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# Spectrum allocation game of directional transmission in multi-hop cognitive radio networks①

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**Abstract**

The spectrum allocation for links in multi-hop cognitive radio networks is addressed. The links rent the vacant licensed bands offered by primary users for implementing directional transmission. To minimize the individual cost, the links share the licensed band and rental fee. An interference model for the directional transmission in cognitive radio networks is proposed to formulate the cooperative and dynamic behavior of the links using the theory of hedonic game, called spectrum allocation game. The game is proved to converge to the core stable state indicating that all links satisfy with their current conditions and do not deviate from their coalitions. Numerical results show that the game improves spectral efficiency and contributes to reducing the individual cost of the links.

**Key words**: cognitive radio, game theory, directional transmission

## 0 Introduction

Cognitive radio is a promising technology to deal with the shortage of spectrum resource by exploiting the underutilized portion of licensed spectrum. The cognitive radio user or secondary user (SU) can access the licensed spectrum when the authorized owner called primary user (PU) is not active. Recent research shows that there exists low utilization and large idle time on many portions of the licensed spectrum[1]. Therefore, a PU could lease some vacant portions of the licensed spectrum bands to SUs to increase income and improve spectrum utilization.

In the cognitive radio network, there exist some multi-hop data flowing from source nodes to destination nodes. Lacking of licensed spectrum bands, the link rents vacant bands from PUs for transmission. So, each link receives the corresponding rewards for serving the flows and pays the rental fees to the PUs for accessing the licensed band. To pursue higher individual interest, the link is driven to seek the lower rental cost on the premise of guaranteeing the traffic demand. Sharing a band among multiple links could effectively cut down the individual expenditure for the links. But, concurrent transmissions over the same band cause severe interference among links. Therefore, the directional antenna can be applied to improve spectrum utilization through supporting more concurrent transmissions. Different from the omnidirectional antenna, the directional antenna is capable of concentrating the energy to the intended direction, thus reducing the interference region. An interference model is proposed for the directional transmission in cognitive radio networks which indicates the mutual interference and spatial reuse among links. Based on the model, a link evaluates if it can share the band with other links with a tolerable interference level.

In this paper, we formulate the procedure of the links cooperating to access the band according to their private interests as the spectrum allocation game. In the game, each link carrying a flow is defined as a player. The set of links sharing the same band is mapped to a coalition. Links could cooperate to establish a coalition to improve their interests which are indicated by their preference functions in the corresponding coalition. The procedure of coalition establishment can converge to the core stability which means that all links are satisfied with their current coalitions without coalition re-establishment. A core partition algorithm is proposed which achieves the link coalition structure under the core stable state of the game.

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The rest of the paper is organized as follows. The next section summarizes the previous work on related topics. Section 2 defines the antenna model and the interference model of the directional transmission. The game of the spectrum allocation in the cognitive radio network is presented in Section 3. Numerical results are shown in Section 4. Finally, Section 5 concludes the paper.

## 1 Related work

In cognitive radio networks, the game on efficient spectrum allocation between PUs and SUs is of great importance and has attracted many researchers[2]. A trading market that multiple PUs sell spectrum opportunities to multiple SUs is proposed in Ref. [3]. The behavior of SUs buying spectrum opportunities is formulated as an evolutionary game. The competition of spectrum opportunity quality of PUs is formulated as a noncooperative game. In Ref. [4], Kasbekar and Sarkar studied the spectrum pricing game in which the PUs could lease the same band through spatial reuse. The two papers modeled the spectrum pricing process as the noncooperative game where each player chose the strategy independently to maximize its payoff.

Cooperative game is also used to investigate the behavior of the rational players who cooperate to achieve higher payoff[5]. Cooperative spectrum access among SUs in cognitive radio networks were studied in Refs[6] and [7]. The dynamic coalition formation game in Ref. [7] could converge to the grand coalition or absorbing states of the internal and external stability. Besides grand coalition, we investigated the coalition formation game[8] where players could establish multiple coalitions. Directional transmission contributes to network capacity improvement and spectrum spatial reuse in multi-hop networks[9-11]. In this paper, we investigate the spectrum allocation for the SUs that implement directional transmission in cognitive radio networks.

