Bayesian Coalition Game for Overlay D2D Spectrum Sharing in Cellular Networks

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Abstract- In this paper, we present a Bayesian coalition game model for spectrum sharing in order to increase the overall spectrum resource capacity in a cellular network with device-to-device (D2D) communication capabilities. The coalition game is used to enforce cooperation among D2Ds competing for the use of the limited spectrum resource. In this paper, D2D users can access the network in an overlaid mode and share their allocated sub-bands with other D2D users using the proposed game which enables coalition formation that guarantee an optimal rate for all users in the network. The paper establishes sufficient conditions needed for stability in the coalitions formed and present simulation results to show that it is possible to increase the overall capacity of the D2D-enabled cellular network without reducing the performance of the licensed cellular users using the proposed game. D2D spectrum sharing using our proposed algorithm was compared with spectrum sharing using the random pairing method to validate our game model. Results show that there was a 44% and 36% increase in cell sum-rate, when our proposed sub-band allocation game was deployed compared to the random pairing method, for the 50 m² and 100 m² cells respectively. The proposed sub-band allocation game also performed better with an increased number of users in the network because of the effective coordination offered by the algorithm.

Keywords- Cellular, coalition game, D2D, overlay, spectrum

1 INTRODUCTION

The explosive growth in demand for wireless communication services continues to put an overbearing load on cellular networks. A promising technology that can be used to offload overloaded cellular traffic is the device-to-device (D2D) communication (Gandotra, & Jha, 2016). In addition to offloading cellular traffic and reducing network delay, D2D offers improved energy savings and increased throughput within the network (Fodor et al, 2012). A major concern that operators have with regards to D2D communication is the issue of interference management within the network.

D2D communication can be classified into two categories based on the mode of spectrum usage. D2D operate within cellular band for in-band communication, while they operate in a separate spectrum band, usually the unlicensed spectrum band, in out-band communication (Kar, & Sanyal, 2018). The in-band is preferred to out-band D2D communication mode because of challenges of managing interference in the unlicensed band. A lot of researchers, therefore, focus on in-band D2D communication mode which is also sub-divided into underlay and overlay in-band communication. Underlay communication is the most preferred of the two in-band modes because it is spectrum-efficient as D2D communication can be done simultaneously with cellular communication. However, controlling interference from D2D devices underlaying cellular networks has been a major concern for researchers.

A lot of research has been done in controlling interference from D2D users underlaying cellular networks. A few papers also considered interference control in D2D communication overlaying cellular networks (Song et al, 2019), (Saidar et al, 2016). Some other papers considered using a minimum distance constraint between cellular users (CUs) and D2D users to limit interference in cellular networks (Lee et al, 2014).

Meibergen (2011) developed a method for determining required minimum distance between D2D users to obtain an optimal network capacity. In the work of Ningombam, & Shin (2018), authors considered a fractional frequency reuse (FFR) scheme as a means of reducing the intra-cell interference. The FFR scheme makes use of a form of minimum distance constraint. In the work of Adekunle & Gbenga-IIlori (2020), authors used graph colouring frequency reuse technique for frequency assignment in communication networks with ultra-dense femtocells to minimize interference. Some other papers also used power control for coordinating spectrum sharing in D2D-enabled cellular networks (Zhang et al, 2017), (Abdallah, Mansour, & Chehab, 2018), (Nguyen, & Rao, 2015).

The overlay in-band communication mode makes use of a non-overlapping portion of the cellular spectrum and relatively suffers the least interference. However, it is not as spectrum efficient as the underlay in-band mode. The problem of spectrum inefficiency in overlay mode has been addressed by a few authors. Osti, Lassila, & Aalto, (2018) developed queuing models to study performance of different resource sharing schemes for both D2D overlay and underlay schemes. Another work also proposed a cooperative spectrum sharing scheme based on non-orthogonal multiple access for overlay D2D communication to guarantee the smooth operation of cellular communication (Feng, Shu, & Li, 2018).

