Joint Resource Allocation for Cellular and D2D Multicast Based on Cognitive Radio

Xiaolu Wu[1], Yueyun Chen[1]
[1] School of Computer and Communication Engineering, University of Science and Technology Beijing (USTB),
Beijing, 100083, China
[e-mail: chenyy@ustb.edu.cn]
*Corresponding author: Yueyun Chen

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Abstract

Device-to-device (D2D) communication is an excellent technology to improve the system capacity by sharing the spectrum resources of cellular networks. Multicast service is considered as an effective transmission mode for the future mobile social contact services. Therefore, multicast based on D2D technology can exactly improve the spectrum resource efficiency. How to apply D2D technology to support multicast service is a new issue. In this paper, a resource allocation scheme based on cognitive radio (CR) for D2D underlay multicast communication (CR-DUM) is proposed to improve system performance. In the cognitive cellular system, the D2D users as secondary users employing multicast service form a group and reuse the cellular resources to accomplish a multicast transmission. The proposed scheme includes two steps. First, a channel allocation rule aiming to reduce the interference from cellular networks to receivers in D2D multicast group is proposed. Next, to maximize the total system throughput under the condition of interference and noise impairment, we formulate an optimal transmission power allocation jointly for the cellular and D2D multicast communications. Based on the channel allocation, optimal power solution is in a closed form and achieved by searching from a finite set and the interference between cellular and D2D multicast communication is coordinated. The simulation results show that the proposed method can not only ensure the quality of services (QoS), but also improve the system throughput.

Keywords: Device-to-device Communication, resource allocation, D2D multicast group, cognitive radio, underlay.

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1. Introduction

With the rapid development of all kinds of services offered by Long Term Evolution (LTE), a huge challenge is to utilize the scarce wireless resources to satisfy the demand of the quality of services (QoS). Improving the spectrum efficiency is one effective method.

D2D technology can improve resource utilization by establishing direct links between terminals without base station (BS) forwarding. The next-generation wireless communication systems, such as LTE-Advanced and Wimax, allow D2D communication as an underlay to the cellular network to improve the spectrum efficiency [1]. Meanwhile, as a more general transmission mode, wireless multicast can offer higher radio resource efficiency for transmitting packets from a single sender to multiple receivers at the same wireless resource than unicast [2]. As radio resources become more and more stringent, multicast techniques have drawn a lot of interests and been applied in various systems [3]. Therefore, multicast service supported by D2D communication enables network resource sharing, which means that the advantages of multicast delivery over multiple unicast deliveries are significant.

Moreover, many studies have shown that the utilization of licensed spectrum is very low [4], and cognitive radio (CR) plays as a promising technology to improve the utilization of licensed spectrum [5][6]. Secondary users (SUs) sense the spectrum conditions and seek to overlay or underlay its signals with those of the primary users (PUs), which improves the spectrum utilization effectively [7][8]. In traditional D2D communications, D2D users can only utilize the temporally idle spectrum to avoid collisions. It's natural to think that D2D with CR function is able to improve the spectrum resource utilization more effectively than conventional D2D technology by dynamic establishment of the transmission links with the help of cognitive terminals. In this paper, we focus on multicast, a more general transmission mode, and investigate the resource allocation algorithm for cognitive D2D underlay multicast communication and cellular communication.

In this paper, we analyze a single cell environment with its BS capable of allocating the best power resource for cellular and D2D underlay multicast communications. A resource allocation optimization method for cellular and D2D multicast communications that D2D users reuse the resources of cellular users is proposed. First we propose a channel allocation method to reduce the interference from cellular to multicast group. The method considers all possible allocation permutations and selects the one that yields the best system performance depending on the channel instantaneous signal to interference plus noise ratio (SINR) between cellular users and D2D multicast users. Then, based on the channel allocation, to maximize the total system throughput under the condition of interference and noise impairment, the optimal transmitting power allocation for the cellular and D2D multicast communication is formulated. The power of cellular users and D2D users are allocated jointly so the effect of interference between D2D communication and cellular communication is coordinated and the system capacity is able to obtain the maximum value. Our work extends the throughput-maximizing power control by giving a minimum service constraint, namely a minimum acceptable SINR of the BS for both users to mitigate the interference and guarantee the quality of services (QoS). This optimization problem is a non-linear programming. It is proven that the optimal power allocation scheme resides on finite possible solutions.

The major contributions of this paper are summarized as follows: 1) The proposed cognitive multicast scheme based on D2D technology is quite different from traditional D2D unicast. 2) The proposed optimized model CR-DUM is a novel model and is well adapted to underlay multicast. 3) By searching from a finite set, a method is adopted to obtain the optimal solution for the proposed problem CR-DUM with low complexity.

The rest of this paper is organized as follows. The related works are introduced in Section II. In Section III we present the system model for D2D underlay multicast communication sharing the resources of the cognitive cellular networks, and formulate the optimal transmitting power allocation for the cellular users and D2D multicast users. The channel allocation schemes and the algorithm of optimal power allocation model for both cellular user and D2D multicast group are introduced in Section IV. In Section V we present and discuss the simulation results. Finally conclusions are drawn in Section VI.

2. Related Work

Recent studies of D2D communication have been more focused on interference coordination between cellular users and D2D unicast users. To control the D2D-to-cellular (D2C) interference, [9] proposed to control the maximum transmit power of the D2D transmitter. To mitigate the cellular-to-D2D (C2D) interference, [10] designed an interference cancellation scheme employing retransmission by the base station. [11] proposed a power optimization to maximize the sum-rate of the cellular and D2D links considering the interference in both directions. [12] showed that by proper power control the interference between cellular communication and D2D communication can be coordinated to benefit the overall performance assuming the cellular network has controlled over the transmit power and the radio resources of D2D links. [13] proposed a practical and efficient scheme for generating local awareness of the interference between the cellular and D2D terminals at the base station, which then exploited the multi-user diversity inherent in the cellular network to minimize the interference. In [14], three D2D resource allocation methods were discussed and the mode selection procedure which can ensure a reliable D2D communication with limited interference to the cellular network was proposed. Optimum resource allocation and power control between the cellular and D2D connections that share the same resources were analyzed in [15] for different resource sharing modes. A novel resource allocation method that D2D users reuse the resources of more than one cellular user was proposed in [16]. [17] proposed a distance-constrained resource-sharing criterion (DRC) for device-to-device communications underlaying cellular systems to mitigate the interference from cellular transmissions to the D2D link. [18] investigated how to employ D2D communication and cognitive radio technology in cellular networks to jointly optimize spectrum utilization.

