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An Overview of Medium Access Control Protocols for Cognitive Radio Sensor Networks †

Jemish Maisuria [1,*] and Saurabh Mehta [2]

1 E. & C. Department, Uka Tarsadia University, Surat, Gujarat 3945350, India
2 E. & T. Department, Vidhyalankar Institute of Technology, Mumbai 400037, India; saurabh.mehta@vit.edu.in
* Correspondence: jemish.maisuria@utu.ac.in; Tel.: +91-823-805-8387

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Abstract: In recent year, the most emerging and growing field of research and development is "Internet of Things" (IoT). This is due to advancement in wireless sensor network (WSN) which operate in the unlicensed industrial, scientific and medical (ISM) spectrum band. However, many wireless technologies operate in the same unlicensed spectrum, make it overcrowded and hence resulted in spectrum scarcity among those bands, the performance of WSN will degrade as their popularity increases. According to FCC report, most of the licensed spectrum is underutilized, sharing of underutilized licensed spectrum among unlicensed devices is a promising solution to the spectrum scarcity issue. Cognitive Radio (CR) is one of the capable technology that allows sensor nodes (as a Secondary Users (SUs)) to detect and use the underutilized licensed spectrum temporarily when Primary Users (PUs) not using it. With recent advances in Cognitive Radio (CR) technology, possible to apply the Dynamic Spectrum Access (DSA) model in WSNs to get access to underutilized licensed spectrum, possibly with better propagation characteristics, but as the existing protocols and algorithms developed for CRNs and WSNs are not directly applicable to CR-based WSNs and required new protocols. In this paper, we present a survey on the novel design of CR-based MAC, identify the main advantages and challenges of using CR technology, and compare the different method of improving energy efficiency. We believe that CR-WSN is the next-generation WSN. In this paper, we also discussed the open issues to motivate new research interest in this field.

Keywords: cognitive radio wireless sensor network; wireless communication; wireless sensor network; energy efficiency; medium access control protocol; cognitive MAC

1. Introduction

In recent year, the most emerging and growing field of research and development is "Internet of Things" (IoT). It's a third revolution in which we are trying to connect the physical world with the imaginary world of electronics. Additionally, ubiquitous objects with cognitive capabilities will be able to make intelligent decisions [1]. The main motivating applications behind this is to automatically connect, monitor and respond to nature's surveillance systems. This is due to the development of Wireless Sensor Network (WSN), in which traffic is always in burst mode. However, too many wireless technologies and equipment, such as interphone, WLAN, WPAN, RFID, Wireless USB, Bluetooth, WI-FI, ZigBee/802.15.4 and so on, use the same unlicensed ISM band and make it overcrowded which affect directly on to the spectrum utilization as well as on energy efficiency. So, it's required to solve the problem of spectrum utilization in presence of other equipment. Cognitive radio (CR) improve version of software-defined radio, has been proposed to overcome the bandwidth limitations by the effective utilization of the spectrum by exploiting the existence of white space/spectrum hole [2], which is defined as the channels that are unused at a specific locations and time by its primary users (PUs). Integrating CR technology with wireless sensor (WS) node (i.e., Cognitive Radio-based Wireless Sensor Networks (CR-WSNs)), can help to overcome bandwidth limitation of WSNs by sensing spectrum hole and utilize that to improve the spectrum utilization and minimize interference with coexisting wireless technologies. But due to the characteristics and limitation of sensor nodes, the coupling of cognitive technology in sensor nodes introduce some more challenges and need to handle some additional task such as spectrum sensing, spectrum sharing, and spectrum management [3].

The remainder of the paper is organized as follows. Section 2 provides the review of related work to differentiate this survey work with another existing survey. Section 3 discuss the CR_WSN architecture. Section 4 describes the design of the energy-efficient protocol for the different layer in CR_WSN. Survey and Overview of MAC in CR-WSN are presented in Section 5. Finally, the conclusion of the paper is summarized followed by references.