Game-theoretic approach has been used in several papers to optimize spectrum usage in D2D-enabled cellular networks. Lyu et al (2015) studied the performance of overlay D2D communication using a non-cooperative game model. This work proposed a Stackelberg game in which the base station in the cellular network acts as the leader to regulate the individual payoff so that interference is controlled, and the total network throughput is maximized. In another work, the authors presented a coalition game model for cooperative decisions in cellular networks underlayed with D2D users for the purpose of reducing interference and improving...
the rate of users in the network (Gbenga-Ilori, & Sezgin, 2016). In most of these previous papers, authors focused on interference management and have assumed that the control of the D2Ds is done by a central coordinating point so that the cellular users are adequately protected since most of these papers considered D2D underlay communication mode. In our work, we focus on an efficient spectrum sharing scheme for D2D overlay communication to guarantee a maximum capacity in the cellular network using a game-theoretic approach.

In order to limit the overhead of the communication network, we propose a D2D-enabled cellular network model in which D2D users request cellular spectrum sub-bands in the overlay mode, with minimal involvement of the base station, and share with other D2D users for efficient spectrum utilization. To maximize the throughput of D2D users, a dynamic Bayesian coalition game is formulated in this work for spectrum sharing. The major contributions of this paper are as follows:
- formulation of a Bayesian coalition game for an efficient spectrum sharing between multiple D2D users in an overlay in-band communication mode,
- proposal of dynamic spectrum allocation game with private beliefs which ensures that spectrum sharing between D2D and cellular users does not cause intolerable high interference to network users,
- proposal of a belief-update metric for the coalition game, and
- evaluation of the proposed game model.

2 System Model

In this work, we formulate a Bayesian coalition game to model the sharing of cellular bandwidth between multiple D2D users to maximize the capacity of communication networks. We consider a network consisting of a set of $D = \{d_1, d_2, \ldots, d_k\}$ rational D2Ds seeking to use the cellular sub-bands for access to the limited frequency bands as shown in Fig. 1. We model a scenario in which D2D users can access the spectrum in the overlay mode and use an exclusively allocated cellular sub-band that they can share with other D2D users. A D2D user is not allowed to apply for more than a sub-band at a time. The base station provides the D2D user with information on the available channel state information (CSI) to reduce interference in the network. It should be noted that the coordination provided by the base station is restricted to the provision of an exclusive sub-band and information on CSI.

Spectrum usage and sharing coordination are not done by the base station but through our proposed game-theoretic model. Since the base station is lightly involved in the communication process, co-channel and adjacent-channel devices may be susceptible to interference and this issue is addressed in our model. Also, exclusive bandwidth is limited since the whole essence of D2D communication was to devise means of using the limited spectrum resources efficiently. There are, therefore, costs attached to using the sub-band in the overlay mode to reduce congestion of the cellular band.

The utility or payoff of a D2D $d_i$ overlaying a cellular sub-band, and sharing the band with other D2Ds, is determined as a function of the rate obtained for $d_i$. The rate that $d_i$ can achieve in an exclusive sub-band is given as:

$$ R = \log(1 + \text{SINR}) $$

where the signal to interference plus noise ratio (SINR) used in equation (1) varies according to:

$$ \text{SINR} = \left\{ \begin{align*}
\frac{P_{d_i} \alpha_i}{\sum_{j=1}^{m} P_{d_j} \alpha_j + \sigma^2} & \quad e_m = d_i, \sum_j d_j, \\
\frac{P_{d_i} \alpha_i}{\sigma^2} & \quad e_m = d_i,
\end{align*} \right. $$

