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Dynamic Spectrum Sharing in Cognitive Radio Networks: a Solution based on Multiagent Systems

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Abstract— **In modern day wireless networks, spectrum utilization and allocation are static. Generally, static spectrum allocation is not a feasible solution considering the distributed and dynamic nature of wireless devices, thus some alternatives must be ensured in order to allocate spectrum dynamically and to mitigate the current spectrum scarcity. An effective technology to ensure dynamic spectrum usage is cognitive radio, which seeks the unutilized spectrum holes opportunistically and shares them with the neighboring devices. Using cognitive radio capabilities, the nodes are not restrained to static spectrum utilization, rather they can choose it on demand. However, dynamic spectrum usage raises several challenges, which need to be addressed in detail. These challenges include efficient allocation of spectrum between licensed (or primary) and cognitive radio (or secondary) users in order to maximize spectrum utilization and to avoid device level interferences. To this extend, we develop a novel solution for spectrum allocation using multiagent system cooperation that enables secondary user devices to utilize the amount of available spectrum, dynamically and cooperatively. 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 used, allowing spectrum to be dynamically allocated by having a series of message exchanges amongst the devices. Simulation results show that our solution achieves up to 80% of the whole utility within the span of few messages, and provides an effective mechanism for dynamic spectrum allocation.**

***Keywords-** Multiagent Systems; Cognitive Radio; Dynamic Spectrum Sharing; Contract Net Protocol; Cooperation; Ad hoc Networks.*

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 (or licensed) user [3], for a long period of time in order to avoid interferences 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 radio spectrum, there is no sufficient spectrum available to all the new unlicensed wireless networks [1] [25]. Thus, research has to be done to address this problem via dynamic sharing and assignment of spectrum. For example, in USA, Federal Communication Commission (FCC) considers to allow sharing of unused portions of TV bands to promote dynamic use of spectrum [2] [4].

One effective technology to alleviate the problem of static spectrum assignment and to maximize dynamic spectrum usage is cognitive radio (CR) [17], 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 primary or secondary users. The parameter alteration is done by having some knowledge about the radio environment factors such as radio frequency (RF) signals, device level interferences, 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) [21] [27] 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, and interactive CR devices [8]. These devices can then be used in a wide variety of network domains (WLAN [48], WRAN [49], MANETs [23]). 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 [5] [28], the question of how to share radio resources in cooperative scenarios is also an important research issue for current researchers [3] [8] [22].

Therefore, in this paper, a MAS based strategy is proposed for dynamic spectrum allocation. Specifically, we consider a cooperative MAS [29] [36], 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 and help neighboring secondary user agents to improve their spectrum usage. Moreover, the cooperation mechanism we develop is similar to that of contract net protocol (CNP) [10] [30], 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 spectrum sharing agreements. 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 they find an appropriate offer (without waiting until the reception of all the neighboring PU agents' responses [14]). Then, after completely utilizing the desired spectrum, SU agents should pay the agreed price to the respected PU agents.

In fact, this work is divided into following four parts:

- First, we present a brief state of the art on various available approaches for spectrum sharing using multiagent systems, game-theoretical approaches and medium access control solutions.
- Second, we detail four different scenarios, in which spectrum sharing challenges need to be addressed in details. We also propose some initiative measures, which are necessary to be taken for efficient utilization of the available spectrum in the mentioned scenarios.
- Third, we present a cooperative framework with the related spectrum sharing algorithms. The proposed MAS is cooperative where PU agents exchange a series of messages to share their spectrum with the requesting SU agents. The more complex scenarios with agents' competitive behaviors will be examined as a part of our future study.
- Finally, 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 related works. Section III presents four scenarios, in which dynamic spectrum sharing is a vital issue. In Section IV, we describe spectrum allocation problem with the help of an example. In Section V, we propose our model with the interlinked working of various modules and their related algorithms. The experimental setup, some results and discussions are given in Section VI. Section VII concludes our work with the future perspectives.

II. PRIOR WORK

Research has been going around for several years in order to apply multiagent systems for decision making process and resource sharing. A rather new application of multiagent systems is for efficient allocation of spectral resources in CR networks. In TABLE I, we give the similarities between an agent and a CR. Basically, both of them are aware of their surrounding environments through interactions, sensing, monitoring and they have autonomy and control over their actions and states. They can solve the assigned tasks independently based on their individual capabilities or can work with their neighbors by having frequent information exchanges.