All the literatures above mentioned focused on how to employ D2D communication in cellular network with limited interference for ordinary unicast mode. A joint sub-carriers and power allocation model based on D2D for general cognitive radio multicast is proposed for Orthogonal Frequency-Division Multiplexing (OFDM) LTE systems in [19]. [20] investigated a D2D multicast group and an interference coordination scheme for D2D multicast in cellular networks. However, while we consider underlay multicast and optimal power allocation scheme, [19] discussed the resource allocation for overlay multicast and the proposed allocation scheme in [20] is not optimal.

What' more, studies of D2D communication only focused on how to allocate the power resources for the D2D user. However, resource allocation always refers to channel and power allocation. The problem of channel selection is also very important, and several literature addressed this topic. Opportunistic spectrum access (OSA), which mainly builds on the cognitive radio technology, has been regarded as a promising solution to lessen the spectrum scarcity problem. [21] investigated the problem of distributed channel selection using a game-theoretic learning solution in an opportunistic spectrum access system and formulated the channel selection problem. [22] investigated the problem of achieving global optimization for distributed channel selections in cognitive radio networks, using game theoretic solutions. A survey of decision-theoretic solutions for channel selection and access strategies for OSA system is presented in [23]. However, existing solutions may not be applied to our system where limited interference scenarios and multicast users are considered. Therefore, in this paper we propose a channel selection method for D2D underlay multicast communication.

Although various studies have been carried out, we are yet to find a method that fully satisfies user requirements while allocating resources effectively. Therefore, in the next section, we propose a resource allocation mechanism that can maximize the performance of the network system while still meeting the user requirements as much as possible.

3. System Model and Problem Formulation

3.1. System Model

We consider a cognitive cellular system with N cellular users (CUEs) as primary users (PUs) and multiple D2D users (DUEs) as secondary users (SUs) in a cell, some of the SUs forming one D2D multicast group to employ D2D multicast communication, as shown in **Fig.1**. We analyze one D2D multicast group and similar analysis can be used for the scenario with more than one D2D multicast group. In the multicast group, we assume that there are one D2D source terminal D_T, and M users as receivers DR_m (m=1,2,…M), which are independently identically distributed (i.i.d) in the area. Note that SUs can either utilize the idle spectrum to set up cellular communication via base station (BS mode) or employ D2D communication using the spectrum of a certain PU with constrained interference (D2D mode) due to the lack of idle spectrum. If SUs utilize the idle spectrum to communicate, it will cause no interference to each other and the analysis is simpler. If SUs employ D2D communication occupying the resources of PUs due to the lack of spectrum, interference between cellular users and D2D users will occur. Hence, we focus on SUs reusing the resources of PUs and analyze the interference. We assume the channel state information (CSI) of all the involved links at the BS so that the BS is capable of coordinating the resources and the transmission power. In this system, some of the SUs which are employing D2D multicast communication form a D2D multicast group. One group only reuses one PU's resource. When the multicast users are willing to establish a D2D multicast communication link, user D_T sends the D2D setup request information to the BS through a common control channel. Then the BS feedbacks the D2D transmission information and allocates the channel and transmission power.

Note that resource sharing operates in both uplink (UL) and downlink (DL) resources of the cellular user. Without loss of generality, we analyze the UL interference scenario and similar analysis can be used for DL interference scenario. The UL interference scenario is shown in **Fig. 1**.

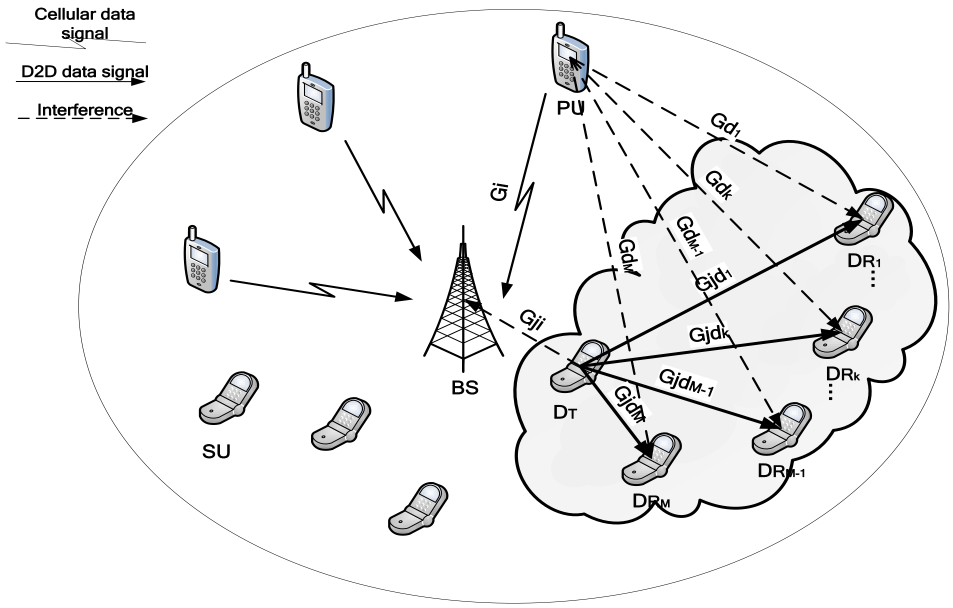

Fig. 1. System model of the cognitive cellular network with D2D underlay multicast groups

3.2 Problem Formulation

Assuming the transmitted symbols to be independent random variables with zero mean and unit variance, the signal to interference plus noise ratio (SINR) for the cellular user is given by

$$SINR_i = \frac{P_i G_i}{\sigma^2 + P_j G_j} \tag{1}$$

where G_i is the channel gain of PU$_i$, G_j is the undesired interference link gain of SU$_j$ to BS. The channel gains are assumed to be constant over each arbitrary time slot. Consider that the channel link is composed of large-scale path loss and statistically independent small-scale quasi-static frequency selective Rayleigh fading [24], so the channel gain is $G_{ab} = L|h_{ab}|^2 d_{ab}^{-\theta}$, where h_{ab} and d_{ab} are the channel coefficient and the Euclidean distance between nodes a and b, respectively, L is a constant that depends on the environment, and θ is the path loss exponent. L and θ are assumed to be a constant for all communication links although they may vary for each link.

