Efficient Spectrum Utilization in Cognitive Radio Wireless Sensor Networks (CR-WSNs)

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Abstract—The radio frequency spectrum is a natural resource which ought to be exploited maximally. It has remained a major source of revenue to many countries of the world today. This brings to the fore the issue of spectrum assignment policy and management. Studies have shown that inefficient policies in spectrum assignment and management have brought about the underutilization of the available spectrum. This perceived problem has limited the deployment of new services such as the wireless sensor networks that are needed for various services and applications. Cognitive Radio is an emerging technology that has an assurance of increasing the efficiency in the utilization of the scarce spectrum resource. Therefore, adding cognitive radio abilities to the existing wireless sensor networks creates a new domain of services which might not only interest the next generation mobile user but also will increase the revenue generation for the licensed spectrum users. This paper provides an overview of the architecture of CR-WSNs, spectrum management/assignment policies and other approaches for increasing spectrum utilization in a Cognitive Wireless Sensor Networks.

Keywords—Cognitive radio wireless sensor networks (CR-WSNs), Dynamic spectrum access, Licensed (Incumbent) user, Nigeria Communications Commission (NCC), Secondary (Cognitive radio) user, Static assignment policy.

I. INTRODUCTION

There is currently a perceived problem of spectrum shortage created by the fast evolution of Wireless Communications Networks. The International Telecommunication Union Recommendation Sector (ITU-R) in ITU-R 2005 and recently in ITU-R 2011d had predicted that the demand for more mobile services would keep increasing towards the year 2020. This predicted growth in data rates would inevitably bring about an increase in the demand for spectrum. This problem of spectrum shortage is not only due to real scarcity of the available spectrum, but also due to inefficient policies in spectrum management. In fact, today’s wireless communication networks are characterized by a fixed spectrum assignment policy, which often leads to wastage of large portions of the already limited available spectrum.

Recent studies have shown that sizeable portions of the assigned spectrum are usually underutilized. Cognitive Radio has been proposed as a promising technology to solve the imbalance between spectrum scarcity and spectrum underutilization. On the other hand, the increased deployment of Wireless Sensor Networks in the unlicensed bands for various applications raises more concern for a better spectrum management policy to be put in place. To drastically reduce the perceived problem of spectrum shortage, Wireless sensor networks enabled with cognitive Radio ability could access the unlicensed bands at will when there is less contention for spectrum resources by other wireless networks sharing the unlicensed bands. In the event that the unlicensed bands become crowded, the CR-WSNs can sense this highly contentious situation, dynamically migrates to the white spaces in the licensed bands with the intention of vacating this band the moment its communications begins to interfere unduly with that of the primary user (PU).

II. OVERVIEW OF A WIRELESS SENSOR NETWORKS

A Wireless Sensor Network is a kind of network that is driven by events. Traditionally, events can trigger wireless nodes to generate bursty traffic. Figure 1, below shows a typical architecture of a Wireless Sensor network [1]. In [2], WSNs has been described as a self organizing ad hoc network, comprising of several number of sensor nodes uniformly distributed within a given area. WSNs have been deployed massively in recent times to monitor several sensitive and critical activities. It is usually deployed in places and terrains that are not easily accessible probably to avoid physical attack of the network facilities. In other words, the self-organizing ability and lifetime of the wireless nodes are very important to designers. Wireless Sensor Networks can consist of hundreds of wireless nodes deployed in a given location with careful design consideration given to the distance between two neighboring nodes. A base station otherwise known as a sink node is responsible for collecting the data from the WS nodes and sending the data collected to the network users through a gateway which is often times the internet or any other appropriate communication channel.
III. COGNITIVE RADIO WIRELESS SENSOR NETWORKS (CR-WSNs)

Incorporating Cognitive Radio capability to a Wireless Sensor Networks results in a Wireless Communication paradigm known as Cognitive Radio Wireless Sensor Networks (CR-WSNs) or simply Cognitive Wireless Sensor Networks (CWSNs). CRWSN is a distributed network of Wireless Cognitive Radio nodes, which can sense an event signal and collaboratively communicating their readings dynamically over available spectrum channel in a multi-hop manner, ultimately to satisfy the application-specific requirements [2]. The International Telecommunication Union Recommendation Sector (ITU-R) has defined a Cognitive Radio System as a radio system that has in-built technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters according to the knowledge it obtained in order to achieve some predefined objectives. In order words, a Cognitive Radio System has got some capabilities to obtain useful knowledge from its environment or location in order to make necessary decisions and adjustments so as to learn from the results. Specifically, CR-WSNs can obtain knowledge of the current spectrum availability or occupancy with a view to making very important decisions on which channel to access and when to access such channels.