TABLE I. COMPARISON BETWEEN AN AGENT AND A CR

Agent	Cognitive radio
Environment awareness via past observations	Sensing empty spectrum portions and primary user signals
Acting through actuators	Deciding the bands/channels to be selected
Interaction via cooperation	Interaction via beaconing
Autonomy	Autonomy
Working together to achieve shared goals	Working together for efficient spectrum sharing
Contains a knowledge base with local and neighboring agents' information	Maintains certain models of neighboring primary users' spectrum usage

In literature, few strands of work have focused on spectrum sharing using MAS [13] [37]; but in these works, several limitations exist. For example, in [37], a 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 [13] 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. The ultimate aim of using auctions is to provide an incentive to CR users to maximize their spectrum usage (and hence the utility), while allowing network to achieve Nash Equilibrium (a solution concept, where each user is assumed to know the equilibrium strategies of the other users, and no user has anything to gain by changing its own strategy). Auctions have traditional drawbacks of users' untruthful behaviors, which can cause serious drawbacks to the working of loyal users.

Game-theory has also been exploited for spectrum allocations in CR networks [6] [11] [18] [19] [39]. 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

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

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, which includes 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 games, sometimes users can provide false information in order to maximize their profits and thus can affect the whole network performance.

According to some current research works, spectrum sharing problems are similar to medium access control (MAC) issues [9] [32], where several users try to access the same channel and their access should be shared with the neighboring users to avoid the interferences. Generally, in MAC-based spectrum sharing solutions, when a CR user uses a channel, it sends a busy signal to the neighboring users through a control channel in order to avoid the interference. To estimate control signals, the authors of [20] suggest a fast fourrier transform-based radio design, which enables CR users to detect the carrier frequency of a control signal without causing any harmful collisions to the neighboring users. Others [23] suggest the use of a global plan to exchange the control information between CR devices. However, maintaining global plans needs a large amount of frequent information to be exchanged between CR users causing complex device level architectural overheads.

III. SPECTRUM SHARING SCENARIOS

Here, we provide some of the possible scenarios, which need the development of new solutions for dynamic spectrum sharing. These scenarios are addressed as a part of a Franco-German project TEROPP [46]. This project aims at developing various efficient spectrum management solutions. Up till now, our contribution to this project is the development of a cooperative approach for opportunistic spectrum allocation. In these scenarios, the current spectrum assignments are static and inter-device collision is a big issue. Therefore, efficient solutions are needed in order to enable dynamic spectrum usage and to avoid interferences. The scenarios are divided into four different domains as follows: (1) Spectrum sharing and interference avoidance in ISM bands, (2) Spectrum sharing in cellular networks, (3) Opportunistic spectrum utilization in TV bands, and (4) Spectrum allocation in ad hoc networks. After detailing and suggesting possible initiatives towards dynamic spectrum access, we will describe our cooperative framework as a solution to enable spectrum sharing under ad hoc network domain. Precisely, multi-hop architectures, topology changes and arrival and departure of nodes at any time are the reasons for developing a cooperative solution for dynamic spectrum sharing under ad hoc network setting.

A. Spectrum Sharing and Interference Avoidance in ISM Bands

Recently, WLAN [26] has been adopted as a common technology by internet home users and companies. Characterized by cheap devices and reasonable data-rates, WLANs can be deployed anywhere. Designed to operate over license-free ISM (Industrial, Scientific and Medical) bands, WLANs are restricted to employ only few orthogonal channels, which is more than enough to provide wireless access in a residential area. However, the huge increment in the number of WLANs operating in the same location introduced a new interference level that could be anarchic. This interference is considered to be the main limitation for WLANs performance and it introduces new challenges to all the neighboring technologies that operate in the ISM bands [26]. Similar problems may arise with the deployment of LTE femto-cells [40]. These small cells, located at a home or a building, can provide better coverage and higher capacity in indoor environments. However, they suffer from interference caused by the neighboring femto-cells. The common point of introducing these two cases is that the interference is most of the times unwanted and it needs to be avoided.

As an interference avoidance solution, we foresee a cooperative environment where the devices in a WLAN or LTE cell can have CR capabilities, which allow them to optimize frequency reuse. They can also select an alternative spectrum portion, in case of any interference. Then, they can send the newly searched spectrum portion information to the neighboring devices in order to avoid the possible collisions.

B. Spectrum Sharing in Cellular Networks

This scenario explains the spectrum sharing issues for cellular networks where the area is administrated by a central entity (such as a base station) and it is able to impose basic etiquettes to the users [7]. The mobile users (having CR capabilities), can perform signal measurements and can apply the etiquettes in order to contribute to an efficient use of the available spectrum. These etiquettes may be in the form of behavioral rules, such as, using correct MAC address, switching to a convenient base station and transmitting measurement reports. In such a context, distributed operational modes will be privileged and different overlay functions may be implemented such as rendezvous facilities [16], in order to optimize frequency reuse and to enable efficient usage of available bands.