Since there are M receivers in D2D multicast group, the multicast capacity is restricted by the terminal with the worst channel condition. That means the weakest link is the one that dominates the end-to-end instantaneous SINR performance. In order to formulate the capacity, first BS allocates the channel for the D2D multicast based on the channel allocation method, and then selects the minimum SINR. The SINR of the D2D multicast communication is expressed as

$$SINR_j = \min\left(\frac{P_j G_{jd_1}}{\sigma^2 + P_i G_{id_1}}, \frac{P_j G_{jd_2}}{\sigma^2 + P_i G_{id_2}}, \cdots \frac{P_j G_{jd_m}}{\sigma^2 + P_i G_{id_m}}\right) \tag{2}$$

where $G_{jd_m} (m = 1, 2, ..., M)$ is the channel gain of D$_{\mathrm{T}}$ to D$_{\mathrm{Rm}}$, $G_{id_m} (m = 1, 2, ..., M)$ is the interference link gain from cellular to D$_{\mathrm{Rm}}$.

Under the assumption that capacity-achieving codes for AWGN channels are employed, we define the achievable throughput of PU$_i$ and SU$_j$ by applying the Shannon capacity formula [25],

$$\begin{aligned} R &= R_i + R_j \\ &= B_i \cdot \log_2\left(1+\frac{P_iG_i}{\sigma^2+P_jG_j}\right) + M \cdot B_i \cdot \log_2\left(1+\min\left(\frac{P_jG_{jd_1}}{\sigma^2+P_iG_{id_1}}, \frac{P_jG_{jd_2}}{\sigma^2+P_iG_{id_2}}, \cdots \frac{P_jG_{jd_m}}{\sigma^2+P_iG_{id_m}}\right)\right) \end{aligned} \tag{3}$$

where B_i is the bandwidth used by PU$_i$, R_i and R_j are the throughput of PU$_i$ and SU$_j$, respectively. Note that there are M receivers in the multicast group, so the total throughput of multicast group is M times the throughput of the worst user.

To facilitate analysis, then

$$R(P_i,P_j) = R_i + R_j = B_i \log_2\left((1+\Gamma_i)(1+\Gamma_j)^M\right) \tag{4}$$

$$\Gamma_i = \frac{P_iG_i}{\sigma^2+P_jG_j} \tag{4a}$$

$$\Gamma_j = \min\left(\frac{P_jG_{jd_1}}{\sigma^2+P_iG_{id_1}}, \frac{P_jG_{jd_2}}{\sigma^2+P_iG_{id_2}}, \cdots \frac{P_jG_{jd_m}}{\sigma^2+P_iG_{id_m}}\right) \tag{4b}$$

where Γ_i and Γ_j are the SINR of PU$_i$ and SU$_j$, respectively.

Finally, we consider the optimization problem for our system model. Since the power is limited, we assume that the maximum power of PUs and SUs are $P_{\max}$ and $P'_{\max}$, respectively. When SUs reuse the resources of PU, PUs' SINR may be decreased. Therefore, we give a priority to the PUs, by considering a minimum limit for transmission data rate that guarantees PUs QoS, which is achieved at a SINR of γ_p. We also assume a minimum transmission data rate of D2D multicast communication which is achieved at a SINR of γ_s in order to ensure fairness.

We maximize the total throughput of PU$_i$ and SU$_j$ as the goal of power control method, and then the optimization problem of transmission power is formulated as:

$$\begin{gathered} (P_i^*, P_j^*) = \arg \max_{(P_i,P_j)\in\Phi} R(P_i,P_j) \\ \text{s.t. } \Phi = \left\{(P_i,P_j) : P_{\min} \le P_i \le P_{\max}, 0 \le P_j \le P'_{\max}, \Gamma_i \ge \gamma_p, \Gamma_j \ge \gamma_s\right\} \end{gathered} \tag{5}$$

where $\Gamma_i \ge \gamma_p, \Gamma_j \ge \gamma_s$ constrain the interference caused by D2D multicast communication and cellular communication, respectively.

4. Resource Allocation Algorithm

In this section, we derive the optimal transmitting power of PU$_i$ and SU$_j$ for two communication services. However, the power allocation is based on the channel allocation. Therefore, we divide this section into two parts. First, we propose the channel allocation method. Second, we derive the optimal power for cellular and D2D communications.

4.1 Channel Allocation

When the multicast users are willing to establish a D2D multicast communication link, how to select the appropriate channel for D2D multicast to avoid the interference is the problem addressed in this section.

In the multicast group, D$_\text{T}$ as the cognitive user selects a free channel if available, and it will cause no interference, so D_T can transmit at the maximum power, i.e. $P_j = P'_{\max}$. If there isn't any free channel, then BS selects a channel occupied by a CUE for D_T.

The channel instantaneous SINR of the D2D multicast communication suffered from the interference between the CUEs and the receivers in D2D multicast group, namely $\Gamma_{C_iD_m}\left(for\, i = 1,2,\cdots\right.$ $\cdots$ can be calculated as

$$\Gamma_{C_iD_m} = \frac{P_j G_{jd_m}}{\sigma^2 + P_i G_{id_m}} \tag{6}$$

where P_i and P_j are the transmitting power of PU_i and SU_j, respectively, σ^2 is the variances of the independent zero-mean additive white Gaussian noise (AWGN), G_{jd_m} is the channel gain of D_T to D_{Rm}, G_{id_m} is the interference link gain from cellular to D_{Rm}. D_{Rm} (m=1,2,…M) is the user in the multicast group.

The objective here is to optimize the end-to-end instantaneous SINRs. Since there are M receivers in D2D multicast group, the weakest link is the one that dominates the end-to-end instantaneous SINRs performance. Therefore, the optimal channel allocation scheme is the one that results in the best channel among the weakest ones.

When calculating $\Gamma_{C_iD_m}$, BS does not allocate the power for D_T at that time. P_i can be the previously transmitting power of the PU_i. And note that P_j is the same in the SINRs expression, to facilitate the calculation, we give $P_j = P_0$ and modify the end-to-end instantaneous SINRs as $\Gamma_{C_iD_m} = \frac{P_0 G_{jd_m}}{\sigma^2 + P_{C_i} G_{id_m}}$. Then $\Gamma_{C_iD_m}\left(for\, i = 1,2,\cdots\right.$ $\cdots$ can be calculated.

To elaborate, let Ψ be the set containing all channel allocation permutations. We consider N CUEs in the cellular mode, thus the set ψ contains N elements. Each element of Ψ consists of all end-to-end instantaneous SINRs, corresponding to one CUE. To simplify the presentation, let ψ_k denote the k-th element of Ψ for k=1, 2, ⋯N, and $\psi_k = \left[\Gamma_{C_kD_m}, for\ m = 1,2,\cdots\right.$, which is a set of the instantaneous SINRs between the k-th CUE and each receiver in D2D multicast group. Let $\Gamma_{k,\min}$ denote the smallest element in ψ_k, i.e., the weakest channel. Accordingly, the channel allocation, denote by ψ_{k*}, has index $k*$:

$$k^* = \arg\max_k \left\{\Gamma_{k,\min}, k = 1,2,\cdots\right. \tag{7}$$

The complexity of the channel allocation is O(M*N), which is not complicated.