where $P_{d_i}$ is the transmit power of the D2D user $d_i$ with exclusive sub-band, $P_{d_j}$ for $j = \{1, 2, \ldots, m\}$ are the transmit powers of the other D2D users if there are more than one D2D users in the exclusive sub-band of $d_i$. The path loss attenuation and the shadowing found in the D2D link are $\alpha$ and $\lambda$ respectively while $\sigma^2$ is the average noise power and $\mathcal{E} = \{e_1, e_2, \ldots, e_n\}$ is the set of exclusive sub-bands available. In this work, we refer to the number of users allowed to share the cellular sub-band as the capacity, $q$, of the cellular sub-band allocated to the D2D user. We assume that $q = n$ where $n$ is the maximum number of D2D user equipment that can share the sub-band. As said earlier, there is a cost attached to obtaining an exclusive sub-band in the overlay mode, and the D2D user that obtains the sub-band bears the cost alone if it is unable to share the use of the sub-band with any other D2D user. However, we assume that the cost is equally divided between the D2D users that agree to form a coalition to share the use of the exclusive sub-band. The list of notations used in this paper is shown in Table 1.

![Fig. 1: D2D spectrum usage in the overlay mode](image)

| Symbol | Definition |
|--------|------------|
| $D$    | Set of all D2D users |
| $\mathcal{E}$ | Set of exclusive sub-bands |
| $\succ$ | D2D user’s preference profile for exclusive sub-band sharing |
| $J$ | Type space of all D2D users |
| $t_{d_i}$ | Type space of $d_i$ |
| $\mathcal{G}$ | Probability distribution over $J$ |
| $U_{d_i}$ | Payoff to $d_i$ for using a sub-band |
| $Y_{d_i}$ | Average cost to $d_i$ for using a sub-band |
| $B_{d_i}$ | Belief function of $d_i$ about $d_j$ |
| $S, \Pi$ | A coalition, Set of coalition structures |
| $w_I, w_{NI}$ | Interference, and Non-Interference condition |
| $q$ | Capacity of exclusive sub-band |
| $V$ | Value of a coalition structure |
We assume that the D2D users are of two types: interfering and non-interfering D2D users. Also, the type of a D2D user is not perfectly known to other D2D users and that is why it is a game of incomplete information. However, a D2D user can estimate the type of another D2D user by maintaining its own belief based on past interactions with that node. We propose a dynamic Bayesian coalition game with a non-transferable utility to model the formation of coalitions among D2D users under the uncertainty of the type of these D2D users. We use the Nash equilibrium to determine the stability of our game. Stability is more complex in a dynamic game like ours due to the uncertainty associated with actions, however, the work proposes a belief update mechanism for the dynamic Bayesian coalition game. The aim is to use the coalition game to maximize the data rate of D2D users sharing the same frequency band and the overall network capacity is shown in equation (3). The optimization problem can be written as:

\[
\begin{align*}
\max_{\mathbf{P}} & \quad P_{d_i} d_i \mathbf{A} i \\
\text{s.t.} & \quad \sum_{j \in J} P_{d_i} d_i \mathbf{A} j + \sigma^2 \geq \gamma_d
\end{align*}
\]

\(\mathbf{P} = \{P_{d_1}, P_{d_2}, \ldots, P_{d_k}\}\) that maximizes the rate in the exclusive sub-band and consequently the overall rate in the network.

### 3 Formation of Exclusive Sub-band Allocation Game

In this work, a D2D user can apply for an exclusive cellular sub-band which it may decide to share with other D2D users. We formulate the sharing of this spectrum as a dynamic Bayesian coalition game in which each D2D user decides which coalition to form that maximizes its payoff in terms of transmission rate and overall bandwidth capacity. It switches coalition if its expected payoff in a new coalition exceeds its current payoff.

**Definition 1:** A dynamic Bayesian coalition game is defined as \(G_d = (\mathbf{D}, J, \phi, U_{d_i}, \mathbf{A}_d)\) [14], where \(\phi\) is the probability distribution over the type in \(J\), \(U_{d_i}\) is the expected payoff of D2D user \(d_i\) and \(\mathbf{A}_d\) is the preference profile of \(d_i\) for all \(d \in \mathbf{D}\).

