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Self-Coexistence Among Cognitive Radio Networks Using Risk-Motivated Channel Selection Based Deference Structure

Kenneth Ezirim* and Shamik Sengupta

Abstract: Among cognitive radio networks there is a persistent trend of competition to acquire under-utilized and idle channels for data transmission. The competition for spectrum resources often results in the misuse of the spectrum resources as networks experience contention in attempt to access unoccupied spectrum bands. The competitive scenario causes cognitive radio networks to incur a huge amount of loss, which constitutes a major problem of self-coexistence among networks. As a way to minimize these losses we present a self-coexistence mechanism that allows cognitive radio networks to coexist with each other by implementing a risk-motivated channel selection based on deference structure. Cognitive radio networks form deference structure community to have more efficient access to a channel of interest and can defer transmission to one another on that channel, thereby minimizing the chances of conflicts. As part of the decision making process to become a member of a deference structure community, cognitive radio networks rely on a risk-motivated channel selection scheme to evaluate the tentative deference structure channel. We provide numerical and simulation results that demonstrates the benefits of the proposed self-coexistence mechanism and show how it helps networks to coordinate their spectrum activities, minimize contention experienced and improve their utility. We also emphasize on the importance of the deference structure community size with regards to the average performance of member networks.

Key words: dynamic spectrum access; cognitive radio; self-coexistence; deference; deference structure

1 Introduction

The cognitive radios (CR) are known to be well equipped devices that can periodically perform spectrum sensing and operate at any unused frequency in the licensed bands[1]. The most important regulatory aspect is that cognitive radios must not interfere with the operation in the licensed bands and must identify and avoid such bands in a timely manner[2,3]. If any of the spectrum bands used by cognitive radios (i.e., secondary users) is accessed by the licensed incumbents (i.e., primary users), they are required to immediately vacate the spectrum band within the channel move time and switch to another channel[4].

In a system of Dynamic Spectrum Access (DSA) networks, there is a consistent need to access the channel in a manner to minimize contention and maximize the derived channel utility. CR networks operating in a spectrum recognize the need to maintain quality of services that will guarantee undisrupted transmission of data. In order to maintain quality of service (QoS), some CR networks may keep backup channels that they can switch to if the primary user suddenly shows up. In the face of spectrum resources scarcity however, it might not be possible to have

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backup channels, as spectrum resources might not be even enough to satisfy the network's channel requirement. The problem is further exacerbated when CR networks have multiple channel requirements. With this scenario in mind, the question of coexistence among CR networks becomes a very important issue. In the face of deficiency in spectrum resources, networks compete viciously to acquire as many channels as possible just to maintain its QoS at a satisfactory level.

In previous works[5-7], the focus on how to improve CR networks' throughput and QoS has been placed on efficient and accurate sensing capability. To further improve accuracy of sensing results, networks embark on collaborative sensing[6,7]. In Ref. [5] a coalition formation framework was suggested which helps cognitive radio network decide which network to collaborate with by sharing sensing results. The problem was approached from a game theory perspective in Ref. [8]. Majority of these works focus on spectrum etiquette only from primary-secondary perspective, i.e., to avoid interference with the primary users. On the contrary, there have been very few works on issues related to self-coexistence among secondary networks. In areas with significantly high primary incumbents (licensed services), open channels will be a commodity of demand. Therefore, dynamic channel access among CR networks will be of utmost importance so that the interference among CR networks can be minimized; else the throughput and quality of service (QoS) will be compromised.

In our work, we are interested in the dynamic spectrum access with focus on *secondary-secondary* spectrum etiquette and self-coexistence mechanism that can foster better performance of cognitive radio networks and reduce the amount of contention they experience. We present the concept of Deference Structure (DS) that networks can exploit to minimize contention by collaboratively accessing spectrum bands. The deference structure concept relies on the ability of CR networks to agree to defer transmission in a channel to a neighboring network with the expectation of reciprocity with sole purpose of avoiding contention. We also present a novel channel selection scheme, otherwise known as risk-motivated channel selection scheme. CR networks rely on this scheme to decide whether to respond to a request to form a deference structure on an advertised channel.

2 Deference Structure Model

2.1 System model

We consider a system of N CR networks operating in the spectrum. The spectrum resources is limited to M channels which is not enough to satisfy the spectrum needs of the networks. In the face of scarcity of spectrum resources, CR networks experience contention while competing for idle spectrum bands.

