Vol. 4, No. 8 August 2013 ISSN 2079-8407
Journal of Emerging Trends in Computing and Information Sciences

http://www.cisjournal.org

Cognitive Radio-based Wireless Sensor Networks As Next Generation Sensor Network: Concept, Problems and Prospects

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ABSTRACT

Research in Wireless Sensor Networks has witnessed a tremendous increase in the last two decades. Apart from military surveillance, wireless sensor network (WSN) have been deployed in the areas of healthcare monitoring, oil-field explorations, nuclear power plant monitoring, underwater activities surveillance, and geo-informatics. However, with the increased deployment of WSN using the unlicensed spectrum band (that is, the Industrial Scientific and Medical-ISM), there is an increasing demand for communication channels within this band due to over-crowding of the band. Critical issues in sensor networks is the need to minimize energy consumption without undermining the quality of service (QoS) provisioning of the network. With the paradigm shift in wireless communications towards Cognitive Radio (CR) technology, it is believed that the problem of scarce spectrum in the unlicensed bands, and short network lifetime rocking the WSN applications in the unlicensed band can be mitigated. In this paper, we present a Cognitive radio-based wireless sensor network (CRWSN), and propose a design concept for this relatively new sensor network paradigm. Also, we highlighted possible prospects and challenges associated with the development and deployment of this paradigm in sensor networks. This, we believe will pave way for the next-generation (NG) sensor network applications.

Keywords: *CR-WSN, Energy, Sensing, Communication, Channels, Spectrum, Next-generation*

1. INTRODUCTION

Communication networks are indispensable component of human life in modern world. They find numerous applications, ranging from social networking, security networks, trade and commerce to educational research and development networks. Among the leading areas of research and development in wireless communications are techniques and mechanisms to implement the most cost effective and efficient utilization of the radio frequency spectrum and energy. Radio frequency spectrum is considered the most expensive and scarce resource among all wireless network resources, and it is closely followed by the energy consumption, especially in low energy, battery powered sensor network devices [1]. However, it has been observed that the scarcity of the frequency spectrum is mainly due to the adoption of a static spectrum assignment policy-a policy that gives exclusive right-of-use (RoU) to a licensed user of a particular licensed spectrum. This exclusive right has led to scarcity of spectrum in the licensed spectrum band, while in the unlicensed bands where wireless sensor networks operates, there is overcrowding due to increase in the number of users in this band.

Wireless Sensor Network (WSN), consists of sensor nodes, which primarily performs the function of monitoring physical quantities in a given environment within which they are deployed [15]. [2] described it as a self-organising ad hoc network,comprisingseveral number of sensor nodes uniformly or randomly distributed within a given area. According to [12], WSN operates within the overcrowded unlicensed band of the radio frequency spectrum. One of such available band is the 2.4GHz band. Other wireless applications sharing this same band include, WiFi, bluetooth, wireless microphone and microwave oven. With the increasing deployment of other wireless applications in this unlicensed band, it is evident that the band has become overcrowded, and this is impacting negatively on the general performance of WSN in this band, especially in a densely populated areas where communication traffic density is high.

However, there is a new paradigm in spectrum access and usage in the licensed band brought about by the advent of Cognitive Radio (CR) technology. In [3], Haykin defines CR as a radio capable of being aware of its surroundings, learning and adaptively changing its operating parameters in real time with the objective of providing reliable ubiquitous spectrally efficient communication. There are three key features of CR; self-awareness, reconfigurability and intelligent adaptive behaviour. With these three features, static spectrum allocation and utilization has given way to a dynamic spectrum access and efficient utilization. Dynamic spectrum access, allows the unlicensed user (regarded as secondary user-SU) opportunistic use the licensed band belonging to another user (regarded as primary user-PU) while the PU is not currently available. As posited by [13], cognitive radios utilize the underutilized spectrum resources along time and frequency and provide efficient dynamic spectrum access.

Leveraging on the advantages of the opportunistic spectrum access provided by cognitive radio technology, wireless sensor networks have the potential of operating at lower licensed spectrum band, for example the TV band with efficient spectrum usage and higher energy efficiency due to range extension [2]. A cognitive radio based wireless sensor network (CRWSN) or cognitive radio-based sensor network (CRSN) is a multichannel wireless network in which the sensor nodes dynamically adapt themselves to the available communcation channel [6].

