Australian Journal of Basic and Applied Sciences, 5(12): 682-689, 2011
ISSN 1991-8178

An Agent Based Architecture for Cognitive Spectrum Management

[1]Atiq Ahmed, [2]M.Mubashir Hassan, [3]Osama Sohaib, [3]Walayat Hussain, [3]M.Qasim Khan

[1]Department of Computer Science and IT, University of Balochistan, Pakistan.
[2]PRISM, Université Versailles Saint-Quentin en Yvelines, France.
[3]Department of Computer Science, BUITEMS, Pakistan.

Abstract: In the recent years, wireless technologies and devices have progressed dramatically that has augmented the demand for electromagnetic spectrum. Some research work showed that spectrum access and provision to user is not possible due to shortage of spectrum but federal communication commission refused to accept this theory and indicated that the spectrum is available since most of the frequency bands are underutilized. In order to allow the use of these frequency bands without interference, cognitive radio was proposed that characterizes the growing intelligence of radio systems can adapt to the radio environment, allowing opportunistic usage and sharing with the existing uses of spectrum. To take this concept a step further, we propose to use intelligent agent for spectrum management in the context of cognitive radio in this paper. In our proposed architecture, agents are embedded in the radio devices that coordinate their operations to benefit from network and avoid interference with the primary user. Agents carry a set of modules to gather information about the terminal status and the radio environment and act accordingly to the constraints of the user application.

Key words: Cognitive Radio, Spectrum Management, Multi-agent Systems, Autonomous Control

INTRODUCTION

During the past few decades, we have perceived an enormous growth in the wireless systems because of the popularity of smart mobile devices. As a consequence, the need for commercial spectrum has increased rapidly. It is very clear that the limited available spectrum is a crucial obstacle to the continued growth of commercial wireless systems and services. In the same way, we are witnessing increasing demands for unlicensed bandwidth, due to the continuing growth of short-ranged radio systems and Wi-Fi. The emergence of certain application domains has further increased this need, such as wireless sensor networks for security applications, home automation, smart grid control and embedded wireless devices, etc. and entertainment systems. Meeting this enormous demand for bandwidth is a major challenge since most easily usable spectrum bands have been allocated. However, many studies have shown that more than 90% of the allocated spectrum is unused or underutilized (Akyildiz, 2011).

It has been proven through signal measurement techniques that the bands are allocated statically to the telecom operators by way of licensing are used in. Also, currently practiced band allocation method is way too rigid which has certain limitations due to which there is almost no frequency bands to be delivered to the newly arriving users. Federal Communications Commission (FCC), the regulator of telecommunications in the United States, expressed their choice to liberalize the TV band when it will go digital for unlicensed use by opportunistic radio systems (Commission, 2004). This is justified by the successful usage of the available frequency bands for unlicensed ISM (Industrial Medical Scientific) IEEE 802.11a/b/g technologies.

Context:

Today, mobile devices with multiple interfaces (GSM, Wi-XX, UMTS, etc.) are used progressively. With the use of unlicensed spectrum in an opportunistic way, the initiation of Wi-MAX and Wi-RAN is made possible. As a result, users desire for service continuity between networks with optimal Quality of Service (QoS). The nomadic nature of users and dynamic radio resource, a distributed management and optimal radio access is more necessary than ever for the coexistence of heterogeneous network access technologies (Ahmed. A, 2011). Thus, we are confronted with the dilemma of effectively radio resource management for the opportunistic use white spaces in the frequency bands with and/or without a license in order to avoid interference.

In this context, the concept of cognitive radio was introduced for the first time by Joseph Mitola (Mitola, 2000) in order to allow the future radio terminal to effectively control and manage the radio resources while avoiding interference. The main idea is to have a radio terminal that can find, collect and learn from its environment and then act to facilitate the user. To perform this task, radio terminal should acquire more intelligence through the cognitive cycle and avail all the opportunities that may arise. Current techniques for encoding/decoding, modulation/demodulation, error control, etc. will be implemented by a piece of software on a physical platform to define and enrich it by the knowledge of the environment collected by cognitive radio.