## 2 System model

In this section, we present the directional antenna model and the corresponding interference model of the SU equipped with directional antenna.

### 2.1 Directional antenna

As summarized in Ref. [10], directional antenna improves the transmission performance of the link between a SU pair and cancels interference beyond its active beam pattern. In this paper, the switched beam antenna model is similar to the models in Refs[9] and [10]. The beamwidth of each beam pattern is defined as angle $\theta$. As shown in Fig. 1, each beam pattern targets to a defined orientation without overlapping with the other one (e. g. region I and region II). To simplify the analysis, the model ignores the backlobe and sidelobe. The reason is that the gain of the mainlobe is 100 times higher than that of the sidelobe[11]. For the directional antenna implemented with multi-element arrays, the directional gain of each beam pattern can be presented by $g_i = \min\{T, 360/\theta\}$, where $T$ is the number of elements of the directional antenna[10].

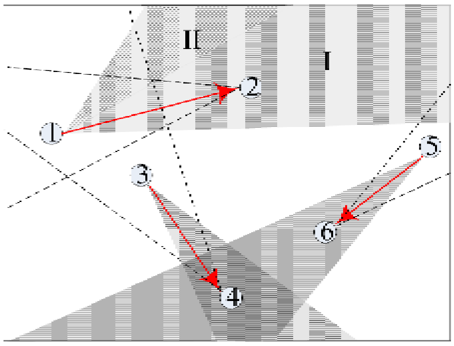


**Fig. 1** Directional transmission

### 2.2 Interference model

For link $(i, j)$, $i$ is the transmitting side and $j$ is the receiving side which are both equipped with directional antennas, so as to orient the received beam-pattern $B_i(i, j)$ to the transmitted beam pattern $B_j(i, j)$. The interference between two links transmitting simultaneously depends on both their locations and their beam patterns. Link $(a, b)$ interferes with link $(i, j)$ if node $j$ is within the range of $B_a(a, b)$ while node $a$ is located in $B_j(i, j)$. Otherwise, link $(a, b)$ and link $(i, j)$ are interference-free. For example, Fig. 1 shows links (1, 2), (3, 4) and (5, 6) could share a band without interference. Moreover, the set of all links interfering with link $(i, j)$ over band $m$ is denoted as the interference set $I(B_j(i, j), m)$. The signal to interference plus noise ratio (SINR) is expressed as

$$SINR_{ij}(m) = \frac{g_i g_j h_{ij} p_i}{\sigma + \sum_{(a,b) \in I(B_j(i,j),m)} g_a g_j h_{aj} p_a} \tag{1}$$

where $p_i$ is transmission power of node $i$. $h_{ij}$ is the channel gain between node $i$ and $j$, which is $k/d_{ij}^{\alpha}$. Here $k$ is the path loss constant. $d_{ij}$ is the distance between $i$ and $j$. $\alpha$ is the path loss exponent. $\sigma$ is the thermal noise and can be considered as a constant. Due to the characteristic of wireless broadcast, the capacity of a link $(i, j)$ is subjected to the interference from other links during concurrent transmissions. The threshold of SINR, say $\beta$, must be met to successfully decode the packets. For link $(i, j)$, the maximum tolerable interference $\xi_{ij}$ can be expressed by

$$\xi_{ij} = \frac{g_i g_j h_{ij} p_i}{\beta} - \sigma \quad (2)$$

The maximum achievable capacity of the link $(i, j)$ is

$$R_{\max, ij} = W\log_2(1 + \frac{g_i g_j h_{ij} p_i}{\sigma}) \quad (3)$$

where $W$ is the bandwidth. The link capacity is

$$R_{ij}(m) = W\log_2(1 + SINR_{ij}(m)) \quad (4)$$

In this paper, we assume that the transmission power of all links is fixed in the cognitive radio network. Therefore, $R_{ij}(m)$ is determined by $I(B_j(i, j), m)$ which is determined by the beam pattern and locations of links over band $m$.