4.2 Power Allocation Algorithm

The power allocation for cellular and D2D multicast communications is a non-linear programming problem. In order to solve the problem, we first analyze the feasible region. We divide the constraints into power constraints $\Omega_1 = \{(P_i, P_j): P_{\min} \le P_i \le P_{\max}, 0 \le P_j \le P'_{\max}\}$ and rate constraints $\Omega_2 = \left\{\left(P_i, P_j\right): \Gamma_i \ge \gamma_p, \Gamma_j \ge \gamma_s\right\}$, then $\Phi = \Omega_1 \cap$. Since Ω_1 is a finite closed region, Φ is a finite closed region or empty set. Note that we can properly set parameters $P_i, P_j, \Gamma_i, \Gamma_j$ to guarantee Φ is not empty, so our discussion is based on the assumption that Φ is a non-empty finite closed region. Since Φ is a closed and bounded set and $R(P_i, P_j)$ is continuous, the optimization problem has a solution [26].

A method introduced in [27] is adopted to solve problem (5). In order to find the optimal power solution (P_i^*, P_j^*) for our model, we first prove the following lemmas.

We assume all gains values are greater than zero because if the communication link of cellular user or D2D user is blocked, then $(P_i^*, P_j^*) = (0, P'_{\max})$ or $(P_i^*, P_j^*) = (P_{\max}, 0)$.

Lemma 1. The optimal solution (P_i^*, P_j^*) has P_i or P_j equal to the maximum power.

Proof: Assuming D_{Rk} is the worst user in the multicast group, and then the SINR of the multicast service is expressed as

$$\Gamma_j = \frac{P_j G_{jd_k}}{\sigma^2 + P_i G_{id_k}} \tag{8}$$

Substitute $(\alpha P_i, \alpha P_j)$ for (P_i, P_j) in (4), for $\forall \alpha > 1, \alpha \in R^+$ and $(P_i, P_j) \in \Phi$, we have

$$R(\alpha P_i, \alpha P_j) = \log_2\left(\left(1 + \frac{P_i G_i}{\frac{\sigma^2}{\alpha} + P_j G_j}\right)\left(1 + \frac{P_j G_{jd_k}}{\frac{\sigma^2}{\alpha} + P_i G_{id_k}}\right)^M\right) > R(P_i, P_j) \tag{9}$$

Hence, the solution of (5) will have P_i or P_j equal to the maximum power $P_{\max}$ or $P'_{\max}$.

By Lemma 1, the optimal power allocation can be selected among the following alternatives:

- Extreme points on the boundaries of Φ: $P_i = P_{\max}$ or $P_j = P'_{\max}$, i.e., P_i's or P_j's corresponding to $\frac{\partial R(P_i, P'_{\max})}{\partial P_i} = 0$ or $\frac{\partial R(P_{\max}, P_j)}{\partial P_j} = 0$, respectively.
- Corner points of Φ.

Lemma 2. The optimal transmitting power allocation (P_i^*, P_j^*) for (5) only exists on the corner points of Φ.

Proof: Let $\partial\Phi$ be the boundary of region Φ. According to Lemma 1, $(P_i^*, P_j^*) \in \partial\Phi$. Note that the shape of region Φ changes with different values of the constrained parameters, so is the shape of $\partial\Phi$. However, $\partial\Phi$ is only composed of the following six lines: $l_1 : P_i = P_{\max}, l_2 : P_j = P'_{\max}, l_3 : \Gamma_i = \gamma_p$, $l_4 : \Gamma_j = \gamma_s, l_5 : P_i = P_{\min}, l_6 : P_j = 0$, as shown in **Fig.2**.

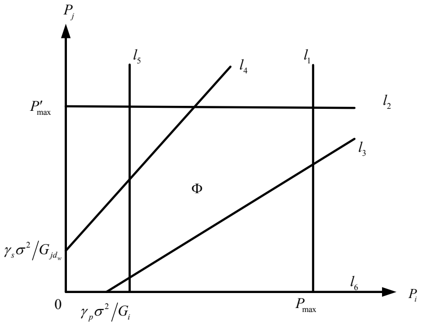

Fig. 2. Feasible region Φ

Let $l'_e = l_e \cap \quad 1,2,3,4,5,6)$ and $Q(P_i, P_j) = (1+\Gamma_i)\cdot(1+\Gamma_j)^M$. Since the logarithm is a monotonically increasing function, we look for extreme points on the boundary by considering $Q(P_i, P_j)$. If $(P_i, P_j) \in l'_2$, then $\frac{\partial^2 Q}{\partial P_i^2} \geq 0$.

The proof is as follows.

According to (8) the SINR of the D2D multicast service is $\Gamma_j = \frac{P_j G_{jd_k}}{\sigma^2 + P_i G_{id_k}}$ (10)

Then $$Q(P_i, P_j) = \left(1 + \frac{P_i G_i}{\sigma^2 + P_j G_j}\right)\left(1 + \frac{P_j G_{jd_k}}{\sigma^2 + P_i G_{id_k}}\right)^M \tag{11}$$

We assume $$Q = (1 + AP_i)\left(1 + \frac{C}{B + P_i}\right)^M \tag{12}$$

where $$A = \frac{G_i}{\sigma^2 + P'_{\max} G_j}, B = \frac{\sigma^2}{G_{id_k}}, C = \frac{P'_{\max} G_{jd_k}}{G_{id_k}} \tag{13}$$

Now, by differentiating $Q(P_i, P'_{\max})$ with respect to P_i we find

$$\frac{\partial Q}{\partial P_i} = A\left(1 + \frac{C}{B + P_i}\right)^M - M(1 + AP_i) \cdot \left(1 + \frac{C}{B + P_i}\right)^{M-1} \cdot \frac{C}{(B + P_i)^2} \tag{14}$$

To see $Q(P_i, P'_{\max})$ is concave or convex we calculate the second derivative $\frac{\partial^2 Q}{\partial P_i^2}$,

$$\begin{aligned}\frac{\partial^2 Q}{\partial P_i^2} &= -AM\left(1 + \frac{C}{B + P_i}\right)^{M-1} \cdot \frac{2C}{(B + P_i)^2} + M(M-1)(1 + AP_i)\left(1 + \frac{C}{B + P_i}\right)^{M-2} \cdot \frac{C^2}{(B + P_i)^4} + M(1 + AP_i)\left(1 + \frac{C}{B + P_i}\right)^{M-1} \cdot \frac{2C}{(B + P)^3} \\ &= M\left(1 + \frac{C}{B + P_i}\right)^{M-1} \cdot \frac{C}{(B + P_i)^3 \cdot (B + C + P_i)} \cdot \left[-2AB^2 - 2ABC + MC + C + 2B + (2 + ACM - 2AB - AC) \cdot P_i\right]\end{aligned} \tag{15}$$

$\frac{\partial^2 Q}{\partial P_i^2}$ is seen to be non-negative if the following inequality is satisfied:

$$-2AB^2 - 2ABC + MC + C + 2B + (2 + ACM - 2AB - AC) \cdot P_i \geq 0 \tag{16}$$

Now, by applying a conclusion in [27], Formula (14), $G_{21}(\sigma_1^2 + P_{\max} G_{12}) \geq G_{11} \sigma_2^2$, we see that implies $G_{d_k}(\sigma^2 + P'_{\max} G_{ji}) \geq G_i \sigma^2$, i.e. $AB \leq 1$ in our proof.

