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A Cooperative Multiagent Based Spectrum Sharing

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Abstract— **A major issue in recent wireless networks is the static utilization and allocation of the available spectrum. An effective solution to this problem is to detect the empty spectrum portions using cognitive radio devices and to share them with the neighboring users, in a dynamic and distributed manner. However, since nodes generally have limited knowledge about their environment, we suggest that cooperative behavior can provide them with the necessary information in order to solve the global issues. To this extend, we develop a novel approach for spectrum allocation using multiagent system cooperation that enables cognitive radio (or secondary user) devices to utilize the amount of available spectrum, dynamically and opportunistically. The key aspect of our design is the deployment of agents on each of the primary and secondary user devices that cooperate in order to have a better use of the spectrum. For cooperation, contract net protocol is considered, allowing spectrum to be dynamically allocated by having a series of exchange of messages amongst the devices. Simulation results show that our approach achieves up to 80% of the whole utility within the span of few messages, and provides an effective mechanism for distributed spectrum allocation.**

Keywords-component; Cognitive Radio; Multiagent Systems; Spectrum Sharing; Contract Net Protocol.

I. INTRODUCTION

In most of the modern day applications, radio spectrum allocation and sharing is a static function in which the spectrum is assigned to a particular dominant primary user (PU) [1], for a long period of time in order to avoid interference and collisions. Parallel to this, to deal with increasing user demands, dynamic spectrum allocation for new wireless networks is necessary. However, since existing wireless networks occupy extensive parts of the available radio spectrum, there is insufficient spectrum available to all new unlicensed wireless networks. Thus, research has to be done to address this problem via dynamic sharing and assignment of spectrum. For example, in Europe and USA, Federal Communication Commission (FCC) considers to allow sharing of unused portions of TV bands to promote dynamic use of spectrum [11].

One effective technology to alleviate the problem of static spectrum assignment and to minimize the insufficient spectrum use is cognitive radio (CR) [10], a radio in modern wireless systems in which a CR (or a secondary user) node changes its parameters (transmission or reception) to share the spectrum dynamically and to avoid the interference with the other licensed (primary) or unlicensed users. The parameter alteration is done by having some knowledge about the radio environment factors such as radio frequency (RF) signal, device level interference, etc. To achieve efficient and dynamic allocation of spectrum between highly distributed CR devices, a balanced, simple and cooperative approach is necessary. Research is therefore in progress on exploring the cooperative spectrum sharing techniques in CR networks. Similar to CR network, a multiagent system (MAS) [2] is a system composed of multiple autonomous agents, working individually or in groups (through interaction) to solve particular tasks. Like CR nodes, agents work dynamically to fulfill their user needs and no single agent has a global view of the network. Each agent maintains its local view and shares its knowledge (when needed) with other agents to solve the assigned tasks.

Recent advances in technology (especially in the domain of programmable integrated circuits and distributed artificial intelligence) have created an opportunity for us to develop a new class of intelligent, autonomous, opportunistic and interactive CR devices [5]. These devices can then be used in a wide variety of network domains (WLAN, WiRAN, MANETs). In addition, an efficiently designed CR with a software agent deployed on it would be capable of interacting with neighboring radios to form a dynamic, loosely-coupled and infrastructure-less collaborative network. While CR physical architecture and its sensing capabilities have received considerable attention [3, 14], the question of how to share radio resources in cooperative scenarios is also an important research issue for current researchers [1, 11, 5].

Therefore, in this paper, an MAS based spectrum sharing strategy is proposed to address the above limitations. Specifically, we consider a cooperative MAS [13], in which the agents are deployed over primary and secondary[1] user devices. By cooperative MAS we mean that the primary user agents exchange a tuple of messages in order to improve the utility of themselves as well as the neighboring secondary user agents. Moreover, the actions of the agents should be chained together to successfully share the unutilized spectrum. The cooperation mechanism we develop is similar to that of contract net protocol (CNP) [6], in which the individual secondary user (SU) agent should send messages to the appropriate neighboring primary user (PU) agents whenever needed and, subsequently, the related PU agents should reply to these agents in order to make a spectrum sharing agreement. We propose that the SU agents should take their decisions based on the amount of spectrum, time and price proposed by the PU agents and should start spectrum sharing whenever

[1] The words secondary and unlicensed user will be used interchangeably throughout the article.