## 3 Spectrum allocation game

A multi-hop cognitive radio network $G = (V, L, M, F)$ is proposed, where $V$ is the set of SU nodes equipped with directional antennas and $L$ is the set of the links. $M$ is the set of available bands provided by PUs. $F$ is the set of end-to-end data flow $s$ in the network. Each flow $f \in F$ with a traffic demand, denoted by $R^f$, traverses a sequence of links from the source node to the destination node. In the procedure of spectrum allocation, the link carrying the flow rents the band from PUs over which supports the traffic demand. Besides, directional transmission improves spatial reuse, with which links share the same band to reduce individual rental fee. In this section, at first, the constrained conditions of directional transmission is studied in the multi-hop cognitive radio network. Then, the behavior of spectrum band is formulated which shares among the links as a game called spectrum allocation game.

### 3.1 Constrained conditions on directional transmission

The SU node is equipped with a full duplex transceiver that is capable of transmitting and receiving simultaneously. If multiple links share the same node $i$ as their transmitter, each of them only achieves part of the time to transmit traffic.

$$\sum_{f\in F}\sum_{(i,k)\in L}\sum_{m\in M} x_{ik}^f(m)\frac{R^f}{R_{ik}(m)} \leqslant 1 \ (i \in V) \quad (5)$$

where when $x_{ik}^f(m) = 1$, it indicates that link $(i, k)$ carries flow $f$ over band $m$, otherwise, $x_{ik}^f(m) = 0$. $R^f/R_{ik}(m)$ is the portion of time assigned to flow $f$ carried by link $(i, k)$ over band $m$. Similarly, if node $j$ is the common receiver of multiple links, the constraint is

$$\sum_{f\in F}\sum_{(k,j)\in L}\sum_{m\in M} x_{kj}^f(m)\frac{R^f}{R_{kj}(m)} \leqslant 1 \ (j \in V) \quad (6)$$

According to Eqs(5) and (6), the assigned time portion for a link sharing a node is uncertain since the link capacity varies with different interference level on the current band. In the procedure of spectrum allocation, the links need fixed time portion assignment to calculate the actual traffic demand for its flow. In this paper, we denote the ratio of the traffic demand to the maximum achievable link capacity as fixed transmission time for a link.

$$r_i(i, j) = \frac{R^f/R_{\max, ij}}{\sum_{l\in F}\sum_{(i,k)\in L} x_{ik}^l R^l/R_{\max,ik}} \quad (j \in V)$$

$$r_j(i, j) = \frac{R^f/R_{\max, ij}}{\sum_{l\in F}\sum_{(k,j)\in L} x_{kj}^l R^l/R_{\max,kj}} \quad (j \in V) \quad (7)$$

$$R_{ij}^f = \frac{R^f}{\min\{r_i(i, j), r_j(i, j)\}} \quad (8)$$

For link $(i, j)$, the transmission time assigned for its flow needs to be considered on its both sides. $r_i(i, j)$ is the time portion shared by $(i, j)$ on its transmitter side $i$. $r_j(i, j)$ is the time portion on the receiver side $j$. The time portion of $(i, j)$ chooses the minimum one of $r_i(i, j)$ and $r_j(i, j)$ as its value which can be supported on both sides. Denotes the actual traffic demand of flow $f$ on link $(i, j)$ which considers nodes sharing of multiple flows. In the process of spectrum allocation, each link must choose the band which is capable of supporting the actual traffic demand.

### 3.2 Game formulation

In the paper, we assume the vacant licensed bands offered by PUs have the same bandwidth and rental price. To cut individual cost, the links prefer to implement directional transmission over the same band and share the rental fee. This behavior can be modeled by the cooperative game theory, called spectrum allocation game.

Let $N = \{1, \cdots, n\}$ denote a finite set of players. A *coalition* is denoted by $\{S \mid S \neq \varnothing, S \subseteq N\}$. A coalition structure or coalition partition is a collection $C = \{S_1, S_2, \cdots, S_K\}$ which partitions $N$. For all $m \neq n$, $S_m \cap S_n = \varnothing$, $\cup_{m=1}^K S_m = N$. $C^N$ stands for the set of all coalition structures of $N$. For each player $i$, let $N_i = \{S \mid S \subseteq N, i \in S\}$ denote the collection of all coalitions which contain $i$. For each coalition structure $C \in C^N$ and each player $i \in N$, let $C(i)$ be the coalition in $C$ which contains $i$.

