is the channel gain between i 'th transmitter and j 'th receiver. σ^2 is the noise power.

In time slot t , the optimization problem is formulated as follows:

$$\max \sum_{k=1}^K w_k(t) R_k(t), \quad (2)$$

$$s.t$$

$$0 \leq p_k \leq p_{\max} \quad \forall k.$$

The weights in each time slot are updated according to the proportional fairness scheduling metric [8]:

$$w_k(t) = \frac{1}{\bar{R}_k(t)} \quad (3)$$

$$\bar{R}_k(t) = \alpha \bar{R}_k(t-1) + (1-\alpha) R_k(t-1).$$

where $\alpha \in [0,1]$ is a forgetting factor. The weight for each user indicates the priority of that user in power control scheme. If a user have a low average rate in the in the previous time slots, its weight increases according to (3) in current time slot. This weighing mechanism guarantees long-term fairness for the users. We will drop the time index t throughout the paper unless it is necessary.

The stated problem is NP-hard and finding the optimal solution is computationally intractable. Here, we employ two sub-optimal solution.

1) *Fast and Distributed Solution*: In this approach, it is assumed that high SINR approximation is valid for each D2D link. Consequently, for the link k , the rate $\log(1 + \text{SINR}_k)$ can be approximated with $\log(\text{SINR}_k)$. Now the objective will be in the form of $\sum_{k=1}^K w_k \log(\text{SINR}_k(P))$. By the change of variable $P = \log(P)$, the problem is turned to a convex form [9]. We find a lower bound for the maximum of weighted sum-rate through this approach. We search for the optimal solution of the convex approximation of the problem (2). In convex problems, the stationary point is a global optimal [10] and $\frac{\partial \sum_{k=1}^K w_k \log(\text{SINR}_k(P))}{\partial p_k} = 0$ leads to the following power updating function for the user k :

$$p_k(m+1) = \min\left\{ \frac{w_k}{\sum_{i=1, i \neq k}^K \frac{w_i h_{ki}}{p_i h_{ii}} \text{SINR}_i}, p_{\max} \right\}, \quad (4)$$

where m is iteration number. It is straightforward to check that the updating function is positive, monotonic and scalable. The convergence to the optimal point is guaranteed for any initial power vector [11]. The power control can be implemented in a distributed way by message passing [12]. The i 'th D2D receiver measures the h_{ki} by pilot transmission from the k 'th D2D transmitter. It can also measure h_{ii} and SINR_i . It then reports $\frac{w_i h_{ki}}{p_i h_{ii}} \text{SINR}_i$ to the k 'th transmitter for its power updating.

2) *Solution based on successive convex approximation (SCA)*: As the second solution, we employ the successive approximation technique. In this approach, the non-convex problem is iteratively approximated with a convex form. In each iteration the convex problem is solved and the problem approximation is updated for the next iteration [9]. The maximization of the weighted sum-rate can be equivalently expressed as minimization of the $\prod_{k=1}^K \left(\frac{1}{1 + \text{SINR}_k} \right)^{w_k}$.

$$\frac{1}{1 + \text{SINR}_k} = \frac{\sigma^2 + \sum_{j=1, j \neq k}^K p_j h_{jk}}{\sigma^2 + \sum_{j=1}^K p_j h_{jk}} = \frac{f_k(P)}{g_k(P)},$$

is the ratio of two posynomials. Employing arithmetic-geometric mean inequality (AM-GM), the posynomial in denominator can be approximated with a monomial. According to weighted AM-GM inequality, we have

$$g_k(P) = \sum_{i=1}^K g_{k_i}(P) \geq \hat{g}_k(P) = \prod_{i=1}^K \left(\frac{g_{k_i}(P)}{\alpha_i} \right)^{\alpha_i}, \quad (5)$$

where $\sum_{i=1}^K \alpha_{ki} = 1$. As [13] suggested, we set $\alpha_{ki} = \frac{g_{k_i}(P_o)}{g_k(P_o)}$, where P_o is the optimal power vector from the pervious iteration.

In each iteration of SCA, the approximation \hat{g} is updated based on the obtained power levels in the pervious iteration. The ratio of a posynomial to a monomial results in a posynomial. The problem is in geometric programming form and can be solved with interior point method.

Proposition 1. *Weighted sum-rate maximization based on SCA approach which is implemented through AM-GM inequality converges to a point that satisfies Karush-Kuhn-Tucker (KKT) conditions.*

Proof. [14] proved for a non-convex problem in the following form

$$\begin{aligned} \min & f_0(x), \\ \text{s. t. } & f_i(x), \quad i = 1 \dots M, \end{aligned} \quad (6)$$

where f_0 is non-convex and $f_i(x)$ is convex $\forall i$, a series of approximations $\hat{f}_i(x) \approx f_i(x)$ satisfying the following conditions converge to a point that meets KKT conditions.