Corresponding Author: Atiq Ahmed, Department of Computer Science and IT, UoB Pakistan
E-mail: atiq.ahmed@uob.edu.pk

New algorithms for detecting gaps such as cyclo-stationary (Zheng. J, 2009) shall be implemented to allow the cognitive radio terminal to operate the environment intelligently, scanning a set of frequency bands and exploit them.

We have organized this paper in the following fashion. Section 2 will provide an overview of the cognitive radio technology. In section 4, we will provide our proposed architecture for intelligent spectrum access and sharing using multi-agent systems (MAS). Section 5 adds some discussion about the proposed architecture and finally, we conclude the paper.

Background of The Cognitive Radio System:

According to Joseph Mitola (Mitola, 2000), "A software radio is a radio channel to which the modulation waveforms are defined by the software". The objective defined in this definition is to use the same communication material for different communications technologies, such as Digital Enhanced Cordless Telephone (DECT) and Global System for Mobile Communications (GSM). This concept is an extension of the Software Defined Radio (Mainwaring. A, 2002) (Abowd G. D., 2000). The idea introduced in this concept is to combine the observations made on local radio environment for radio equipment with the available knowledge of its capabilities (hardware / software) to make a decision on how to change equipment's behavior i.e., its radio parameters to achieve a desired level of performance. In other words, through cognitive radio, a device is able to self-assess its capabilities, self-select the most appropriate waveforms, to decide and act autonomously (within the limits of its knowledge of the radio environment and its hardware capabilities) and to meet its own needs by making best use of its radio environment.

I. Cognitive Cycle:

In addition to these basic concepts, architecture of the cognitive radio can be expressed by a cognitive cycle that is a multi-fold process and consists of several steps as depicted in the Figure 1.

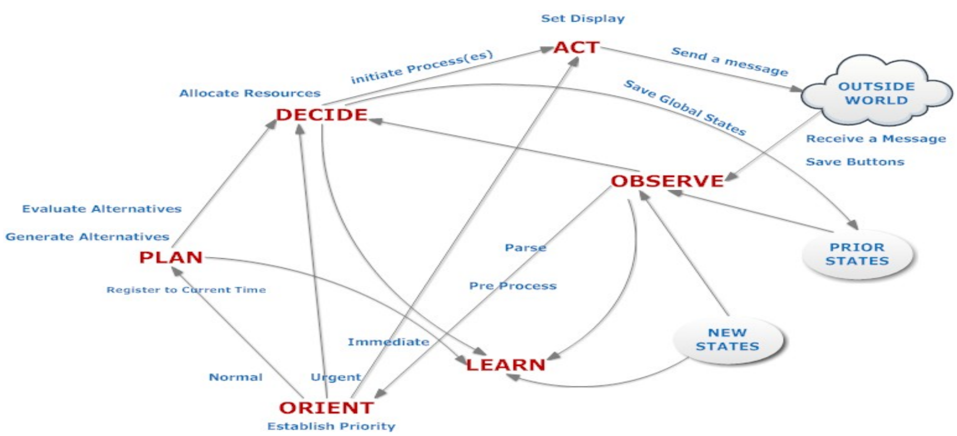

Fig. 1: Cognitive Cycle (Mitola, 2000)

According to Figure 1, following interpretations can be made:

- During the Observe phase, the embedded agent in the terminal collects all the internal and external stimuli like RF environment, battery level, etc.. These stimuli are intended to identify the context of radio equipment and communication needs of the user;
- Orient phase judges the urgency of the communication to be established to structure a priority order that can be normal, urgent or immediate action(s);
- Plan phase aims at generating and evaluating the alternatives in order to allocate necessary resources which are appropriate for a user or which are needed by a specific user. This can be done with or without the assistance of the network;
- Decide phase allocates radio resources to different data processing units in order to implement the proper radio resource allocation. For example, in case of terminal mobility if the radio signal suddenly deteriorates due to any reasons (weather conditions, distance, high mobility, etc.), this step helps us decide to switch the communication session on a better radio frequency channel;
- Finally, Act Phase initiates tasks with dedicated resources and for a fixed period to a spectrum user.