In the spectrum allocation game, each link carrying a flow is defined as a player. Each set of links sharing the same band is defined as a coalition. When a link joins a coalition, it will access the same band with other members of the coalition. As mentioned above, the link must guarantee traffic demand of its carrying flow in a coalition. Therefore, the link needs to take into account the interference level from other links in the same coalition according to Eqs (1) and (4).

Case Ⅰ: interference-free. Link $(i, j)$ is non-interfering to coalition $S_m$, if $\forall (a, b) \in S_m$, $(a, b) \notin I(B_j(i, j), m)$. In this situation, $(i, j)$ does not experience any interference from $S_m$ and achieves the maximum link capacity $R_{\max, ij}$.

Case Ⅱ: intolerable interference. In this case, link $(i, j)$ suffers severe interference in $S_m$. The situation is $\exists (a, b) \in S_m$, $(a, b) \in I(B_j(i, j), m)$, $SINR_{ij}(m) < \beta$ or $R_{ij}(m) < R^f_{ij}$. In this case, link $(i, j)$ is incapable of guaranteeing its traffic demand and seeks another coalition.

Case Ⅲ: tolerable interference. In this case, link $(i, j)$ endures bearable interference from coalition $S_m$. The condition is $\exists (a, b) \in S_m$, $(a, b) \in I(B_j(i, j), m)$ and $R_{ij}(m) >= R^f_{ij}$. The link experiences tolerable interference and still can support the traffic demand.

For each link, there exists a tolerable interference level satisfying the actual traffic demand that is expressed by

$$\xi^f_{ij} = \max\{\frac{A}{B} - \sigma, \xi_{ij}\} \ (A = g_i g_j h_{ij} p_i \ B = 2^{\frac{R^f_{ij}}{W}} - 1) \tag{9}$$

where $\xi^f_{ij}$ is the tolerable interference level of link $(i, j)$ that carries flow $f$. $A/B - \sigma$ is the tolerable inference for flow $f$ obtained from Eq. (4). $\xi_{ij}$ is the maximum tolerable interference defined by Eq. (2). If the aggregate interference in a coalition is below the level, $(i, j)$ could join the coalition. Otherwise, the coalition is not suitable for $(i, j)$ because the link cannot guarantee $R^f_{ij}$. Let the interference proportion $(m)$ denote ratio of the interference from link $(a, b)$ to $\xi^f_{ij}$ when the two links are both in the same coalition $S_m$. We have

$$\omega^{ab}_{ij}(m) = \frac{g_a g_j h_{aj} p_a}{\xi^f_{ij}} \ ((a,b) \in I(B_j(i, j), m)) \tag{10}$$

If $(a, b)$ is interference-free to $(i, j)$, $\omega^{ab}_{ij}(m) = 0$. For link $(i, j)$, the eligibility of a coalition is evaluated by the utility function $u_{ij}(S_m)$ which indicates if the current interference level in coalition $S_m$ can guarantee $R^f_{ij}$.

$$u_{ij}(S_m) = 1 - \sum_{(a,b) \in I(B_j(i, j), m)} \omega^{ab}_{ij} \tag{11}$$

For link $(i, j)$, coalition $S_m$ is acceptable if $u_{ij}(S_m) > 0$. Otherwise, the coalition is unacceptable. Based on the utility function, we define the preference function of the link as

$$v_{ij}(S_m) = \begin{cases} -\infty & u_{ij}(S_m) < 0 \\ |S_m| - 1 & u_{ij}(S_m) \geqslant 0 \\ 0 & singleton \end{cases} \tag{12}$$

The preference function of a link takes into account both the traffic demand and the spectrum spatial reuse. For an unacceptable coalition, the preference function achieves minus infinity which means the coalition is excluded by the link. If the coalition is acceptable, spatial reuse (reducing individual cost) is further considered. From the view of the link, the preference function value is the number of links which transmit simultaneously and share the rental over the same band. A special case is the singleton coalition when the link monopolizes the band. Under such condition, the preference function of the link achieves zero. The value of singleton is greater than the value of any unacceptable coalition because the singleton is the acceptable coalition to any link. It is less than values of other acceptable coalitions due to inefficient spatial reuse.