A hospital can be considered as an application example of this scenario, where the number of users cannot be determined in a precise way. With the CR capability, a given terminal (a doctor's iPhone or a PDA) might be able to sense the best possible spectrum band. This band can then be shared and coordinated with the neighboring devices by having a series of interactions using multiagent systems and by taking into account the number of current users and their priorities. The shared band information can then be sent to the BS agent for the administrative purposes.

C. *Opportunistic Spectrum Utilization in TV Bands*

The European countries are working on improving their TV services by stopping the broadcast of PAL (phase alternative line) signals and using DVB-T (digital video broadcasting-transmitter) standards instead [41]. This process will create a sufficient amount of unused spectrum resources especially in the case of digital dividend [45]. Let us explain the exploitation of ultra high frequency (UHF) bands to understand the concept of numerical dividend. Generally, UHF bands are split in channels, where channels 21 to 69 were originally assigned to TV services. These channels are 8MHz in width, and the channel 21 corresponds to the bands 470-478 MHz. A DVB-T covers a city and its neighboring sectors, and uses 6 UHF channels to broadcast 36 TV programs. For example, in France, nearly 100 DVB-transmitters are used for broadcasting TV programs [42]. In a given place, we can expect that the TV services use only 6 among 49 UHF channels, leaving 43 channels as unutilized. These huge amounts of empty spectral resources justify the world interest for TV bands.

In a conference held under WRC'07 (World Radiocommunication Conference) [44], discussions about the utilization of the TV bands have already been started. The researchers have decided to assign the UHF channels 60 to 69 to IMT (International mobile telecommunication) services. Another initiative is taken by the European countries with the creation of the task group 4 (TG4) [43]. TG4 is responsible for measuring the performance of DVB-transmitters in order to utilize the unused TV bands opportunistically. These measurements will then be compared with the results obtained from mobile devices working in WiMAX.

To summarize, we provide here a few steps to be taken for the opportunistic utilization of spectral resources in digital dividend as following:

- At first, DVB-transmitters must have the capabilities of cognitive radios for sensing, characterizing and monitoring the unutilized TV bands. This is possible with the development of efficient signal processing techniques.
- Then, because DVB-transmitters normally share their spectral resources with the radio microphones, therefore more precise spectrum sharing techniques must be deployed.
- Finally, some techniques must be ensured in order to differentiate between a DVB-T and a microphone signal.

D. *Spectrum Allocation in Ad hoc Networks*

Here, we give an example of an SU equipped with CR capabilities and agent functionalities. The user is in a remote or an emergency situation, where it does not have direct access to radio resources and its access technology requires an energy that the user does not own. In this situation (as shown in Figure 1), SU senses the nearby signals of primary users PU1 and PU2 (step 1) and cooperates with the agents deployed on them (step 2). This cooperation process allows SU to act on primary users' responses by utilizing their available spectrum (step 3). Thus, the cognitive radio capability of an SU plays the role of interoperability, such that it can receive the information about neighboring users' spectrum bands and their access technology. Likewise, the role of the deployed agent is to cooperate and modify SU's software configuration by loading the necessary algorithms that fit the best to the current state (step 4).

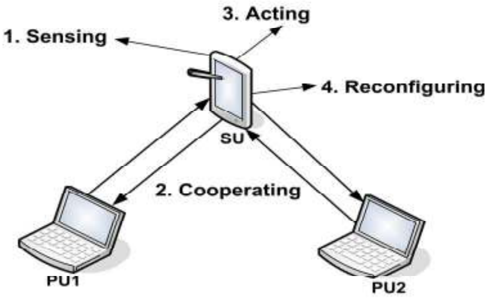

Figure 1. Description of an ad hoc scenario

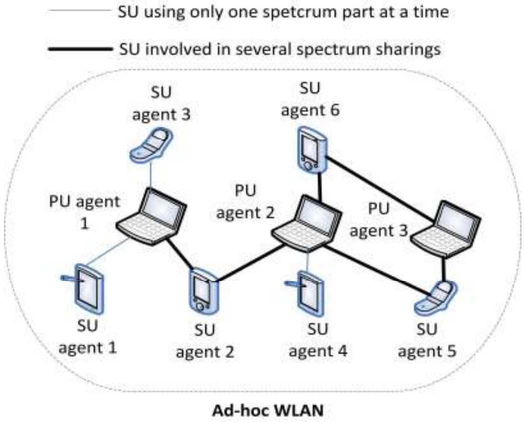

Figure 2. Ad hoc WLAN with three primary and six secondary users

IV. PROBLEM STATEMENT

In the above scenario, we have presented the role of an agent and a CR in an ad hoc emergency situation. However, considering a more general and practical perspective, we address the spectrum allocation challenges in a private ad hoc area or a well identified administrated perimeter such as a campus, a conference center or a hospital. Note that our proposed algorithms can also be easily applied for the emergency ad hoc network scenario.