There are enormous prospect in deploying CRWSN, such as, improved channel utilization and communication reliability in a multichannel environment. Alongside the prospect of deploying this intelligent sensor network also comes various challenges such as, implementation of RF front-end for cognitive radio sensor network considering low cost and resource-constrained nature of sensor nodes, problem of error control in a multichannel environment and redundancy.

The name cognitive radio-based wireless sensor network (CRWSN) and cognitive radio-based sensor network (CRSN) are used interchangeably in the rest of this paper as both names refer to the same thing. So also are the acronyms for both names.

The rest of the paper is organised as follows; Section II provides an overview of the classical wireless sensor network. Section III gives the description of cognitive radio technology and dynamic spectrum sensing. Section IV provides the model of wireless sensor network based on cognitive radio technology. In section V, we raised some open research questions and challenges associated with the development and deployment of cognitive radio-based wireless sensor network. Section VI covered prospects and potential benefits derivable from deploying CRWSN, and section VII is the conclusion.

2. TRADITIONAL WIRELESS SENSOR NETWORKS OVERVIEW

Regarded as the second largest network after the internet, wireless sensor networks (WSN) are becoming a hot area of global concern [11]. Wireless sensor networks consists of several number of low-cost autonomous electronic devices otherwise known as sensor nodes, which are capable of remotely sensing, processing and communicating in an ad hoc manner. These sensor nodes senses physical quantities such as sound intensity, temperature change, noise levels, object movement, light intensity, pressure differentials over a given region or geographic location [2]. The sensor nodes in a practical wireless sensor networks needs not be uniformly distributed over the region, but they form a multihop network which communicates through mesh networking in order to complete a particular set objective. While the nodes could be few in number, there is no particular limit as to the number of sensor nodes that should constitute the sensor network. A given wireless sensor network could be made up of sensor nodes in their hundred of thousands deployed to monitor certain ambient condition in a particular geographic region.

Although the concept of wireless sensor network has been around for some time, it is still considered a developing technology that is open to more research and development. According to [4], the earliest sensor network was the Sound Surveillance System (SOSUS). This system was used to monitor Soviet Union’s submarines acoustically during the cold war era [4]. Ever since this time, WSN has evolved with increased processing capabilities and wide range of applications.

Designing wireless sensor networks with the capability of prolonging network lifetime catch the attention of many researchers in wireless network field [7]. Operation mode selection scheme was proposed in [14] for the purpose of energy efficiency. As mentioned earlier, WSN is a self-organising ad hoc network with sensor nodes scattered in a sensor location often called sensor field. Each of the nodes has the capability of collecting data about their region of deployment and reporting to the coordinating center, which could be a sink node or base station. Information from the various sensor node can be sent for external use via the sink node. Another important compenent in a WSN is the gateway. The gateway is another node more powerful than the sensor nodes, and it performs such functions as, data aggregation, node organisation, status assignment, which are local network management functions. Figure 1 describes a typical wireless sensor network architecture.

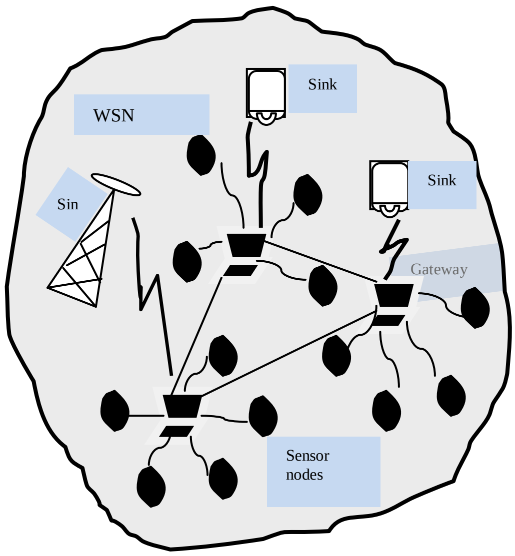

Fig 1: A Simple Wireless Sensor NetworkModel

This architecture is widely adopted for WSN because it provides the network with better quality of service and minimised energy consumption. This inturn will increase the network life. WSN as an ad hoc network has some unique characteristic features; these are summarized in table 1.