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they find an appropriate offer (without waiting until the reception of all the neighboring PU agents' responses [8]). Then, after completely utilizing the desired spectrum, SU agents should pay the agreed price to the respected PU agents.

In fact, this work brings following two main contributions:

- First, we present a cooperative[2] framework with the related spectrum sharing algorithms.
- Second, we conduct extensive simulations to verify the working of the proposed cooperative algorithms for dynamic spectrum sharing in the context of cognitive radio networks.

The rest of the paper is organized as follows. The following section briefly presents some related works. Section III describes the spectrum allocation problem with the help of an example. In Section IV, we propose our model with the interlinked working of various modules and their related algorithms. The experimental setup and some results are given in Section V. Section VI concludes our work with the future perspectives.

II. RELATED WORK

In literature, few strands of work have focused on spectrum sharing using MAS [17, 12]; but in these works, several limitations exist. For example, in [17], an MAS is used for information sharing and spectrum assignments. All the participating agents deployed over access points (APs), form an interacting MAS, which is responsible for managing radio resources across collocated WLANs. The authors have not provided any of the algorithms and results for their approach. The work in [12] considers a distributed and dynamic MAS based billing, pricing and resource allocation mechanism where the agents work as the auctioneers and the bidders to share the spectrum dynamically. The protocol used for radio resource allocation between the CR devices and operators is termed as *multi-unit sealed-bid auction*, which is based on the concept of bidding and assigning resources. We argue, however, that in cooperative systems, communication should be targeted towards improving overall system utility and that the whole system should be less complex including the complexity in time required to calculate the optimal spectrum allocation.

Generally, game-theory has also been exploited for spectrum allocations in CR networks [4, 7, 18]. In game-theoretical approaches, each SU has one individual goal i.e., to maximize its spectrum usage and the Nash equilibrium is considered to be the optimal solution for the whole network (or game). Furthermore, it incorporates two basic assumptions: first, the rationality assumption, that is, the participating primary and secondary users are rational so that they always choose strategies that maximize their individual gain. And, second, the users' common knowledge assumption with the definitions of their preference relationship. These assumptions may behave well by allowing each user (or player) to rationally decide on its best action, although in most of the competitive and non-cooperative games, sometimes users can provide false information in order to maximize their profits and thus can affect the whole network performance.

III. PROBLEM DESCIPTION

The proposed scenario (Figure 1) addresses the spectrum allocation challenges in a private area or a well identified administrated perimeter such as a campus, an airport, a conference center or a hospital. There is an ad-hoc WLAN [9], deployed in the area with sets of primary $PU = (PU_1, PU_2 \ldots\ldots PU_n)$ and secondary $SU = (SU_1, S_2 \ldots\ldots SU_m)$ users. To allow nodes to communicate, the agents are deployed at each of them Whenever an SU device detects an empty portion of the spectrum as needed by its user, its agent starts communicating with the relative PU agent (having that empty spectrum part), until a spectrum sharing agreement is been made.