. In our proposed scenario (Figure 2), there is an ad hoc WLAN [15], deployed in the area with sets of primary $PU = (PU_1, PU_2 \ldots.. PU_n)$ 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.

A. 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

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

And

$$l_{ji} \le s_{ji} \le u_{ji}$$

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 Example

In static circumstances, the spectrum portions are assigned to primary users and in response the internet service providers get their spectrum price. As an example consider a primary user PU_j, who has bought a portion of a spectrum of the size of 8MB (Figure 3). During the peak office timings (t_0-t_1), the assigned portion may remain busy (or used) due to high user traffic such as for video conferencing and lecturing, but most of the other times (t_1-t_2 and t_3-t_n) the spectrum can remain unused. Obviously at free timings, PU_j 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 solution, a given secondary user SU_i will be able to choose the best spectrum band/channel dynamically. This choice is made in cooperation with the agent embarked on PU_j [35], by taking into account the amount of spectrum needed, the respected time limit and the related price.

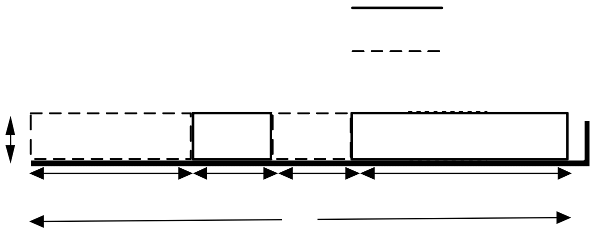

Figure 3. An example of a primary user's spectrum utilization during a day

V. COOPERATIVE SOLUTION FOR DYNAMIC SPECTRUM SHARING

In this section, we explain the proposed cooperative spectrum sharing scheme, with primary and secondary user's internal architectures and their algorithmic behaviors.

A. Agent

We start here by defining an agent 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. These loosely-coupled units then work together to form a multi-agent system [21] [27]. Generally, an agent is appropriate and relevant for an SU node in a sense that it allows the introduction of various artificial intelligence (AI) techniques [12] to CR networks and helps an SU node to behave more efficiently 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 other nodes.

B. Contract Net Protocol

In multiagent literature, several approaches exist for cooperation [12]. Amongst these approaches, contract net protocol (CNP) [30] [34] is the most simple way for agents' cooperation and decision making. In CNP (Figure 4), the collection of agents is called *contract net* and several agents can form these nets in order to solve the assigned tasks. Each agent can either be a *manager* or a *contractor*. Basically, the *manager* agent initiates a task to the *contractor* agents by sending *Call for Proposals (CfPs)* messages. As a result, various eligible contractors show their interest (in solving the task) by sending their *proposals*. The *manager* selects the best proposal (via *accept*) and the contract is then awarded to the selected contractor. The selected contractor solves the assigned task as agreed with the corresponding manager. Due to its simple and efficient nature, our proposed approach is based on bilateral message exchange and task allocation mechanisms of CNP.

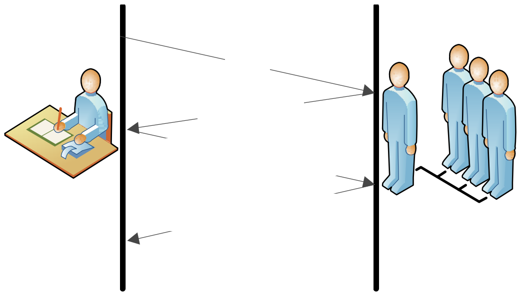

Figure 4. Message exchange in CNP

C. *Working of the Proposed Solution*

The SU based design (Figure 5 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 [28], cooperative centralized detection [5], 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 [33] to create a capacity based descending ordered list of all available 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 *CfP* message based on the inputs from *SUI* and *SC*:

  CfP (SUID, 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) PU agents. By available PUs, we mean that the PU agents have not yet left the one-hop neighborhood and they have some unused spectrum to share. Moreover, *ACM* is also responsible for selecting the most suitable received *proposal*.

Having received the *CfPs*, the interested PU agents send their proposals to the corresponding SU agents. The proposal is in the following form:

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. Note that the PU agent only contains *AKM* and *ACM* modules, where *AKM* manages the neighborhood information and *ACM* selects the most suitable *CfP* via cooperation.

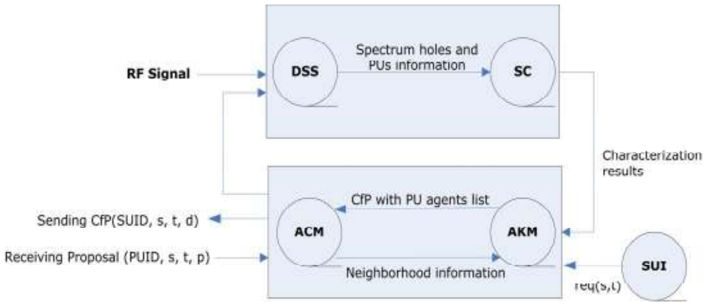

Figure 5. Working of CR and agent modules

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*, for which the deadline is not yet expired.