Because multicast receivers are always more than one, so $M \geq 1$.
Then

$$MC + C + 2B \geq C + C + 2B = 2(B + C) \geq 2AB(B + C) \tag{17}$$

$$-2AB^2 - 2ABC + MC + C + 2B \geq 0 \tag{18}$$

and $$2 + ACM \geq 2 + AC \geq 2AB + AC \tag{19}$$

$$2 + ACM - 2AB - AC \geq 0, P_i \geq 0 \tag{20}$$

So $$(2 + ACM - 2AB - AC) \cdot P_i \geq 0. \tag{21}$$

Finally $\frac{\partial^2 Q}{\partial P_i^2} \geq 0$.

At the same time, if $(P_i, P_j) \in l'_1$, then $\frac{\partial^2 Q}{\partial P_j^2} \geq 0$. So $Q(P_i, P_j)$ is convex when $(P_i, P_j) \in l'_1 \cup$. Then (P_i^*, P_j^*) only has the possibility to exist on the end points of $l'_e (e = 1, 2)$.

If $(P_i, P_j) \in l'_4$, $\Gamma_j = \frac{P_j G_{jd_k}}{\sigma^2 + P_i G_{id_k}} = \gamma_s$,we have $\hat{P}_j = \frac{\gamma_s(\sigma^2 + P_i G_{id_k})}{G_{jd_k}}$.

Consider $Q(P_i) = (1 + \Gamma_i(P_i, \hat{P}_j))(1 + \Gamma_j(P_i, \hat{P}_j))$, and take the first derivative with respect to

P_i ,

$$\frac{\partial Q(P_i)}{\partial P_i} = \frac{G_i G_{jd_k}\left(\sigma^2 G_{jd_k} + \gamma_s G_j \sigma^2\right)}{\left(\sigma^2 G_{jd_k} + \gamma_s G_j\left(\sigma^2 + P_i G_{id_k}\right)\right)^2} \geq 0 . \tag{22}$$

Since (22) is non-negative, Q is increasing in the line of l_4'. At the same time, if $(P_i, P_j) \in l_3'$, $\frac{\partial Q(P_j)}{\partial P_j} \geq 0$. Obviously if $(P_i, P_j) \in l_5' \cup$, Q is monotonically increasing with P_i or P_j . Therefore, (P_i^*, P_j^*) only has the possibility to be obtained on the end points of $l_e'(e = 3,4,5,6)$. Based on the above analysis, Lemma 2 holds.

We denote the intersection of $P_i = P_{\max}$ with $\Gamma_i = \gamma_p$, $\Gamma_j = \gamma_s$ by X_1, X_2 ,respectively, the intersection of $P_i = P_{\min}$ with $\Gamma_i = \gamma_p, \Gamma_j = \gamma_s$ by X_3, X_4, and the intersection of $P_j = P_{\max}'$ by Y_1, Y_2. Additionally, we denote $C_1 = (P_{\min}, P_{\max}'), C_2 = (P_{\max}, 0)$, $C_3 = (P_{\max}, P_{\max}'), C_4 = (P_{\min}, 0)$, and the intersection between $\Gamma_i = \gamma_p$ and $\Gamma_j = \gamma_s$ by X. According to Lemma 2, we know that the optimal power allocation resides only on corner points of the feasible region Φ . Thereby, we conclude that the optimal power allocation to (5) with feasible region Φ resides in the set $\Delta\Phi = \{X, X_1, X_2, X_3, X_4, Y_1, Y_2, C_1, C_2, C_3, C_4\}$.

Some of the points in $\Delta\Phi$ are mutually exclusive because they cannot fulfill the maximum transmit power constraint simultaneously. Note that there are at most five corner points in feasible region Φ , and some of them may be the optimal solution. Without loss of generality, as an illustration, the feasible region Φ when the optimal power allocation (P_i^*, P_j^*) falls within $\delta\Phi = \{X_2, X_3, X_4, Y_1, C_3\}$ is shown in **Fig. 3**. So we can easily derive the optimal solution by traversing the corner points. The optimal power solution is solved in closed form and achieved from a finite set. With the CSI of all involved links, the base station is able to maximize the sum throughput of the system by using the optimal resource allocation solution.

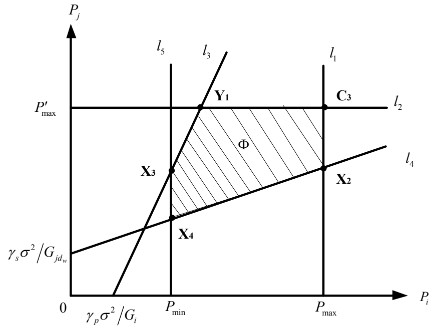

Fig. 3. Feasible power allocation region Φ when the optimal power allocation (P_i^*, P_j^*) falls within $\delta\Phi$

5. Simulation

In this section, we resort to the numerical simulation to evaluate the system performance of the proposed resource allocation method performed in a MATLAB environment. We consider a normalized circular cell, and the base station is located at the center of the cell. The users including *N* cellular users as PUs, one multicast source terminal as SU and *M* multicast receivers forming a multicast group, and other idle users are randomly distributed in the cell.

M=5, N=10. B=10^3Hz. The multicast users share the spectrum of only one cellular user and reuse the resources of the cellular user which BS selects for the D2D communication. The channel link is composed of large-scale path loss and statistically independent small-scale quasi-static frequency selective Rayleigh fading. The channel coefficients are outcomes of independent Rayleigh distributed random variables with mean equal to 1, and the path loss exponent θ=4, the environment constant L=1 for all the links. For the rate constraints, we assume $\gamma_p = 0dB$ equals $\gamma_s = 0dB$ to ensure the fairness. For the maximum power constraints we assume $P_{\max} = P'_{\max} = 1W$.

