Mode Selection, Power Adaptation and Channel Assignment in Device-to-Device Communication

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***Abstract*- Device-to-Device (D2D) communication is a technique that allows two devices to communicate with each other in the licensed band without the requirement of a base station. The major advantage of D2D communication is that it allows reuse of spectrum resources and thereby improves spectral efficiency. However, it has to deal with interference mitigation and resource allocation. This paper focuses on mode selection, power adaptation and channel assignment for bandwidth efficient and energy efficient D2D communication. In the scheme used here, distributed mode selection is formulated as an evolutionary game and channel allocation uses a graph theoretical approach such that interference is minimum, while power control is performed using channel inversion. The simulations show that the D2D communication improves capacity, reduces power consumption and performs effective bandwidth allocation.**

Keywords-mode selection; evolutionary game; graph theoretical approach; channel inversion.

I. INTRODUCTION

Until recent years, cellular communication was having a fixed infrastructure. However, surveys show that 5 billion devices are connected to the cellular network at present [1], global data traffic has increased to 74 % Compound Annual Growth Rate (CAGR) in 2015 and current infrastructure is unable to handle the huge traffic. As a solution to this problem, different methods were suggested [2] like: Device to device (D2D) communication, densification of Base Station (BS), cognitive radio etc. D2D communication is one among the most popular techniques that are used nowadays. In the conventional cellular communication system, even when mobile users are communicating in close proximity, they are required to follow the fixed infrastructure. This proves to be quite complex, in addition to wastage of resources. D2D communication is quite effective in such situations. A properly designed D2D network can have the following advantages [2] [3]: increase in spectral efficiency, reduced latency, increase in throughput, low power consumption, resource conservation, improved capacity etc.

The potential D2D user equipments can operate in one of the following three communication modes [4]:

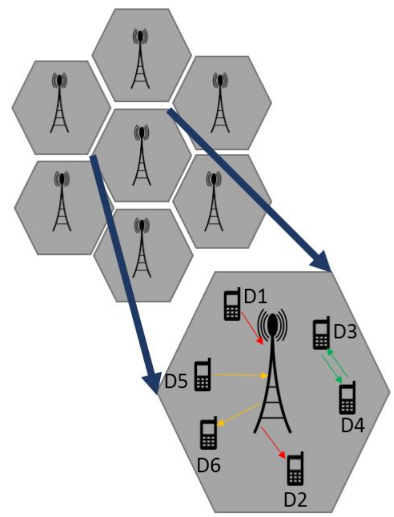

Fig. 1. System Model of D2D Communication

1) Reuse mode: In the reuse mode, the D2D users do not need a BS, instead they communicate directly. They share the resources of the cellular users or the D2D users in cellular mode who have exclusive channels allocated to them.
2) Cellular mode: In cellular mode, the D2D users use the BS to transmit just like the cellular users. Sometimes, even when the transmitter and receiver are in close proximity, a reuse or dedicated mode can not be used due to deep fades. In such cases, those D2D users use the cellular mode.
3) Dedicated mode: The D2D users in dedicated mode can communicate with or without BS but they cannot reuse the spectrum resources. So, they also require dedicated orthogonal frequency bands. This mode is preferred when the signal quality is required to be very high with no interference.

Figure 1 shows the system model where (D1, D2) transmitter-receiver pair are in cellular mode, (D3, D4) are in reuse mode and (D5, D6) are in dedicated mode.

In this paper, we propose a scheme for D2D communication

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which includes mode selection, power adaptation and channel assignment. Initially, the users are distinguished into cellular or potential D2D users based on the threshold distance. The potential D2D users will have to choose a suitable mode among the three modes, and for distributed mode selection an evolutionary game model is developed. The utility function used for the game by each user is a function of the rates of all users which are computed based on their respective modes. The transmit power used for rate calculation is a controlled power computed by suitable power control schemes. At the convergence of the evolutionary game, based on the number of users in each mode, the channel allocation is done by the BS.

The rest of this paper is organized as follows. In Section II, we provide a brief literature review on closely related existing works. In Section III, we describe the system model, problem addressed and techniques adopted for mode selection, power adaptation and channel assignment. In Section IV, we describe the simulation setup and results, thus giving a performance evaluation. Section V gives conclusion and future prospects of this work.