We prove that the spectrum allocation game belongs to the hedonic game. Hedonic coalition game[12] is a type of cooperative game based on coalitions of players. In a hedonic coalition, the payoff of a player solely depends on the composition of the coalition to which this player belongs[13]. For each player, there exists a preference sequence to all coalitions which contain the player. A hedonic game is a pair $(N, \succcurlyeq)$, where $\succcurlyeq = \{\succcurlyeq 1, \cdots, \succcurlyeq N\}$ is the profile of preferences. For player $i \in N$, a preference relation $\succcurlyeq_i$ is a complete, reflexive and transitive binary relation over the set of all coalitions that contain $i$. Let $\succ_i$ denote the strict preference, i.e. $S1 \succ_i S2$, indicates that player $i$ strictly prefers to join $S1$ over $S2$. $S1 \sim_i S2$ presents the indifference relation to player $i$[5,13].

From each link, both its capacity and spatial reuse in a coalition depend on the other links. The link evaluates its payoff according to the preference function in each coalition and establishes the preference sequence of all coalitions. The preference relation is given by

$$v_{ij}(S_1) > v_{ij}(S_2) \Leftrightarrow S_1 \succ_{ij} S_2 \quad S_1 S_2 \in \mathcal{N}_{ij} \tag{13}$$

Therefore, the spectrum allocation game satisfies the definition of the hedonic game.

### 3.3 Stability analysis of the spectrum allocation game

The coalition acceptable for its entire member links is defined as an available coalition. Available coalition structure is the set of available coalitions. In the spectrum allocation game, if multiple links share the same band, the coalition established by them must be an available one. The procedure of the spectrum allocation will be completed when it converges to the stable state in which each link is satisfied with its current coalition. Each possible outcome of the game is a coalition structure which contains some available coalitions. In this paper, the core stability is investigated which is most commonly used in the cooperative game[14].

**Definition 1**: In hedonic game $(N, \succcurlyeq)$, $C \in C^N$ is core stable or a core partition, if there exists no coalition $S$ such that $S \succ_i C(i)$, $\forall i \in S$.

The core partition expresses the group stability which allows coalition deviations, which means that players can establish a new coalition arbitrarily if each of them can get higher payoff in the new coalition than the current one. In the spectrum allocation game, the behavior of the links conforms to the rule of the coalition deviation due to their cooperation to share the same band. It is proved that the spectrum allocation game can achieve the core stability.

Let $R(N, \succcurlyeq)$ denote the collection of all individual rational coalitions in a hedonic game $(N, \succcurlyeq)$ that is

$$R(N, \geq) = \{S \in 2^N \backslash \{\varnothing\} \mid \forall i \in S,\ S \geq_i \{i\}\}$$

In the spectrum allocation game, the collection of all rational coalitions is the set of all available coalitions for each link. From Eqs(11) and (12), all unavailable coalitions are excluded from $R(N, \succcurlyeq)$ since the values of the preference functions is less than that of singleton.

**Definition 2**: A hedonic game $(N, \succcurlyeq)$ is size monotonic if for each player $i \in N$ and $S_m$, $S_n \in R(N, \succcurlyeq) \cap N_i$, $|S_m| \geqslant |S_n|$ implies $S_m \succcurlyeq_i S_n$[14].

According to Eqs (11) and (12), the available coalition with larger size has a greater preference function value. From the preference relation (Eq. (13)), the link prefers the available coalition with larger size. Therefore, the spectrum allocation game is size monotonic. We adopt the following theorem proved in Ref. [15].