Due to high level of contention, CR networks might not be able to meet their goals of conducting transmission without interference and maintaining QoS. CR networks can use different approaches to improve the situation. Some CR networks display altruistic behavior[9] and may decide to help related networks by deferring transmission to them. Others might decide to form a coalition such that they utilize the spectrum resources in turns. The outcome of this sort of behavior is the formation of a DS that allows networks to cooperatively access a channel of common interest. A DS is an agreement between networks, specifying the order of deference among network as well as transmission time allocated to each network.

A **DS community** is a coalition of CR networks that strictly follow a deference structure to access a channel. A channel j is considered a DS channel if there is at least one DS that guides the way channel j is accessed by the DS community. A CR network that is part of a deference structure community is referred to as a DS network (insider), whereas non members are referred as non-DS networks (outsiders). Members of a given DS community do not contend with each other but might contend with other CR networks that are not part of the community. DS channel is shared among members in a manner that ensure that each member gets a fair share of the spectrum band.

A CR network initiates the formation of a DS on a channel when the risk of transmitting on that channel has exceeded the acceptable threshold. Other networks in the system would respond to the request only if the computed risk of contention on the advertised channel is significantly high. Some other factors such as kinship of the networks and expected improvement in performance encourage networks to respond to the request. After the formation of the DS community, coordination is achieved via the exchange of control messages among members.

2.2 Deference structure implementation

DS mechanism is implemented by CR networks to mitigate the amount of contention experienced while operating on a channel, which hinders effective transmission and degrades QoS. The process of formation of a DS on a channel can be initiated by any CR network that urgently needs to improve its utility on a channel. The initiator network broadcasts a request to other CR network declaring its interest to form a coalition on a channel. There is a possibility of having more than one network in the system declaring interest in the same channel. One of the possible ways of resolving such bottlenecks could be for CR networks responding only to the request coming from a network with the lowest identity.

Response to a request depends on the relatedness of the CR networks, urgency to operate in a contention-free spectrum band or altruistic predisposition of CR networks to help other networks in anticipation of reciprocity in the future. In the case where response is motivated by the desire to minimize contention, CR networks use a Risk-motivated Channel Selection Scheme (RCSS) to evaluate the risk of contending in the advertised channel with respect to other available channels in the spectrum. In some cases, networks respond if the risk factor is well above anticipated level. We shall discuss the RCSS later in this section.

When CR networks form a DS community, they reach an agreement on how they will opportunistically operate on the channel of common interest. CR networks are not allowed to be part of another DS community on the same channel but can collaborate with other networks on different channels for different purposes. This approach encourages scalability and allows the networks to operate freely in other spectrum bands.

Besides the goal of minimizing contention, the sharing of spectrum resources among CR networks in a deference structure community has to be fair. One way of ensuring fairness in the system would be to assign each participating member network equal transmission time slots.

2.3 Deference structure protocol

The formation and coordination of a deference structure community rely on message exchanges among the CR networks. This provides the means for interested CR networks to declare interests, priorities and conditions for joining DS community. We rely on the 802.11 Medium Access Control (MAC) protocol to implement the deference structure protocol, especially with regards to contention handling mechanism.

Communication in our DS model is conducted via a Common Control Channel (CCC) during a Beacon Period(BP). We consider BP as a period in the super frame when networks communicate and coordinate activities within their DS communities. In contrast with the beacon periods implemented in Refs. [10-12], we allow a variable BP which can be as long as the transmission slot time. This helps to avoid scalability issues associated with fixed BP and allow communication to continue by using part of the transmission slot time.

At the beginning of the DS formation, an initiator broadcasts a request (REQ) message to all CR networks, advertising the channel that it desires to form a deference structure on (see Fig. 1). The REQ contains, among other information, the identifier of the initiator network, the advertised channel identifier (frequency), and the priorities (high data rate, long range transmission etc.). Interested CR networks respond by sending to the initiator an RSP message, which contains a network's identifier as well as its spectrum requirements (desired duration to use the channel, urgency to transmit time-sensitive data etc.). The initiator receives the RSPs and schedules the networks according to their various requirements in a manner that ensures fairness to all participating networks. The initiator later multi-casts the Deference Structure Message (DSM) to member networks. DSM contains the DS which describes the order in which networks take to access their common channel. The order is expressed using a prioritized list which members adhere to assuming they are all honest