Algorithm 1: Behavioral Algorithm for an 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 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
```

Algorithm 2: Behavioral Algorithm for a 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
```

Above we have presented a cooperative framework for spectrum allocation that can generate highly effective behavior in dynamic environments and achieve better utility of the participating agents. The proposed solution is based on multiagent system cooperation with the deployment of agents over primary and secondary users. The experimental evaluations presented in the following section will confirm the efficiency of our proposal for dynamic spectrum allocations.

VI. EXPERIMENTS AND RESULTS

In this section, we present some simulation results, conducted in order to validate the working and performance 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 and mobile ad hoc network. By mobile 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 an amount of spectrum within one hour limit (i.e., $0 \le T1 \le 60$Minutes) and similarly this limit is within two hours, as in case of T2 (i.e., $0 \le T2 \le 120$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 of 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 assume that each PU has random available spectrum portions and the neighborhood of SUs and PUs is randomly changing. Also, we follow the assumption that once agreed, PUs would not be able to withdraw their commitments and they should share their spectrum with the corresponding SUs for the agreed time period. Further, 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 and, which gives good utility values 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. All the experiments were realized using JADE [47] on a PC with 3GB memory and 2.4 GHZ dual processor.

B. Results

In Figure 6, 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 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 performance of agents in terms of their average utility values has decreased slightly with the increased number of agents.

Figure 7 illustrates the spectrum 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 relative to time, 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. Figs. 8 and 9 plot the overall mean times (or holding time), for which the spectrum is required and utilized for a total of 10 to 120 agents. When time limit is T1, the results are almost fully satisfied, for 80 to 120 agents, while the time values are somewhat lesser at T2. Both the results are super linear and coherent with those of Figure 7, which displays that the spectrum sharing remains high even with the larger number of agents.

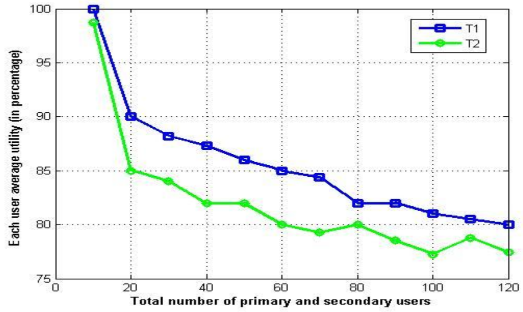

Figure 6. Agents' percentage utilities

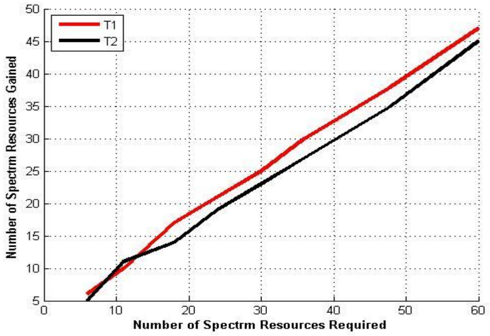

Figure 7. Spectrum resource requirement and utilization by SUs

Figure 10 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 number of agents even if the time values are high, the number of supported SUs is almost the same. However, with large number of agents (more than 50), the number of supported SUs at T2 are slimly lesser than T1. Therefore, in ad hoc situations, if we increase the time values along with an increment in number of agents, the results will be slightly less optimal.