The potential advantages of such systems over traditional Wireless Sensor Networks include: improved spectrum efficiency utilization and increased flexibility in spectrum management that can give room for the deployment of new mobile wireless applications. The architectural model of CR-WSN shown in figure 2, shows a primary user (incumbent user) communicating within a licensed band, and a secondary user also known as a cognitive user operating in the unlicensed band and also waiting to use opportunistically the licensed band during the idle periods of primary users.

IV. SPECTRUM ASSIGNMENT POLICIES

The main objective of any spectrum assignment policy should be to maximize the utilization of the available scarce spectrum resource. Recent studies have shown that the spectrum scarcity being envisaged today and its attendant spectrum under-utilization have been blamed on the fixed or static spectrum assignment policy as enforced in various countries today [3].

Figure I: A typical Architecture of a Wireless Sensor Networks [1]

Figure II: The Architecture of a cognitive radio wireless sensor network (CR-WSNs) [1].
In this static or fixed assignment policy, licenses are usually issued to users or operators for the usage of certain frequency bands. When this license is issued, an operator or a user has the exclusive right over the allocated spectrum on a long-term basis. This method of spectrum assignment policy has resulted in the allocation of the entire spectrum in many countries today. As a result, the deployment of new wireless services like WSNs which are utilized for very crucial, emergency and mission critical services becomes very difficult. In addition, the price involved in acquiring licenses under the fixed static assignment policy is usually very costly. This does not include the cost of acquiring and deploying a robust network infrastructure that could guarantee services to the end users. In addition, monitoring and enforcing laid down rules from the regulatory bodies under fixed static spectrum assignment policy raises some legal issues between the licensed users and regulators.

In a dynamic assignment policy, new services can be accommodated by redefining the spectrum that has been assigned to existing services that utilize the spectrum sparsely [4]. The DSA policy can proactively make open the licensed spectrum frequency bands to unlicensed users on the condition that unlicensed users do not interfere unduly with the communications of licensed users. Under this new spectrum management system, an unlicensed user in addition to having all the rights to access the unlicensed spectrum could be allowed to access opportunistically the licensed spectrum bands as long as it does not constitute a harmful interference to licensed users during its communication periods. Cognitive Radio has emerged as a promising technology to enable the access of the intermittent periods of unoccupied frequency bands called white spaces, thereby increasing spectral efficiency [5, 6]. The different agencies and bodies saddled with the responsibility of managing frequency spectrum in different countries have begun investigations into this purported claim about spectrum scarcity. This has led to several spectrum occupancy measurements that have been conducted mostly in the United States, Europe and recently Asia to ascertain the utilization level of the allocated spectrum. From the study conducted in [4], it was observed that a large portion of the assigned spectrum was used sporadically. The spectrum usage was concentrated over certain portions of the spectrum leaving spectrum holes or white spaces on other portions of the spectrum. To corroborate the claim of [4], the federal communications commission in the United States conducted another study in [7], which reported temporal and geographical variations in the utilization of the assigned spectrum.

V. Dynamic Spectrum Access Models

The main idea behind Dynamic Spectrum Access lies in the ability of the CR-WRSNs to identify licensed radio frequency bands which are free or underutilized (spectrum holes or white spaces), using them to communicate and vacating those bands the moment its communications begins to interfere with the communication of incumbent users. In the dynamic spectrum model (Peng et al 2006), it is assumed that the primary users may not always use the spectrum. Hence, the secondary users can opportunistically utilize the spectrum when it is not being occupied by the licensed users. Three main functions in dynamic spectrum access have been captured in [8], and they include: spectrum awareness, cognitive processing and spectrum access. Spectrum awareness creates awareness about the radio frequency environment while spectrum access provides the ways to use the available spectrum opportunistically for efficient reuse. Cognitive processing relies on the intelligence of the radio which helps to make important decisions like learning from the environments, adjusting its operating parameters based on the results learned from its environment. As illustrated in figure 3 below, dynamic spectrum access strategies have been broadly categorized under three models.