2. Related Work

There are several medium access control protocols are designed for WSN as well as for CRN. Comparison and surveys of them are also published. But that protocols are not directly applicable to CR-WSN due to the limitation of wireless sensor node which is resource limited device. Recently, several studies on CR-WSN's protocols have been proposed and some of the papers also published which have already done a review on CRSN. Advantage and issues related to the CRSN have been discussed in [3,4]. The survey presented mainly concentrates on some of the origin cognitive frameworks and cognitive radio architectures/engines are compared. In one survey of new proven technique to increase the bandwidth of wireless network presented. Channel bonding along with cognitive radio technology not even increase bandwidth but also help to reduce delay. In the paper, the author presented the different CB schemes and highlight an issue regarding CB in CRSN. The work in [5], aims at surveying of the different spectrum access and management initiatives taken to overcome spectrum scarcity. In that paper authors also outlined the open problem and research challenges in dynamic spectrum sharing. Authors suggested the different challenges according to the different category of spectrum allocation, interference management, protocols and standards, policy and regulatory issues and security, etc. But the author has not provided more discussion on protocol issues. In this paper, we presented basically the survey on the MAC protocol. The authors in [6], discuss the radio resource allocation in CRSN. In that, they have presented very good survey and comparison of different radio resource allocation schemes like centralized, distributed and cluster-based. Authors also discuss the different performance criteria and advantages and limitation of them. In [7], authors presented the survey on MAC protocol for the CRN. They have introduced the classification according to the cognitive MAC cycle. The survey map all the existing protocol according to C-MAC cycle. In that, they presented classification mainly based on three basic task spectrums sharing, spectrum sensing, and control channel management. In [8], also authors provide the brief survey of different MAC protocol for CRN. In paper [9], authors presented the survey of MAC protocol for cognitive radio body area networks and discuss the application specific requirement and issues in CRBANs.

3. CR-WSN Architecture

CR-WSN is a network of WS nodes with an extra feature of cognitive capabilities. According to Joshi G. P. et al., CR-WSNs consist of many spatially distributed energy-constrained, self-configuring, self-aware WS nodes with cognitive technology [3]. They are not only using the white space/idle channel but also protect the rights of primary users (PUs), provide opportunistic channel access to WS nodes, dynamic spectrum access, improve the energy efficiency and reduce the overall delay. White spaces can be used as interweave, underlay or overlay patterns. In interweave pattern, CR nodes occupy the free space when PUs are idle. In the underlying paradigm, CR nodes use the licensed band using low-power to the limited range and it's in the present or absent of PUs. Both the SUs and PUs can transmit at the same time till it does not affect the transmission of PUs or up to some limit. Whereas in the overlay model, CR users use the licensed bands along with the PUs in cooperation manner by changing its communication characteristics. Figure 1 shows the CR-WSN architecture. CR-WSNs can be modeled as Ad Hoc CR-WSN, Clustered CR-WSN, Heterogeneous and Hierarchical CR-WSN or Mobile CR-WSN. For the comparison of ordinary WSNs, Ad Hoc CRNs and CR-WSNs refer [6]. In CR-WSN, communication unit having a modification of CR capabilities using which the sensor node alters its transmission parameters such as carrier frequency, transmission power, and modulation. The CR-WS nodes have mainly four functionalities: spectrum sensing, spectrum management, spectrum sharing, spectrum mobility [10]. Instead of paying for the expensive licenses, CR-WSNs can offer wireless services by investing the comparatively small amount of capital in their infrastructure, and spectrum sensing technologies [6]. Country wise spectrum incompatibility problem can be solved. It can provide financial advantages to the PUs by renting or leasing their license spectrum band if underutilized. The probability of detection is the main metric to evaluate the Quality of Services (QoS). CR-WSNs have same hardware limitation as conventional WSNs. There may be frequently changed in the topology of the network due to the PUs activity. One most challenging issue is the channel selection in CR-WSNs. Due to limited energy, the energy consumption is also an essential design issue in CR-WSNs.

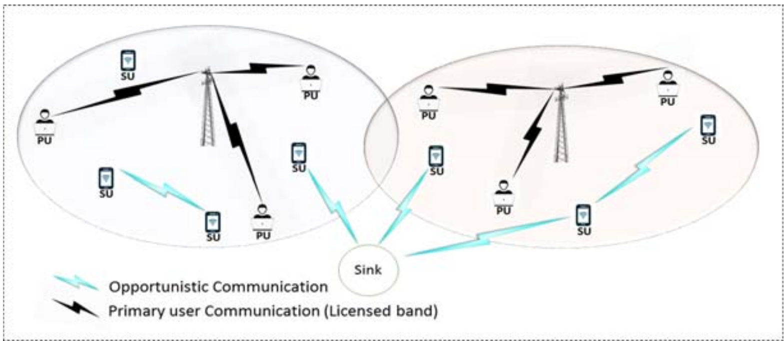

Figure 1. A typical cognitive radio wireless sensor network (CR-WSN) architecture.