Based on the proposed channel allocation and power control method in Section III and Section IV, for different channel conditions the optimal power is obtained and the sum throughput of the system is calculated. By inspection of the simulation results of power allocation, as illustrated in **Fig. 4**, we see the regular pattern of the two users with different channel gains, the user with the highest signal to noise ratio (SNR) always transmits at full power. D2D multicast source terminal transmits at full power with a higher probability because the multicast group enables network resource sharing and obtains a great gain if the SNR is good.

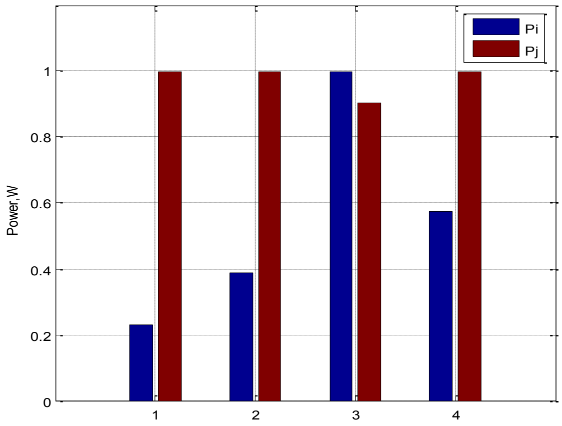

Fig. 4. Power allocation for different gains

By allocating the channel and power of cellular and D2D communications we calculate the sum throughput and compare the results with different M, i.e. different number of the multicast receivers. The relation between sum throughput and SNR of PU's channel link is illustrated in **Fig. 5**. The sum throughput increases with the increase of both SNR of PU's channel and M. With the increase of multicast receiving users, the multicast group obtains a higher throughput, so the sum throughput gets higher. What's more, as M varies, by observing the trends of the increment of sum throughput, a conclusion is drawn that when the multicast receiving users gets more, the system can obtain a huger sum throughput. **Fig. 5** shows that when the SNR of PU's channel is low, power allocation for both users does not change so the sum throughput is almost constant. As the SNR of PU's channel is greater than 20dB, the sum throughput begins to increase with the increase of SNR of PU's channel link because the power allocation changes to get better performance.

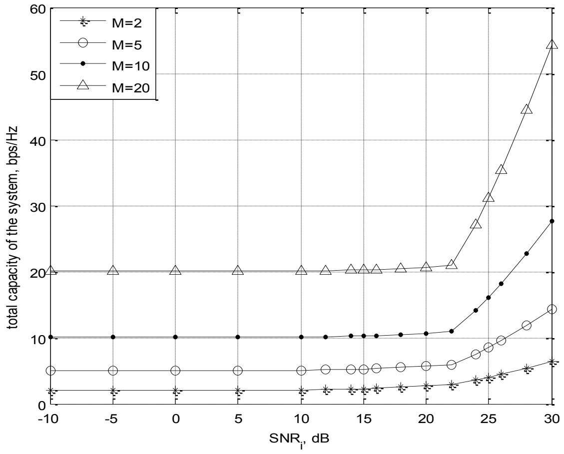

Fig. 5. Relation between sum throughput and SNR of PU's channel

Relation between sum throughput and SNR of the worst user's channel link in multicast group is illustrated in **Fig. 6**. The sum throughput increases with the increase of both SNR and *M*. As the increase of multicast receivers, the multicast group obtains a higher throughput, so the sum throughput gets higher. From the figure we see, when the SNR of the worst user is low, power is allocated for cellular user mostly, so the throughput is not very high. When the SNR of PU's channel is between $0dB$ and $10dB$, power allocation for both users is always achieved at $\Gamma_j = \gamma_s$, so the sum throughput is almost constant. As the SNR of the worst user's channel link starts to increase to above $15dB$, the sum throughput gets higher and higher because the power allocation changes to get better performance and the multicast users contribute a large throughput.

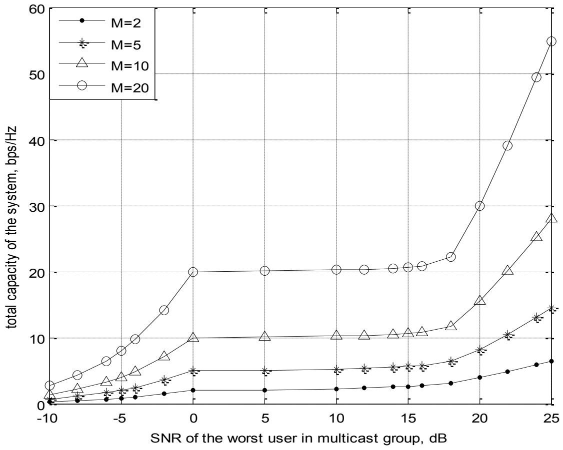

Fig. 6. Relation between sum throughput and SNR of the worst user's channel in multicast group

As G_i of PU channel link changes, SINR of PU is also changing. The relation between the total capacity of system and the SINR of PU is illustrated in **Fig. 7**. The capacity of primary user and secondary users are also illustrated. **Fig. 7** shows that capacity of primary user is increased with the increase of SINR of PU, while capacity of secondary users does not change with the increase of SINR_i until SINR_i reaches $2.8752dB$. The reason is shown in **Fig. 8**, which illustrates the power allocation for primary user and secondary user. When G_i changes and

SINR$_i$ is lower than 2.8752*dB*, the optimal power is always obtained at Y_2, which is on the line of $l_4 : \Gamma_j = \gamma_s$. Because $C_j = B_i \log_2 \Gamma_j = B_i \log_2 \gamma_s$, therefore the capacity of secondary users does not change; and because $C_i = B_i \log_2 \frac{P_i \cdot G_i \uparrow}{\sigma^2 + P_j G_{ji}}$, the capacity of primary user is increased with the increase of SINR$_i$. When SINR of PU is higher than 2.8752*dB*, the optimal power is obtained at Y_1', which is on the line of $l_3 : \Gamma_i = \gamma_p$. $C_j = B_i \log_2 \frac{P_j G_{jd_w}}{\sigma^2 + P_i \downarrow \cdot G_{id_w}} \uparrow$, so the capacity of secondary users begins to increase.

