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COALITION FORMATION FOR THROUGHPUT ENHANCEMENT IN COGNITIVE RADIO WIRELESS NETWORKS

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ABSTRACT

Recently there have been numerous studies exploring the benefits of the coalition formation in a cognitive radio network and it has been shown that coalition formation tends to improve the performance of cognitive radio. In this paper we use the concepts from matching theory, specifically we use Gale-Shapley algorithm, to form the coalition among cognitive radio user for collaborative spectrum sensing under target detection probability constraint. In the proposed model we modify Gale-Shapley algorithm for the cognitive radio users to form coalitions of varying size to improve their individual gains (.e.g. throughput and probability of false alarm). We show using simulations that using the modified gale shapely algorithm for coalition formation yields significant gains in term of reduced false alarm probability and increased throughput per cognitive radio user as compared to non-cooperative scenario.

Keywords: cognitive radio, spectrum sensing, distributed algorithms, stable matching, gale shapely algorithm.

INTRODUCTION

At present most of the spectrum bands suitable for wireless communication has been already allocated to different services, often requiring licenses for operation. With the increasing market of handheld device the traffic demands for wireless networks is increasing exponentially and there is not enough spectrum bands left to accommodate the growing demands. The current license-free bands are not enough for future services as they are already congested hence making it difficult to accommodate new technologies. Due to this there is a common belief that we are running out of usable frequency hence threatening the expansion of high speed ubiquitous broadband network. However, recent survey made by a Spectrum Policy Task Force (SPTF) within FCC indicates that the actual licensed spectrum is largely under-utilized.

A remedy to spectrum scarcity is to improve spectrum utilization by allowing unlicensed users to access under-utilized licensed bands dynamically when licensed users are absent. This idea of spectrum utilization is called Dynamic spectrum access (DSA). One of the solutions, that promise efficient and flexible DSA, is cognitive radio (CR). Cognitive radio is a novel technology which improves the spectrum utilization by allowing unlicensed users also termed as secondary users (SUs) to borrow or share the unused radio spectrum from licensed users also termed as primary users (PUs). As an intelligent wireless communication system, cognitive radio is aware of the environment, selects the communication parameters (such as carrier frequency, bandwidth and transmission power) to optimize the spectrum usage and adapts its transmission and reception accordingly.

In order to be able to use the licensed spectrum band the CRs need to sense the spectrum which is currently not in use by PU. For this purpose CRs can act cooperatively or non-cooperatively. However, it has been shown in the literature that cooperation results in improved performance. In order to design cooperative algorithm for coalition formation there has been a recent surge in literature that proposes new mathematical tools for coalition formation among CRs. The most notable one being is game theory. Though game-theoretic approaches are widely studied and offer lots of benefit it still has shortcomings. First, classical game theoretic algorithms such as best response will require some form of knowledge on other players' actions, thus limiting their distributed implementation. Second, most game-theoretic solutions, such as the Nash equilibrium, investigate one-sided (or unilateral) stability notions in which equilibrium deviations are evaluated at the level of a single player rather than the entire set of players. The existence of equilibria in game-theoretic methods requires special properties for the objective functions, such as convexity, which may not always be satisfied in practical situation.

Recently matching theory is being used to overcome shortcoming of game theoretical approaches for resource allocation in wireless network. Matching theory is often referred to as a branch of game theory, which studies the design and performance of platforms for transactions between agents. In practice, matching theory studies who interacts with whom and how and provides a mathematical framework attempting to describe the formation of mutually beneficial relationships over time. There have been many application of matching market models for resource allocation and management in wireless networks.

In [1], application of two-sided stable matching is presented for resource allocation in wireless networks and studied the distributed implementation of the algorithm and its efficiency. In [2-4], stable matching has been used for channel assignment in cognitive radio. In [2-3], one to