**Theorem 1**: If hedonic game $(N, \succcurlyeq)$ is size monotonic, then it has a core partition.

So, there must exist a core partition which is the core stable coalition structure in the spectrum allocation game. According to the preference relation in Eq. (13), the process of coalition deviation in the game can terminate within finite steps and reach the core stable state. In the spectrum allocation game, the core stability means that all links cannot establish a new available coalition with larger size. Following the work in Ref. [15], we propose the algorithm achieving the core partition as presented in Algorithm 1. Function **Maxcoalition** traverses all available coalitions to seek the one with the largest size. As shown in Lines 6 and 7, a link is allowed to join a coalition unless there is no intolerable interference between the link and any member of the coalition. Function **Corepartition** calls Maxcoalition repeatedly until all links are added into corresponding coalitions which constitute the core partition. Variable *Core* contains the core partition (in Line 23) in which all links satisfy their current coalitions and achieve the stable state.

**Algorithm 1.** Core partition in the spectrum allocation game

```
static  LS;  //The set of all links carrying flow traffics
static  OptS_m;  //Current optimal solution
static  S_m;  //Current solution
static  n,cn,optn;  //element number of LS, S_m and OptS_m
Maxcoalition (index)
1:  if index > n then
2:      OptS_m <- S_m;  optn <- cn;
3:      return
4:  end if
5:  (i, j) <- LS[index];
6:  if no intolerable interference between (i, j) and any
    member of S_m then
7:      S_m <- S_m + {(i, j)};  cn <- cn + 1;
8:      Maxcoalition (index + 1);
9:      cn <- cn - 1;
10: end if
11: if cn + n - index > optn then
12:     S_m <- S_m - {(i, j)};
13:     Maxcoalition (index + 1);
14: end if
Corepartition( )
15: Core <- [ ];  //Store the core partition
16: while LS ≠ NULL do
17:     cn <- 0;  optn <- 0;
18:     OptS_m <- [ ];  S_m <- [ ];
19:     Maxcoalition(1);
20:     Core <- Core + {S_m}
21:     LS <- LS - S_m
22: end while
23: return Core
```

## 4 Examples and simulation results

In this section, numerical results of the proposed spectrum allocation game in different circumstances are evaluated. The topology of the cognitive radio network in the simulation is depicted in Fig. 2 where 60 nodes are randomly deployed over a 1000m × 1000m area. Each node is an SU equipped with a directional antenna. There exist at most 5 data flows simultaneously in the network. The transmission power of each link is fixed to 5mW and the thermal background noise $\sigma$ is 100dBm. The path loss constant $k = 1$ and path loss exponent $\alpha = 4$ are adopted. SINR threshold $\beta$ is set to 3dB and it is assumed PUs lease their vacant bands to SUs with fixed bandwidth 0.8MHz.

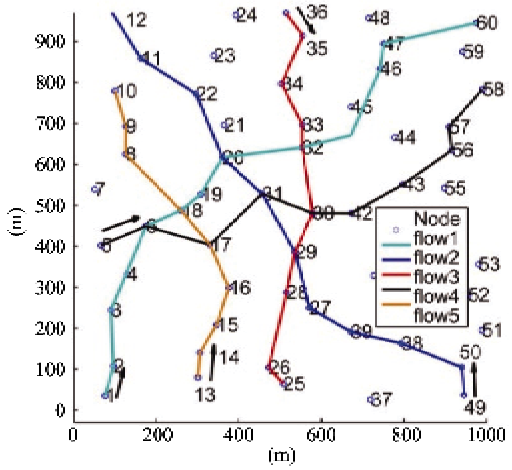

**Fig. 2** Network topology

Fig. 2 shows the routing topology in the simulation. Five flows in concurrent transmissions are denoted. Each of them has a traffic demand that must be supported by its component links. The traffic demand of all flows is set to 1Mbps. Fig. 3 illustrates the number of coalitions of the core partition under different circumstances. The beamwidth is set to 15°, 30°, 60°, 90°, 120° and 360° respectively. The number of flows increases progressively according to the index of flows in Fig. 2. When the beamwidth is 15° or 30°, the game converges to one grand coalition with varying number of flows. The result shows that small beamwidth can help improve the spatial reuse efficiently that allows more links to transmit concurrently. In contrast, omnidirectional (360°) transmission performs worse in terms of spectrum utilization than the directional transmission, because the accumulative interference becomes stronger with increasing number of flows over the same band. Some links have to rent other bands to support the traffic demand. When the beamwidth is 60°, 90°, 120°, the size of core partition changes slightly, i.e. from 1 to 2, with increasing number of flows. This also shows that the directional transmission is superior to the omnidirectional transmission in spectrum spatial reuse.

