Channel Access in D2D Multiuser Networks: A Game Theoretical Approach

Abiodun Gbenga-Ilori[1] and Aydin Sezgin[2]
[1]Department of Electrical and Electronics Engineering, University of Lagos
[2]Institute of Digital Communication Systems, Ruhr-Universität Bochum
Email: gbengailori@unilag.edu.ng, aydin.sezgin@rub.de

I. Introduction

The ever growing demand for higher data rates and capacity has put a lot of demand on the present communication networks leading to the proposal of employing Device-to-Device (D2D) communication for 4G and 5G networks. Traditionally, two cellular user equipment (UEs) that need to communicate must go through the base station before communication with each other is established, even if the two UEs are within close proximity. This leads to delay and inefficient use of spectrum resource. With D2D communications, UEs in close proximity can communicate directly without going through the base station by forming a mobile cloud. A mobile cloud can be defined as an opportunistic cooperative cluster of wireless devices in close proximity which are capable of communicating with other devices while preserving their connection to an underlay cellular access network simultaneously, [1]. This means that the traffic to the base station can be reduced with D2D communication. Interference management is, however, key to experiencing the potential benefits that D2D communication in cellular networks has to offer.

We propose a coalition game model for the optimisation of spectrum resource in terms of achievable data rates, while protecting licensed cellular users from interference, in multiuser cellular networks that allow D2D communication. A key assumption in this paper is that D2D links are rational and only seeks to maximize their payoff. We therefore consider game theory as a tool to analyze D2D spectrum access.

The key contributions of this paper can be summarized as follows:

- formulation of a coalition game to model the data rate gain possible with deploying D2D communication in cellular networks,
- proposal of the a cellular sub-band allocation game (CSAG) scheme that is based on matching markets with private beliefs which ensures that spectrum sharing between D2D links and cellular users does not cause intolerably high interference to cellular users,
- A comprehensive performance evaluation of the proposed game model.

II. Preliminaries

We assume that the reader is familiar with common notions of game theory and we therefore do not define these concepts here but suggest the reference, [2].

TABLE I
List of Notations.

$Symbol$	$Definition$
$\mathcal{D}$	Set of D2D links
$\mathcal{C}$	Set of cellular devices with sub-band
$\mathcal{L}$	Set of licensed sub-bands
d_i, c_i	The i^{th} D2D link and cellular device with sub-band respectively
$\mathcal{P}, \succeq$	D2D link's preference profile for cellular and exclusive sub-band sharing respectively
$\mathcal{Q}$	Priority profile of cellular device with sub-bands
$\mathcal{J}$	Type space of D2D links
P_r	Probability distribution over $\mathcal{J}$
$\mathcal{U}_{d\,i}$	Average payoff to d_i for using a sub-band
$\mathcal{Y}_{d\,i}$	Average cost to d_i for using a sub-band
$b_{d\,i}$	Belief function of d_i
$\mathcal{S}$	A coalition
Π	Matching from $\mathcal{D}$ to $\mathcal{C}$
q_c	Capacity of cellular sub-band
β_{d_i}	Probability that a licensed sub-band is allocated to d_i

The payoff of a D2D link sharing a cellular sub-band in the cellular sub-band allocation phase is determined as a function of the rate obtained for the link between the D2D transmitter and D2D receiver. The rate that can be achieved in a licensed sub-band is given as

$$\mathcal{R}_l = \log_2 (1 + \mathsf{SINR}_{R_l}), \tag{1}$$

where the Signal to Interference plus Noise Ratio (SINR) used in (1) varies according to:

$$\mathsf{SINR}_{R_l} = \begin{cases} \frac{P_{d\,i}\alpha_i\lambda_i}{\sum_{j=1}^{k} P_{d\,j}\alpha_j\lambda_j + P_c\alpha_c\lambda_c + \sigma^2} & \mathcal{L} = d_i, \sum d_j, c, \\ \frac{P_{d\,i}\alpha_i\lambda_i}{P_c\alpha_c\lambda_c + \sigma^2} & \mathcal{L} = d_i, c \\ \frac{P_{d\,i}\alpha_i\lambda_i}{\sigma^2} & \mathcal{L} = d_i, \end{cases} \tag{2}$$

where P_{di} is the transmit power of the D2D link d_i, P_{dj} is the transmit power of other D2D links d_j if there is more than one D2D link in the cellular sub-band and P_c is the transmit power of the cellular device. α and λ are the path loss attenuation and the shadowing found in the D2D to D2D link or the cellular device to base station link while σ^2 is the average noise power. In this work, we refer to the number of D2D links allowed to share the licensed cellular sub-band as the capacity of the cellular sub-band q_c and we assume that $q_c = n$ where n is the number of UEs within the sub-band.