II. Related Work

Many works in the literature have addressed one or more of the issues of mode selection, power control and channel allocation in D2D communication. In [5] the authors discuss a joint mode selection and power allocation scheme for D2D communication. They employ an exhaustive search based mode selection, and consider the number of device pairs to be known and the utility used in this case is power efficiency, which is the ratio of capacity to total power. The problem defined is to identify the mode that maximizes the utility. However, the drawback of this model is that the D2D users are assumed to be in reuse modes only and the other possible modes are not considered.

The authors of [6] focus on channel allocation to D2D users while in reuse mode. They consider a centralised algorithm, i.e., the BS makes the decisions. The utility used for channel allocation is the achievable transmission rate of the cellular users. Ultimately, to efficiently allot the resources with minimum interference, we need to maximize the utility. For this, graph theoretical algorithms like maximum and minimum weighted bipartite matching are used and the channels are mapped to the cellular and D2D users in the cell. However, the limitation here is that they consider D2D users only in reuse mode. The cellular and dedicated mode possibilities are not considered. Moreover, there is no power control happening.

Zhu and Hossain [4] discuss an evolutionary dynamic game model for mode selection. The mode selection is first randomly done and then allowed to dynamically adapt according to the performance (average rate) and cost (spectrum access fee). In the real scenario, there is always limited rationality and the evolutionary game model gives the best solution under such situations. The payoff of each user is computed based on his strategy and that decides whether to change or not change his strategy. The steps are repeated until an evolutionary stable state is reached. Wang et al. speak of a stackelberg game in [7]. However, the limitation in these works is lack of power control and channel assignment.

In [8], an evolutionary approach for resource allocation is followed where utilities are formulated in terms of average rate, interference and cost of unit bandwidth and power consumption for each mode. However, multiple D2D users cannot be allotted to the same channel. In [9], joint mode selection, scheduling and power control are together formulated as an optimization problem. The optimization is done using a mixed integer linear programming formulation, which also does not consider all three modes of D2D communication.

This work, however, considers all three possible modes of D2D communication. A multicell scenario is considered for the analysis. But, unlike [4], we do a power adaptation which is lacking in most of the existing works. A channel assignment is also done in addition to the the mode selection using Evolutionary Game Theory (EGT). Along with guarantee on convergence through EGT, the different performance parameters like rate, transmission power, system power efficiency and system spectral efficiency are studied in this work to clearly emphasize the merits of the proposed scheme.

III. Proposed Work

A. System Model and Problem Statement

We consider uplink communication in a multicell scenario with focus on a single cell having a single BS at its centre. There are 'N'number of transmitting users whose positions within the cell are characterized by a Poisson Point Process (PPP) [4]. This PPP model is represented by: $\phi = \{(X_i, y_i)\}$ where X_i gives the spatial location of i^{th} transmitting user and y_i gives the location of receiver of i^{th} transmitting user X_i. The Euclidean distance between the transmitter and the receiver is calculated as D_i=$\|Xi - yi\|$. Based on the distance between transmitter and receiver, the cellular and D2D users can be distinguished. If the Euclidean distance between the transmitting user and its receiver is greater than a threshold distance, then he becomes a cellular user; otherwise, he becomes a potential D2D user. The potential D2D users have to choose one of the three possible modes, namely, cellular mode, reuse mode and dedicated mode. Here a distributed mode selection is done. The populations in cellular, reuse and dedicated modes at any instant are denoted by x_c, x_r and x_d, respectively; and the population state by $\mathbf{x} = (x_c, x_r, x_d)$. The density of users in each mode can be given as in [4]. We consider a general path loss model along with Rayleigh fading. So, the fading channel power gain is exponentially distributed.

In an attempt to enhance the spectral and energy efficiency, we develop a game model for mode selection in D2D communication using evolutionary game theory and also perform a power adaptation using a suitable scheme. This information of population state on convergence of the game is used to model the channel allocation using graph theoretic models. Finally, the performance of this model in doing mode selection, power allocation and channel allocation need to be analyzed in terms on transmission power, rate etc. The notations used in the following subsections are summarized in Table 1.