This cycle illustrates how cognitive radio includes some forms of learning from the environment and how it acts/ reacts to the variable network conditions. It is very different from the existing cycle where the radio equipment follows the network instructions blindly (Andrew R. C., 2010) (Pablo R., 2006).

II. Cognitive Radio Standardization:

Major efforts are under way for the standardization of cognitive radio. Indeed, the contribution of this technology in the field of flexible spectrum management by integrating environmental knowledge is remarkable. This motivates the manufacturers of hardware/software, telecom operators, as well as the major standardization bodies to work together for bringing this technology to its peak. The Working Group has approved standards and approved two applications of cognitive radio that is 802.22 and 802.11h.

IEEE 802.22 (WiRAN): This standard has been defined to allow cognitive radios that do not have a license to operate at a high power in rural areas. The idea is to exploit opportunistically the white spaces in the under-utilized TV band spectrum in the context of not interfering with licensed systems that operate in that band. This standard aims to design an interface that covers the cognitive radio physical layer (PHY) layer and Medium Access Control (MAC). The typical architecture of the 802.22 standard is as follows (Figure 2):

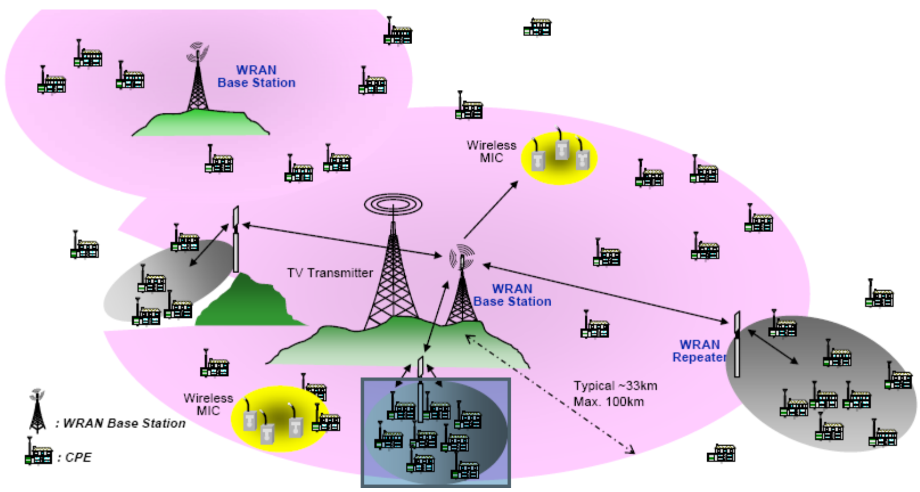

Fig. 2: WiRAN infrastructure for Cognitive radio (Akyildiz I. F., 2008)

The standard specifies a point to multipoint broadcast centered on the Base Station (BS) associated with a group of Customer Premises Equipments (CPEs). The BS controls media access in its cell and transmits Down Stream to the CPEs, which in return responses back to the BS using Up Stream. In 802.22 systems, the Primary User (PU) is the highest priority user that has analog / digital television relays, TV receivers, and wireless microphones. The WiRAN also has secondary users that include BSs and CPEs. These devices must avoid interfering with the PU. In this standard, the BS works as a brain that is aware of its environment, and establishes the best decisions regarding spectrum management and overall system optimization. The CPEs also contribute to this task by sending their observations (e.g., availability of spectrum in the neighborhood) to the BS.

IEEE 802.11h: IEEE 802.11h is not really a standard for cognitive radio but it has characteristics of cognitive functions. For example, a WLAN is able to estimate the characteristics of a transmission channel and the packet loss rate (Observation), WLAN is able to determine if it operates in the presence of a radar, a bad channel or other WLANs (Orientation), on the basis of the encountered situation the WLAN can decide to adjust its the frequency (Decision). These characteristics make it a strong candidate for the cognitive radio systems.