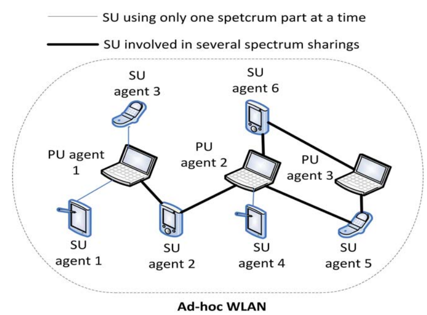

Figure 1. Working Ad hoc WLAN with PU and SU agents

A. Problem Formalization

Let $G = (N, A)$ be a directed network consisting of a set of mobile nodes N such that $(SU \cup PU) \in N$ and a set of directed arcs A. Each directed arc $(i, j) \in A$ connects a secondary user SU_i to a primary user PU_j. Similarly, we can denote the directed arc $(j, i) \in A$ to show the direction of connection from PU_j to SU_i. The secondary users are cooperating with the neighboring primary users to have a spectrum sharing deal. We assume that s_{ij} is the amount of spectrum a secondary user *'i'* is desiring to get from a primary user *'j'*. Similarly, t_{ij} is the amount of time for which *'i'* wants to utilize the spectrum and p_{ij} is the price it is willing to pay to *'j'*. For the primary user *'j'* on the other hand, s_{ji} is the amount of spectrum it is willing to share with *'i'*, t_{ji} is the respected time limit and p_{ji} is the price it is expecting to get after sharing its spectrum. We can formulate the above model for each secondary user *'i'* as:

$$\text{Maximize} \sum_{(i,j)\in A} s_{ij} t_{ij} \qquad (1)$$

Subject to

$$\text{Minimize} \sum_{(i,j)\in A} p_{ij} \quad \forall\ SU \in N \qquad (2)$$

Similarly for primary users:

$$\text{Maximize} \sum_{(j,i)\in A} p_{ji} \qquad (3)$$

Subject to

[2] The MAS is cooperative in a sense that PU agents help SU agents in order to fulfill their spectrum requirements via an exchange of interactive messages while at the same time, they maximize their own utility values. The more complex scenarios with agents' competitive behavior will be examined as a part of our future study.

$$\text{Minimize} \sum_{(j,i)\in A} s_{ji} t_{ji} \quad \forall \ PU \in N \qquad (4)$$

And $$l_{ji} \leq s_{ji} \leq u_{ji}$$

where l_{ji} and u_{ji} are the lower and upper bounds of available spectrum of primary user *'j'*. This means that the secondary user *'i'* cannot ask for an amount of spectrum above this limit.

B. An Illustrative Example

In static circumstances, the spectrum portions are assigned to primary users and in response the internet service providers get their spectrum price. For an example consider a primary user PU_i, who has bought a portion of a spectrum s_i, of the size of 2MB (Figure 2). During the peak office timings (t_0-t_1), the assigned portion may remain busy due to high user traffic such as for video conferencing and lecturing, but most of the other times the spectrum can be partially unused (t_1-t_2, and t_3-t_4). Obviously at free hours (t_4-t_n), PU_i can utilize its spectrum portion for other activities (e.g., watching video songs) but generally people prefer these kinds of activities to be performed on week-ends. With our proposed approach, a given secondary user SU_j will be able to choose the best spectrum band/channel dynamically. This choice is made in cooperation with the agent embarked on PU_i [16], by taking into account the amount of spectrum needed s_j, the respected time limit t_j and the related price p_j.

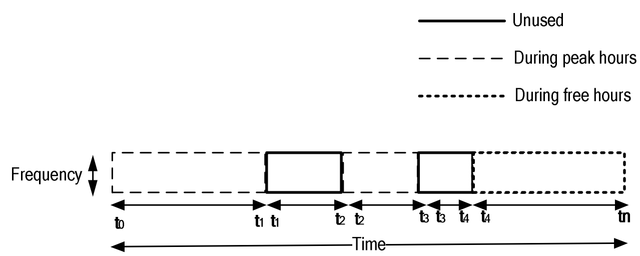

Figure 2. Spectrum utilization by PU_i at different time intervals

IV. MULTIAGENT BASED SPECTRUM ALLOCATION

In this section, we explain the cooperative spectrum sharing, with primary and secondary user agent's internal architecture and algorithmic behavior.