The average payoff of the D2D link d_i for any coalition strategy $\mathcal{S}$ chosen in the underlay mode, given its private beliefs $\mathcal{B}_{d_i}$, is given as:

$$\mathcal{U}_{d_i}(\mathcal{S},\mathcal{J}) = \sum_{t_{-d_i}\in\mathcal{J}_{-d_i}} b_{d_i}(\mathcal{J}_{-d_i})[(\mathcal{U}_{d_i}(\mathcal{S},\mathcal{J}) - \mathcal{Y}_{d_i}(\mathcal{S},\mathcal{J}))]. \tag{3}$$

$\mathcal{S}$ is the coalition formed while $\mathcal{J}$ is the type space of D2D links where t is the typical type of a D2D link whether it is an interfering or non-interfering link. $\mathcal{Y}_{d_i}$ is the cost paid by a D2D link for using a licensed sub-band and this cost is $\mathcal{Y}_{d_i} \leq y_g + y_i$. Here y_g is the loss of spectrum gain in the case where coalition was impossible, and y_i is the penalty paid if interference results from d_i's use of the sub-band. $b_{d_i}(\mathcal{J}_{-d_i})$ is the vector showing the probability distribution of the D2D link d_i over the types of others in the network and

$$b_{d_i}(\mathcal{J}_{-d_i}) = \prod_{t_{-d_j}\in\mathcal{J}_{-d_i}} P_r(t_{d_j} = t_{d_j}^{d_i}). \tag{4}$$

The goal is to maximize the overall rate of the network by seeking a Bayesian coalition equilibrium for the game described above such that

$$\begin{aligned}&\mathcal{U}_{d_i}((\mathcal{S}^*_{d_i},\mathcal{J}_{d_i}),(\mathcal{S}^*_{-d_i},\mathcal{J}_{-d_i}),\mathcal{J})\\ &\quad\geq \mathcal{U}_{d_i}((\mathcal{S}_{d_i},\mathcal{J}_{d_i}),(\mathcal{S}_{-d_i},\mathcal{J}_{-d_i}),\mathcal{J}).\end{aligned} \tag{5}$$

III. Cellular Sub-Band Allocation Game

The coalition game is a many-to-one matching problem referred to as a cellular sub-band allocation problem, [3].

Algorithm 1 Cellular Sub-Band Allocation Algorithm

INPUT: $\mathcal{D},\mathcal{C},\mathcal{P},\mathcal{Q}$

OUTPUT: An Optimal matching Π^* between D2D links

1: Each D2D link $d \in \mathcal{D}$ decides its preference by

$$\mathcal{P}_d = \arg\max_{J_d\in\mathcal{J}} \mathcal{U}_{d_i}(\mathcal{S},\mathcal{J})$$

2: D2D to cellular sub-band matching

Step 1: Each D2D link $d \in \mathcal{D}$ sends their request to their most desired cellular user with licensed sub-band $c \in \mathcal{C}$. For each cellular user with a sub-band, D_c^1 for all $D_c^1 \in \mathcal{D}$, is the set of D2D links that proposes to c at step 1. Each cellular with a sub-band c tentatively accepts the best D2D links $D_{best}^1 \mid \mathcal{Q}$ up to its capacity $q_c = n$, for all $D_{best}^1 \in \mathcal{D}_c^1$. It rejects the other D2D links $\mathcal{D}_c^1 \setminus D_{best}^1$.

Step k(k $\geq$ 2): Each D2D link rejected in the previous $k-1$ rounds sends requests to its next best cellular sub-band that has not rejected it yet. For each $c \in \mathcal{C}$, D_c^k is the set of D2D links that sends request to c at step k. Each cellular with a sub-band c tentatively accepts $D_{best}^k \cup D_{best}^{k-1} \mid \mathcal{Q}$, and rejects $\mathcal{D}_c^k \cup \mathcal{D}_c^{k-1} \setminus D_{best}^k \cup D_{best}^{k-1}$ for each $D_{best}^k \in \mathcal{D}_c^k$, $D_{best}^{k-1} \in \mathcal{D}_c^{k-1}$.