III. Centralized approaches for Spectrum Management:

By nature, cognitive radio led to a radio resource management and distributed independently. Therefore, a major challenge is to model, analyze and scale a system. The complexity of this task comes into play when the decision, locally, made by a cognitive system may influence the decisions of other cognitive radios in the system. In these cases, the study of cognitive radio systems can be addressed by tools such as game theory or multi-agent systems (MAS). In this section, we present some of the approaches that are based on the concepts of artificial intelligence such as, game theory and MAS (Liang M., 2010) (Jocelyne E., 2011) (Ghosh C., 2009) (Wu C., 2010) (H., 2009). These approaches are mostly centralized and are based on the market mechanisms and contribute to flexible spectrum management.

Game theory has the source and theoretical tools for addressing the issues of cooperation and conflict in systems and also, developing certain cooperative strategies to achieve a level of satisfaction for whole system. When this technique is applied to the cognitive radio, it allows managing the problems of access control in particular to the radio resource by (Ren W., 2009) (Ma M., 2007) (Neel J.O.D., 2006):

- Distributed and autonomous power control in cognitive radio equipment;
- Appropriate waveform selection;
- Establishment of a spectrum sharing strategy based on the theory of market.

The application of both these tools in the cognitive radio is very promising. Nevertheless, significant research efforts are needed more than ever in this field to better understand its potential. Resource management in the context of game theory has also received significant attention by the research community in the field. A model in (Mark F., 2007) is proposed, in which the communicating nodes share a single collision domain. Each node contains a number of radio devices that the proposed model can allocate to the channels. Multiple devices can be assigned to a single channel but this deteriorates the channel's total rate in case where more devices access it again and again. The authors claim that the solution congregates to a load balancing solution despite the non-cooperative nature of the users. (Fan W., 2007) and (Bany S.H.A., 2010) model SINR based power allocation and transmission rates in order to maximize the users over multiple channels. They take into consideration information based theoretical method for resource sharing in networks. A protocol is also proposed and implemented for their scheme.

Following this in (Kloeck C., 2006), it is described that the radio resources can be allocated to users through a prior negotiation in future radio systems like Beyond 3rd Generation (B3G). In this approach, a bidding strategy allows users and operators to negotiate spectrum allocation. Users and the operator are denoted by intelligent agents in the auction. The proposed strategy includes several phases and the agents embedded in the terminals include a learning module that enables them to develop a bidding strategy independently. Similarly, (Elhachimi J., 2010) propose an adaptive agent based approach that unifies the distribution of spectrum in the regional access networks. However, both these approaches have ignored the QoS constraints in distributing the spectrum.

In (Xie J., 2007), a radio resource management technique is proposed to avoid interference using MAS between multiple WLANs that operate in the ISM band. Intelligent agents are placed in the access points, and MAS consists of backbone that connects all the access points in the system. Agents interact with each other through the backbone and exchange the state of spectrum availability in their respective coverage area. These interactions allow measuring the availability of spectrum and avoiding interference between different WLANs. A similar pattern is used in (Galani A., 2010), where heterogeneous wireless networks are used at the place of WLANs. This scheme seems to be more promising than (Xie J., 2007) as it shows induced management of signaling loads and time delays.

To the best of our knowledge, these proposals are based on centralized resource allocation and management in the context of cognitive radio. If we consider the case of WIRAN in rural areas, we can assume that the network load is not important because of the limited number of users and centralized management can be taken into account due to its simplicity but we cannot ignore the fact of a single point of failure that may crash the whole management system. In case of unavailability of the BS due to any malfunctioning, the system will no longer be accessible in the network. Indeed, the implementation of these centralized systems is made possible through the technological development of BS. The BS has a long battery life; also, it has redundant communications links in case of power failure. However, in terms of cost it is very expensive.