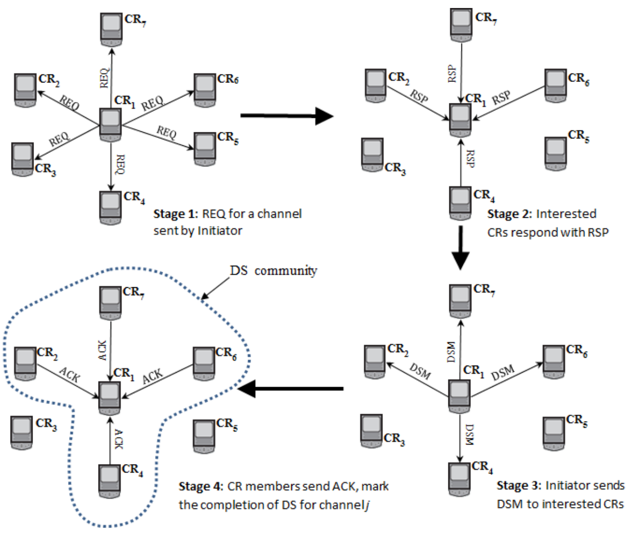

Fig. 1 Deference structure formation process.

networks. Multicast of DSM is followed by an acknowledgment (ACK) from the recipients, which marks the completion of the DS formation cycle.

3 Risk Motivated Channel Selection Scheme

During channel selection, CR networks normally make decision about which of the available channels is best to select. A CR network's choice is based on its knowledge about the activity of the channel (channel profile information/history). The process of channel selection involves ranking of the channels that can be based on their throughput, QoS or duration of licensed owners in the channels. We consider the ranking of channel according to the risk of encountering contention in the channel. We assume that the channels are homogeneous.

On receiving a request from an initiator, a CR network has to make a decision precisely whether to accept the request or not. DS formation requests always come with the channel(s) of interest included in the REQ packet. The CR network has to quickly decide whether it is beneficial to be part of the DS on channel(s) offered. The RCSS enables CR networks to quickly assess the risk of contending on a channel. Using this scheme, a CR network makes decision not only on whether or not to operate in a specific spectrum band but also whether to respond to a request to form a deference structure community.

Since DS formation involves only one channel at a time, the CR networks use the risk motivated channel selection scheme to decide whether to respond to the REQ request packet from the initiator. CR networks rank their channels according to risk of contention on them. If the channel requested is the highest ranked risk channel or the risk of contention on that exceeds a certain predetermined threshold, the CR network would respond to the request. By responding, the CR network declares its interest to form a coalition with other nodes interested in DS formation.

The risk factor of a channel j is a measure of the vulnerability of a network to experience contention while transmitting in j. In channel ranking, channels are sorted in ascending order using their risk factor. The best channel is one with the lowest risk factor. Risk factor of a channel is quantified not just to reflect the possibility of contention in a channel but the persistence of contention on the channel. Risk factor is an expected value and is expressed as

$$E\,[R(j)] = p(X = j) \cdot p(O(j) = 0) \cdot C(j)$$

where $p(X = j)$ is the probability of selecting channel j for transmission and $p(O(j) = 0)$ is the probability that the outcome of using channel j would be contention. C_j is the amount of contention experienced by the network in channel j. Risk factor is computed instantaneously based on accumulated channel profile information from the time it commenced operation. Since the computation of risk factor is based on a network's experience on the channel, the probabilities and contention are computed using accumulated data from spectrum usage reports. We rewrite the above expression as follows

$$E\,[R(j)] = \frac{t_j}{T_A} \cdot \frac{t_j^{'}}{t_j} \cdot \sum_t C_t(j)$$

where T_A is the number of transmission slots that the network has been active, t_j represents the fraction of T_A that has been used for transmission specifically on channel j and $t_j^{'}$ represents the number of transmissions in channel j that resulted in contention. It is evident that $\sum_t C_t(j) = t_j^{'}$. Therefore

$$E\,[R(j)] = \frac{t_j}{T_A} \cdot \frac{t_j^{'}}{t_j} \cdot t_j^{'}.$$

On further reduction we get $E[R(j)]$ as

$$E\,[R(j)] = \frac{(t_j^{'})^2}{T_A}.$$

This channel selection approach resolves the case where two channels share the same probability of contention $p(O(j) = 0)$ but different amount of exposure to contention. Assuming a CR network has experienced 2 and 5 contentions on channels CH_1 and CH_2 respectively in an attempt to transmit on both channels for durations $t_1 = 4$ and $t_2 = 10$. Computing $p(O(j) = 0)$ would yield 0.5 for both channels but their risk factors $E\,[R(i)] = 1$ and $E\,[R(2)] = 2.5$ vary. This implies that it is riskier to choose CH_2 over CH_1 for transmission. This is quite evident because CH_1 has not been used as much as CH_2 and therefore we cannot conclude based on which channel has a higher chance of contention.