A. Agent

We start here by defining an agent is as a dynamic and loosely coupled unit, having the capabilities of performing a task autonomously, based on the knowledge received from its environment and/or through other agents' interactions [13]. These loosely-coupled units then work together to form a multi-agent system. Generally, an agent is appropriate for an SU node in a sense that it allows the introduction of various artificial intelligence (AI) techniques to CR networks and helps an SU node to behave more autonomously by having frequent interactions with its neighboring devices. Once in place, cooperative multiagent systems have the potential of increasing the SU capabilities in a variety of ways. For example, a single SU agent is limited in its knowledge (and information) about spectrum access, but a bundle of SU agents can collectively identify spectrum holes and can communicate them to the other nodes.

B. Cooperative Framework

The SU based design (Figure. 3 and Algorithm. 1) consists of the following five different interlinked modules.

- First, the *dynamic spectrum sensor (DSS)* is used to sense the empty spectrum portions (or spectrum holes). Several techniques exist for spectrum sensing such as PU's weak signal and its energy detection [14], cooperative centralized detection [3], etc. For DSS, it is necessary that the sensing is performed by considering a real-time dynamic environment, because it is not obvious at what time a spectrum band is occupied or when it is free.
- The second module *spectrum characterizer (SC)* characterizes the spectrum holes based on the Shannon's theorem [15] to create a capacity based descending ordered list of all non-busy[3] PUs.
- *Secondary user interface (SUI)* which is the third part sends a *request* message to the SU device agent, whenever a user wants to have a portion of spectrum (for internet surfing, watching high quality videos, etc).
- The fourth part, agent's knowledge module (AKM) gets PU characterization information from SC which serves as a motivation for agents that subsets of PUs having vacant spectrum spaces are available. This list is not permanent rather it is updated and maintained on regular time intervals based on the information provided by SC module. Moreover, AKM creates a *Call for proposal (CfP)* message based on the inputs from *SUI* and *SC*:

  CfP (CRID, s, t, d)

  Where *SUID* is the secondary user ID (or the secondary user's agent identification) and it is used to help PU to reply back to the corresponding SU, *s* is the amount of spectrum needed by the SU, *t* is the desired time limit (or holding time) for the spectrum utilization, and *d* is the deadline to receive the primary users' proposals.
- Finally, *agent coordination module (ACM)* geo-casts the *CfP* to the neighboring (and currently available[4]) PU agents. Moreover, *ACM* is also responsible for selecting the most suitable received *proposal*.

Having received the *CfPs*, the interested PU agents[5] send their proposals to the corresponding SU agents. The proposal is in the form such that:

Proposal (PUID, s, t, p)

Where *PUID* is the primary user's agent identification, *s* is the amount of spectrum PU is willing to give to the respected SU, *t* is the proposed spectrum holding time, and *p* is the price PU is willing to receive.

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[3] Each PU maintains a flag whose value is true when it is busy.

[4] Availability means that the PU agents have not yet left the one-hop neighborhood.

[5] The PU agent contains *AKM* and *ACM* modules, where *AKM* manages the neighborhood information and *ACM* selects the most suitable *CfP* via cooperation.