- 1) $f_i(x) \leq \hat{f}_i(x) \quad \forall x$
- 2) $f_i(x_o) = \hat{f}_i(x_o)$, where x_o is the optimal point of the pervious iteration.
- 3) $\nabla f_i(x_o) = \nabla \hat{f}_i(x_o)$

Our optimization problem can be recasted as

$$\begin{aligned} \min & t \\ \text{s. t. } & \prod_{i=1}^K \left(\frac{f_i(P)}{g_i(P)} \right)^{w_i} \leq t \quad i = 1 \dots M. \end{aligned} \quad (7)$$

(5) implies that $g_i(P) \geq \hat{g}_i(P)$. Hence, $\prod_{i=1}^K \left(\frac{f_i(P)}{g_i(P)} \right)^{w_i} \leq \prod_{i=1}^K \left(\frac{f_i(P)}{\hat{g}_i(P)} \right)^{w_i}$ and first condition is met. Substituting the approximation parameters $\alpha_{ki} \quad \forall i \quad \forall k$, $\prod_{i=1}^K \left(\frac{f_i(P_o)}{g_i(P_o)} \right)^{w_i} = \prod_{i=1}^K \left(\frac{f_i(P_o)}{\hat{g}_i(P_o)} \right)^{w_i}$ and condition (2) is qualified. It is straightforward to verify condition (3) By getting derivative of the constraint. \square

The implementation of this solution needs a central node e.g. a base station. All the channel gains should be reported to the central node. After performing the power control action, the central node broadcasts the assigned power levels to the users.

The solution through SCA approach converges to a sub-optimal point which can be the global optimal point in some occasions. The high SINR approximation provides a lower bound for the global optimal solution where in high-SINR regime the bound is tight

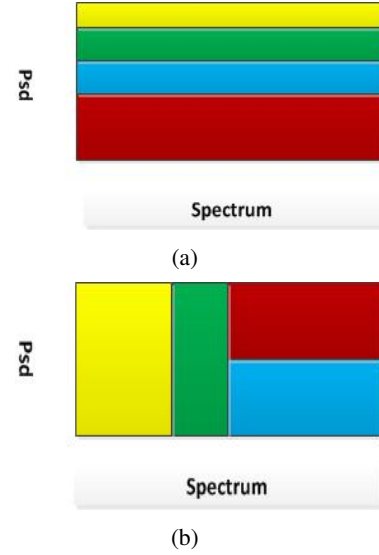


Fig. 1. (a): Spectrum sharing and power control. (b): Frequency-time scheduling

The complexity of high SINR approximation based on (4) is $O(K)$. The SCA approach based on AM-GM entails K operations in each iteration to convert the problem to a convex form. The problem can then be solved using CVX which employs interior point method. The complexity of interior point method is reported in [15] as $\frac{\log(K/t^0\zeta)}{\log(\xi)}$ where t^0 is initial point, $0 < \zeta \leq 1$ is the stopping criterion and ξ is used for updating the accuracy of interior point method. Therefore the complexity of SCA (based on AM-GM) approach is $K \frac{\log(K/t^0\zeta)}{\log(\xi)}$

B. Frequency-Time Scheduling

In this scenario, The available spectrum band W is partitioned to $\frac{K}{2}$ sub-channels, where K is the active users on each time slot. The users are randomly paired for transmission on the same sub-channel. If the two links which are selected to reuse the same sub-channel are highly coupled, the sub-channel is furthered partitioned between users. To make a decision on spectrum reusing or spectrum partitioning, we employ the criterion introduced by [16].

We assume that user i and user j are paired to transmit in a sub-channel. [16] proved that if the following condition is held between the channel gains of two interfering links:

$$\frac{h_{ij}h_{ji}}{h_{ii}h_{jj}} \geq \frac{1}{4}, \quad (8)$$

spectrum partitioning with bandwidth portions $w_i = \frac{p_i h_{ii}}{p_i h_{ii} + 2p_j h_{ji}}$ for the user i and $w_j = \frac{p_j h_{jj}}{p_j h_{jj} + 2p_i h_{ij}}$ for the user j leads to higher rates comparing to concurrent

transmission of both users in spectrum band W . The achievable rates based on this strategy are as follow:

$$R_i = w_i \log\left(1 + \frac{p_i h_{ii} + 2p_j h_{ji}}{\sigma_w^2}\right), \quad (9)$$

$$R_j = w_j \log\left(1 + \frac{p_j h_{jj} + 2p_i h_{ij}}{\sigma_w^2}\right).$$

Fig. (1) demonstrates both scenarios. In first model, the D2D pairs reuse the spectrum band with different transmit power levels. Based on the users' weights, the allocated power levels differ in each time slot. In second model, the interference is managed through frequency division. Each user receives no interference or a mild level of interference. Random pairing is performed independently in different time slots.