Vol. 4, No. 8 August 2013 ISSN 2079-8407
Journal of Emerging Trends in Computing and Information Sciences

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Table 1: Unique features of Wireless Sensor Networks

Characteristics	Explanation
Power constraints	This is a very stringent constraint in WSN because sensor nodes operates in a harsh remote location with minimum or no human intervention. It is very important to develop energy-efficient protocols which will guarrantee a longer battery life of the sensor nodes.
Traffic Distribution	Depending on the location and the type of application, communication traffic pattern in sensor network differs.
Data Fusion	As a result of limited bandwidth and power constraint, it becomes necessary to aggregate packets into one before relaying it to the monitoring node. This operation reduces bandwidth consumption, and media access delay resulting from multiple packet transmission.
Node Mobility	Generally, sensor nodes are designed for limited or no mobility.
Deployment Density and Network size	Node density in a sensor network depends largely on the region of deployment and application area. The number of nodes in a sensor network ranges from 3 to several hundred of thousands.

3. COGNITIVE RADIO TECHNOLOGY

The concept of Cognitive Radio (CR) was first introduced by Mitola in [5]. CR technology aims at making use of the network resources currently used in wireless communication systems more efficiently. CR allows opportunistic use of the licensed spectrum band by an unlicensed user with minimum allowable interference to the licensed user, and without compromising on the desired quality of service required by the unlicensed user.

At the heart of CR development are the following characteristics;

- Flexibility and agility: This is the ability to change the waveform and other radio operational parameters while on the move.
- Sensing: This is the ability to observe and measure the state of the radio environment, including spectral occupancy. For the device to change its operation based on the current knowledge of the RF environment, sensing is very necessary.
- Learning and Adaptability**:** This is the ability to analyze sensory input, to recognize patterns, and modify internal operational behaviour based on the analysis of the new situation.

With these characteristic features, CR has the capability to sense the spectrum and determine vacant band [6]. And by changing its operating parameters, CR can make use of the available sensed band in an opportunistic manner. This makes it possible for CR to operate both in the licensed and unlicensed bands of the radio spectrum.

Figure 2. shows the simplified Cognition Cycle (CC). CC is one of the most important concepts used in cognitive radio technology. The cognition cycle depicts how the cognitive radio responds to external stimuli within its radio environment. The cognitive radio senses and observes its operating environment in the observe state. It then orient itself in accordance with the sensing outcome. Depending on whether the outcome of the sensing requires immediate priority, urgency or normal transition, the orient state can transit to Act, Decide and Plan states respectively. In the plan state, most stimuli are dealt with deliberatively rather than reactively. An incoming network message would normally be dealt with by generating a plan, which is the normal path. The Plan phase should also include reasoning over time. Normally, deliberate responses are preplanned, while reactive responses are learned by being informed or preprogrammed. In the decide state, the radio decides on one of the various plans. The outcome of the decision leads to an action such as resources allocation in the act state. In the act state, a particular chosen action is executed, while the consequence of the chosen is learnt in the learn state. Learning is a function of the other states of the cognition cycle. Initial learning is controlled by the observe stage in which all sensory perceptions are continuously compared with all prior experiences to continually evaluate occurrences and to remember time since last occurrence of the stimuli from primitives to aggregates.