4. Energy-Efficient Protocol Design

As discussed in the previous section energy conservation is a key factor for improvement of network performance and lifetime. So, the system protocols and hardware need to be designed by considering energy aspects. Some of the issues that directly affect the energy efficiency or consumption are discussed herein [11] (packets collision, idle listening). Energy efficient design is required at each layer of the communication protocol stack [4]. The CR based physical layer extra task is spectrum sensing and altering the transmission parameters (like operating frequency, modulation, and power) according to spectrum negotiation and the decision by CR engine. As the node's physical layer is responsible for cost and energy expenditure of system. So, efficient low-cost transceivers and processor design required to reduce energy consumption in DSA [11]. Flow control is responsibility of MAC sublayer. It's a challenging task to provide fair and efficient medium access to every single node in densely deployed and resource-limited WSNs. In CR-WSNs all the nodes can change its transmission parameters according to the environment conditions. So, before doing communications the transmitter and receiver node should pass through negotiation phase which consumes extra energy and increases delay as compare to traditional WSNs. According to [11], energy dissipation can be reduced by reducing traffic, prolonging sleep time of RF module and introducing efficient collision avoidance mechanism. The improvement in energy efficiency can be obtained by speeding up the convergence of network redundant data; choosing energy-efficient routing to forward data with multi-hop method etc. Basically, in sensing based application like rainfall monitoring when rainfall occur lots of data will be sensed and collected by network and if it directly sends to base station without being processed then congestion will be there in the network. According to the [11], recommended solution is to utilize data fusion and distributed database techniques to refine data, and ultimately prolong network lifetime and improve communication efficiency.

5. Medium Access Control Protocols in CR-WSNS

CR-WSNs operates in an environment where it should use the available spectrum holes or white spaces. To support this capability of CR-WSNs, the redefinition of the protocol stack is required which introduce some new communication protocols or mechanism for efficient spectrum utilization and to protect rights of PUs [7,12,13]. Although there are some issues in MAC protocols, the hidden terminal problem in multichannel scenario, spectrum sensing error as a miss detection and false alarm, selection of common control channel for control signaling, spectrum sensing delay in each phase, interference with PUs which violate the rights of PUs, synchronization of SUs nodes. According to[8], CR MAC protocols design can be divided in two ways—(i) standardized effort (IEEE 802.22 working group); and (ii) application-specific protocols. Also, it can be classified into two type centralized approach and distributed approach. According to [14], CR MAC protocols can also be classified into three broad categories—Split-phase, Dedicated control channel and Frequency hopping. Survey and comparison of different cognitive MAC are described below:

In [15] the proposed scheme by authors, it selects its operating parameters according to the channel sensing outcomes and the energy consumed. In that decision-making process, they have used Partially Observable Markov Decision process framework (POMDP). They have suggested the tradeoff between the long sensing and short channel sensing to reduce the energy consumption and to protect the PUs rights on the channel. But in the scheme, the extra energy consumes in the backup channel maintenance. In this paper [16], authors suggested a model in which PUs are more privileged users of the spectrum, unlike SUs. Only the common control channels (CCC) are dedicated to the SUs and all the traffic channels are accessed opportunistically. SUs used common control channel to coordinate the traffic channel and make contention on CCC to access of traffic channel negotiation. In this CSMA-based MAC transmitter node who want to send the data/information start first the spectrum sensing at medium and search for the most suitable channel according to low noise & maximum vacancy. After completion of the sensing, it comes again to the common control channel and asks for channel contention. If the CCC is busy it waits for some random backoff time otherwise, it transmits traffic channel information and request to the beacon (Cognitive-RTS). At the receiver side, receiver node receives the C-RTS beacon and search for the availability of channel in its vacant channels list prepared by sensing previously or do spectrum sensing.

In this paper [17], authors have suggested cluster based MAC protocol for effective and energy efficient spectrum access. The main benefit of the cluster-based protocol is its provide protection from the multi-channel hidden terminal problem. This cluster-based (KoN-MAC) protocol is a split phase protocol. In which the frame is composed of channel sense and selection phase, data transmission phase, channel schedule phase and sleep phase. In KoN-MAC protocol channel selection is based on the channel weight. Weight is basically a number which is derived from the previous states of the channel like idle, busy, communication and collision. CR-WSN MAC is energy efficient and spectrum aware multi-channel medium access control protocol which is based on asynchronous duty cycle (sleep/awake cycle) approach. As the multi-channel scheme outperforms the single-channel protocols in terms of communication performance and energy consumption but it's having its own issues and used ccc for control signaling [18]. All the nodes follow its own Sleep/Awake cycle. On the wake-up, the node first performs spectrum sensing and entry each available channel in the free channel list and wait for the incoming request for time or send a request for data transmission if it has data to send otherwise go to sleep mode again. The transmission on the negotiated channel is divided into two phases: data send phase and channel sense phase to periodic channel sensing. CRB-based MAC protocol is a receiver-based protocol it's different from the conventional sender based protocol. In this paper [19], a novel MAC protocol is suggested which provide low overhead spectrum access, jointly considers spectrum sensing and duty cycling to provide balance tradeoff between spectrum efficiency and energy efficiency. In CRB-MAC preamble sampling is used to tackle idle listening and support sleep/awake modes without using synchronization overheads. It also uses the broadcast approach with opportunistic forwarding to multiple receivers to reduce the number of retransmission. In MAC protocol, the packet size also the one of the key parameter to improve the performance [20]. Many types of research on packet size optimization have been done so far [21,22]. If the packet size is longer then it directly affects the system performance by the greater number of collisions and if smaller packet size increases the overhead. So, it's required to make a tradeoff between short and long packet sizes. Distributed joint channel selection and dynamic packet size optimization suggested in the paper [23]. Constrained Markov decision process is used to optimize packet size.