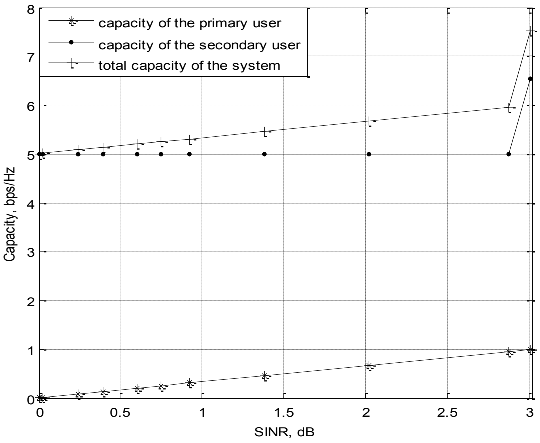

Fig. 7. Relation between capacity and SINR of PU

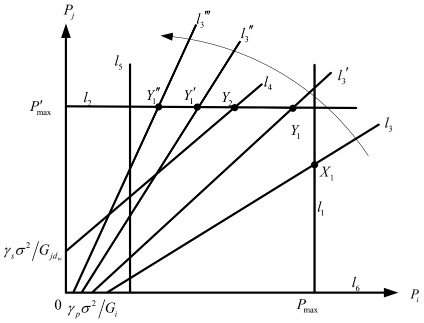

Fig. 8. Power allocation for the system with the change of PU channel gain (Gi)

Fig. 9 shows that the total throughput of cellular user and D2D multicast users in a cell as varying $P'_{\max}$ for the proposed power control method, where D2D multicast constraint of maximum transmit power ($P'_{\max}$) changes between 0*dBm* and 30*dBm*. We compare our proposed method with the maximization power method, one method without controlling power, i.e. the cellular user and multicast source terminal always transmit at the maximum power. In **Fig. 9**, our proposed mechanism always has higher total throughput than maximization power control method since it controls the transmission (Tx) power of D2D multicast source terminal to a certain level and minimizes interference to cellular users using same resources. Besides, we respectively consider $\gamma_s = 0dB, 5dB, 10dB$. **Fig. 9** illustrates when

γ_s increases, the throughput gets higher. The reason is the interference is limited from BS to multicast users by the minimum acceptable SINR of the multicast group, so the multicast group gets a higher throughput. Meantime, results that BS selects the channel of cellular user for D2D communication randomly and using our method are compared in **Fig. 9**. The left(blue) lines represent the proposed channel allocation method, while the right(black) lines represent the random method, namely D_T senses and selects the channel randomly. It is shown that our channel allocation method can get better performance. In addition, when the maximum power continues to increase to a certain value, the throughput is not increased but rather tends to a constant value. This inspired us how to set the maximum power.

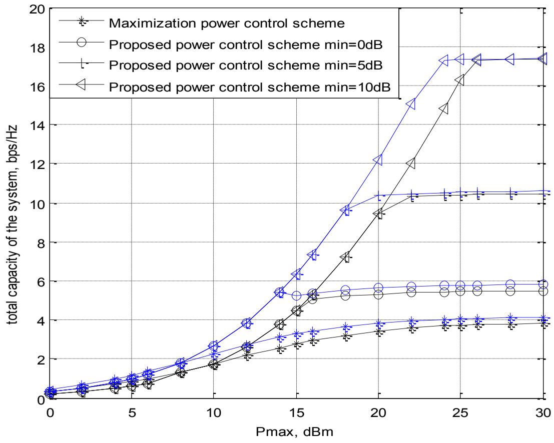

Fig. 9. Relation between sum throughput and $P'_{\max}$

Fig. 10 shows the interference on primary user and secondary users as varying $P_{\max}$. We compare our proposed method with the maximization power method. The interference on primary user of the two power allocation scheme is the same. Because multicast can contribute a large capacity, BS always allocates the multicast full power. However, the maximization power control method always has higher interference on secondary user than our proposed mechanism since our proposed allocation method controls the transmission power of cellular users, in order to obtain an optimal capacity.

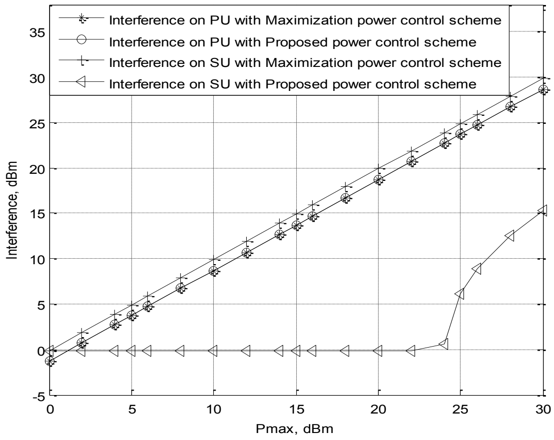

Fig. 10. Relation between Interference and the maximum power $P_{\max}$

6. Conclusion

In this paper, based on cognitive radio we analyzed the resource allocation optimization for D2D underlay multicast communication with the cellular network in a single-cell environment. We proposed a joint power allocation method for cellular users and D2D multicast groups that D2D user reusing the resources of a cellular user based on the channel allocation. We assumed the base station is able to allocate the optimal power for transmitters with the CSI of all involved links. With the channel gain information the proposed power method maximizes the network capacity. The optimal power allocation for the network capacity maximization is found to be not complicated, that the user with the highest signal to noise ratio (SNR) always be allocated more transmission power. The set of minimum transmission data rate for both cellular user and D2D multicast user mitigated the interference and ensured services. The results showed that our proposed power control method had better performance than maximization power method in most situations because severe interference was effectively coordinated. Moreover, the proposed method for both cellular users and D2D multicast users were expected to have higher frequency efficiency.

In future work, we will extend to take into account the scenario where CUEs are using more than one channel and with multiple cells.

References

[1] P. Jänis, C. H. Yu , K. Doppler, C. Ribeiro, C. Witjing, K. Hugl, O. Tirkkonen and V. Koivunen, "Device-to-Device Communication Underlaying Cellular Communications Systems," *International Journal of Communications, Network and system Sciences*, vol.2, no.3, pp. 169-178, June 2009. Article (CrossRef Link)

[2] S. Hua, Y. Guo, Y. Liu and S. S. Panwar, "Scalable video multicast in hybrid 3G/Ad-hoc networks," *IEEE Transactions on Multimedia*, vol.13, no.2, pp.402-413, April 2011. Article (CrossRef Link)

[3] Y. Zhou, H. Liu, Z. Pan, L. Tian, J. Shi and G. Yang, "Two-Stage Cooperative Multicast Transmission with Optimized Power Consumption and Guaranteed Coverage," *Selected Areas in Communications, IEEE Journal on*, vol. PP, no. 99, pp. 1-11, May 2013. Article (CrossRef Link)

[4] Federal Communications Commission, "Notice of Proposed rule making and order," FCC Document ET Docket No.03-222, 2003.