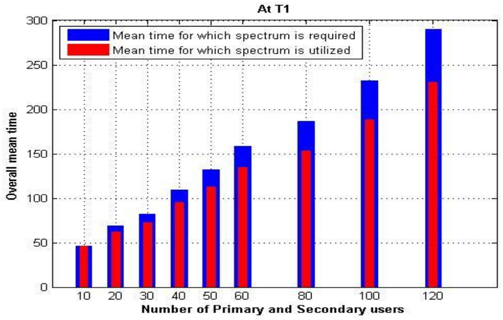

Figure 8. Spectrum holding time at T1

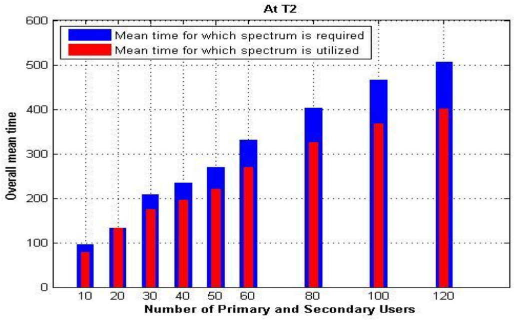

Figure 9. Spectrum holding time at T2

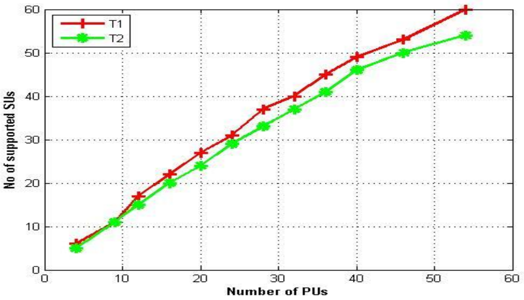

Figure 10. Supported SUs

The number of cooperation messages transmitted and received in the entire system with the success rate (in percentage) is shown in Figure 11 (and Table II). According to Figure 11, the values of exchanged messages are almost leveled off for the middle periods (from 30 to 70 agents). Further, Table II 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.

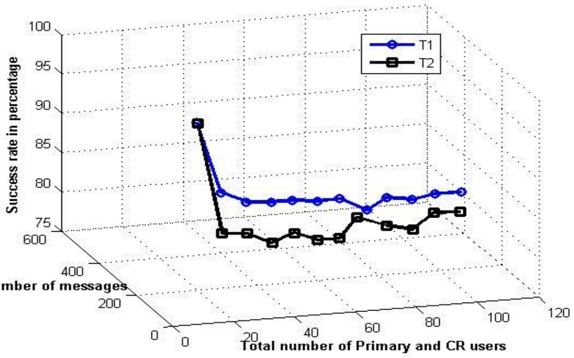

Figure 11. Number of messages with success rate

TABLE II. SUCCESS RATE AND NUMBER OF MESSAGES AT T1 AND T2

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

Another important aspect of our approach is the analysis of how the performance varies as the amount of participating agents increases. In this context, Figs. 12 and 13 show the overall spectrum loss, 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 are not able to find 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. Note that the other factors such as collisions, device level interferences and delays are not considered here.

C. Discussion Related to Results

The above experiments and results prove that our solution is an effective one in order to provide dynamic spectrum sharing for CR networks and it can provide better utility of agents with the exchange of few cooperation messages. However, there are some important points related to our results, which need further discussion. First, we assume that the ad hoc environment is interference free; however, this assumption is not always true. In reality, the transmission power of most of the devices is so high that they can easily interrupt the working flow of neighboring devices, causing interferences. Thus, addressing spectrum sharing under interference enabled ad hoc networks is still an issue and several researchers are working on solving this issue to the modest details [31] [38].

Next issue is related to the limited number of agents we have used to perform our experiments. Since, JADE only allows a maximum of 100 to 120 agents on a single machine; therefore we have only shown the behavior of our approach with limited number of agents. In order to prove the consistent working of our model with large number of agents, we are working on developing mathematical model based on Markov chain. This model will also help us to verify other parameters such as communication cost and agents' utility. Though, these mentioned issues need to be addressed in detail, still our model is flexible enough to replicate the real-world network settings where spectrum sharing can be performed in the similar cooperative way.

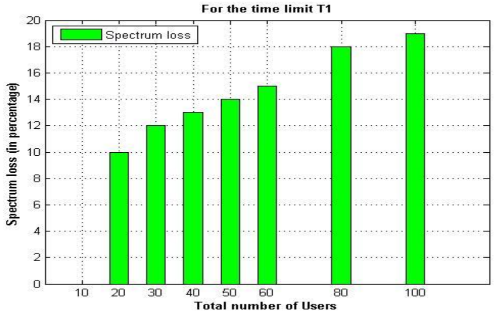

Figure 12. Spectrum loss at T1

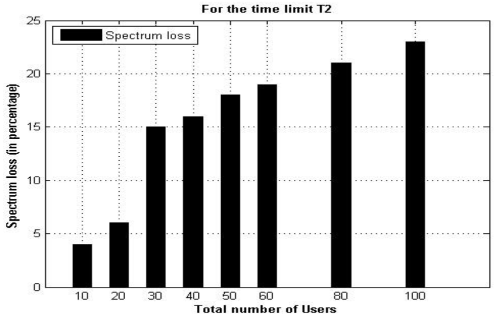

Figure 13. Spectrum loss at T2

VII. CONCLUSION AND FUTURE PERSPECTIVES

In this paper, we developed 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 and primary user 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 communication 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 user interferences and collisions. We intend to examine this problem as a part of our continuing work. We are currently working on a mathematical analysis of our approach using Markov chain. 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.

ACKNOWLEDGEMENT

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REFERENCES

[1] "Spectrum policy task force report," ET Docket No. 02–135, (November 2002).