In this paper, we propose a distributed intelligent agent based approach for spectrum management that will make decisions on the basis of environmental knowledge. In the next section, we provide our proposed architecture that handles with spectrum management in the context of cognitive radio.

Cooperative Agent Based Spectrum Management:

With the growth of the size and complexity of communication systems, it has become clear that the assumption of controlling and monitoring the systems through a central entity is no longer valid. Traditionally, network analysis, diagnosis and management have been done manually by a number of people. As the Internet continues to grow in reach and in density, we have seen increasing problems in understanding how it works, where it runs into problems and how to address those problems. With the increased scale, penetration, and distribution of the Internet, those traditional manual approaches require an increasing number of people to be involved, and the management task itself becomes increasingly complex. Therefore, a central problem is to make the network self-knowledgeable, self-diagnosing, and perhaps in the future self-managing with very little human intervention (Dobson, 2006).

I. Description of the approach:

According to Ferber (Ferber J., 1999), "an agent is an entity that is autonomous, real or abstract in nature, which can act upon its environment. An agent in the multi-agent system can communicate with the other agents, and the resulting behavior is a result of its observations, knowledge and interactions with other agents". The multi-agent systems are proved to be an appropriate tool for automated system management due to their characteristics of decentralization and distribution, reactivity, proactivity, cooperation, autonomy and adaptation, etc. (Ahmed A., 2010) in order to achieve a balance network operation and make the most out of the available radio resources in order to avoid interference. These operative decisions will be based on the hardware capabilities of the radio terminal like for example, energy consumption, network type, transmission power, modulation, etc.

Certain policies will be needed that will help us to provide the selection of a type of radio access networks compared to another (the one with better QoS), changing the transmission power of a system, and to have the ability to use and negotiate the available spectrum according to a predefined policy. The association of MAS with cognitive radio can ensure a bright future for the optimal management of frequencies compared to rigid control techniques practiced by telecoms regulators. In this case, new services will emerge that allows telecom operators to develop value-added services and gain operating expenditure (OPEX) and capital expenditure (CAPEX) costs, and merge the users in their choice of services.

In case of unlicensed bands usage, the cognitive radio terminals must coordinate and cooperate for better spectrum usage without interfering with each other (Spectrum sharing) or affect the communications of the primary users for spectrum access. We propose a distributed radio resource management without using a central entity to coordinate the various tasks of spectrum allocation. Autonomous cognitive radio devices will be coordinated so as not to interfere with communications from the PU. We are also looking to trace the information collected by sensors on the occupation of the spectrum at the highest level (reference to OSI model) for intelligent information processing. This processing will allow the radio to exploit unoccupied bands by taking into account the terminal capacity and also transmission requirements of the user application.

Cognitive radio model introduced by the "Open Spectrum" leads to an autonomous and distributed radio resource management. In general, the detection algorithms allow gaps to know if a specific frequency band is free or not so that the radio terminal can use for its transmissions. But this solution does although effective in any case, on the state of the radio terminal, much less the constraints of transmission of the user application. The various complex tasks in order to have a flexible and without interference require the addition of new features that lead to the need to entrust these tasks to intelligent agents to manage the radio resource.

II. Agent cooperation

Our approach is based on the cooperative MAS which are altruistic in nature. These are the systems in which, agents have common interests. They collaborate by sharing their knowledge and expertise to increase their individual and collective gain (Jennings N.R., 2001). The MAS are proving to be the most suitable due to their aspects of situated view, cooperation, and coordination, distributed in order to achieve a balance network operation and make the most use available of radio resources by avoiding interference. The intelligent agent based decisions will possess the ability to use and negotiate the spectrum according to a predefined policy.