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ARPN Journal of Engineering and Applied Sciences

one stable matching is presented where the value function (also known as utility) of the secondary and primary users are chosen to be identical because the CRs cannot measure the performance of the PUs. It is shown that the stable matching of CR to PUs channel is unique. In [4] the same model used in [3] is applied to interweave cognitive radio with identical utility for CRs and PUs. In [5] many-to-one stable matching is applied and the utility of the PUs modeled based on the interference leakage from CRs and the utility of the CRs are the achievable throughput in PU channels. Stable matching framework is applied in a single radio cell for channel assignment in [6] where two-sided stable matching takes the users uplink and the downlink transmissions into account for the calculation of utilities. In [7], the stable matching framework is used in downlink for cross-layer scheduling of a single cell. The utility of a user is the sum rate and the utility of the resources includes the user queue state of the buffer. Stable matching is used in physical layer security [8], where transmitter and receiver are paired to friendly jammer. In [9], uplink user association in small cell networks is presented using many-to-one stable matching along with coalitional games where utilities are based on QoS and coverage aspects.

It can be seen from the literature that matching theory is a suitable tool for developing distributed cooperative schemes in cognitive radio network. We make use of the existing concept and develop it further for forming coalitions among cognitive radio users. In particular we focus on existing gale shapely algorithm.

SYSTEM MODEL

We consider a scenario where a PU base station is located at the center of the cell and there are multiple CRs in the vicinity of the PU. The CRN consists of n CR pairs/links that can be connected in mesh topology. The total spectrum is composed of $K(< n)$ orthogonal frequency channels. The PU in the network is modeled as an ON/OFF source, where "ON" means that the PU is actively transmitting. The goal of user in CRN is to increase their achievable sum-rate via utilizing the given primary (licensed) spectrum band. For this purpose the CRs will cooperate to organize themselves in coalitions of varying size as shown in Figure-1.

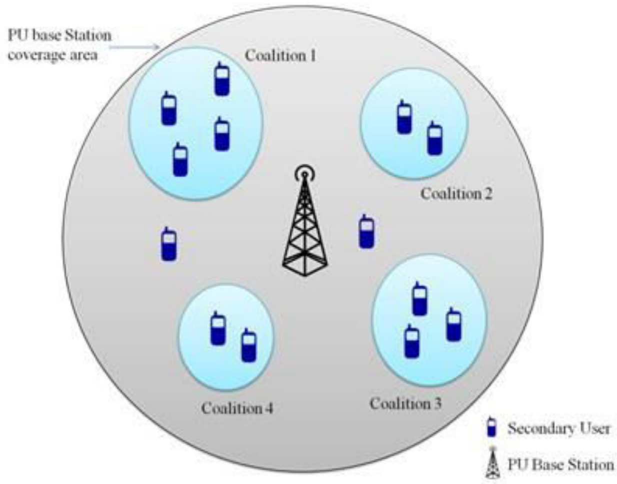


Figure-1. Coalition formation in the cognitive radio network.

In cognitive radio the first step toward making use of the idle licensed spectrum is to perform spectrum sensing. In spectrum sensing there two main parameter for determining the performance of spectrum sensing which are probability of false alarm (P_f) and probability of detection (P_d). Higher P_d will result in less interference for the primary users where as a lower P_f results in underutilized spectrum and lost transmission opportunity hence reducing the throughput of *CRN*. A high detection probability requirement may lead to a high false alarm probability for an individual CR if its γ_i is low. Energy detection performance of CR gets worse when the SNR is low. Due to poor sensing performance the CR will not be able detect the idle spectrum band hence reducing the achievable throughput of that CR. To overcome this issue, cooperative spectrum sensing has been introduced to achieve better performance by taking advantage of the spatial diversity in multiuser CR networks.

Consider a network where the PU is located in the middle of the cell. The CRs are distributed uniformly around the cell. The received signal-to-noise ratio (SNR) for i^{th} CR user from the PU is given by:

$$\gamma i = \frac{P_i}{\sigma^2} \quad (1)$$

where σ^2 represents noise power and $P_i = \mu P_{PU/d_i^\alpha}$ is the signal power received by CR i. P_{PU} is the primary user's signal power, d_i is the distance between the primary user the i^{th} CR, α is the path-loss exponent and μ is a scalar. We consider a BPSK primary user signal and circular symmetric complex Gaussian (CSCG) noise. For the CSCG noise the probability of false alarm for CR i for a chosen detection threshold λ_i using energy detection for spectrum sensing is given by [10]:

ARPN Journal of Engineering and Applied Sciences

$$P_{f,i}(\lambda_i) = Q\left(\left(\frac{\lambda_i}{\sigma^2} - 1\right)\sqrt{N}\right) \quad (2)$$

where $Q(\cdot)$ is the tail probability for the standard normal distribution and N represents the time- bandwidth product, given as $N = \tau_s W$, where τ_s is the sensing duration and W is the bandwidth. For a selected threshold λ_i, the probability of detection of CR i is approximated by [10]:

$$P_{d,i}(\lambda_i, \gamma_i) = Q\left(\left(\frac{\lambda_i}{\sigma^2} - \gamma_i - 1\right)\sqrt{\frac{N}{2\gamma_i + 1}}\right) \quad (3)$$

For protecting the primary user from harmful interference that may be caused by CR transmission, the detection probability is asset to a target value P_d'. The probability of false alarm of each CR i for the targeted P_d' can be derived using Equation. (2) and (3) and is written as:

$$P_{f,i}(P_d', \gamma_i) = Q\left(\sqrt{2\gamma_i + 1}Q^{-1}(P_d') + \sqrt{N}\gamma_i\right) \quad (4)$$

Before the CR can start cooperating and form coalitions each CR user will perform local spectrum sensing independently. A local sensing decision by individual CRs are transmitted over the narrowband common control channel (CCC) to a CR selected as a coalition head. For simplicity of implementation we consider OR fusion rule is used by the coalition head to combine the individual CR sensing decisions within a coalition. After combining the local spectrum sensing results, the resulting probabilities of detection and false alarm of a coalition head becomes the probabilities of detection and false alarm of each CR i that is the member of S. Since all decision are taken independently the detection probability of the coalition S using OR rule for decision fusion is given as:

$$P_{d,S} = 1 - \prod_{i=1}^{|S|}(1 - P_{d,i}) \quad (5)$$

For a given P_d', the individual CRs target probability of detection in a coalition using OR fusion rule is written as (assuming same target probability of detection for every CR, as in [12] :

$$P_{d,i}' = 1 - (1 - P_d')^{1/|S|} \quad (6)$$

Using the OR rule, the false alarm probability $P_{f,S}$ of the coalition S is given as:

$$P_{f,S} = 1 - \prod_{i=1}^{|S|}(1 - P_{f,i}) \quad (7)$$

It can be observed from (4) that for a given P_d' and N, the CRs whose received SNR γ_i is low have incentives to form coalitions because it help reduce the $P_{f,i}$ (due to the increase in $Q^{-1}(P_d')$) term which in turn decreases $P_{f,i}$). However, for a given $P_{f,i}$ the coalitional false alarm probability given by (7) also increase with the size of coalition $|S|$. Therefore, each coalition can have certain number of CRs.

a) Throughput of CR

The CR user when performing spectrum sensing cannot transmit data at the same time. In a non-cooperative CRN with periodic spectrum sensing, each CR perform spectrum sensing within duration of τ_s and data is transmitted in $T_f - \tau_s$ duration, where T_f is the total frame length. For the non-cooperative case, the average throughput of the CR i is given as [11]:

$$R_i = P_{H_0}(1 - \frac{\tau_s}{T_f})(1 - P_{f,i})r_i \quad (8)$$

where P_{H_0} is the probability of primary user absent and r_i represents the transmission rate of the CR i to its receiver when the primary user is absent. When the CRs form coalition then the CRs cannot transmit data until the local decision is combined at coalition head and the results are transmitted back to the coalition members. The coalition head waits for the local decisions from all the CRs to arrive in order to make final decision. As the number of CR in a coalition increases the time for final decision on spectrum sensing also increases. Therefore the average throughput of CR in coalition formation scenario while considering delay in combining results can be written as:

$$\hat{R}_i = P_{H_0}(1 - \frac{\tau_s}{T_f} - \frac{\tau_c}{T_f}(|S| - 1))(1 - P_{f,S})r_i \quad (9)$$

where τ_c is the time spent on reporting a sensing decision to the coalition head. From (9) it can be seen that the throughput for each CR is function of coalition size $|S|$, probability of false alarm P_f, sensing time and decision combining time. For a target detection probability P_d' the CRs may form coalitions to reduce their false alarm probability and therefore increase their average throughput given by (9).