A. Dynamic Exclusive Use Model

Under this model, the basic structure in the static assignment policy is maintained in the sense that spectrum resources are still allocated exclusively to the licensed users. The dynamic exclusive model therefore introduces some element of flexibility in order to improve spectrum utilization efficiency. Two approaches of dynamic exclusive model have been proposed. They are spectrum property rights [9, 10] and dynamic spectrum allocation [11]. The spectrum property rights approach allows licensed users to lease or share spectrum for profit and to freely choose their own technology. It is important to note here that the sharing or leasing of spectrum resources under this approach is not mandated by the regulation bodies. On the other hand, the dynamic spectrum allocation introduced by the European DRiVE project [11], aims to improve spectrum utilization efficiency through dynamic spectrum assignment by exploiting the spatial and temporal traffic information statistics of different services. That is to say that spectrum is allocated to services for exclusive use in a given region at a given time. The approaches utilized in the dynamic exclusive-use model cannot guarantee total elimination of spectrum white spaces and this could result in the generation of bursty traffic by the CR-WSNs.
B. Open Sharing Model

The open sharing model otherwise known as spectrum commons model encourages open sharing of spectrum resources among peer spectrum users. Every user under this model has equal rights to use the spectrum. The proponents of this model are backed up by the success recorded by wireless services operating in the unlicensed Industrial, Scientific and Medical band (ISM band) (e.g WiFi). Three types of spectrum commons model [12, 13] were highlighted as uncontrolled commons, managed commons and private commons. When the uncontrolled commons is implemented, no entity has exclusive license to the spectrum band. The managed commons strives to avoid the tragedy of commons by imposing some restrictions on when and how to use the spectrum resource. The concept of private commons was introduced by the federal Communication Commission (FCC) in its second report on the elimination of barriers to the development of secondary markets for the scarce spectrum. This model encouraged the use of advanced technologies which allowed multiple users to access the spectrum.

C. Hierarchical Access Model

Under the hierarchical access model, unlicensed users make use of the spectrum in such a way that interference to licensed users is limited to the minimum. Three approaches to this model have been proposed [14] and they include: inter-weave, underlay and the overlay. The inter-weave strategy consists in utilizing the white spaces or spectrum holes unused by licensed users to establish communication between unlicensed users. The underlay strategy ensures that secondary user’s communications are always maintained below the maximum allowable interference temperature at the primary user’s receiver [14]. Finally, the overlay approach allows the SUs cooperating with the Pus while transmitting their own signal.

In other words, SUs devote part of its transmit power to enhance the primary signal and facilitate its detection at the primary receiver. In exchange for this gesture, they may be allowed to increase the interference temperature above the level permitted in the underlay approach. It is believed that this approach may be widely accepted by licensed users owing to the fact that the SUs contributed in improving the detection of Pus.
As a result of the above mentioned factors, comprehensive and clear-cut policies are needed in Nigeria and even beyond to ensure proper and efficient management of the spectrum resource. In [16], spectrum management has been defined as the process of regulating the use of radio frequencies to promote efficient utilization and gain a net social benefit. The government of Nigeria charged the Nigerian Communications Commission (NCC) with the responsibility of developing and adopting polices in accordance with the policy objectives given below which will ensure that this scarce resource is well managed in its area of responsibility.

**NCC Frequency Management Policy Objectives [15]:**

- To control and encourage the use of spectrum as an instrument for developing telecommunication which is an essential infrastructure for stimulating the economic growth and social development of the nation.
- To promote competition in the assignment of frequency in order to ensure innovative and efficient use of the radio spectrum (as a scarce resource).
- To achieve optimum pricing of spectrum in order to discourage wastage or speculative acquisition of the scarce resource.
- To generate moderate revenue for government.
- To ensure equitable and fair allocation of spectrum to benefit the maximum number of users.

In order to achieve the above management policy objectives, NCC was empowered to perform the following functions: [15]

- **Spectrum Planning:** Plan the spectrum in order to make adequate provision for various services based on their relative importance to Nigeria’s socio-economic goals and also make forecast for future requirements.
- **Frequency Assignment:** Evolve fair, equitable and transparent procedures and conditions for the allocation and assignment of spectrum.
- **Spectrum Farming:** Continually and systematically phase out ageing technologies in order to free up new spectrum space for allocation to emerging technologies and new services.
- **Licensing:** Develop effective rules, operational procedures/guidelines for the purpose of regulating the use of spectrum in order to encourage sharing and ensure minimum interference with other users.
- **Technical Specifications:** Define technical utilization rules and specifications for radio frequency equipment and also administer equipment type approval and authorizations.