[5] Z. Zhang, K. Long and J. Wang, "Self-organization paradigms and optimization approaches for cognitive radio technologies: a survey," *IEEE Wireless Communications*, vol.20, no.2, pp.36-42, April 2013. Article (CrossRef Link)

[6] Z. Zhang, K. Long, J. Wang, F. Dressler, "On Swarm Intelligence Inspired Self-Organized Networking: Its Bionic Mechanisms, Designing Principles and Optimization Approaches," *IEEE Communication Survey & Tutorials*, vol. PP, no. 99, pp. 1–25, July 2013. Article (CrossRef Link)

[7] J. Mitola and G. Q., Jr. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, vol.6, no.4, pp.13-18, August 1999. Article (CrossRef Link)

[8] S. Hu, Y. Yao and Z. Yang, "MAC protocol identification approach for implement smart cognitive radio," in *Proc. of IEEE International Conference on Communications (ICC) Workshop*, pp.5608-5612, June 2012. Article (CrossRef Link)

[9] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, "Device-to device communication as an underlay to LTE-advanced networks," *IEEE Communications Magazine*, vol.47, no.12, pp. 42-29, December 2009. Article (CrossRef Link)

[10] H. Min, et al., "Reliability improvement using receive mode selection in the device-to-device uplink period underlaying cellular networks," *IEEE Transactions on Wireless Communications*, vol.10, no.2, pp. 413-418, February 2011. Article (CrossRef Link)

[11] C. H. Yu, O. Tirkkonen, K. Doppler and C. Ribeiro, "On the performance of device-to-device underlay communication with simple power control," *IEEE Vehicular Technology Conference (VTC)*, April 2009. Article (CrossRef Link)

[12] C. H. Yu, O. Tirkkonen , K. Doppler and C. Ribeiro, "Power Optimization of Device-to-Device Communication Underlaying Cellular Communication," in *Proc. of International Conference on Communications (ICC)*, pp.1-5, June 2009. Article (CrossRef Link)

[13] P. Jänis, V. Koivunen, C. Ribeiro, J. Korhonen, K. Doppler and K. Hugl, "Interference-aware resource allocation for device-to-device radio underlaying cellular networks," *IEEE Vehicular Technology Conference (VTC)*, pp.1-5, April 2009. Article (CrossRef Link)

[14] K. Doppler, C. H. Yu, C. Ribeiro and P. Jänis, "Mode selection for Device-to-Device Communication underlaying an LTE-Advanced Network," *IEEE Wireless Communications and Networking Conference (WCNC)*, April 2010. Article (CrossRef Link)

[15] C. H. Yu, K. Doppler, C. Ribeiro and O. Tirkkenen, "Resource Sharing Optimization for Device-to-Device Communication Underlaying Cellular Networks," *IEEE Transactions on Wireless Communications*, vol.10, no.8, pp.2752-2763, August 2011. Article (CrossRef Link)

[16] B. Wang, L. Chen, X. Chen, X. Zhang and D. Yang, "Resource Allocation Optimization for Device-to-Device Communication Underlaying Cellular Networks," *IEEE Vehicular Technology Conference (VTC)*, May 2011. Article (CrossRef Link)

[17] H. Wang, X. Chu, "Distance-constrained resource-sharing criteria for device-to-device communications underlaying cellular networks," *Electronics Letter*, vol.48, no.9, pp.528-530, April 2012. Article (CrossRef Link)

[18] P. Cheng, L. Deng , H. Yu, Y. Xu and H. Wang, "Resource Allocation for Cognitive Networks with D2D Communication: An Evolutionary Approach," *IEEE WCNC: Mobile and Wireless Networks*, April 2012. Article (CrossRef Link)

[19] Y. Chen, X. Xu, Q. Lei, "Joint Subcarriers and Power Allocation with Imperfect Spectrum Sensing for Cognitive D2D Wireless Multicast," *KSII Transactions on Internet and Information Systems*, vol.7, no.7, pp. 1533 – 1546, July 2013. Article (CrossRef Link)

[20] D. Wang, X. Wang, Y. Zhao, "An Interference Coordination Scheme for Device-to-Device Multicast in Cellular Networks," *IEEE Vehicular Technology Conference (VTC)*, September 2012. Article (CrossRef Link)

[21] Y. Xu, J. Wang, Q. Wu and A. Anpalagan, "Opportunistic Spectrum Access in Unknown Dynamic Environment: A Game-Theoretic Stochastic Learning Solution," *IEEE Transactions on Wireless Communications*, vol.11, no.4, pp.1380-1391, April 2012. Article (CrossRef Link)

[22] Y. Xu, J. Wang, Q. Wu and A. Anpalagan, "Opportunistic Spectrum Access in Cognitive Radio Networks: Global Optimization Using Local Interaction Games," *IEEE Journal of Selected Topics in Signal Processing*, vol. 6, no.2, pp.180-194, April 2012. Article (CrossRef Link)

[23] Y. Xu, A. Anpalagan, Q. Wu and L. Shen, "Decision-Theoretic Distributed Channel Selection for Opportunistic Spectrum Access: Strategies, Challenges and Solutions," *IEEE Communications Surveys & Tutorials*, vol.15, no.4, pp.1689-1713, April 2013. Article (CrossRef Link)

[24] C. H. Chen, C. L. Wang and C. T. Chen, "A Resource Allocation Scheme for Cooperative Multiuser OFDM-Based Cognitive Radio Systems," *IEEE Transactions on Communications*, vol.59, no.11, pp.3204-3215, September 2011. Article (CrossRef Link)

[25] T. M. Cover and J. A. Thomas, "Elements of information theory," New York: Wiley, 1991. Article (CrossRef Link)

[26] J. L. Troutman, "Variational calculus and optimal control: Optimization with elementary convexity," 2nd ed. New York: Springer-Verlag, 1996. Article (CrossRef Link)

[27] A. Gjendemsjo, D. Gesbert, G. E. Oien and S. G. Kiani, "Optimal power allocation and scheduling for two-cell capacity maximization," in *Proc. of International symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, pp.1-6, April 2006. Article (CrossRef Link)

Xiaolu Wu is currently a graduate student and working toward the master degree in the School of Computer & Communication Engineering, University of Science and Technology Beijing, China, in 2013. Her research areas are radio resource management and cognitive radio. Email: wuxiaolu0429@foxmail.com

Yueyun Chen is an associate professor in the School of Computer & Communication Engineering, University of Science and Technology Beijing, China. She received a Bachelor degree from South China University of Technology, and a Master degree and a PhD from Beijing Jiaotong University. Her current research interests include wireless and mobile communications, including MIMO beamforming, signal processing, radio resource management, cognitive radio, cooperative communications, optimization theory on communications. Email: chenyy@ustb.edu.cn