In this approach, the cognitive radio terminals that wish to transmit information may use the information from their neighborhood with the help of agents to determine the status of the spectrum occupation. Group formation or more specifically, coalition formation will identify the environmental information without requiring any huge computational effort at the cognitive radio terminal. This helps in conserving the energy resources of the autonomous cognitive radio terminal. Also, keeping in mind the dynamic state of the radio resources and secondary users, the embedded agents in each cognitive radio device can build their preference models in terms of selecting a device with high level of QoS. These preference models will allow conserving time in dynamic and changing network conditions. In other words, the agent will know that in which part of the network it can find the appropriate information for making a proper decision. This functionality can only be obtained when agents cooperate with each other and share their knowledge. Due to this, they can make more precise and optimal decision about the spectrum sharing and allocation. We refer to this phenomenon as the situated view of an agent where, the knowledge comes either from cooperation with other agents or it is collected locally by the residing agent. Our proposed architecture for intelligent spectrum management is depicted in the Figure 3.

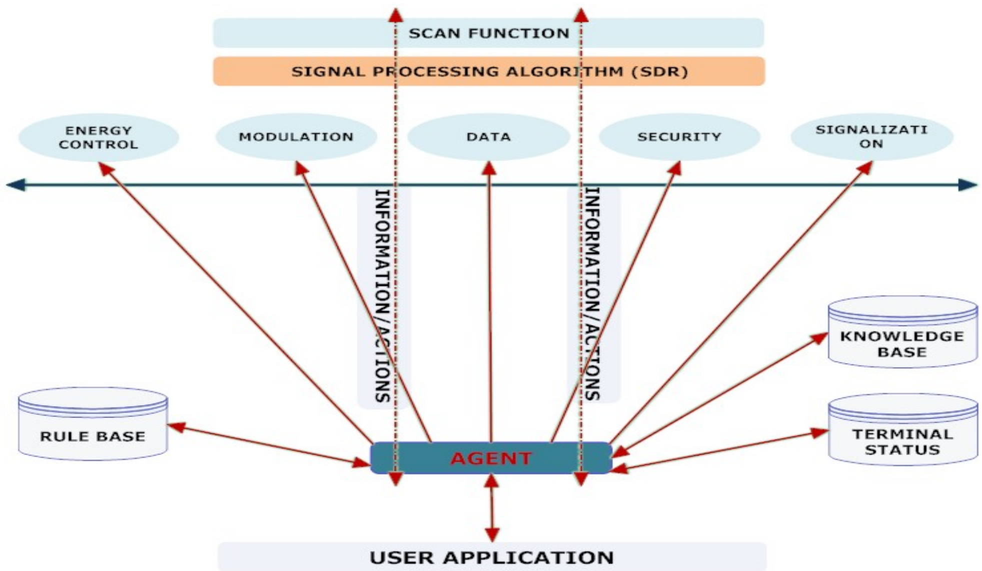

Fig. 3: Proposed Agent-based Architecture

We delegate an intelligent agent that is responsible for managing a set of modules on each cognitive radio device. This agent oversees all the operations, including the methods of free band detection, modulation types, management of signal processing algorithms, signaling channel management, management of data channels, energy control, security, QoS, etc. These operations will be delegated to specialized modules that are responsible for collecting information about the radio environment and terminal conditions. This information will be stored in a shared knowledge base, which will be consulted by all the agents for information storage or retrieval when and where needed. Later, this information will be fed back to the agent who will decide and inform the specialized modules to react accordingly. The agent is able to build several plans or solutions to be adopted in view of the dynamic radio resource and the state of cognitive radio terminal. The agents interact with other agents in the system through the signaling module which decreases the signaling overhead of using a separate protocol. These interactions are aimed at obtaining the precise information about the availability of the radio resource, the presence or absence of a user and the link quality, etc. After obtaining these observations through the scan function, they are stored in the "knowledge base" along with the terminal hardware/software updates in the under "terminal state" in the knowledge base. The agent has full control of the radio terminal and knowledge of its radio environment. The purpose of the knowledge base is to model and store knowledge or data and to allow their consultation/use anytime by the agents. According to user needs, the agent satisfies real time constraints of the user application.