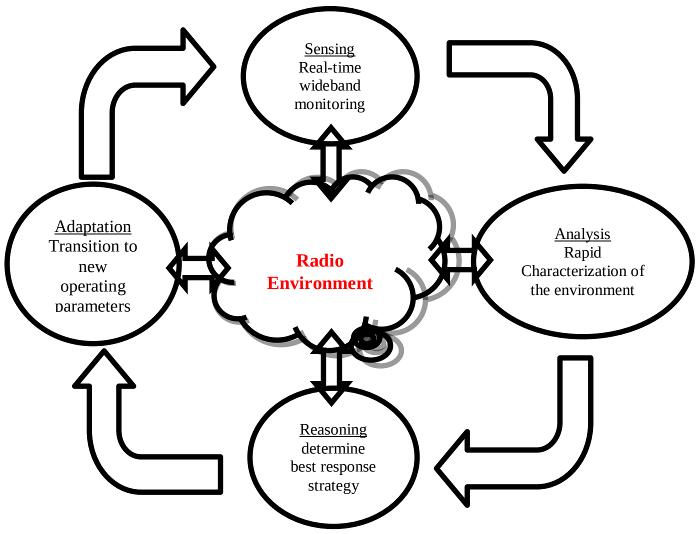

Fig 2: Simplified Cognition Cycle

Vol. 4, No. 8 August 2013 ISSN 2079-8407
Journal of Emerging Trends in Computing and Information Sciences

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4. CONCEPTUAL DESIGNOFCRWSN

4.1 Cognitive Radio Network Architecture

As illustrated in figure 3,CRSNmodel consists of a licensed primary user operating within a licensed band, and unlicensed secondary user trying to use the licensed band when the primary user is not available.

Cognitive Radio Wireless Sensor Network (CRWSN) is a distributed network of wireless cognitive radio sensor nodes, which sense an event signal and collaboratively communicate their readings dynamically over available spectrum channel in a multi-hop manner, ultimately to satisfy the application-specific requirements [2]. This is the next generation sensor network paradigm. Most WSNs applications operate under IEEE 802.15.4 standard and operates in the unlicensed band. The most commonly used unlicensed band for WSN operations is the 2.4GHz band. This is due to flexibility and low cost operating within this band. However, in recent time, the unlicensed band has become crowded with other wireless networks such as WLANs, WBANs and WiMAX operating within this band. This leads to the building of CRWSN in order to solve the problems associated with coexistence of multiple networks in the unlicensed spectrum band.

The low spectrum utilization in the licensed spectrum leaves a large amount of resources for WSNs to serve traffic with strict quality of service requirements. Without having to access dedicated licensed spectrum, it is possible to build WSNs with a low cost. There is little restriction on the air interfaces, coverage area and network topology. MAC protocol and resource allocation can be designed based on specific application requirements and network conditions in order to meet various QoS requirements.

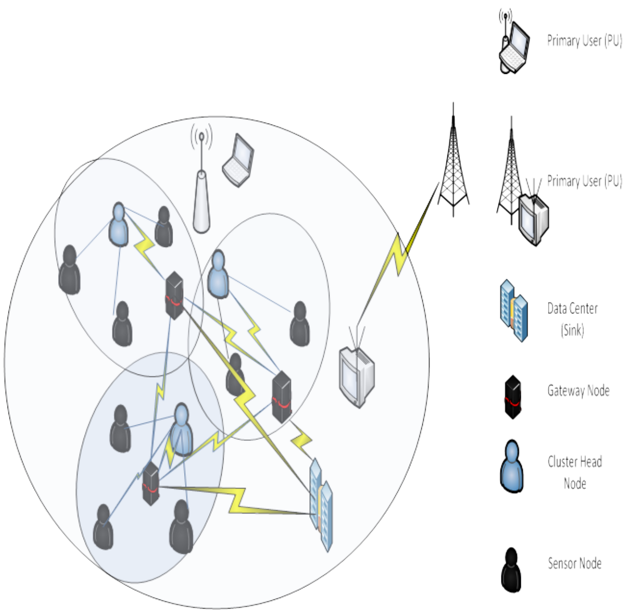

Fig 3: CRWSN Network Model

4.2 Cognitive Radio Hardware Structure

The cognitive radio-based sensor network hardware is typically composed of the power unit, sensing unit, processing unit, the cognitive radio platform and the RF unit. This is shown in figure 4. For application specific network, there could be present location finding unit and mobilizer unit. Cognitive radio sensor network is different from the traditional wireless sensor node basically with the presence of the RF unit of the cognitive radio sensor nodes. The cognitive engine enables the CR sensor nodes to dynamically adapt their communication parameters.