When applied in the deference structure model, the channel selection approach improves the cumulative utility among members of DS communities. Collaborative sharing of spectrum information and reporting of transmission outcomes by CR networks provide the data to estimate the risk factor of a channel.

4 Expected Utility in a Deference Structure Model

In a typical wireless scenario, CR networks operate with no knowledge of which channels it neighbors is going to access. Since spectrum is limited there is a potential chance of CR networks contending in one or more channels while attempting to transmit data. In a system of N CR networks accessing M channels, the probability of an i-th network to contend in a channel j is given as

$$p_{ij} = \sum_{l=0}^{N-1} \binom{N-1}{l} q^l (1-q)^{N-l-1} \quad (1)$$

where l is the number of networks transmitting in channel j, q is the probability of the i-th network accessing the same channel with another CR network.

Let $\beta_{ij}(t)$ be the utility derived by the network i transmitting in channel j at timeslot t and $C_{ij}(t)$ be the contention cost. We represent the contention cost as a proportion of the utility that could have been gained if there was no record of contention on the channel. So the contention cost is expressed as,

$$C_{ij}(t) = \alpha \cdot \beta_{ij}(t) \quad (2)$$

where $0 < \alpha \leq 1$. α is the fraction of the utility (transmission data) that was lost due to contention. The expected utility for network i is given as

$$E[U_{ij}] = \sum_{t=1}^{T} \left[(1-p_{ij}) \cdot \beta_{ij}(t) - p_{ij} \cdot C_{ij}(t)\right] \quad (3)$$

Substituting Eq. (2) in Eq. (3) we have

$$E[U_{ij}] = \sum_{t=1}^{T} \left[(1-p_{ij} - \alpha \cdot p_{ij}) \cdot \beta_{ij}(t)\right] \quad (4)$$

After the formation of a DS community on channel j, members follow an order to access the channel, avoiding conflict with one another. This reduces the number of potential conflicts that a member network would experience on the channel. Assuming there are k CR networks that form the DS community, then the probability of contention reduces to

$$p_{ij}^* = \sum_{l}^{N-k-1} \binom{N-k-1}{l} q^l (1-q)^{N-k-l-1} \quad (5)$$

It is quite evident that p_{ij}^* would be much less than p_{ij}. The expected utility in being part of the DS community of k CR networks can be expressed as

$$E[U_{ij}^*] = \sum_{t \in T_A}^{|T_A|} \left[(1-p_{ij}^* - \alpha \cdot p_{ij}^*) \cdot \beta_{ij}(t)\right] \quad (6)$$

where T_A is the number of timeslots when network i is actively transmitting and not deferring to another member CR network in the DS community. T_A is less than T because T is distributed over the members in such a way that induces fairness and encourages altruism in sharing the spectrum resources. Under altruistic conditions CR networks might not get the same expected utility but sacrifices some portion of its transmission timeslots to help other networks achieve their goals. In that case prior to the formation of the DS community, members anticipate that the expected utility of the DS community would be more than the cumulative expected utility of members exploiting channel j in the absence of any coordination. Therefore

$$E[U_j^k] \geq E[U_j] \quad (7)$$

where $E[U_j^k]$ is the expected cumulative utility of DS community and $E[U_j]$ is the cumulative expected utility of members before joining the DS community. It can also be derived that

$$E[U_j] = \sum_{i=1}^{k} E[U_{ij}] \quad (8)$$

and

$$E[U_j^k] = \sum_{i=1}^{k} E[U_{ij}^*] - Z_j^k \quad (9)$$

where Z_j^k is the cost incurred by the DS community which includes one-time cost of forming the community and the cost of coordinating the activities of the DS community.

The problem, therefore, is to find the optimal k that maximizes the expected utility and minimizes the cost of coordination, as shown in Eq. (10).

$$k^* = \underset{k \in [0..N]}{\operatorname{argmax}} \left(E[U_j^k]\right) \quad (10)$$

5 Numerical and Simulation Results

We have conducted some experiments to show that the benefit of having DS in a system of networks. In the simulations we assume that the spectrum resources are limited in supply and some CR networks are predisposed to forming deference structure community with other networks. The CR networks are distributed and communicate via control channel to exchange messages. Communication over the control channel is conducted using the MAC protocol for cognitive radios CR-MAC. To evaluate the result obtained from our simulations we use the following metrics: average utility, convergence time and Jain's fairness index.