b) Utility for coalition formation

Let $N = \{1, \ldots, n\}$ be a finite set of players. Each non-empty subset S ($S \subseteq N$, $S \neq \emptyset$) of N is called a *coalition*. A *partition* Π of the set N is a set of coalitions such that every element in N is in exactly one of these coalitions i.e., $\Pi = \{S_1, S_2, \ldots, S_k\}$, where $S_i \cap S_j = \emptyset$, $i \neq j$ and $\bigcup_1^k S_i = N$. For each coalition S, we define a *function* $v(S)$, called utility of the coalition S. This utility is used in for evaluating whether CRs will form coalition or not. When two or more CRs form a coalition S, then any CR within S is selected as a coalition head to combine the individual CR sensing decisions within the coalition. The decisions to form coalitions by the CRs are based on consensus, that is, a coalition is formed only if it is acceptable to everyone involved. We also assume that CRs are myopic, that is, CRs care only about their current payoffs. In this paper function $v(S)$ is defined as:

$$v(S) = Q_{f,s} = 1 - \prod_{i \in S} [(1 - P_f)(1 - P_{e,i,k}) + (P_f P_{e,i,k})] \quad (10)$$

Where,

$$P_{e,i,k} = Q(\sqrt{2\gamma_s}) \quad \text{(For AWGN Channel)}$$

Where Q(.) is the Gaussian probability density function , γ_s is the SNR and $P_{e,i,k}$ is the bit error rate. The bit error rate is considered because the local decision has to be transmitted from CRs to coalition head which may be received in error.

c) Gale-shapley algorithm

According to Gale-Shapley algorithm [12] there exist stable matching for any given preference lists. The Gale-Shapley algorithm takes the men & the women sets M, W and preference lists of men & women sets PL(M), PL(W) as input and finds a stable matching in $O(n^2)$ time. Consider two disjoint sets of size n, the men and the women. Associated with each person is a strictly ordered preference list containing all the members of the opposite sex. Person p prefers q to r, where q and r of the opposite sex to p, if and only if q precedes r on p's preference list. A *matching* μ is a one-to-one correspondence between the men and the women. If man m and women w are matched in μ, then m and w are called *partners* in μ, and we write $m = p_\mu(w)$, $w = p_\mu(m)$; $p_\mu(m)$ is the μ-partner of m, and $p_\mu(w)$ the μ-partner of w. A man m and women w are said to *block* a matching μ, or to be a *blocking pair* for μ, if m and w are not partners in μ, but m prefers w to $p_\mu(m)$ and w prefers m to $p_\mu(w)$. A matching for which there is at least one blocking pair is called *unstable*, and is otherwise *stable*.

MODIFIED GALE-SHAPLEY ALGORITHM FOR COALITION FORMATION

The Gale-Shapley algorithm cannot be directly used for coalition formation. The Gale-Shapley algorithm uses two different sets however in our scenario we have only one set .i.e. the CRs. We adapt Gale-Shapley algorithm to be used for single set of users and use it as a component of our coalition formation algorithm. In our algorithm the men and the women sets are both equal .i.e. that is M=W. We refer to set of men and women to as CRs users. Since we use same sets some elements of the sets can be matched to itself that is they do not prefer being matched to anyone in the set. Initial partition is a set of singletons $\Pi = \{\{1\}, \{2\}, \ldots, \{n\}\}$. Let $\Pi = \{S_1, \ldots, S_k\}$ be the next obtained partition. The preference list for a coalition S_i, $i = 1..k$, defines relation $\succcurlyeq_{S_i}$ as:

$$S_i : S_{i_1} \succcurlyeq_{S_i} S_{i_2} \succcurlyeq_{S_i} \cdots \succcurlyeq_{S_i} S_{i_k}, \quad \text{where,} \quad S_{i_j} \in \Pi, \quad j = 1, \ldots, k. \quad (11)$$