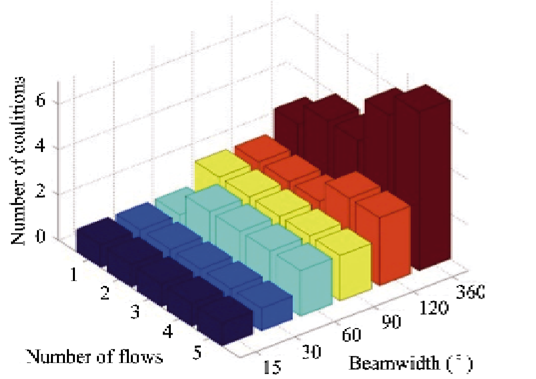

**Fig. 3** Number of coalitions under different circumstances

We further analyze the composition of the core partition with regard to varying beamwidth. In order to reduce the individual rental, links tend to establish a larger coalition shown in Fig. 4. The traffic demand is set to 1Mbps. The bars indicate the component coalitions of a core partition. The height of the bar indicates the number of links in the coalition. When the beamwidth is small, the size of a coalition is very large and the links in the coalition pay lower individual cost. With increasing beamwidth, the number of coalitions also rises while the size of each coalition becomes small. For the omnidirectional transmission, i.e. the beamwidth is 360°, there are 7 small coalitions in which the corresponding links have to pay higher rental cost.

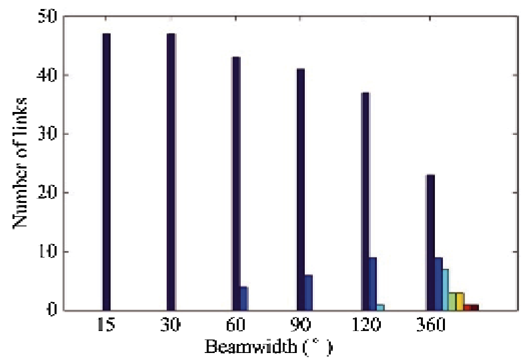

**Fig. 4** Composition of core partition

The traffic demand of the flows also affects the core partition. For each link, increasing the traffic load means reducing its tolerable interference level. Fig. 5 shows the number of coalitions versus the varying traffic demand. When the beamwidth is 30°, the number of coalitions only increases to 2 from 1 with increasing traffic demand. For the omnidirectional transmission, the link inevitably suffers from the accumulated interference from other links during concurrent transmissions. In that case, some links have to deviate current coalitions and establish other new coalitions in order to support the increasing traffic demand. In the spectrum allocation game, the directional transmission with small beamwidth shows remarkable capability of supporting high traffic demand.

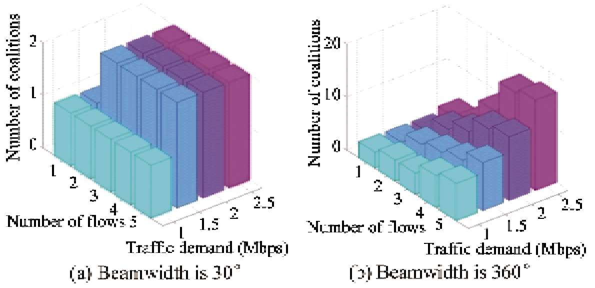


**Fig. 5** Number of coalitions vs. varying traffic demands

## 5 Conclusion

A game theoretic model is introduced to study the procedure of the spectrum allocation in cognitive radio networks. Links have the incentive to access the same band to reduce their individual rental. Then the cooperative spectrum is formulated to access among links as the spectrum allocation game. Furthermore, this game is proved to be core stable. From the numerical results, it is observed that the directional transmission can increase the size of single coalition and reduce the number of coalitions. Due to the advantage of spatial reuse, the directional transmission shows better capability to support high traffic demand which contributes to more interests for the links.

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