3: The algorithm terminates when no D2D link is rejected.

Each D2D link has strict preferences over all cellular sub-bands, and each cellular device with licensed sub-band have strict priorities over all D2D links. Note that priorities do not represent cellular sub-band's preferences as priorities are determined by the base station according to its channel state information (CSI).

The two-sided, many-to-one matching market used in this work is described by the Gale-Shapley's Deferred Acceptance (DA) mechanism, [4]. This is an allocation mechanism that has been shown to be optimal and stable. A cellular sub-band allocation problem consist of a well ordered pair $(\mathcal{P},\mathcal{Q})$ of preferences and priorities. For each allocation matching problem $\Pi(\mathcal{P},\mathcal{Q})$ the algorithm operates as described in Algorithm 1. The algorithm has been shown to yield a unique stable matching in $O(n^2)$ time, [4].

Proposition 1. *The cellular sub-band allocation algorithm produces a stable matching and the final matching is D2D link-optimal.*

Proof: Supposing cellular sub-band c from the set $\mathcal{C} = \{c_1,\cdots,c_m\}$ receives requests from D2D links $\mathcal{D} = \{d_1,d_2,\cdots,d_t\}$. Let us assume that c accepts $\{d_1,\cdots,d_n\}$, according to its capacity $q_c = n$, and rejects the other D2D links $\mathcal{D}\setminus\{d_1,\cdots,d_n\}$. We show that D2D links $\mathcal{D}\setminus\{d_1,\cdots,d_n\}$ are impossible matches for c under the cellular sub-band allocation algorithm since $\{d_1,\cdots,d_n\}$ prefers c to all other sub-bands, except for those that rejected them in the previous matching steps. Suppose that in contrast, we assume that $\{d_1,\cdots,d_{n+1}\}\setminus d_n$ are matched to c, and every other D2D links are matched to sub-bands that are possible for them. This implies that d_n must have been matched to a less desired sub-band, making the matching unstable since d_n and c will be blocking d_{n+1}. Hence c is an impossible match for d_{n+1} under the cellular sub-band allocation algorithm. This is because the algorithm ends only when no D2D link is rejected from its tentative sub-band allocation and in this case the algorithm will end only when c has rejected d_{n+1} and accepted d_n and every other D2D links is matched to sub-bands that are possible for them. This shows that the resulting allocation is stable and D2D link-optimal. ■

D_{best}, described in algorithm 1, is the best D2D links for the cellular user c given its priority profile $\mathcal{Q}$. To determine D_{best}, a power control optimization scheme is used. The aim is to use CSI available at the BS to determine the optimal transmit power for D2D devices that maximizes the SINR of the cellular link while satisfying the individual target SINR constraints for both the cellular and D2D links. The optimization problem can be written in matrix form as:

$$\begin{aligned}\underset{\mathbf{P}}{\text{maximize}} \quad & \frac{\mathbf{G}_c^T\mathbf{P}}{\mathbf{G}_d^T\mathbf{P}+\sigma_c^2},\\ \text{subject to} \quad & (\mathbf{I}-\mathbf{F})\mathbf{P} \geq \gamma,\\ & \mathbf{0} \leq \mathbf{P} \leq \mathbf{P_{max}},\end{aligned} \tag{6}$$

where $\mathbf{P} = [P_c, P_1,\cdots,P_q]^T$, denotes the transmit power vector for the cellular and D2D devices, $\mathbf{G}_c^T = [G_{c,c},0,\cdots,0]$, $\mathbf{G}_d^T = [0,G_{c,1},\cdots,G_{c,q}]$, and $\mathbf{P_{max}} = [P_{c_{max}},P_{d_{max}},\cdots,P_{d_{max}}]^T$. The identity matrix is $\mathbf{I}$, while $\mathbf{F} = [F_{q,l}]$ is the normalized channel gain matrix with the elements given as follows:

$$F_{k,l} = \begin{cases} \frac{\gamma_d G_{q,l}}{G_{q,q}} & if q \neq l \\ 0 & if q = l. \end{cases} \quad (7)$$

The target SINR vector $\boldsymbol{\gamma}$ is defined as

$$\boldsymbol{\gamma} = \left[\frac{\gamma_c \sigma_c^2}{G_{c,c}}, \frac{\gamma_{d_1} \sigma_{d_1}^2}{G_{1,1}}, \cdots, \frac{\gamma_{d_q} \sigma_{d_q}^2}{G_{q,q}} \right]^T. \quad (8)$$

The solution of the above quasi-convex optimization problem is $\mathbf{P} = [P_c, P_1, \cdots, P_q]$ that maximizes our SINR for cellular receiver by choosing the best n D2D transmit power amongst P_1 to P_q. The n D2D with these transmit powers forms D_{best} vector in our algorithm 1.