The above equation represents that the CR appearing first on the list is the most preferred. Now the Gale-Shapley algorithm runs with the two identical sets *Π* and the same preference lists for both sets as input. Let the preference list of the set *Π* be denoted as *PL (Π)*. Whole process repeats for new partition that are formed after applying first round of Gale-Shapley algorithm until the output of the algorithm is stable matching of partition *Π* to itself. The preference list is generated for each repetition using utility function $v(S)$, as presented in Equation. (10). If S_i and S_j are coalition that are formed after application of first round of Gale-Shapley algorithm then coalitions are joined and become a new coalition $S_i \cup S_j$ if the algorithm allows otherwise they remain as independent coalition. Algorithm stops when Gale-Shapley algorithm gives an identity matching i.e., no more matching further is possible. One thing to note is that the output of modified Gale-Shapley algorithm is stable since the final outcome is identity matching .i.e. each CR is matched to itself (in case of coalition formation each coalition is matched to itself) and would not deviate from this matching. Also the goal of original Gale-Shapley algorithm is to have one to one matching between men and women. However in our case, although each round gives one to one matching between each CR (coalition), the algorithm is repeated multiple times by generating new preference list to achieve many to many matching until no more further matching is possible. The proposed distributed algorithm to form coalitions consists of following stages:

1. **Local spectrum sensing**: In this phase each CR in the network perform spectrum sensing using energy detection method in order to calculate the false alarm probability. This information is needed so that the CR users can calculate the utility for forming coalitions.

2. **The discovery phase**: At this stage each CR discovers neighbouring CRs as well as information required to perform matching and eventually coalition formation.

3. **Computing utility and Preference list generation**: After discovery phase and recovering all the information needed the CR users calculate the utility with all other CR user in the network for possible cooperation. The utility is calculated using the (12) based on the target probability of detection P_d'. The utility calculated from all the users is used to generate preference list PL_i, where PL_i preference list of i^{th} user in the CRN.

ARPN Journal of Engineering and Applied Sciences

4. **Matching algorithm**: Now that we have the ordered preferences of all users in the network, we can proceed to apply the matching algorithm to obtain the stable matching. For a given network structure, during matching process, each coalition attempts to merge with other coalitions in its vicinity in a pair wise manner. The stable matching algorithm proceeds in several rounds until each coalition is matched to itself.

The following is a pseudo-code of our Coalition Formation (CF) algorithm. The algorithm takes the number of players n and a characteristic function $v(S)$ as input and finds a partition of $N = \{1,2,\ldots,n\}$.

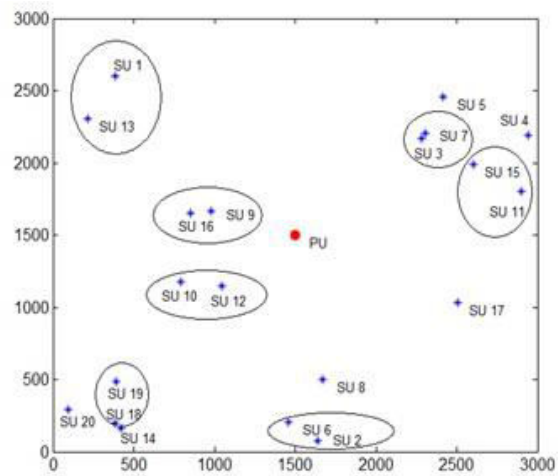
a) CF algorithm

Input: Set of players $N = \{1,2,\ldots,n\}$, characteristic function $v(S)$;
Output: Partition of the set N.
Repeat
$m = 1$
Step1: Each CR (coalition) discovers the other CRs (coalition) in the network.
Step 2: Each CR calculates utility function $v(S_{i,j})$ with other CRs (coalition) in the network to generate preference list.
$v(S) \leftarrow \{v(S_1), v(S_2), \ldots, v(S_k)\}$ (Utility of coalitions)
PL (Π) ←**PL Algorithm** (*Π, Π,v(S)*) (Preference list)
Step 3: The CRs (coalitions) arrange the preference list in decreasing order.
Step 4: Modified Gale-Shapley: The CRs (coalitions) starts sending and receiving proposals for coalition formation which includes the potential utility if they form coalition.
***Step 5:* If** $v(S_{i,j}) < v(S_i)$
Match and form coalition
Else
No matching (i.e. matches to itself)
End
$\Pi_m \leftarrow \{S_1, S_2 \ldots\ldots S_k\}$ (New partition)
$m \leftarrow m + 1$
Until:
$\Pi_{m-1} == \Pi_m$ (Previous partition is similar to current partition)