As promising as this hardware architecture is in terms of dynamic spectrum access for sensor nodes, there are noticeable challenges posed to a resource-constrained wireless sensor networks. Wireless sensor networks are constrained by resources such as power, low complexity processing device, communication and memory. As a result of these limitations, the cognitive radio capability is also affected.

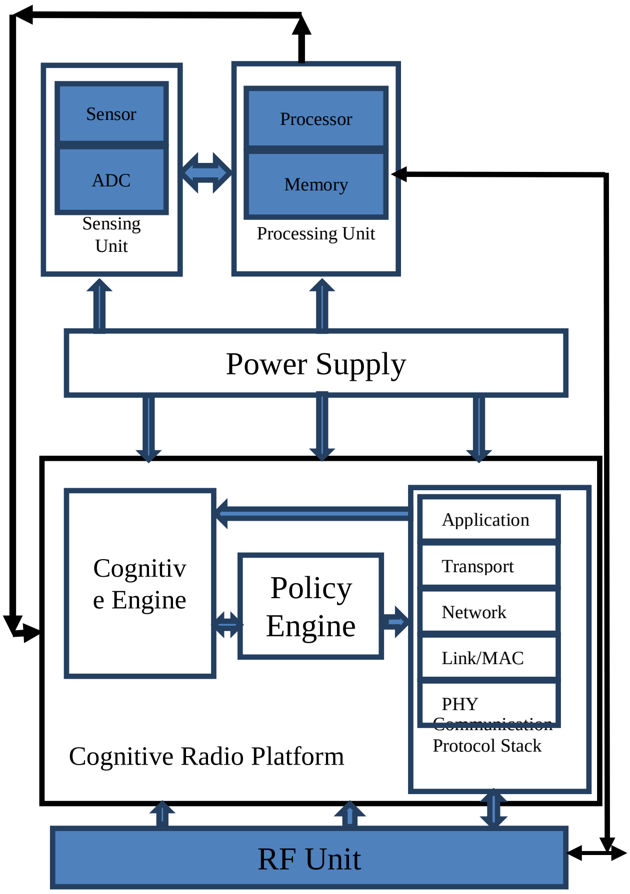

Fig 4: Hardware Architecture of a CRWSN

For instance, it will be necessary to consider low energy consumption spectrum sensing design and energy saving protocols in order to prolong the network lifetime. Therefore, we suggest that for a better system architecture for CRWSN, there should be adaptive, dynamic MAC protocol using reinforcement learning technique. Also, there should be cross-layer energy management protocol integrating the physical and the MAC layer.

4.3 Cognitive Radio-based Sensor Network Topologies

Cognitive radio-based sensor networks are application dependent. Therefore, depending on the application requirements, different network topologies are being proposed.

Clustered Topology: As shown in figure 3., a cluster-based topology is appropriate for effective operation dynamic spectrum management in CRWSN. Generally, it is important to dedicate a special channel to exchange various data like, spectrum sensing results, spectrum allocation data, licensed user discovery, and control information. In certain application area, it may not be possible to find such a dedicated channel throughout the network. However, it has been shown that finding a dedicated channel in certain restricted application area is very possible by using space correlation of channel availability.

In cluster-based topology, some sensor nodes are elected as cluster head, that is, the leader of the cluster. The cluster head may be assigned other responsibilities such as spectrum sensing, and local bargaining of spectrum. Therefore, a new cluster head and cluster selection algorithm should be developed for cognitive radio sensor network taking cognisance of the resource constraint nature of the network.

Hierarchical heterogenous Topology: It is possible to introduce hierarchy into the network, whereby special nodes equipped high power source capable of longer transmission range. These nodes may be used as relay nodes such as available in mesh networks. This gives rise to a heterogenous and hierarchical topology consisting of ordinary CRSN nodes, high-power relay nodes and the sink.

The introduction of the heterogeneity brings about additional challenge in the face of the efficient dynamic spectrum access benefits brought about by the special nodes in the network. Problems such as, increased communication overhead, deployment of sensor and special sensor needs be resolved in this topology.
Ad Hoc topology: This is an infrastructureless topology. The nodes communicate directly with the sink in a multihop, ad hoc fashion. Spectrum sensing may be performed by each node individually or cooperatively in a distributed manner.