VI. SPECTRUM MANAGEMENT POLICY

Unlike most natural resources, the radio spectrum as a result of its unique features is not consumed by usage. This natural resource is therefore infinitely renewable. In Nigeria, for example, radio frequency spectrum is one of the key natural resource which is of great economic value as a result of its direct application in telecommunications, broadcasting, military operations, and scientific research in addition to a range of other socio-economic activities such as social services, law enforcement, education, healthcare and transportation. As such, many industries depend heavily on the efficient utilization of radio frequency spectrum [15].

**Figure 3: Approaches of the Hierarchical Access Model [14].**
In addition, regulatory bodies may be tempted to favour highest bidders at the expense of prospective users that have the technology that can use the spectrum more efficiently. No matter the success rate in managing the spectrum under this approach, it is not usually very clear to which extent the assigned spectrum is utilized. In what looks like an attempt to shift from the former approach, a new spectrum management system has been proposed in Nigeria by NCC. The Commission is putting in place a modern Spectrum Management and Monitoring System (SMMS) [18]. As part of the SMMS implementation, detailed information is required about current and continuing utilization of frequencies assigned to telecommunications operators, equipment operating on those frequencies and sites/locations where they are deployed. The information is required for creating a geo-location database on the utilization of radio spectrum frequencies and associated information that would be constantly updated. The records will provide an invaluable resource for: facilitating resolution of interference, spectrum planning, policy; and the overall spectrum management strategy of the Commission.

VII. GAME THEORY APPROACHES FOR IMPROVING SPECTRUM UTILIZATION

Generally speaking, cognitive radio networks have been proposed for better utilization of spectrum in wireless networks such as CR-WSNs. The cognitive radio should be able to adjust its operating parameters with perceived changes in the environment. The proponents of the game theory believe that traditional approaches for resource allocation is not applicable to self-organizing networks such as CR-WSNs. Game theory has the ability to analyze and model the interactions among users and allocates resources to users. Game theory is a mathematical tool that analyzes various interactions between rational players [19]. It is a collection of modeling tools which helps in solving interactive decision problems. Game theory was first introduced in 1944 by J. Von Neumann and O. Morgenstern and it has been applied ever since to various fields. Recently, game theory has gained a lot of attention in the field of cognitive radio networks [20]. Game theory according to [21] describes a game as: \( G = \langle N, A, \{ u_i \} \rangle \) where \( N \) represents the decision makers or players, \( A \) represents Action Space and \( U \) represents utility set. Every player has its own action space \( A_n \) which is the set of actions which includes all possible actions that a player can choose from. The total action space is calculated by multiplying all the action sets (i.e. \( A = A_1 \times A_2 \times A_3 \times \ldots \times A_n \)).
On the other hand, Utility Set (U) is a set consisting of utility or payoff functions for all players (where \( U = U_1, U_2, U_3, \ldots, U_n \)). With regards to cognitive radio networks, two major types of game theory have been proposed in the literature as cooperative game theory and the non-cooperative game theory [20, 22]. The cooperative game theory considers that all cognitive radio users are cooperative and aims to maximize total network performance by achieving a Nash bargaining state. Individual user shares vital information like utility with other network users. The non cooperative game theory considers the cognitive radio users as rational users who aim to maximize their own utility in terms of spectrum resources. This type of game converges at Nash equilibrium state with individual user not having access to the strategies and payoff of other users. The Nash equilibrium [23] is defined as a set of strategies for all the users such that no user can improve his/her utility by unilaterally deviating from the equilibrium strategy as long as other users adopt the equilibrium strategies. It does imply that the Nash equilibrium indicates that no individual user would have the incentive to choose a different strategy. In cognitive networks, the competition and cooperation among the cognitive network users can be modeled as a spectrum sharing game [23]. Specifically, the SUs who compete for unlicensed spectrum are the players in the open spectrum sharing model. In the licensed spectrum sharing model, the Pus can lease their unused spectrum bands to the SUs and the players in this type of model include the Pus and SUs. The strategy space for each type of player will therefore depend on the type of spectrum sharing model adopted. For example, the strategy space of SUs in open spectrum sharing may include the transmission parameters they may want to adopt. These parameters include: access rates, transmission powers, time duration etc. On the other hand, the strategy space for the licensed sharing model include the licensed bands that the Pus may want to rent and how much they would be charged for leasing such licensed frequency bands. The utility functions for different users are then defined accordingly in order to characterize various performances criteria. In open spectrum sharing, the utility function for the SUs is usually defined as a non-decreasing function of the quality of service (QoS) which they receive by utilizing the unlicensed band. The utility function for the Pus in the licensed sharing model often represents the monetary gains they derive by leasing the licensed bands. Serious research effort has been made by several researches on using game theory to solve the problem of spectrum allocation in cognitive radio networks.