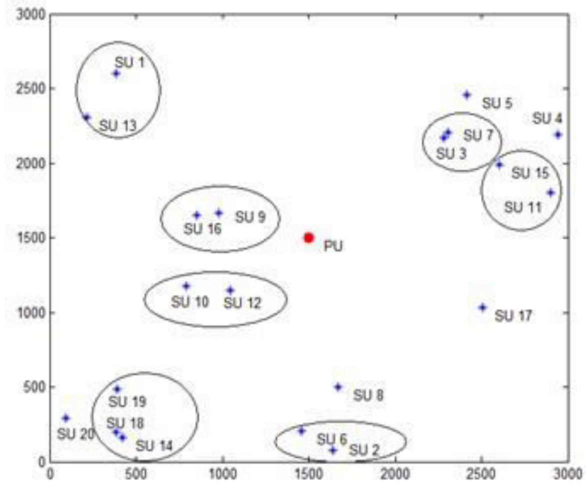
Following is a pseudo-code of PL algorithm. The algorithm takes a partition $\Pi = \{S_1, S_2, \ldots, S_k\}$ and a characteristic function $v(S)$ as input and returns preference list *PL(Π)* of *Π*

b) Preference list algorithm

Input: Partition $\Pi = \{S_1, S_2, \ldots, S_k\}$, characteristic function $v(S)$;
Output: Preference list *PL (Π)* of the partition Π.
for $i = 1$ **to** k
for $j = 1$ **to** k
$v(S_{i,j}) \leftarrow v(S_i \cup S_j)$ (Calculated from Eqn. (10))
End
$v(S_{i,t_1}) \succcurlyeq v(S_{i,t_2}) \succcurlyeq \cdots \succcurlyeq v(S_{i,t_k}) \leftarrow$ **Sort** $v(S_{i,1}), v(S_{i,2}), \ldots, v(S_{i,k})$
$\mathrm{PL}(S_i) \leftarrow (v(S_{i,t_1}) \succcurlyeq v(S_{i,t_2}) \succcurlyeq \cdots \succcurlyeq v(S_{i,t_k}))$
End
$\mathrm{PL}(\Pi) \leftarrow (\mathrm{PL}(S_1), \ldots, \mathrm{PL}(S_k))$;
return PL(Π)



(a)



(b)

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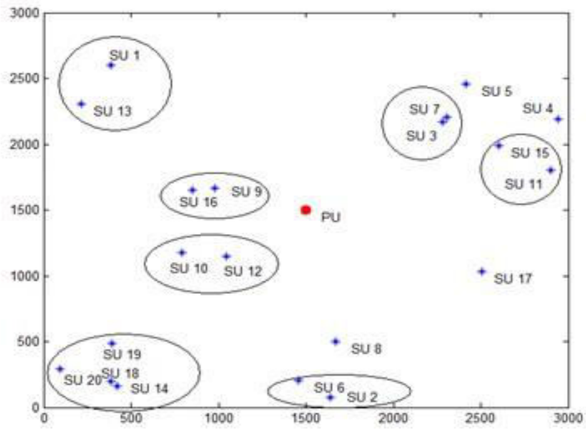

(c)

Figure-2. Snapshot of coalition formation for 20 CR users using modified Gale-Shapley algorithm (a) round 1(b) round 2 (c) round 3.

RESULTS

For the simulation we considered the following network setup: The PU is placed at the centre of 3km x 3km square area with the CRs randomly placed around the PU. We set the PU transmit power PPU = 100 mW, the CR transmit power for reporting the sensing bits Pi = 10 mW, the target probability of detection Pd = 0.9 and the noise power is set to σ2 = −90 dBm. For path loss, we set μ = 3 and κ = 1. The time bandwidth product m is set to 6000. Simulation results are averaged over 1000 random locations of the CRs.

Figure-2 shows the snapshot of the evolving network structure resulting from the application of proposed algorithm. In the first round Figure-2(a) the CR pairs with their neighbour which results in better utility in terms of reduced false alarm. Then in the next round, Figure-2(b), the algorithm proceeds and new members are added to the coalition. Round 3, Figure-2(c) presents the final coalition that results and no more matching is possible after this.