According to G. A. Shah and et al., Cognitive Adaptive MAC (CAMAC) protocol which works on mainly three tasks to improve spectrum utilization and energy efficiency: (i) On-demand spectrum sensing; (ii) Limiting the number of spectrum sensing nodes; and (iii) Applying a duty cycle [20]. In this proposed protocol, fast sensing is to reduce time delay and fine sensing to protect the rights of PU. CAMAC operated in three phases: Spectrum Measurement phase, CCP and DTP. In this paper [21], authors have described the case where the WLAN and WSN are operated in the same region. WSN packets always lost in existence of WLAN. But WLAN traffic is not always continuing in nature rather it's bursty with long white space. So, it is feasible to utilize the same hole by the CRSN to operate in co-existence. COG-MAC is the extended version of carrier sense based MAC. In this article [22], authors have suggested a protocol that dynamically adjusts the channel negotiation period according to the network density. In many CCC based protocol suffers from CCC bottleneck problem (Saturation of CCC) due to channel utilization limitation, bandwidth waste in channel negotiation and long channel access delay. Small channel negotiation (CN) window is a bottleneck in a dense network environment and large CN window size increase the time delay in a sparse network.

Table 1. Comparison of MAC protocols.

Ref. Paper	CCC	No. of Tx-Rx	Performance Improvement	Channel Access	Description & Advantages	Limitation
[15]	No	Single	Low Computational Complexity & Delay	POMDP	Long and short sensing Backup channel based	Extra energy consumption in backup channel
[16]	Yes	Single	Bandwidth & Energy efficient	CSMA	CSMA-based MAC protocol for CCC Bandwidth efficient Low packet delay	Cannot achieve the QoS requirement of sensor
[17]	No	Single	Energy efficient	Channel Weight	Protection from multichannel hidden terminal problem Cooperative sensing High Throughput Lower packet loss	It just sense fewer channels
[18]	Yes	Single	Energy efficient	Energy level	High throughput and QoS. Periodic channel sensing Duty cycle based	No advantage in increasing the number of retransmissions
[19]	No	Two	Low overhead	Energy level	A receiver based approach Efficient and reliable Improve frequency agility Broadcast-based	Extra energy consumption in broadcast
[20]	Yes	Single	Energy efficient & Delay	Slotted ALOHA	On-demand spectrum sensing Limited number of sensing nodes Fast and fine sensing	Energy consumption is high for sensing nodes
[21]	No	Single	Energy efficient	CSMA	Single hop distance optimization approach Energy efficient Packet size optimization	High Complexity
[22]	Yes	Two	Delay	CSMA	Dynamically adjustable channel negotiation phase Reduce the bandwidth waste	Cost increase due to two transceivers

6. Conclusions

Cognitive radio technology is a potential technology for future wireless systems like the Internet of Things, WSNs, and M2M systems and provides benefit in co-existence of different wireless technology by improving spectrum utilization. However, when we introduce cognitive capability in WSNs, due to limitation of WSN and to support cognitive capabilities redefinition of protocol stack is required by considering following factors like: the radio environmental, primary user's activities and secondary user's operation limitations such as number of radios, single/multi-band operation, hardware limitation etc. The Cognitive MAC layer and its mechanisms provide a solution to these challenges and improving the secondary user's performance. Many kinds of literature are available for cognitive radio network and its MAC protocol but not much survey on CRSN's MAC layer. In this paper, we have presented a brief survey of the different novel design of MAC for CR-WSNs with their pros and cons. According to a survey, we can conclude that the main tasks of cognitive MAC are environment sensing, channel negotiation, and data transmission. We believe our work is helpful for future research.

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