III. SIMULATION RESULTS

To evaluate the performance of the proposed algorithms, $N = 4$ transmitter-receiver (Tx-RX) pairs are distributed randomly in a circle of radius $r = 100\text{m}$. The TX-RX distance has a uniform distribution in $[15\text{m } 25\text{m}]$. The channel gains include a path-loss component and a fast fading gain with exponential distribution. The path-loss exponent is considered 4. The noise power is -90 dB and the available bandwidth is 100 KHz . The maximum transmit power is 20 dBm . The results are obtained through a block of $T = 16$ time slots. The path-loss component is constant within the block.

Fig. (2) demonstrates the instantaneous rate of a user in power control scheme obtained by both solutions. The distributed solution based on high SINR approximation is denoted by HSA. The centralized solution based on successive convex approximation inequality is indicated by AGM. As the priority of the users varies in each time slot. We proceed with HSA algorithm which has a lower complexity and a more smooth behavior.

In the next step, we compare the power control scheme with frequency-time scheduling. Fig. (3) depicts the average spectral efficiency CDF and the average rate CDF of a link in the network. The average rate of a user is obtained as follows

$$\bar{R} = \frac{1}{T} \sum_{t=1}^T R(t). \quad (10)$$

The low-interference or no-interference regime that a user experience in different time slots results in better link spectral efficiency for frequency-time scheduling. Fig. 3(a) presents this fact. However, Fig. 3(b) indicates that users have higher rates comparing to frequency-time scheduling. In power control scheme, each user can transmit on the whole spectrum band. On the contrary, a



Fig. 2. The instantaneous rate of a user over a block of time slots in power control schemes

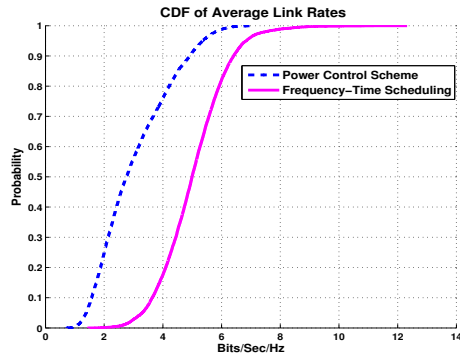
portion of the spectrum band is assigned to each user in frequency-time scheduling. This reduces the users' rates and system spectral efficiency. Fig. 3(c) demonstrates that system spectral efficiency is superior in power control scheme. Our observations confirm that power control scheme is more efficient than frequency-time scheduling. Fig. 3(d) shows that average rate of a D2D link decreases as number of D2D pairs increases. As interference rises due to number of concurrent transmission of D2D pairs, power control can not preserve users' QoS. A joint scheduling and power control can be applied to boost system efficiency.

IV. CONCLUSION

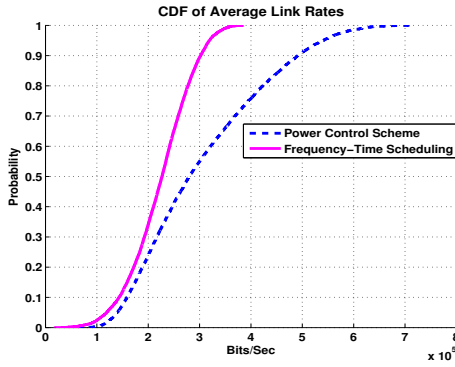
In this paper, we devised a power control scheme for a system of D2D links. A centralized and a distributed solution were proposed for the power control and their performance were compared. Moreover, a frequency-time scheduling was developed for the D2D network. Simulation observations indicate superior performance of the power control to frequency-time scheduling in terms of system spectral efficiency.

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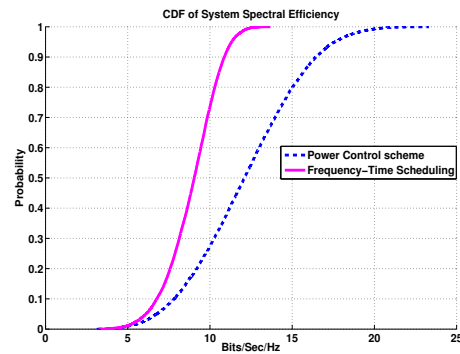
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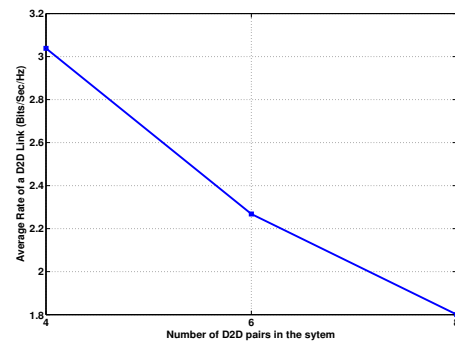
(a)



(b)



(c)



(d)

Fig. 3. (a): CDF of average spectral efficiency. (b): CDF of average link rate. (c): CDF of system spectral efficiency. (d) Average spectral efficiency of a D2D link

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