New members are added to coalition in each round if the overall false alarm of the coalition is reduced. It can be seen that the CRs have organized themselves into coalition of varying size. The CRs that are far away from the PU (at the edge of the simulation area) tends to form larger coalition since it results in improvement of the utility. The CRs will tend to form coalition as long as there utility improves collectively. The CRs closer to PU tend to stay alone (.i.e. do not form coalition) as they do not benefit from the coalition formation. Figure-3 shows the decrease in the false alarm rate with increasing number of CR users using the proposed coalition formation algorithm For the target detection probability of Pd = 0.9 and Pd = 0.99. The users are dropped randomly around the PU base station and the CR measures the local Pf and generates the preference list for possible coalition formation. The user form coalition only when the resulting Pf from the cooperation is lower than their existing Pf. The Figure-3 suggest that as the number of CR in the network increase the number of CR participating in also coalition increases which results in lower Pf . This due to the fact the each CR will have higher number of CR in the vicinity willing to cooperate. The CR user nearby tends to cooperate as compared to CR users far away as seen in Figure-2. Also, increased Pd constraint results increased false alarm rate which is also depicted in Figure-3.

Figure-4 shows the improvement in the average throughput after the coalition formation takes with number of CR users in the network. As expected as the coalition formation takes place the resulting false alarm decrease which in turn increases the throughput as described by Equation. (9). Hence the proposed coalition formation yields an improvement in the average throughput as compared to the non-cooperative solution.

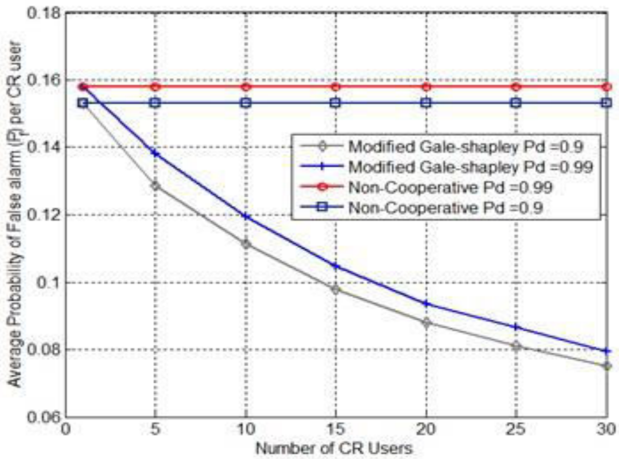

Figure-3. Average false alarm per CR user for different network sizes using modified Gale-shapely.

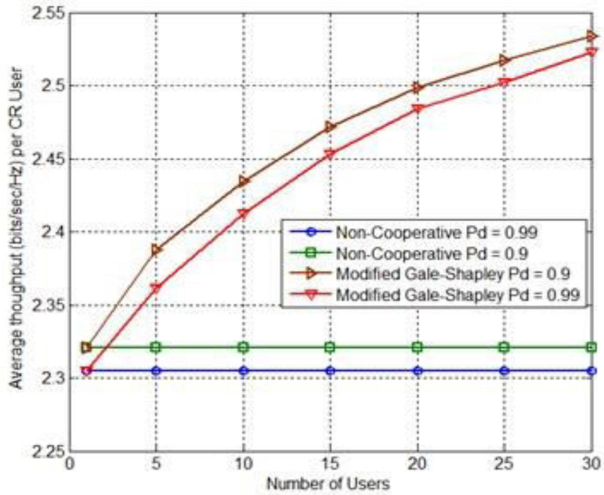

Figure-4. Average throughput per CR user for different network sizes using modified Gale-shapely.

CONCLUSIONS

We proposed a modification of well-known gale shapely algorithm to achieve cooperation among the cognitive radios for spectrum detection and sharing. This algorithm results in formation of stable coalition of cognitive radio. In order to form cooperative group each cognitive radio prepares a preference list of other radio in the vicinity with which the cognitive radio wants to cooperate and hence form coalition. Each cognitive radio makes an offer to cognitive radio in its preference list. The cognitive radio can accept or reject the offer based on preference list. Finally, using simulations, we investigate various aspects of the proposed algorithms and analyse their performance. The proposed algorithms results in improved spectrum detection performance and hence results in improved spectrum efficiency.

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