We use a Bayesian coalition game with non-transferable utility (NTU) to model the scenario because utilities are awarded to each D2D instead of the coalitions as a whole (Chan, & Leung, 2013). The type of a D2D user \(d_i\) is contained in a set \(\{\mathbf{T}_r, \mathbf{T}_{rNI}\}\) and \(\mathbf{T}_r\) and \(\mathbf{T}_{rNI}\) represent an interfering and non-interfering D2D user respectively. We have assumed that the type of a user does not change after coalitions are formed and remain the same until an ongoing transmission is completed. The common prior probability of a D2D user \(d_i\) about the type of a D2D user \(d_i\) is given as \(\mathbf{A}_{d_i} = \phi_{ij}\) while as \(\mathbf{A}_{d_i} = \mathbf{T}_{rNI}\) = 1 - \(\phi_{ij}\). Also, \(\mathbf{A}_d\) is the preference relation of D2D user \(d_i\) over a coalition \(S\), where \(S_1 \neq d_i, S_2\) indicate that \(d_i\) prefers to be a member of coalition \(S_2\) at most as much as \(S_1\). The goal of every D2D user is to form a coalition that maximizes its payoff. A coalition partition is a set \(\mathbf{P} = (S_1, S_2, \ldots, S_k)\) which partitions all D2D users \(\mathbf{D}\), such that \(S \in \mathbf{D}\) are disjoint and \(\bigcup_{k=1}^{k} S_k = \mathbf{D}\), where \(\{S_1, S_2, \ldots, S_k\}\) are called coalitions. A coalition partition \(\mathbf{P}_i\) is Pareto efficient if there exists no other partition \(\mathbf{P}_j\), such that \(\mathbf{P}_i \neq \mathbf{P}_j\), where a D2D user is better off without making another D2D user worse off. A coalition \(\mathbf{P}_i \subseteq \mathbf{P}_j\) weakly blocks a partition \(\mathbf{P}_k\) if for some D2D users \(D \in \mathbf{D}\), and \(D \in S_i\), it holds that \(S_i \neq \mathbf{P}_i\) and for at least one D2D user \(d_i \in S_i\), we have \(S_i \neq \mathbf{P}_i\). A coalition \(\mathbf{P}_i \subseteq \mathbf{P}_j\) strictly blocks a partition \(\mathbf{P}_k\) if for all D2D users \(D \in \mathbf{D}\), and \(D \in S_i\), it holds that \(S_i \neq \mathbf{P}_i\).

We define the value \(V\) of a coalition structure as the sum of values of coalitions that are elements of that coalition structure, that is, \(V(\mathbf{P}_i) = \sum_{S \in \mathbf{P}_i} V(S)\), for all \(S \in \mathbf{P}_i, \mathbf{U}(\emptyset)\). This means that given its beliefs, no D2D user has the incentive of either acting alone or forming another coalition. It should be noted that since the preference of players is based on their expected payoff given their beliefs about other players’ types, the D2D users will always prefer to share its allocated sub-band in order to reduce the bandwidth cost paid to the operator and maximize their payoffs as given in equation (4).

\[
U_{d_i}(S, J) = b_{d_i}(J_{-d_i})[U_d(S, J) - Y_{d_i}(S, J)]
\]

\(Y\) is the cost paid by a D2D user for using a sub-band. The cost of using an exclusive sub-band is \(Y_{d_i} \leq y_s + y_g + \gamma_i\), where the cost of obtaining an exclusive sub-band is \(y_p\), while \(y_g\) is the loss of spectrum gain in the case where the coalition was impossible, and \(\gamma_i\) is the penalty paid if interference results from \(d_i\)’s use of the sub-band. The vector showing the probability distribution of D2D user \(d_i\) over the types of others in the network is \(b_{d_i}(J_{-d_i})\) and is given as:

\[
b_{d_i}(J_{-d_i}) = \Pi_{t_{-d_i} \in J_{-d_i}} \phi(t_{d_i}) = t_{d_i}
\]