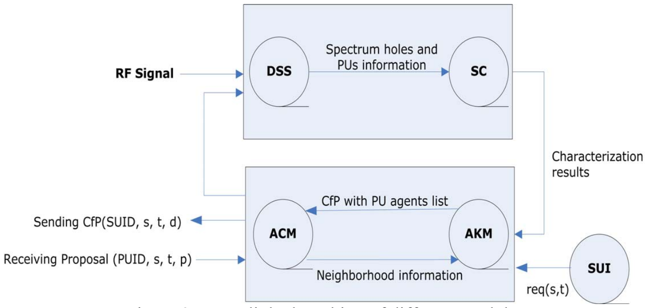

Figure 3. Interlinked working of different modules

Algorithm 1: Working of SU

Init – Let PU be the set of primary users in secondary user agent's one-hop neighborhood and ℓ is the time interval based on the information provided by the SC module in order to maintain capacity based ordered list of primary users.
/ SU characterizes each non-busy primary user on the basis of capacity*/*
For each i{ i∈ PU) } do
Eval (SNR(i))
/ SNR: is the primary user's signal to noise ratio obtained through DSS */*
Eval (B(i))
/ B: bandwidth of PU given by DSS*/*
$C(i)= B(i) \log_2 [1 + SNR(i)]$
/ c: capacity calculated using Shannon's theorem*/*
End For
*/*Sending of CfP message*/*
If PU != {}
For each i ∈ PU
*/*Geo-cast CfP*/*
Send CfP (SUID, s, t, d) to PU(i)
End for
End If
*/*L is a list for saving received proposals*/*
For each received proposal 'm' do
Characterize m using $\frac{s(m)\times t(m)}{p(m)}$ and add it in L
End For
If L={} and the deadline to receive proposals has expired
Recreate CfP
Else If L={i} where i is the only element in L and deadline for proposal reception has expired
Send an accept message to i
Else
Send accept to primary user corresponding to the best proposal
Send reject to all other primary users
End If

Each PU maintains an ordered list of *CfPs* in its cache based on the values of *s* and *t* for the purposes of future cooperation (algorithm 2). At the same time, the receiving SU locally sorts fetched *proposals* and an *accept* message is sent to the most suitable proposal. The information of selected PU is also sent to *AKM* (of SU) for future interactions. In case of an *accept* message from the selected SU, the spectrum sharing is started based on agreed parameters from both the sides. PU can still respond to further *CfPs* if it wants its other unused spectrum portions to be shared. If the PU receives a *reject* message from SU, it continues sending proposals to further available *CfPs* in its cache, for which the deadline is not yet expired.

Algorithm 2: Working of PU

While busyflag = false do
If received message = CfP
*/*K is a list for saving received CfPs*/*
For each received CfP 'n' do
Characterize n using $\frac{p(n)}{s(n)\times t(n)}$ and add it in K, where p(n) is related price according to required spectrum
End For
For best CfP in K do
Construct a proposal (PUID,s,t,p) and send it to corresponding secondary user
End For
End If
If received message = accept
Start spectrum sharing with selected secondary user
End If
If received message = reject OR some unused spectrum parts are still available
Continue analyzing further CfPs for spectrum sharing
Else
Set busyflag = true
End If
End While

V. EXPERIMENTAL EVALUATION

In this section, we present some simulation results, conducted in order to validate the performance and working of the proposed spectrum allocation algorithms. We start by examining the achieved utility of both primary and secondary users and then compare the time values for which the spectrum is being utilized. We also present the spectrum gain and loss with the amount of messages used for cooperation. The words (PU, PU agent, SU, SU agent respectively) are used interchangeably throughout the following section.

A. Simulation Setup

We perform our simulations under the assumption of a noiseless, partially-mobile radio ad-hoc network. By partially ad-hoc we mean that the nodes in the neighborhood of each of the SUs change. We randomly place a number of primary and secondary users in a specified area where each of the devices contains an agent deployed over it for cooperation purposes. For simplicity, two different fixed values of times (such as T1 and T2) are assumed, where "Time 1" (T1) represents the short-term case and "Time 2" (T2) is the longer period. When T1 is considered the SU agents can ask for the amount of spectrum within one hour limit (i.e.,$0 \leq T1 \leq 60$Minutes) and similarly this limit is within two hours, as in case of T2 (i.e.$0 \leq T2 \leq 120$Minutes). These two approximations capture the same amount of time values in real wireless environments without delving into complex situations. Our simulation starts with the total number of 6 SUs and 4 PUs, and for each next round there is an addition 10 agents (i.e. 6 SUs and 4 PUs). The simulation is conducted for 10 subsequent rounds, with a total 20 hours per day, for both T1 and T2 respectively and the average values of parameters are taken to draw the graphs.