Although, with this type of topology, communication overhead is no problem. However, hidden terminal is a challenge that needs be overcome as it leads to error in primary user detection and eventual performance degradation of the primary user network.

5. CHALLENGESWITH CRWSN

There are diverse open research issues and challenges associated with the development and deployment of CRWSN. In general, the issues raised in this section are as a result of the integration of the cognitive radio functions and the intrinsic characteristic of the traditional wireless sensor networks. We describe the open issues, its importance and suggest ways to address them.

- Node Development: Development of efficient and practical cognitive radio-based sensor network is one of the major issues for in CRWSN. Considering the design principles and operation objective of the sensor network, the limitations of the nodes, hardware and software requirements for sensor nodes with cognitive radio capabilities, there is the need for extensive study in order to come up with such an efficient and practical nodes.
- Node Deployment: There is the need for proper mathematical analysis for optimum node deployment for various topologies for the purpose of developing efficient and practical node deployment mechanisms. Where there exists information about the primary user activities, spectrum characteristics may provide improvement of the network lifetime and transmission quality.
- Optimal Network Coverage: As a result of the primary user activity couple with node failure, the spatial location of sensor nodes may vary. Under this condition, to maintain maximum network coverage, it is certain some nodes may have to transmit with more power, which results in power and energy consumption. But on the other hand, connectivity may be achieved at longer ranges with lower frequencies which helps to save transmission energy. It then becomes necessary to consider dynamic spectrum management while analysing optimum network coverage. Also, new topology schemes which addresses tradeoff between network lifetime and network coverage should be introduced.
- Coordinated and Uncoordinated Operation: Operations such as spectrum sensing, spectrum detection, spectrum allocation, spectrum sharing, and spectrum handoff may be performed individually by sensor nodes or cooperaetively among sensor nodes. It therefore becomes necessary to carry out detailed comparison between the coordinated and uncoordinated network operation for efficient communication in a resource-constrained CRSN.
- Clustering Issue: For a cluster-based CRWSN, clustering and hierarchy formation increases communication overhead which may be increased due to node mobility and spectrum handoff. Therefore, for applications using cluster-based and hierarchical topologies,

dynamic spectrum aware cluster formation and maintenance techniques must be investigated.

6. PROSPECTSAND POTENTIALSOFCRWSN

There are lots of prospect and potentials derivable from deploying CRWSN. WSN with cognitive radio node will have the follow potential benefits attributable to the its dynamic spectrum access features;

- Opportunistic Channel usage for bursty traffic: Sensor nodes with cognitive radio capability may opportunistically access multiple channels to solve the problem of collision during packet transmission in a densely deployed sensor network.
- Dynamic Spectrum Access: With CRWSN, network performance can be maximized by means of dynamic spectrum access. Sensor nodes can dynamically and opportunistically access licensed or unlicensed bands.
- Power Consumption Reduction using Adaptability: Energy consumption in time-varying wireless communication channels is due to packet losses and retransmissions. With the adaptability feature of CRWSN, sensor nodes are able to change their operating parameters to adapt to the channel conditions. This will enhance the transmission efficiency, andthereby reduce power used for transmission and reception.
- Overlapping of Multiple Concurrent Sensor Networks: With dynamic spectrum management capability of CRWSN, multiple overlapping sensor networks can co-habit the same area serving different application purpose.

7. CONCLUSION

Cognitive radio-based wireless sensor network is a new paradigm for the next generation wireless sensor network. There are lots of prospect and potentials attributable to this new research area in sensor networks. In this paper, we have x-rayed cognitive radio-based wireless sensor network. We presented a design concept for the network, considered possible architectures and network models. We also analyze hardware architecture for resources-constrained cognitive radio sensor network. Based on possible models highlighted, we pointed out open research challenges associated with this new research area, and we suggested possible solution pathways to mitigate these challenges. We also described prospects of deploying WSN with CR features.

Topmost of these prospects is, improved spectrum utilization in a multichannel sensor network that is resource-constrained. Relatively at the moment, research in this area is scarce, and we believe our work will serve as a motivation for the research community to explore this promising research area.

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