5.1 Benefit of deference structure mechanism in a system of CR networks

In our experiment we observed that the presence of DS in the system impacted positively on the system utility. To measure the impact of deference structures on the system we let $N = 12$ and varied the number of channels M. The CR networks were allowed to dynamically form DS community of variable sizes. The result obtained shows that under the above stated conditions, the utility derived from a system of CR networks with deference structure implementation is better than the utility of the same system with no deference structures (see Fig. 2). In Fig. 2 we can see that for all values of M the utility of the DS system is greater than the utility of the Non-DS (NDS) system. This result indicates that the presence of DSs in a system improves the performance of the system as a result of the reduced contention experienced by the insider networks.

We also investigated the individual benefit derived by the CR networks upon joining a deference structure community. For this experiment we allowed the CR networks to initially compete for the spectrum and dynamically form deference structure communities as the number of losses they incur exceed a predefined threshold. A CR network can be a member of multiple DS communities but the channels for those communities must be distinct. This implies that a CR network is not allowed to belong to multiple DS communities with the same channel of interest. In our experimental setup we choose $N = 10$ CR networks. The experiment was conducted in two different settings — with deference structure and without deference structure. Results obtained from the experiment are illustrated in Fig. 3. Comparing the result from the two settings

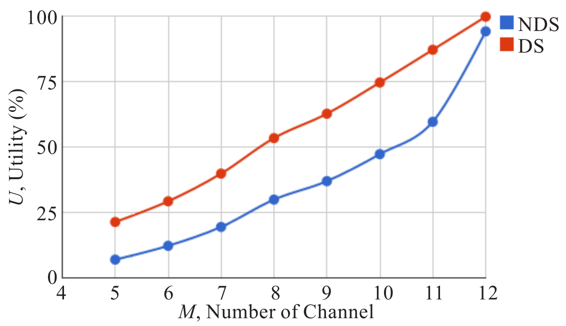

Fig. 2 Performance of system of CR networks (N=12) with multiple channel requirement. NDS - no deference structure, DS - with deference structure.

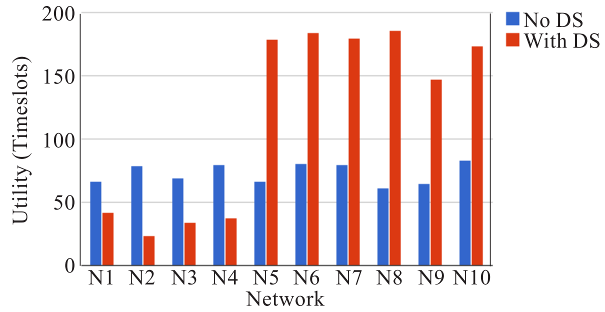

Fig. 3 Performance of CR networks in non-DS and DS settings.

we can see that the cumulative performance of the insider networks $\{N_5, N_6, N_7, N_8, N_9, N_{10}\}$ that are part of a deference structure community improved dramatically. The outsider networks $\{N_1, N_2, N_3, N_4\}$ cumulative performance degraded compared to their performance in the non-DS setting. The Jain's fairness index for the insider gave a value of 0.99, revealing the high degree of fairness in the DS communities.

5.2 Impact of DS community size k on utility of CR networks

We investigated the impact that DS community size has on the performance of the deference structure communities formed in a system of cognitive radio networks. Our observation revealed the dependency of the system utility on the average size of the deference structure communities formed for each channel. As expected, the CR networks upon reaching a certain level of contention broadcast request to form deference structure. The number of member CR networks allowed to be admitted to the community, designated as k, was varied during the simulation and we recorded the utility for each value of k.

As was discussed before, the major benefit of being part of a deference structure community is that the members do not get into conflict with one another. Figure 4 depicts the result of another experiment that we conducted to uncover the dependency of the system on k. In this experiment, we set $N = 50$ and $M = 35$. As seen in Fig. 4 the utility derived by the insider networks are far better than the utility derived by the outsider networks. The trend suggests that as k increases, which corresponds to an increase in the number of insider networks, the average utility of the insiders gradually increases, while that of the outsiders decreases.