TABLE I
MAJOR SYMBOLS USED IN THE PAPER

Symbol	Definition
X_i	spatial location of i^{th} transmitting user
yi	location of receiver of the i^{th} transmitting user
D_i	Euclidean distance between transmitter and receiver of i^{th} user
I_c^l	interference experienced by a cellular user on channel ‘l ’
P_r	transmit power of potential D2D user in reuse mode
$g_{0,i}$	fading gain from interferer ‘i ’to target receiver
η	path loss exponent
P_c	transmit power of cellular mode user
ϕ_r^l	set of potential D2D users in reuse mode who cause interference to cellular user on channel ‘l ’
$\hat{\phi}_c^l$	set of potential out of cell interferers who cause interference to cellular user on channel ‘l ’
R_c	random variable that denotes the distance between target receiver and its transmitter
h_c	fading gain between target receiver and its transmitter
W	noise power
μ	parameter of exponential fading channel power gain
υ	threshold SINR
λ_r^l	density of users in reuse mode on channel ‘l ’
λ_b	density of BSs in the multicell scenario
B	amount of bandwidth for each subchannel
F_c	amount of spectrum for cellular users
$E(N_c(A))$	mean number of users in cellular mode
I_r^l	interference experienced by a reuse mode user on channel ‘l ’
D	random variable that denotes the distance between D2D transmitter and receiver
ξ	learning rate
k	number of channels reused
p	medium access probability
F_d	amount of spectrum for dedicated users
$E(N_d(A))$	mean number of users in dedicated mode
$\mathbf{x}$	population state
$\tau_i(x)$	data rate of user using strategy ‘i ’
c_i	access fee for strategy ‘i ’

B. Rate analysis for different D2D communication modes

Initially, the D2D users have all been randomly assigned a mode and corresponding to their mode, the rate of each D2D user needs to be computed. It is to be noted that the D2D users in cellular mode suffer from interference due to D2D users in reuse mode who are using the same channel and also due to out of cell cellular interferers who are using the same channel. Likewise, the D2D users in reuse mode suffer interference from cellular users whose channel is being reused and also from other reuse mode users who reuse the same channel. However, the dedicated mode users suffer no interference. The rate analysis for different communication modes is done to compute the average rate achieved by users, following the approach in [4].

In cellular mode, the net interference of a user on channel *‘l’* due to reuse mode users and out of cell interferers is given by (1).

$$I_c^l = \sum_{X_i \epsilon \phi_r^l} P_r g_{0,i} \|X_i\|^{-\eta} + \sum_{X_i \epsilon \hat{\phi}_c^l} P_c g_{0,i} \|X_i\|^{-\eta} \qquad (1)$$

It is to be noted that the target receiver is the BS, whose location is assumed to be at the origin. Signal-to-interference-plus-noise ratio (SINR) can be computed as:

$$SINR_c^l = \frac{P_c h_c r_c^{-\eta}}{W + I_c^l} \qquad (2)$$

The expected value of Shannons rate with respect to the different random variables involved is given by:

$$\bar{\tau}_c = E_{R_c, h_c, g_{0,i}, \phi_r^l, \hat{\phi}_c^l}\left[log\left(1 + SINR_c^l\right)\right] \qquad (3)$$

Therefore, the average spectrum efficiency can be computed using (4):

$$\bar{\tau}_c = \int_0^\infty \frac{p_c\left(\lambda_r^l, \upsilon\right) d\upsilon}{1+\upsilon} \qquad (4)$$

where $p_c\left(\lambda_r^l, \upsilon\right)$ can be derived as:

$$\begin{aligned} & p_c\left(\lambda_r^l, \upsilon\right) \\ & = \int_0^\infty exp\left(\frac{-W\mu\upsilon r_c^\eta}{P_c}\right) exp\left(-\lambda_r^l r_c^2 \left(\frac{\upsilon P_r}{P_c}\right)^{\frac{2}{\eta}} K(\eta)\right) \\ & \quad exp\left(-2\pi\lambda_B \int_R^\infty \left(1 - \frac{\mu}{\mu + sP_c t^{-\eta}}\right) tdt\right) f_{R_c}(r_c) dr_c \end{aligned} \qquad (5)$$