The PU agent's utility is calculated as the price paid by SU agents for spectrum utilization divided by the amount of spectrum it has shared for the respected time period (holding time) as required by the SUs. The SU agent's utility is represented as its spectrum usage for the required time divided by the corresponding price paid to the PUs. Thus, by assigning weights or priorities to each of the mentioned parameters, the appropriate utility values for both the primary and secondary users are chosen.

We also assume that each PU has random available spectrum portions and the neighborhood of SUs is randomly changing. The total number of cooperation messages (*CfP*, *proposal*, *accept* and *reject*) generated in the system, determine the cooperation cost. Thus, the cooperation strategy that is better (both between T1 and T2) in terms of less number of messages is considered as the most cost efficient. The total number of resources successfully shared (over the number of resources required) presents the success rate, while the number of non-allocated spectrum portions (due to disagreements between primary and secondary user agents) measures the overall spectrum loss.

B. Results

In Figure 4, we compare the average utility of each primary and secondary user at T1 with those at T2 for different numbers of users (10, 20, 30…). The figure depicts that when time limit is T2, the utilities are a bit less compared to the results obtained at T1. This is because the environment is partially mobile and some of the users are slightly hesitant to share their spectrum for longer periods. We observe that when there are 10 agents, the average utility values are almost identical for both T1 and T2, showing the optimal behavior. But in other cases, the average utility values are different, showing that the optimality of agents in terms of their average utility values has decreased slightly with the increased number of agents.

Figure 5 illustrates the resource requirements and utilization over time periods T1 and T2. In the beginning (with 10 required resources), all of them are completely shared; whereas when the required spectrum resources arrives at the middle values (such as 30 to 40), approximately 90% of them are shared. This spectrum sharing trend continues following the same pattern reaching bigger values (such as 50 and 60), with achieved sum of resources comprised between 45 and 50. Thus, the performance degradation in terms of spectrum sharing is not high, even with large resource requirements.

Our approach is also time critical, because in CR networks the spectrum holding time is one of the most important factors to be considered. Again, we run the simulation with several values of primary and secondary user agents. Figures 6(a) and 6(b), plot the overall mean times (in minutes) for which the spectrum is required and utilized for a total of 10 to 120 agents. Both the experiments were realized on a PC with 3GB memory and 2.4 GHZ dual processor. When time limit is T1, the results are between 80 to 85%, for 80 to 120 agents, while having somewhat lesser values (of around 75 to 80%) at T2. Both the results are super linear and coherent with those of Figure 5 which displays that the spectrum sharing is 80 to 85% even with the larger number of agents.

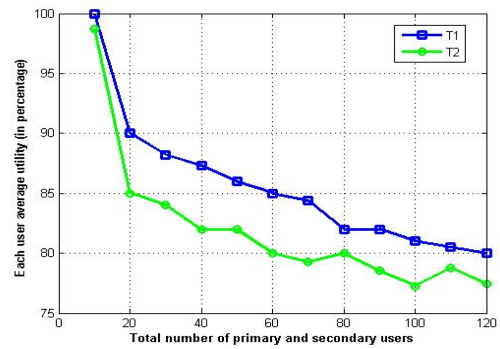

Figure 4. Overall utilities of agents

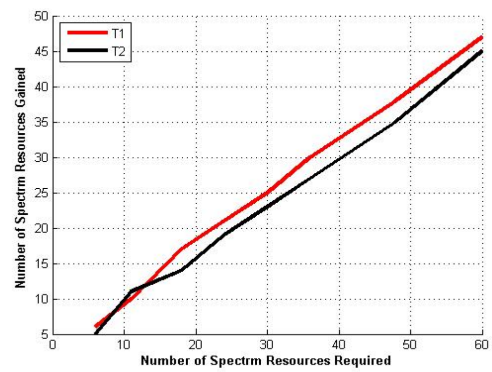

Figure 5. Total resource usage by SUs

Figure 7 depicts the maximum number of supported SUs by the neighboring PUs. Supported SUs are those which have completely gained the required spectrum. We observe that when there are 10 to 15 PUs, the number of supported SUs is literally the same for both T1 and T2. This means, for limited agents even if the time values are high, the sum of supported SUs is almost identical, but in the other cases (with more than 50 PUs), the number of supported SUs (at T2) are slimly minor, compared to those of T1. This shows that in partially ad-hoc situations, with large values of times the results are marginally less optimal.