In Fig. 5, the variation of the average utility and

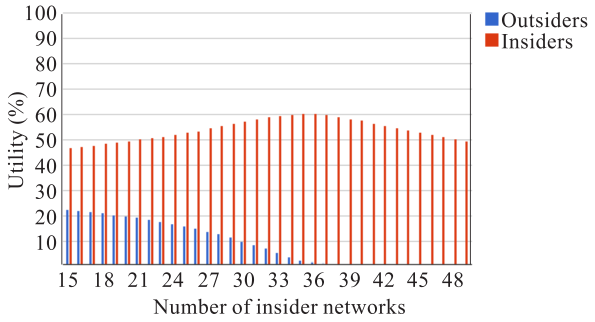

Fig. 4 Comparison of the average utility of insider and outsider networks.

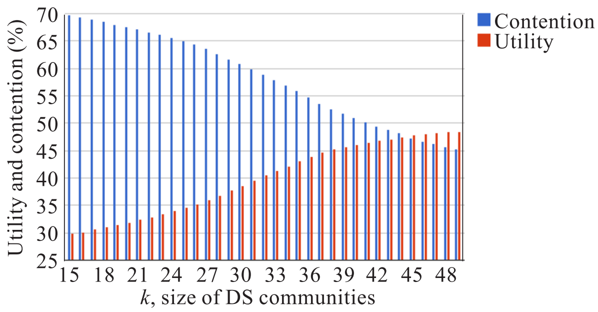

Fig. 5 Variation of utility and contention with k.

contention with the size k of the DS communities are shown. In this setting we set $N = 50$ and $M = 35$. We observe that the increase in the size of the community has a positive impact on the average utility derived in the system. The amount of contention experienced by the member networks is on the decline as k increases.

Even though formation of deference structures is beneficial to the CR networks, there is a tipping point after which adding an additional CR network would lead to a decline in the utility. This trend is caused by the cost of coordinating the DS members, which increases proportionally as k increases. Also, the members share the spectrum resources in turns and members could require a considerably amount of time to occupy the spectrum band. As k increases, more members will have to wait longer to take their turns. Members wait to avoid contending with another member that might be transmitting in the same band. An increase in k with a fixed M entails a reduction in the number of transmission slots that each member network gets to conduct data transmission. This impacts greatly on the utility of the CR networks as well as on the cumulative utility of the deference structure communities.

Figure 6 depicts the variation of the utility of CR networks that belong to a DS community for different values of M. With a fixed number of spectrum band M, the cumulative utility increases up to a peak and starts to decay with the increase of k. The peak utility is attained when $k \approx M$ and at this period having additional members would increase both the coordination cost and waiting cost. This impacts the system and causes the utility to drop. It is therefore necessary for the initiator network to estimate the optimal k prior to the formation of the DS community in order to keep the coordination and waiting costs minimum. By so doing the limited spectrum resources can be maximally utilized to the benefit of the insider networks.

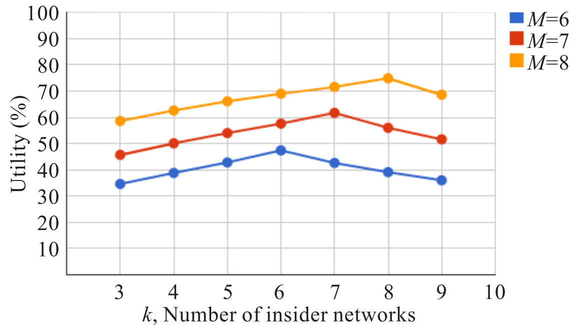

Fig. 6 Performance of deference structure community of size k with varying M, number of spectrum bands. The optimal k corresponds to the peak of the curve.

6 Conclusions

In this paper we studied the impact of deference structures on the utility of a system of CR networks. We provided analysis of DS valuation as well as utility estimation showing explicitly the conditions under which the formation of DS community would be favorable to the CR networks. We proposed a RCSS that helps CR networks decide which deference structure to join. The DS mechanism as well as the protocol that allows for the formation and coordination of deference structures were also discussed in this paper. We demonstrated via simulation the relationship between size k of the DS community and the utility derived by the CR networks. We were able to show that the existence of DS communities is beneficial, as utility is observed to increase as k increases. The simulation results obtained also demonstrate the impact of size k of DS communities on the performance of the member networks and suggest the determination of an optimal k for the best network performance.

Acknowledgements

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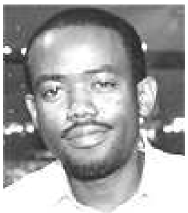

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