III. Discussion:

In the near future, cognitive radio technology will allow more flexible use of spectrum and greater freedom with respect to the current policies for spectrum management that are way too rigid to be applied. It will also enable operators to deploy smart radio access infrastructure which are of course, less expensive. The effective deployment of cognitive radio as defined by (Mitola, 2000) is still a futuristic vision as there are different problems that need to be tackled for its successful deployment in the current radio environment. For example, digitization of the RF signals, power management in mobile devices, security testing software as well as regulatory issues.

In future mobile communication systems, users can express their requirements in terms of QoS and choose an access network according to the their given preferences like, terminal state, battery level, etc., without using any central entity to exchange data fragments. Adaptation to changes in dynamic factors that affect networks encompasses detecting and reacting to the changes in the environment. Information collection about any dynamic factor is basically change detection and it is significant to the efficiency of a network's adaptation method as a network's capacity to adapt in a new environment depends on the information collected while detecting a change. On the other hand, if any action is taken by the network for improving its performance is usually referred to as reacting to the change. In this case, the correctness of the gathered information decides about the reaction correctness of the network. The delay and cost of the information gathering impacts various characteristics like, the convergence time and overhead of the whole adaptive scheme. Users can form an ad hoc network and share data while avoiding interference with communications from the primary user. This is the reason that we delegated these complex tasks to cooperative agents who will be responsible for spectrum management, through a process of coordination, to benefit from a flexible network.

Conclusion And Perspectives:

In this work, we presented agent based architecture for effective spectrum management in the context of cognitive radio. Intelligent agents were delegated to deal with the complex tasks of retrieving terminal status and spectrum information. In the proposed work, agents cooperate with each other to best decide about spectrum sharing and allocation. In view of this work, we intend to improve the current agent architecture in order to add new features of the radio. As a perspective of this work, we plan to design algorithms for efficient use of radio resource. These algorithms will consider the impact of the use of in-band or Out-band transmission channels for the information exchange between the cognitive radios with the help of agents.

REFERENCE

Abowd, G.D., E.D. Mynatt, 2000. Charting past, present, and future research in ubiquitous computing ACM Trans. Computer Human Interaction. ACM. 7: 29-58.

Ahmed, A., L.M. Boulahia, D. Gaïti, 2011. An intelligent agent-based scheme for vertical handover management across heterogeneous networks, Annals of Telecommunications. Springer, 66: 583-602.

Ahmed, A., R. Amoud, L. Merghem-Boulahia, D. Gaiti, 2010. An agent-based approach for vertical handover in heterogeneous wireless networks, IEEE/ACS International Conference on Computer Systems and Applications (AICCSA) IEEE/ACS, pp: 1-8.

Akyildiz, I.F., B.F. Lo and R. Balakrishnan, 2011. Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey Physical Communication (Elsevier) Journal, 4: 40-62.

Akyildiz, I.F., W.Y. Lee, M.C. Vuran, S. Mohanty, 2008. A Survey on Spectrum Management in Cognitive Radio Networks, IEEE Communications Magazine., 46: 40-48.

Andrew, R.C. B.D. Carl, P. Jeremy, H.R. Jeffrey, 2010. Dynamic reconfiguration of software defined radios using standard architectures. Physical Communication. Elsevier., 3: 73-80.

Bany, S.H.A., M. Krunz, O. Younis, 2010. Cooperative Adaptive Spectrum Sharing in Cognitive Radio Networks. ACM Transactions on Networking. ACM/IEEE, 18: 1181-1194.

Commission Federal Communications, 2001. Notice of Proposed Rule Making and Order [Report]. FCC, ET Docket n° 04-186.

Dobson, S., *et al.*, 2006. A survey of autonomic communications. 2006. ACM Transactions on Autonomous and Adaptive Systems (TAAS). ACM. 1: 223-259.

Elhachimi, J., Z. Guennoun, 2010. Multi-agent system for radio resource management of a heterogeneous network. 5th International Symposium on I/V Communications and Mobile Network (ISVC). IEEE. pp: 1-4.