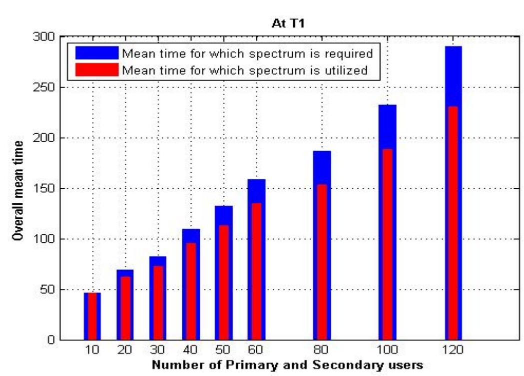

Figure 6(a). Spectrum utilization time at T1

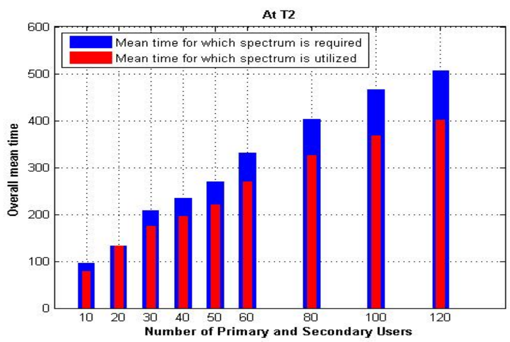

Figure 6(b). Spectrum utilization time at T1

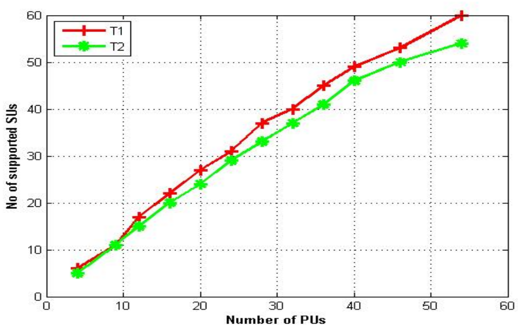

Figure 7. Cooperation cost with success rate

The number of cooperation messages transmitted and received in the entire system with the success rate (in percentage) is shown in Figure 8 (and Table 1). For both the time limits T1 and T2, there is a significant saving in the number of exchanged messages, indicating a greater efficiency in terms of cooperation cost. According to Figure 8, the values of exchanged messages are almost leveled off for the middle periods (from 30 to 70 agents). Further, table 1 depicts that the average number of messages (per agent) remains between 4 to 5 even with the increased number of agents. We can also see that the approach is linear in terms of messages and success rate. Particularly when time limit is T2 (around 90 to 120 agents), the performance of the approach substantially degrades (reaching below 80%), but nevertheless it remains steady.

Another important aspect of our approach is the analysis of how the performance varies as the amount of participating agents increases (i.e. the scalability). A good scalability is achieved when the performance of a network does not degrade drastically with the size of the system and the loss remains minimum. In this context, Figures 9(a) and 9(b) show the overall spectrum loss[6], which is the loss caused by the unused spectrum, due to spectrum sharing disagreements. As the agents' demands augment, the percentage of spectrum loss grows on a steady pace. This is because some of the SUs have not found the neighboring non-busy PUs or due to the relative change in their neighborhood. From the figures, it is also clear that the amount of overall spectrum loss (for both the time limits T1 and T2) is minimum (10 to 15%), when the number of users are at the middle stages (i.e. around 50). Spectrum loss then reaches bit higher values (16 to 22%), with increase number of agents, but still there is not a rapid degradation in the overall system performance.