Gesualdo Scutari et al [24] proposed a non-convex game and used the optimization theory to analyze comprehensively the existence and uniqueness of a standard Nash equilibrium. Their proposed algorithm can be used for both cooperative and non-cooperative cognitive radio network scenarios. The authors in [25] considered using the cooperation game theory to solve the potential problems that might arise when a PU and multiple SUs share the spectrum. At first, the authors designed a static game where all the SUs had to adopt the initial strategies and the mutual information and then afterwards, had to adjust their strategies iteratively according to the last state observations. Wenson Chang et al [26] proposed a novel spectrum leasing game for the underlay cognitive radio network using rate-based pricing strategy for PU. This strategy can decrease significantly the communication signaling overhead. In addition, both the PU and the SU can simultaneously maintain a high transmission rates such that spectrum efficiency can be improved upon. The research done in [27] Proposed a network assisted cooperative game theory which guarantees the PU’s required QoS. The authors in their proposal developed a framework for spectrum allocation where a group of SUs access the spectrum of PUs operating in a Cellular OFDMA based network. According to the proposal, both PUs and SUs send to the PU’s base station their power limitation and channel state information and the base station responds by calculating the optimum sub-channel and power allocation for all the users. In [28], the authors assume the players to be selfish (players who seek to maximize their own profits) and that the PU do not have knowledge of their environment such that they are unaware of the presence of SUs, and the SUs are allowed an opportunistic access to the spectrum. In summary, there is no gainsaying the fact that game theory has been widely used in developing algorithms that can enhance spectrum utilization in cognitive radio networks. However, the major drawback of this approach is that utility functions and the game formulation must be carefully structured in order to achieve the required Nash bargaining state or equilibrium as this may not always be guaranteed. In addition, most propositions on the use of game theory for solving one problem or the other in cognitive radio networks have not been extended to the domain of cognitive radio wireless sensor networks.

**VIII. OTHER APPROACHES FOR IMPROVING SPECTRUM UTILIZATION**

In this section, we provide a brief overview of other approaches used for improving the utilization of the scarce spectrum according to available literature.
Elias Z. Tragos et al [29] highlighted other approaches which could increase the efficiency of the spectrum utilization in cognitive networks as: Heuristics, Graph theory, and Fuzzy Logic.

A. Heuristics Approach

The heuristics approach is targeted at developing iterative algorithms which aims to find at each iteration, the best solution (for example the best available channel with higher utility) for the SU. The advantage of this approach is its simplicity and ease of implementation and in many cases; they can find high quality solutions. However, there is no known analytical methodology for studying their convergence properties and they get stuck in local optimal solutions which can be far from the global solution. In addition, heuristics approaches appear to be problem-independent in theory, whereas most of the developed heuristic approaches are problem-specific and cannot be used for other problems. Finally, the problem of finding an optimal solution for cognitive spectrum assignment or management has often high complexity and determining good solutions becomes very difficult.

B. Graph Theory Approach

The graph theory approach visualizes every network as a graph where the vertices correspond to the network nodes and the edges correspond to the connections between the nodes. Network graphs have been used extensively in the domain of cognitive spectrum assignments especially for cases where the structure of the network is known a priori [30]. Several techniques according to the available literature have been used in solving the graph-based spectrum assignment problems. The most common technique is to construct the network conflict graph that captures the interference between neighbor SU nodes [31, 32]. A conflict graph can be simple, weighted, multipoint or dynamic [29]. The weights on the edges represent the interference model or the required channel separation between the links in the weighted conflict graph. In cases where it is believed that a single SU is transmitting to multiple receivers, the multi-point conflict graphs are preferred. On the other hand, the dynamic conflict graph approach is used to capture the possible changes in the interference due to previous assignments. Two types of cognitive radio network graph have been identified in [33] as: Node Contention Graph and Link Contention Graph. In node contention graph, cognitive users are represented by nodes while edges indicate that two nodes are in the interfering range of each other. In the link contention node, the vertex represents active flows while the edges represent a contention between different flows.