Fan, W., K. Marwan and C. Shuguang, 2010. Spectrum Sharing in Cognitive Radio Networks. Technical Report / University of Arizona. TR-UA-ECE-2007-1.

Ferber, J., 1999. Multi-Agent System: An Introduction to Distributed Artificial Intelligence. Addison Wesley Longman.

Galani, A., K. Tsagkaris, N. Koutsouris and P. Demestichas, 2010. Design and assessment of functional architecture for optimized spectrum and radio resource management in heterogeneous wireless networks. Int. J. Netw. Manag. John Wiley & Sons, Inc., 20: 219-242.

Ghosh, C., D.P. Agarwal, M.B. Rao, 2009. Channel capacity maximization in cooperative cognitive radio networks using game theory.SIGMOBILE Mob. Comput. Commun. Rev. ACM, 2(13): 2--13.

Jennings, N.R., 2001. An agent-based approach for building complex software systems. Commun. ACM.\ 44: 35-41.

Jocelyne, E., M. Fabio, C. Antonio, 2011. Eitan A**.** Non-cooperative spectrum access in cognitivenext termprevious termradionext term networks: A previous termgamenext term theoretical model Computer Networks. Elsevier, 55: 3832-3846.

Kloeck, C., H. Jaekel, F. Jondral, 2006. Multi-agent radio resource allocation Mob. Netw. Appl. Kluwer Academic Publishers., 11: 813-824.

Li, H., 2009. Multi-agent Q-learning of channel selection in multi-user cognitive radio systems: a two by two case. Proceedings of the 2009 IEEE international conference on Systems, Man and Cybernetics. - [s.l.] : IEEE Press, 2009. – pp: 1893-1898.

Liang, M., Q. ZHU, 2010. Game-theoretic spectrum sharing for cognitive radio based on the expectation of primary users. The Journal of China Universities of Posts and Telecommunications. Elsevier B.V., 17: 6-12.

Ma, M., D.H.K. Tsang, 2007. Efficient spectrum sharing and power control in cognitive radio networks. First International Workshop on Cognitive Wireless Networks, pp: 2: 1-2:7.

Mainwaring, A., D. Culler *et al.*, 2002. Wireless sensor networks for habitat monitoring. Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications. NY, USA. ACM

Mark, F., *et al.* 2007. Non-cooperative multi-radio channel allocation in wireless networks. Infocom. IEEE, pp: 1442-1450.

Mitola, J., III Cognitive Radio, 2000. an Integreted Agent Architecture for Software Defined Radio. PhD Thesis Royal Institute of Technology Stockholm KTH.

Neel, J.O.D., 2006. Analysis and Design of Cognitive Radio Networks and Distributed Radio Resour Management Algorithms. PhD Thesis / Virginia Polytechnic Institute and State University.

Pablo, R., A.F. Bruce, The Software Defined Radio as a Platform for Cognitive Radio. Cognitive Radio Technology / ed. F. Bruce A. Newnes.

Ren, W., Q. Zhao, A. Swami, 2009. Power control in cognitive radio networks: how to cross a multi-lane highway. IEEE J.Sel. A. Commun. IEEE, 27 : 1283-1296.

Wu, C., K. Chowdhury, *et al.* 2010. Spectrum management of cognitive radio using multi-agent reinforcement learning. Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems: Industry track. - [s.l.] : International Foundation for Autonomous Agents and Multiagent Systems, pp: 1705-1712.

Xie, J., I. Howitt and A. Raja, 2007. Cognitive Radio Resource Management Using Multi-Agent Systems. 4th IEEE Consumer Communications and Networking Conference. IEEE. pp: 1123-1127.

Zheng, J., C.H. Chen, J.Y. Cheng, S. Lei, 2009. Cognitive radio: methods for the detection of free bands. International Conference on Networks Security, Wireless Communications and Trusted Computing. IEEE. 2: 343-345.