where,

$$K(\eta) = \frac{2\pi^2}{\eta sin(\frac{2\pi}{\eta})} \qquad (6)$$

$$s = \frac{\mu\upsilon r_c^\eta}{P_c} \qquad (7)$$

$$f_{R_c}(r_c) = \frac{2r_c}{R^2}, if: x\epsilon[0, R] \qquad (8)$$

Equation (8) gives the Probability Density Function (pdf) of the distance from any user to the BS located at the centre, for the PPP model of the user distribution. The expected amount of spectrum resource allocated to cellular users is given by:

$$B_c = \frac{F_c B}{E(N_c(A))} \qquad (9)$$

Therefore, the average rate for a user in cellular mode is given by:

$$\tau_c = B_c \bar{\tau}_c \qquad (10)$$

Similarly, in reuse mode, the net interference of a user on channel *‘l’* from cellular users whose channel is being reused and other reuse users who also reuse the same channel is computed. Accordingly, the interference at the receiver is given by :

$$I_r^l = \sum_{X_i \epsilon \phi_c^l} P_c g_{0,i} \|X_i\|^{-\eta} + \sum_{X_i \epsilon \phi_r^l \backslash \{0\}} P_r g_{0,i} \|X_i\|^{-\eta} \qquad (11)$$

The average spectrum efficiency is then found as:

$$\bar{\tau}_r = \int_0^\infty \frac{p_r\left(\lambda_r^l, \upsilon\right) d\upsilon}{1+\upsilon} \qquad (12)$$

where $p_r\left(\lambda_r^l, \upsilon\right)$ can be derived as:

$$\begin{aligned} & p_r\left(\lambda_r^l, \upsilon\right) \\ & = \int_0^\infty exp\left(\frac{-W\mu\upsilon d^\eta}{P_r}\right) exp\left(-\lambda_r^l d^2 \upsilon^{\frac{2}{\eta}} K(\eta)\right) \\ & \quad exp\left(-\lambda_B d^2 \left(\frac{\upsilon P_c}{P_r}\right)^{\frac{2}{\eta}} K(\eta)\right) f_D(d) d_d \end{aligned} \qquad (13)$$

where,

$$f_D(d) = 2\pi\xi d e^{-\xi\pi d^2}, d \geq 0 \qquad (14)$$

which is the Rayleigh pdf of the distance between a potential D2D tx-rx pair, for the PPP model of the user distribution.

The expected amount of spectrum resource for users in reuse mode is given by :

$$B_r = kpB \tag{15}$$

where, *k* is the number of channels reused and *p* is the medium accesss probability. Hence, the rate is given by :

$$\tau_r = B_r \bar{\tau}_r \tag{16}$$

In dedicated mode, however, there is no interference since the channel is dedicated completely for that D2D user. Hence, SINR is reduced only due to noise and no interference. The average spectrum efficiency is obtained as:

$$\bar{\tau}_d = \int_0^\infty \frac{p_d\left(\lambda_r^l, \upsilon\right) d\upsilon}{1+\upsilon} \tag{17}$$

The expected amount of spectrum resource for users is:

$$B_d = \frac{F_d B}{E(N_d(A))} \tag{18}$$

Therefore, the rate of transmission is:

$$\tau_d = B_d \bar{\tau}_d \tag{19}$$

C. Mode selection using EGT

For mode selection using evolutionary game, we choose a payoff function which depends on the average achievable rate as well as the cost [4]. The payoff (utility) is given as:

$$U(i,x) = \bar{w}(\tau_i(\mathbf{x})) - c_i \tag{20}$$

where c_i is the price of access per user per unit of time. '*i*'represents the strategy (mode) chosen by the user which can be c, r or d. '**x**'represents the population state and $\bar{w}(\tau_i(\mathbf{x}))$ is $\alpha\tau_i(\mathbf{x})$ where 'α' is a constant and $\tau_i(\mathbf{x})$ is the rate of user using strategy *i*. Using Equations (10) or (16) or (19) the payoff for each user is computed based on his chosen mode. After that, each user sends his utility information to the BS through a control channel and the average population payoff is computed by the BS and broadcast to all potential D2D users. If the payoff of the user is less than the average, then the user randomly selects from the modes other than his present mode such that the payoff is greater than the average payoff. These steps are repeated iteratively until the population state reaches an evolutionary stable state. The corresponding strategy is called the evolutionary stable strategy (mode) for each potential D2D user.