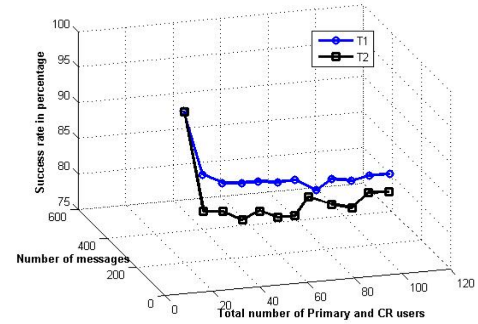

Figure 8. Cooperation cost with success rate

Table 1. Success rate with the amount of messages exchanged

No of agents	Number of messages		Success Rate (in %)	
	T1	**T2**	**T1**	**T2**
10	45	41	100	98.7
20	81	72	90	85
30	117	115	88.23	84
40	159	161	87.31	82
50	185	176	86	82
60	253	261	85	80
70	271	262	84.41	79.3
80	325	366	82	80
90	388	392	82	78.53
100	416	434	81	77.26
110	475	483	80.5	78.77
120	503	516	80	77.42

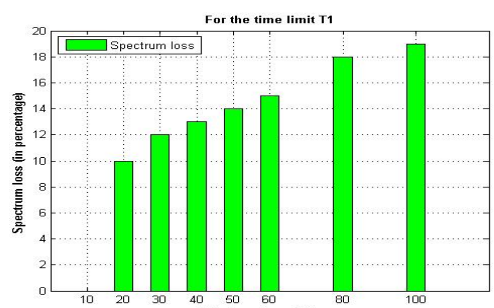

Figure 9(a). Total spectrum loss based on T1

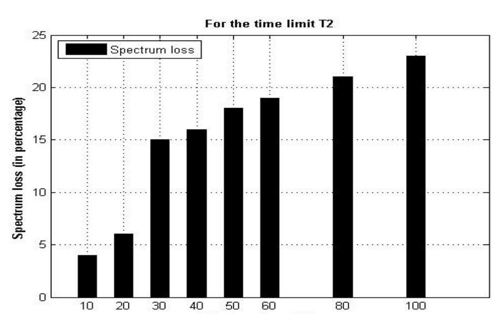

Figure 9(b). Total spectrum loss based on T2

[6] The other factors such as collisions, device level interferences, delays are not considered here.

Briefly, in the evaluation section, we experimentally analyze the working and performance of our proposed algorithms based on the MAS cooperation for spectrum allocation in CR networks. The experimental results help us verifying the cooperative behavior of a secondary user agent in order to make a spectrum sharing agreement with the neighboring primary user agents. The proposed approach converges well in a sense that it can find good utility based solutions using a small bilateral exchange of messages. The approach seems to scale well as the number of agents increases.

VI. CONCLUSION AND FUTURE PERSPECTIVES

In this paper, we develop a cooperative framework for spectrum allocation that can generate highly effective behavior in dynamic environments and achieve better utility of the participating devices. The proposed approach is based on multiagent system cooperation and implemented by deploying agents on cognitive radio devices. Experimental evaluations confirm the efficiency of our algorithms for distributed and decentralized environments. The results show that the proposed approach can absorb the high spectrum sharing demands by introducing the cooperation between primary and secondary user devices. Furthermore, the proposed approach improves the overall utility and minimizes the spectrum loss with a minimum message cost. The spectrum allocation success rate is almost 80% even with large number of agents. While we only proposed a specific cooperation strategy to maximize system utility, the proposed cooperation framework can be extended towards minimizing other key problems such as inter secondary users interferences and collisions. We intend to examine this problem as a part of our continuing work. We are currently working on a theoretical analysis of our approach using Petri nets. In addition, the proposed approach assumes that nodes are highly cooperative while in real systems, nodes can be selfish or competitive, so more precise work is needed to explore the competitive behaviors. We will also try to compare the results with game-theoretical approaches to have an even better validation of our work.

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