In our paper, each D2D link can dynamically update its beliefs about other D2D links. The belief updating mechanism used is based on Bayes' theorem, [5]. We consider a situation where D2D link d_i observes another D2D link d_j to determine if it is an interfering or non-interfering link. We assumed in the paper that two things are observed by the d_i. The first is the received power from d_j, represented as P_{d_j}, which must be less than a maximum power threshold. The second thing observed is the distance between d_i and d_j represented as δ_d, which must be greater than a minimum distance threshold. If $P_{d_j} > PowerThreshold$ or $\delta_d < DistThreshold$, then d_i assumes that d_j is an interfering link. $PowerThreshold$ is the maximum allowable power received by d_i from any D2D link that would like to share its exclusive sub-band while $DistThreshold$ is the minimum distance between d_i and any other D2D link that wants to share the sub-band. These thresholds are determined based on the number of observations. The D2D links make use of the belief factor to determine its preference profile and form coalition that will maximize its payoff.

IV. Numerical Analysis

In order to evaluate the performance of our algorithm, we simulated a cellular network with multiple D2D links and cellular users that are randomly located in a square-shaped coverage area. We have considered two types of coverage areas; 50 m square area with 2 cellular devices and 7 D2D users and 100 m square area with 8 cellular devices and 20 D2D users. Every cell is served with one base station. The length of the D2D links vary from 10 m to 20 m in our simulations.

We compare D2D spectrum sharing without our coalition game but with random pairing in figures 1 (a) and (b) with spectrum sharing using our proposed coalition game in figures 2 (a) and (b). The cellular power used for our simulations is 24 dB and convex optimization is used to determine the optimal D2D transmitter power for various scenarios. Figure 2 shows an improved cell sum rate compared to figure 1. We observe that interference does not put any constraint on the capacity of the network even with the increased number of D2D links because of the matching used in our algorithm.

Results from our numerical analysis showed that, with our model, it is possible to achieve about twice the sum rate

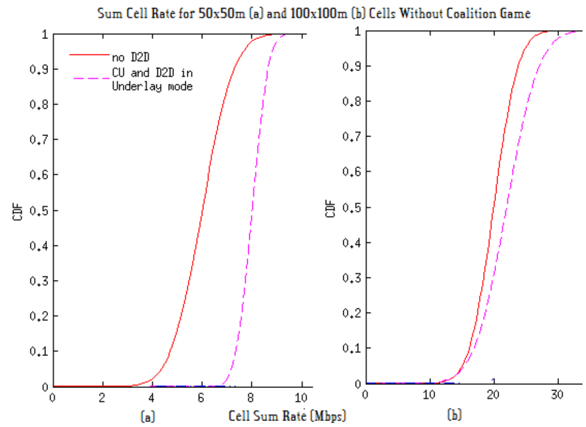

Fig. 1. CDF without the coalition game for both 50m and 100m square cell sum rate.

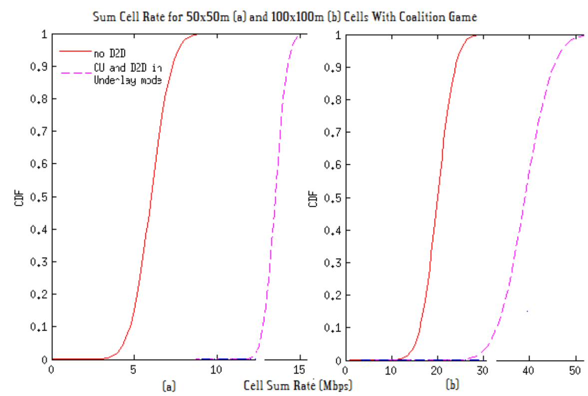

Fig. 2. CDF using the coalition game for both 50m and 100m square cell sum rate.

when D2D underlays cellular networks compared to when the network is used by cellular devices alone.

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