D. Power Control

In this work, a channel inversion is used for power control. The channel inversion method helps to compensate for large scale path loss, but not small scale fading. The main advantage of channel inversion is that it reduces the transmit power consumed by good links and gives more transmit power to only poor links. Also, by means of channel inversion, we can determine the transmit power with limited channel state information. Here, we assume that the received power is unity [10].

E. Channel Allocation

We assume that the channel gain of each cellular mode user is known at the BS so that the maximum bipartite matching can be used to allocate channels to all the cellular mode users. Whatever channels are not allocated to the cellular mode users and are free can now be allocated to the dedicated mode users using again maximum bipartite matching. Further, to allocate channels to the D2D users in reuse mode, we make use of the minimum weighted bipartite matching algorithm. The reuse mode users will be allocated channels that are already allocated to the cellular mode users. However, the channels allocated to the dedicated mode users will not be available for reuse [6].

Bipartite matching is a matching between two sets of vertices such that every edge has one end point in one set and the other end point in the other set. A perfect matching has a maximum number of edges matched between the two sets such that there is a minimum number of free nodes in each set. Maximum matching M is one in which the total weight of selected edges $W_M >$ weight of edges of any other matching M'. Minimum matching M is one in which the total weight of selected edges $W_M <$ weight of edges of any other matching M'. For the maximum bipartite matching algorithm used for channel allocation of cellular mode and dedicated mode users, edge weights are channel gains. And for the minimum bipartite matching algorithm used for reuse mode users, edge weights are the interferences.

IV. NUMERICAL RESULTS

The analysis has been done for the D2D network that has incorporated the algorithms described, and the simulation parameters are listed in Table 2 [4] [10].

TABLE II
SIMULATION PARAMETERS

Radius of the cell *R*	500m
Total number of users *N*	40
Total number of channels	40
Out of cell interferers	5
Mode selection threshold distance D_{th}	150m
Intensity of BS λ_b	$\left(\pi 500^2\right)^{-1} m^{-2}$
Intensities of user equipments λ	100x$\left(\pi 500^2\right)^{-1} m^{-2}$
access fee $[c_c, c_r, c_d]$	$[.2, 0, .5]$
mean of exponential distribution μ	1
D2D distance parameter ξ	10x$\left(\pi 500^2\right)^{-1} m^{-2}$
medium access probability p	1
path loss exponent η	3
Bandwidth of each subchannel B	180KHz
Noise power W	-90dBm

The evolution of population state of all users during mode selection is shown in Figure 2. The initial population of D2D users in each mode is assumed to be known. Using Equation (20) the population state evolves with time. In Equation (20) the values of c_i are chosen such that D2D users will have more incentive to move into the reuse or dedicated rather than the cellular mode. This is because the reuse mode can exploit the proximity gain to achieve a higher average rate