One major drawback of the proposed algorithms based on graph theory as shown from available literature to the best of our knowledge have considered networks with SUs only. Future works on algorithm proposals or developments based on the graph theory ought to expand the existing scope to accommodate PUs and with particular attention given to CR-WSNs.

C. Fuzzy Logic Approach

Fuzzy logic techniques have been used conventionally for decision making and in designing optimization algorithms. A fuzzy logic controller consists of four modules which include [29]: a fuzzy rule base, a fuzzy inference engine and fuzzification/defuzzification module. The fuzzy rule base consists of a set of rules usually in the form of “IF – THEN”, which is based on a prior knowledge, questionnaire or SU measurements. The fuzzy logic controller can accept inputs like the arrival rate of PUs or SUs, information on channel availability, the distance between network users (like PUs or SUs) etc. The FLC then takes decision which is based on pre-defined rules. In cognitive radio networks, the fuzzy logic approach has been used mostly where configuration of the cognitive radio network is known a priori. In [34], a cooperative spectrum sensing scheme based on fuzzy logic technique was proposed. The proposed technique takes into cognizance the reliability of the sensing results at different cognitive radio nodes. The final decision about the presence of PU is done based on the combined results from several cognitive radio nodes whose decisions are weighted. The credibility of the sensing node is determined in a training stage with fuzzy evaluation. The authors in [35] used fuzzy decision making for cognitive network access where cognition refers to the detection of the user’s needs and the provision of adequate wireless services. The fuzzy decision making proposed here chooses the most appropriate access opportunity by using cross-layer information, past history, shared knowledge among different devices through a knowledge base. An approach using a fuzzy logic system that detects the effective spectrum access for SUs was proposed in [36]. The SUs are selected on the basis of spectrum utilization, degree of mobility and distance from SUs to the PU. The fuzzy logic proposed here was designed primarily to control the spectrum assignment and access procedures in order to prevent multiple users from colliding inside overlapped spectrum portions. One major drawback of the fuzzy logic approach with regards to CRNs is that it is not scalable. The reason behind this is that a lot of rules are required for solving dynamic spectrum access problems which leads to improvement in the utilization of the spectrum.
D. Markov Decision Process (MDP) Approach

The viability of using Markov decision process to optimize decisions that could impact the utilization of radio frequency spectrum was proposed in [37]. These decisions may include: admission decisions, modulation choice decisions, transmitter power level decisions, and other decisions that could improve the utilization efficiency of the scarce spectrum. The authors formulated three distinct hypotheses, developed the hypotheses and conducted experiments to access each of the hypotheses. The empirical results from the experiments were all in support of the formulated hypotheses. However, the research dealt primarily on admission optimization decision. In other words, the research work can be extended in the future to accommodate decisions like choice of modulation and transmitter power level decisions. In another development, the problem of cognitive access of multiple continuous-time Markovian channel was considered in [38]. According to the authors, the problem was simplified by restricting the spectrum sensing policy to a periodic sensing scheme and this changed the problem from a partially observable Markov decision process with constraint to a constrained finite state Markov decision process. At the end, the authors referred the resulting algorithm as “optimal spectrum access with periodic sensing (PS-OSA). The structure and the fundamental limit of a single continuous-time Markovian channel was investigated in [39]. In their work, the authors considered the optimal transmission policy with arbitrary sensing and transmission periods which is comparably small.

IX. CONCLUSION

This paper has presented an overview of the different approaches for improving the utilization of the scarce radio frequency spectrum. It has highlighted the architecture of CR-WSNs as well as policies employed in spectrum management and assignment. There is therefore no gainsaying the fact that many research papers have proposed different approaches for improving spectrum utilization efficiency in cognitive wireless networks. However, a major revelation from this paper shows that a lot of research work is needed urgently to expand this new domain of research to address peculiar issues relating to resource-constrained and self organizing networks like CR-WSNs.

REFERENCES