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

\[
U_{d_i}(\{S_{d_i}, J_{d_i}\}, J_{-d_i}) \geq U_{d_i}(\{S_{d_i}, J_{d_i}\}, (S_{d_i}, J_{-d_i}))
\]

In other words, D2D \(d_i\)’s utility is at equilibrium if the utility for playing its best strategy \(S_{d_i}\) while others are playing their best strategy is greater or at least equal to the utility \(d_i\) gets for playing any other strategy. This means that if every other player of the game plays \(S_{d_i}(J_{-d_i})\) and \(d_i\) plays \(S_{d_i}(J_{d_i})\), then no D2D user has any motivation for changing their strategy. In the following sections, we will establish the existence of this equilibrium in our game.

**Proposition 1:** Any coalition described in Algorithm 1 will always converge to a Nash-Stable coalition structure. Proof. The sequence of shifts of the coalition formations will always converge to \(\Pi^*\) since there can be \(2^n - 1\) distinct non-empty coalitions and \(\Pi_n\) different coalition structures using Bell number. Therefore, the transformation is a finite process. If there exists a D2D user \(d_i\) which is in a coalition structure \(S_k\), such that...
\((S \cup d_i) >_d (S_j)\) where \(S_j \in \Pi_2\), then the coalition is not stable and the coalition formation process shifts from \(\Pi_1\) to \(\Pi_2\). The process will converge to a Nash equilibrium when \(d_i\) prefers its current coalition which has a higher utility to joining any other coalition with lower utility. The worst-case happens when a D2D user decides to form a singleton which is not an acceptable choice for any D2D user as shown in Proposition 2.

Proposition 2: D2D users always have a strict preference for forming a coalition \(S >_d [d_i], \forall S \in \Pi\) to forming a singleton coalition.

Proof: We show that the only time a singleton coalition is stable is when it satisfies \(V(d_i) > V(S)\), for all \(S \in \Pi\) and this case if not likely. Since the cost of sharing a sub-band is divided among members of a coalition, then no D2D user has an incentive to want to utilize the exclusive sub-band alone. This is because the cost is deducted from the payoff and a D2D user can maximize its payoff by reducing this cost through sharing of the exclusive sub-band. Since the maximum number to share a sub-band is assumed to be \(n\), then we show that \(\left| U_d(S_i, J_d) - \frac{1}{n} U_d(S_i, J_d) \right| > \left| U_d([d_i], J_o) - \frac{1}{n} U_d([d_i], J_o) \right|\), for all \(d_i \in D\). In other words, \(V(S) > V(d_i)\) and therefore the singleton is always unstable in this game. A D2D user always prefers to form a coalition whenever possible to being in a singleton.

Algorithm 1. Coalition Formation Algorithm

**INPUT:** \(d_i, S_j, \exists d_i >_d S_j\)

**OUTPUT:** Nash-stable coalition \(\Pi^*\) that maximizes \(U_d\)

**Require: Initialize** \(\Pi(t) = \{S_1(t), S_2(t), ..., S_k(t)\}, t = 0, d_j \in S_j\) and \(d_k \in S_k\)

1. **repeat** At time \(t\), \(d_j\) considers making a decision, using its preference profile, to leave coalition \(S_j(t) \in \Pi(t)\) and form a coalition \(S_j(t) \in \Pi(t) \setminus S_j(t)\) with \(d_k\) that has an exclusive sub-band. \(d_j\) computes its present payoff \(U_d(S_j(t), J(t))\) from the coalition \(S_j, d_j\) then computes its expected payoff \(U_d_d(S_j(t), J(t))\) from the coalition \(S_k, d_j\).

2. if \(U_d(S_j(t), J(t)) > U_d_d(S_j(t), J(t))\) then

3. \(d_j\) sends its request to form a coalition with \(d_k\) and share its exclusive sub-band,

4. \(d_k\) computes its payoff \(U_d_k(S_k(t), J(t))\) from the coalition with \(d_j\).

5. if \(U_d_k(S_k(t), J(t)) > U_d_d(S_k(t), J(t))\), then

6. the coalition between \(d_j\) and \(d_k\) is formed.