[2] "Unlicensed Operation in the TV Broadcast Bands," Federal Communications Commission, First Report and Order and Further Notice of Proposed Rulemaking. 06-156, October 2006.

[3] B. Canberk, I.F. Akyildiz, and S. Oktug, "Primary user activity modelling using first-difference filter clustering and correlation in cognitive radio networks," Elsevier Science Journal on Ad hoc Networks, vol. 7, pp. 810-836, 2009.

[4] C. R. Stevenson, C. Cordeiro, E. Sofer, and G. Chouinard, "Functional requirements for the IEEE 802.22 WRAN standard," Technical Report, September 2005.

[5] D. Cabric, S.M. Mishra, and R.W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," Proc. Asilomar Conference on Signals, Systems and Computers, pp. 772–776, 2004.

[6] D. Niyato and E. Hossain, "Competitive pricing for spectrum sharing in cognitive radio networks: dynamic game, inefficiency of Nash equilibrium, and collusion," IEEE Journal on Selected Areas in Communications, vol. 308, pp. 192-202, 2008.

[7] D. Raychaudhuri and X. Jing, "A spectrum etiquette protocol for efficient coordination of radio devices in unlicensed bands," Proc. IEEE International Symposium on Personal Indoor (PIMRC 03), pp. 172–176, 2003.

[8] E. Jung and X. Liu, "Opportunistic spectrum access in heterogeneous user environments," Proc. IEEE New Frontiers in Dynamic Spectrum Access Networks (DySPAN 08), pp. 1-11, 2008.

[9] F. Akyildiz, W-Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," International Journal of Computer and Telecommunications Networking, vol. 50, pp. 2127-2159. 2006.

[10] F-S. Hsieh, "Developing cooperation mechanism for multi-agent systems with Petri nets," Engineering Applications of Artificial Intelligence Journal, vol. 22, pp. 616-627, 2009.

[11] G. Hosseinabadi, H. Manshaei, and J-P. Hubaux, "Spectrum sharing games of infrastructure-based cognitive radio networks," Technical report on LCA-REPORT-08-027, 2008.

[12] G. Weiss, "A modern approach to distributed artificial intelligence," MIT press, 2000, USA.

[13] H. J. Kloeck and F. Jondra, "Multi-agent radio resource allocation," ACM Mobile Networks and Applications, vol. 11, pp. 813-824, 2006.

[14] H. M. Kelash, H. M. Faheem, and M. Amoon, "A multiagent system for distributed systems management," Transactions on, Engineering, Computing and Technology, vol. 11, 2006.

[15] I. Doghri and H.K.-B. Ayed, "Towards fair P2P auctions over MANETs," Proc. International Conference on Computer and Information Technology, pp. 658-663, 2008.

[16] I. Romdhani, M. Kellil, H- Y. Lach, A. Bouabdallah, and H. Bettahar, "Mobility-aware rendezvous point for mobile multicast sources," Proc. International Wired/Wireless Internet Communications conference (WWIC 04), pp. 62-73, 2004.

[17] J. Mitola, "Cognitive radio: an integrated agent architecture for software defined radio," PhD Thesis, KTH Royal Institute of Technology, Sweden, 2000.

[18] J. O'Neel, "Analysis and design of cognitive radio networks and distributed radio resource management algorithms." PhD Thesis, Virginia Tech, USA, 2006.

[19] J. Zhang and Q. Zhang, "Stackelberg game for utility-based cooperative cognitive radio networks," Proc. ACM International Symposium on Mobile Ad hoc Networking and Computing (MOBIHOC 09), pp. 23-32, 2009.

[20] K- C. Huang, X. Jing, and D. Raychaudhuri, "MAC protocol adaptation in cognitive radio networks: an experimental study." Proc. International Conference on Computer Communications and Networks (ICCCN 09), pp.1-6, 2009.

[21] K. P. Sycara, "Multiagent systems," Artificial Intelligence Magazine, vol. 19, pp. 79-92, 1998.

[22] K.R. Chowdhury, M.D. Felice, and I.F. Akyildiz, "TP-CRAHN: A transport protocol for cognitive radio ad hoc networks," Proc. IEEE Conference on Computer Communications (INFOCOM' 09), pp. 2482-2490, 2009.

[23] L. Ma, X. Han, and C-C. Shen, "Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks," Proc. IEEE New frontiers Dynamic Spectrum Access Networks (DySPAN'05), pp. 203-213, 2005.

[24] L. Panait, and S. LukeOn, "Cooperative multi-agent systems learning: state of the art," Proc. Autonomous Agents and Multi-Agent Systems (AAMAS'05), pp. 387–434, 2005.

[25] M. Mchenry, "Spectrum white space measurements," New America Foundation Broadband Forum, June 2003.