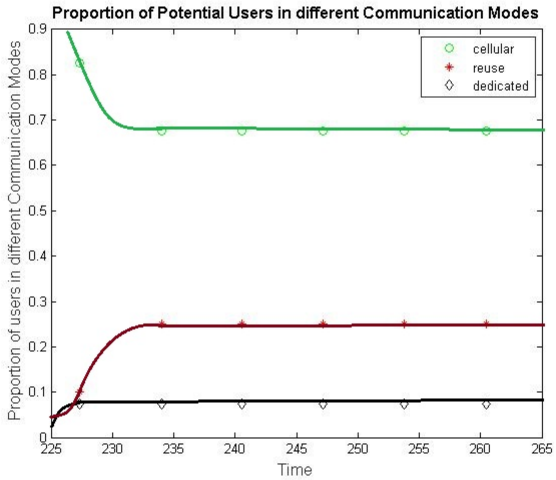

Fig. 2. Proportion of users in each communication mode

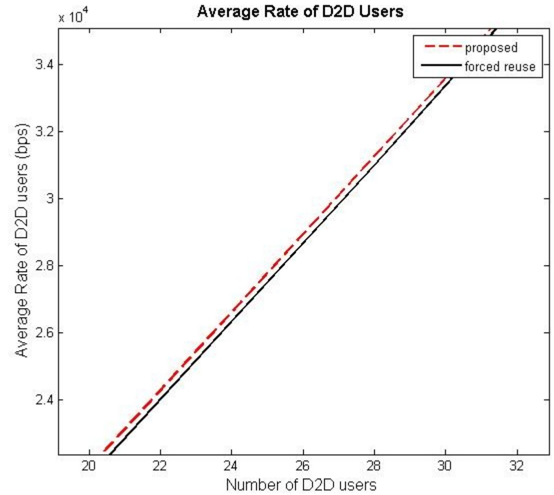

Fig. 4. Average Rate of D2D users

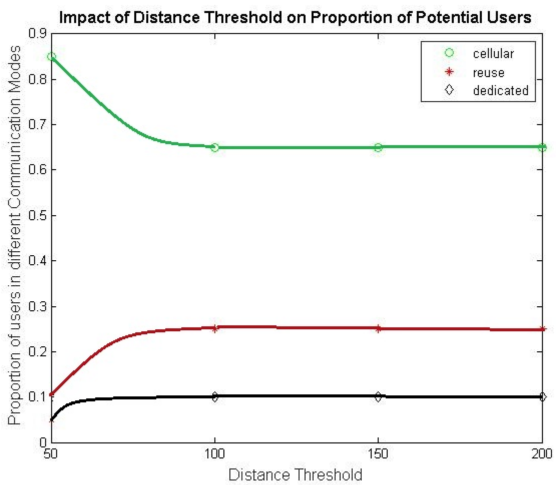

Fig. 3. Impact of distance threshold on proportion of users in different modes

and better spectral efficiency than cellular mode, while using dedicated mode can achieve the best performance. Therefore, the reuse and dedicated modes are the dominant modes in D2D users. Hence, the plots are increasing for reuse and dedicated mode and decreasing for cellular mode. Soon, the population converges to equilibrium at which no user has the incentive to deviate.

The impact of distance threshold on proportion of users in different modes is shown in Figure 3. The threshold distance decides the number of users in cellular and D2D modes. When the threshold distance increases, users who are currently cellular users become D2D users. Since reuse and dedicated modes are dominant, the number of users in these modes increases initially and converges to equilibrium. Similarly, the cellular mode is a dominated strategy and, hence, the population of users in cellular mode decreases.

In Figure 4, we plot the average rate of the D2D users and we see that the average rate in the proposed scheme is much higher than the forced reuse scheme, clearly due to the presence of dedicated mode users in the former. Figure 5 shows that the transmission power decreases when more D2D users arise. This is because transmission power is higher for cellular and dedicated mode than reuse mode according to the power control. In case of forced reuse mode, all D2D users are in reuse and hence the power largely decreases. If we plot the bandwidth utilization, it is clearly a decreasing curve because the bandwidth is consumed only by the cellular and dedicated mode users and as the number of D2D users increase, the population in cellular mode decreases while the population in reuse and dedicated modes increases. However, for a forced reuse mode, bandwidth is consumed only by the cellular users. Likewise, in Figures 6 and 7, we observe increasing plots for system power efficiency (ratio of average data rate to total power) and spectral efficiency (ratio of average data rate to total bandwidth) due to the same reasons. In both the case of spectral efficiency and power efficiency, we see that the proposed scheme gives a better performance.

We consider the total number of users as 40 which includes both cellular (C) and D2D users. They are divided into 28 cellular and 12 D2D users using threshold distance. By mode selection, we can identify the number of D2D users in the respective modes-cellular mode (Cd), dedicated mode (Dd) and reuse mode (Rd). We also consider out of cell interfering cellular users (OE). On reaching the equilibrium of the evolutionary game, all the 28 cellular users are in cellular mode, while the D2D users do not go to cellular mode, instead they prefer reuse and dedicated modes and split into 7 D2D users in reuse mode and 5 D2D users in dedicated mode. The resulting channel allocation is shown in Table 3.