7. The coalition is then updated as:

\[\Pi(t + 1) = (\Pi(t) \setminus \{S_j(t), S_j(t)\}) \cup \{S_j(t), d_j\} \cup (\{S_j(t) \setminus d_j\})\]

8. else \(\Pi(t + 1) = \Pi(t)\)

9. **end if**

10. **else** \(\Pi(t + 1) = \Pi(t)\)

11. **end if** update \(t = t + 1\)

12. **until** the optimum coalition structure \(\Pi^*\) that guarantee Nash stability is obtained

3.1 Belief Updating Mechanism

In our paper, each D2D user can update its beliefs about other D2D users since this a dynamic game. The belief updating mechanism used is based on Bayes’ theorem (Gelman et al, 2013). We consider a situation where a D2D user \(d_i\) observes another D2D user \(d_j\) to determine if it is an interfering or non-interfering user. We assumed in the paper that two things are observed by the \(d_i\). The first is the received power of \(d_j\), represented as \(P_{d_j}\), which must be less than a maximum power threshold. The second object observed is the distance between \(d_i\) and \(d_j\), represented as \(d_{ij}\), which must be greater than a minimum distance threshold. If \(P_{d_j} > Power\_Threshold\), or \(d_{ij} < Dist\_Threshold\), then \(d_i\) assumes that \(d_j\) is an interfering D2D. Power\_Threshold is the maximum allowable power received by \(d_j\) from any D2D user that would like to share its exclusive sub-band while Dist\_Threshold is the minimum distance between \(d_i\) and any other D2D user that wants to share the sub-band. These thresholds are determined based on the number of observations, so they are not fixed. \(w_1\) and \(w_2\) are the probabilities that \(d_i\) attaches to the event that coalition will be formed given that \(d_j\) is an interfering or non-interfering user. Also, \(1 - w_1\) and \(1 - w_2\) are the probabilities \(d_i\) attaches to the event that coalition will not be formed given that \(d_j\) is an interfering or non-interfering user.

\(d_i\)'s belief about \(d_j\) interfering is given as:

\[
B_{d_j\_t}(I) = \frac{(1-w_1)B_{d_j\_t-1}(I) + (1-w_2)B_{d_j\_t-1}(\neg I)}{(w_1B_{d_j\_t-1}(I) + w_2B_{d_j\_t-1}(\neg I))},
\]

and \(d_i\)'s belief about \(d_j\) not interfering is given as:

\[
B_{d_j\_t}(\neg I) = \frac{(w_1B_{d_j\_t-1}(I) + w_2B_{d_j\_t-1}(\neg I))}{(w_1B_{d_j\_t-1}(I) + w_2B_{d_j\_t-1}(\neg I))}.
\]

In time slot \(t\), the D2D user \(d_j\) can then update its belief probability as the weighted sum of its belief at time slot \(t - 1\) and the new belief at time \(t\) as shown below:

\[
B_{d_j\_t}(I) = \tau B_{d_j\_t-1}(I) + (1 - \tau)B_{d_j\_t-1}(\neg I),
\]

where \(\tau\) is an adjustable weight constant based on the concept of the exponential moving average for estimating unknown parameters (Pourahmadi, 2001), such that \(0 < \tau < 1\) and \(\tau = \frac{1}{t+1}\). The D2D user \(d_i\) uses equation (9) to determine its preference profile and form a coalition that will maximize its payoff.