[26] M. Sawan, H. Yamu, and J. Coulombe, "Wireless smart implants dedicated to multichannel monitoring and microstimulation," IEEE Circuits and Systems Magazine, vol. 5, pp. 21-39, 2005.

[27] M. Wooldridge, "An Introduction to Multiagent Systems," John Wiley & Sons Press, 2002, England.

[28] N. Sahai, Hoven, and R. Tandra, "Some fundamental limits in cognitive radio," Proc. Allerton Conference on Commonunication, Control and Computing, 2004.

[29] P.J. Denning and C. Martell, "Coordination," Springer Verlag, 1998, USA.

[30] R. G. Smith, "The contract net protocol: High-level communication and control in a distributed problem solver," IEEE Transactions on Computation, vol. 29, pp. 1104–1113, 1980.

[31] S. J. Kim and G. B. Giannakis, "Optimal resource allocation for MIMO ad hoc cognitive radio networks," Proc. International Conference on Communication, Control and Computation, pp. 39-45, 2008.

[32] S. Kumar, V. S. Raghavan, and J. Deng, "Medium access control protocols for ad hoc wireless networks: a survey," International Journal of Ad hoc Networks, vol. 4, pp. 326-358, 2006.

[33] T. C. Clancy, "Dynamic Spectrum Access in Cognitive Radio Networks," PhD Thesis, University of Maryland, USA, 2006.

[34] T. Sugawara, T. Hirotsu, S. Kurihara, and K. Fukuda, "Effects of fluctuation in manager-side controls on contract net protocol in massively multi-agent systems," Proc. IEEE International Conference on Distributed Human-Machine Systems (DHMS'08), 2008.

[35] U. Mir, L. Merghem-Boulahia, and D. Gaïti, "Utilization of a cooperative multiagent system in the context of cognitive radio networks," Proc. IEEE International Workshop on Modelling Autonomic Communications Environments (MACE'09), pp. 100-104, 2009.

[36] U. Mir, L. Merghem-Boulahia, and D. Gaïti, "A cooperative multiagent based spectrum sharing". in Proc. Advanced International Conference on Telecommunications (AICT'10), pp. 124-130, Barcelona, 2010.

[37] X. Jiang, H. Ivan, and R. Anita, "Cognitive radio resource management using multi-agent systems," Proc. Conference on Consumer Communications and Networking, (CCNC'07), pp. 1123-1127, 2007.

[38] Y. Su and M. Schaar, M, "A new perspective on multi-user power control games in interference channels," IEEE Transactions on Wireless Communications, vol. 8, pp. 2910–2919, 2009.

[39] Z. Ji and K. Liu, "Dynamic spectrum sharing: A game theoretical overview," IEEE Communications Magazine, vol. 45, pp. 88-94, 2007.

[40] http://mobiledevdesign.com/tutorials/lte-femtocells-0603/, Feb. 03, 2011

[41] http://www.dvb.org/ , Jan. 12, 2011

[42] http://www.dvb.org/about_dvb/dvb_worldwide/france/, Jan. 31, 2011

[43] http://www.ero.dk/TG4, June. 06, 2010

[44] http://www.itu.int/ITU-R/index.asp?category=conferences&rlink=wrc-07&lang=en, Sept. 02, 2007

[45] http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/topics/reorg/pubcons_digdiv_200907/index_en.htm, Sept. 04, 2009

[46] TEROPP,http://era.utt.fr/fr/projets_de_recherche/carnot_teropp.html, Jan. 11, 2011

[47] http://jade.tilab.com/, July. 07, 2010

[48] http://ayman.elsayed.free.fr/msc_student/wlan-tutorial.pdf, June 2002

[49] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4085653, Feb. 08, 2007

APPENDIX

Abbreviations

ACM agent coordination module, 6
AI artificial intelligence, 5
AKM agent's knowledge module, 6
APs access points, 2
CfP call for proposal, 6
CNP contract net protocol, 2
CR cognitive radio, 1
DSS dynamic spectrum sensor, 6
DVB-T digital video broadcasting- transmitter, 4
FCC federal communication commission, 1
ISM industrial, scientific and medical, 3
JADE java application development framework, 8
LTE long term evolution, 3
MAC medium access control, 3
MANETs mobile ad hoc networks, 1
MAS multiagent system, 1
PAL phase alternative line, 4
PDA personal digital assistant, 3
PU primary user, 2
PUID primary user's agent identification, 6
RF radio frequency, 1
SC spectrum characterizer, 6
SU secondary user, 2
SUI secondary user interface, 6
SUID secondary user's agent identification, 6
TG4 task group 4, 4
UHF ultra high frequency, 4
WRAN wireless regional area network, 1
WLAN wireless local area network, 1
WRC world radiocommunication conference, 4