V. Conclusion

In this paper, we have investigated some of the problems faced when D2D communication happens in the licensed band; in particular, the mode selection, power adaptation and

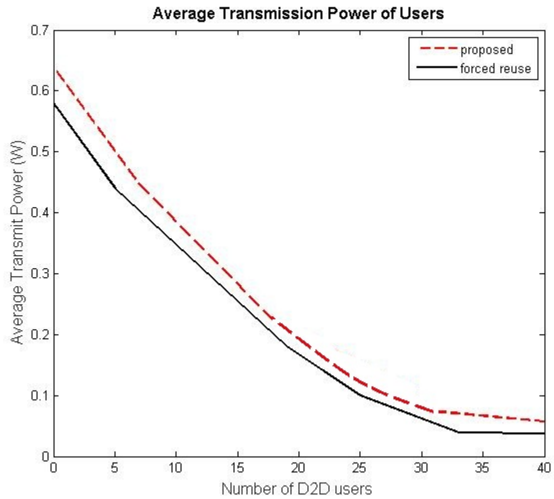

Fig. 5. Average Transmission power of users

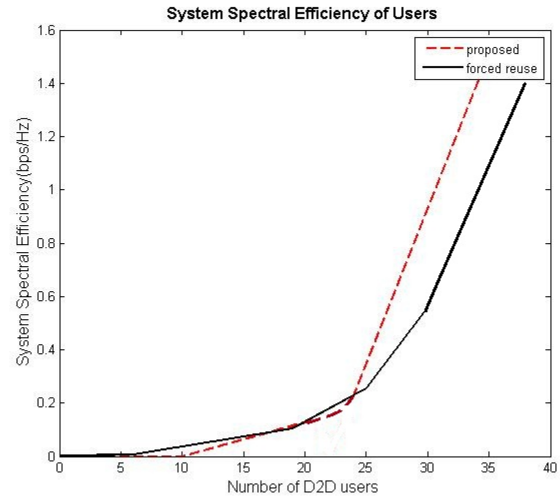

Fig. 7. System Spectral Efficiency of users

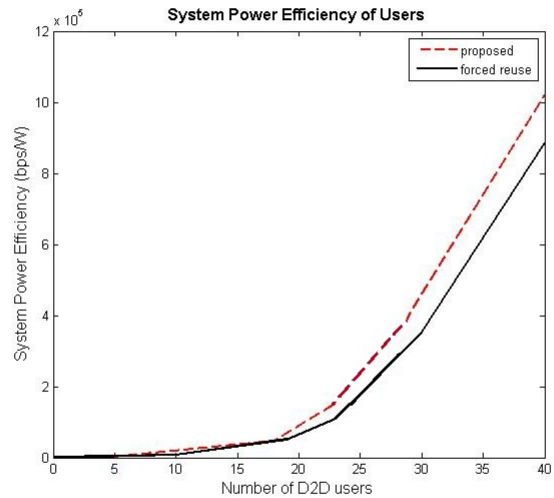

Fig. 6. System Power Efficiency of users

TABLE III
CHANNEL ALLOCATION

Channel	User	Channel	User
1	C6	21	C3
2	C5	22	C24
3	C13	23	C26
4	C11	24	C14,Rd6
5	C21,Rd3	25	NOT USED
6	C4,Rd7	26	C9,Rd2
7	C2	27	O4
8	NOT USED	28	C15
9	O3	29	Dd4
10	Dd2	30	C17
11	C23	31	NOT USED
12	C22	32	C8,Rd1
13	C16	33	C10
14	O2	34	C1
15	C25,Rd4	35	C27
16	C19	36	C12
17	C28,Rd5	37	O1,Dd5
18	O5	38	Dd3
19	C18	39	Dd1
20	C20	40	C7

channel assignment. We formulated the mode selection as an evolutionary game under a multicell scenario. The advantage of using evolutionary game model was that it gave room for each user to gradually adapt until it reaches the stable strategy. To save the total transmit power, we have adopted a channel inversion method. Channel allocation was done using a simple graphical approach. Simulation results showed the following. The average rate of D2D is very large for the proposed scheme compared to a forced reuse scheme. Average transmission power is a decreasing function for the scheme and so the system power efficiency is increased for our scheme compared to the pure reuse scheme. However, if we consider the bandwidth usage, the proposed scheme consumes more bandwidth due to the presence of dedicated mode users but is less compared to the high data rate hence achieving better spectral efficiency.

This work can further be improved by introducing the idea of spectrum partitioning so that we can partition the amount of spectrum available to the cellular and dedicated users. Power adaptation can also be done using improved algorithms rather than channel inversion.

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