4 Performance Evaluation

Evaluation of the performance of our algorithm has been done by simulating a cellular network with D2D users randomly located within the coverage area served by a base station. We have considered two types of coverage areas to show the impact of the size of a coverage area and
the number of users on the performance of our proposed game model. The 50 m² coverage area has 2 CUs and 10 D2D users while the 100 m² coverage has 8 CUs and 20 D2D users. The length of a D2D link used in these simulations varies from 10 m to 20 m. Table 2 shows the values of other important parameters used in our work. The simulation was done with MATLAB. For this simulation, the cost deducted from the utility is assumed to be \( y_b = \frac{1}{0.5}, y_g = \frac{1}{0.2}, \) and \( y_l = \frac{1}{0.3}. \)

| Parameter          | Value                      |
|--------------------|----------------------------|
| Cell size          | 50 m², 100 m²              |
| \( \gamma_d, \sigma^2 \) | 2 dB, -174 dBm             |
| Carrier Frequency  | 2 GHz                      |
| System Bandwidth   | 5 MHz                      |
| Pathloss exponent  | 4                          |
| Simulation runs    | 100                        |

Table 2: Simulation Parameters and Values

We first consider D2D sub-band sharing with the random pairing method where D2Ds are randomly assigned to D2Ds with sub-bands for spectrum sharing. We later compare the performance of the random pairing method with our proposed optimal sub-band allocation coalition game. Fig. 2 and Fig. 3 show the effect of the random pairing method on the network capacity for both the 50 m² and 100 m² cells. The figures show the cumulative distribution function (CDF) for the sum rate within the network for CUs only and the D2D-enabled network.

Fig. 2: Random pairing 50 m² cell

Fig. 3: Random pairing 100 m² cell

Our analysis shows that the random pairing method performed fairly well with a smaller number of D2D users within the cell. As cell size and number of users increase, the sum-rate drops because many of the D2D users were denied spectrum access using the overlay mode and this can be seen in the comparison of Fig. 2 and Fig. 3. The 50 m² cell achieved a cell sum-rate increase of 29% with the D2D-enabled cellular communication while the 100 m² cell was able to achieve a cell sum-rate increase of just 18% with the D2D-enabled cellular communication.

Fig. 4 and Fig. 5 show the network sum-rate using our proposed sub-band allocation game. It can be observed that, compared with the random pairing method, a large number of D2D users in the network does not reduce the cell sum-rate as much compared to what was observed in the random pairing method. Results from Fig. 4 also show that the cell sum-rate achieved with D2D overlaid cellular communication in the 50 m² cell was about 86% more than cell sum-rate with CU communication only. Fig. 5 shows that, for the 100 m² cell, the increase achieved with D2D-overlaid cellular communication reduced to about 61% compared with CU communication only due to an increase in the number of users in the cell and interference constraint.

Fig. 4: Coalition game 50 m² cell

Fig. 5: Coalition game 100 m² cell

It should be noted that even the bigger cell performed well with the proposed sub-band allocation game because of the coordination offered by the algorithm. In the random pairing method, the cell sum-rate dropped by 38% as the cell size and the number of users increased. However, with our coalition game, the cell sum-rate dropped by just 25% as the cell size and the number of
users increased. Also, there was 44% and 36% increase in cell sum rate when our proposed sub-band allocation game was deployed compared to random pairing for the 50 m² cell and 100 m² cell respectively. This further validates the efficacy of our proposed game as the algorithm performed better with coordinating spectrum sharing for improved network capacity.

Fig. 6 and Fig. 7 show how the D2D transmitter power varies from the base station in the overlay mode for the 50 m² and 100 m² cells using two different D2D link distances; 10 m and 20 m. The D2D transmitter power discussed here is that used for communication with the D2D receiver in a D2D link. Generally, it was observed that the D2D transmitter power increases as the distance between the D2D transmitter and base station increases. However, D2D power allocation was better when the D2D link distance is shorter. This is due to interference constraints since the D2Ds have a higher potential of interfering with other devices in the network when the length of their link is longer. This result is particularly obvious in Fig. 6 where cell size is smaller as compared to Fig. 7 with larger cell size.

5 CONCLUSION
In this paper, we develop a spectrum sharing scheme using the Bayesian coalition game for D2D-enabled cellular networks to increase the data rate capacity of the network. Results from our numerical analysis show that our proposed sub-band allocation game was able to achieve an increase in cell sum-rate while guaranteeing interference-free communication for cellular devices.

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