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Issues in Realization of Cognitive Radio Sensor Networks*

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Abstract

Recently, significant growth in the applications of the wireless sensor networks (WSNs) operating in unlicensed spectrum bands has been made. In the meantime, existing unlicensed bands are becoming congested and overcrowded. On the other hand, Cognitive Radio (CR) technology has been proposed as the key technology for future wireless communication that exploits dynamic spectrum access strategies. Since this offers more flexible way to utilize the wireless spectrum than traditional radio technology based on a fixed spectrum access policy, it is thought that the key feature of cognitive radio, i.e., dynamic spectrum access can be applied in WSNs to access the underutilized spectrum bands to transmit their readings in an opportunistic manner to the next hops and finally to the sink. In cognitive radio sensor networks (CRSNs), obtaining the information about spectrum holes on channel, negotiating among primary users and secondary users for spectrum allocation, synchronizing transmission parameters are the important functions of CR medium access control protocols. In this paper, we mainly focus on investigating the major issues to be considered with the existing communication protocols and algorithms devised while realizing the cognitive capability into wireless sensor networks. We also discuss the main challenges on the basis of dynamic spectrum management and extra energy expenditure to apply the cognitive capability into wireless sensor networks.

Keywords: *wireless sensor networks (WSN), cognitive radio (CR), medium access control (MAC)*

1. Introduction

A wireless sensor network is composed of a large number of sensor nodes, which are densely deployed. They are able to observe a wide variety of ambient conditions which include temperature, humidity, vehicular movement, lighting conditions, pressure, the presence or absence of certain kinds of objects, *etc.* [1]. For current WSN solutions, a key feature is operation in unlicensed frequency band i.e. the worldwide available 2.4 GHz band. However, other popular wireless applications such as Bluetooth, WiFi and other proprietary technologies also share the same band. As a result, the unlicensed band is becoming

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overcrowded and eventually one network may degrade the performance of the other. That is why; coexistence in unlicensed band is one of the key issues in research.

On the contrary, frequency spectrum is statically allocated to licensed users i.e., primary users (PUs) only, in a traditional wireless communication system. Since licensed users may not always occupy the allocated radio spectrum, this static spectrum allocation results in spectrum underutilization. Thus, new spectrum allocation policies were introduced to allow unlicensed users i.e., secondary users (SUs) to access radio spectrum when it is not occupied by PUs. However, when PU comes back into operation, the SU should vacate the spectrum instantly to avoid interference with the primary one. These new spectrum allocation policies are expected to improve spectrum utilization while satisfying the increasing spectrum demand for emerging wireless applications [2].

In the past few years, even though significant progress has been made in the field of cognitive radio, this research area is still at immature stage because various research issues and challenges have to be addressed and solved. Basically, each cognitive radio user in the cognitive network must determine which portion of the spectrum is available, select the best available channel, coordinate access to this channel with other users and finally vacate the channel when a licensed user is detected without causing the user interference.

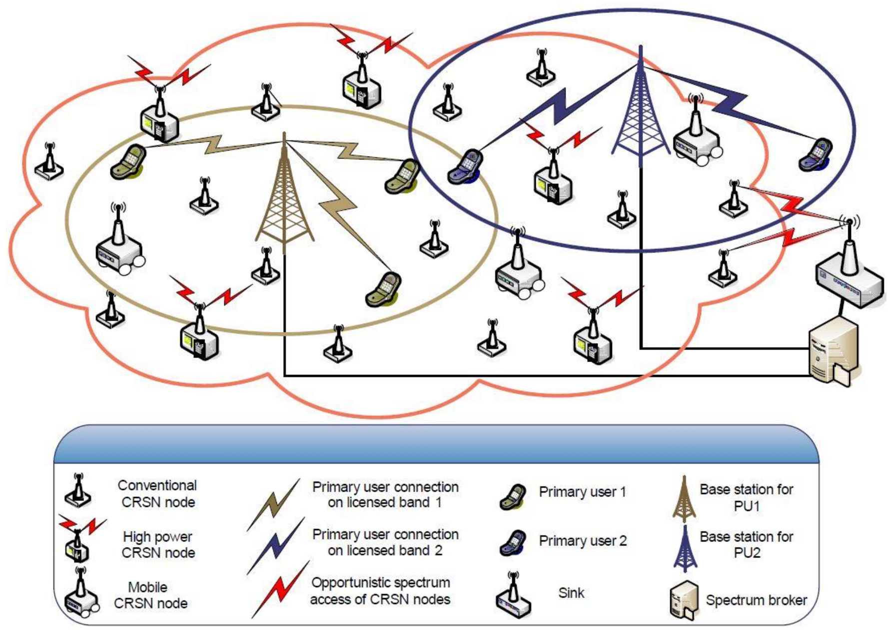

Figure 1. A typical cognitive sensor network (CRSN) architecture

A wireless sensor network (WSN) composed of sensor nodes equipped with cognitive radio is called cognitive radio sensor network (CRSN). In general, a CRSN can be defined as a distributed network of wireless cognitive radio sensor nodes, which sense event signals and collaboratively communicate their readings dynamically over available spectrum bands in a multihop manner to ultimately satisfy the application-specific requirements [3]. A typical CRSN architecture is shown in Figure 1. over which the information obtained from the field is conveyed to the sink in multiple hops. The main duty of the sensor nodes is to perform sensing on the environment. In addition to this conventional sensing duty, CRSN nodes also perform sensing on the spectrum. Depending on the spectrum availability, sensor nodes transmit their readings in an opportunistic manner to their next hop cognitive radio sensor nodes, and ultimately, to the sink. The sink may be equipped with cognitive radio capability, *i.e.*, cognitive radio sink. However, it is a great challenge to adopt the CR principle to sense the underutilized spectrum dynamically. Moreover, applying the existing protocols and algorithms for CRNs and WSNs in CRSNs is the key issue raised in research.

Medium Access Control has an important role in several cognitive radio functions: spectrum mobility, channel sensing, resource allocation, and spectrum sharing. When a primary user is detected, spectrum mobility allows a SU to vacate its channel and to access an idle band [4]. Channel sensing is the process of collecting the information about spectrum usage and maintaining the information of available channels dynamically. Several techniques for channel sensing in the physical layer have been proposed in this literature. This sensing is abstracted in the MAC layer to identify whether the channel is occupied by PUs or not. Available channels are assigned to cognitive users opportunistically by resource allocation. There may be multiple cognitive users trying to access the spectrum. SUs should coordinate their access to the available spectrum channel. Spectrum sharing is employed to prevent multiple users colliding. MAC layer functions in a cognitive radio can be summarized as follows [4]:

- To obtain information on channel occupancy. This information will be used by a SU to decide whether to transmit data or not and whether to switch to a new channel or not.
- To perform negotiation among PUs and SUs for spectrum allocation, and also among SUs to perform channel sensing and channel access.
- To synchronize transmission parameters (*e.g.*, channel, time slot) between transmitter and receiver.
- To facilitate spectrum trading functions (*e.g.*, spectrum bidding and spectrum pricing), which involve PUs (or primary service providers) and SUs (or secondary service providers).

Recently, number of studies associated to CR MAC protocols and WSN have been proposed and a few publications have already been made reviewing the CRSN. In [3], advantages and limitations for the realizations of CRSN have been discussed. Furthermore, using multiple channel availability provided by CR capabilities to overcome the problems caused by the dense deployment and bursty communication nature of sensor networks has also been discussed. Performance of a CR-based WSN with standard Zigbee/802.15.4 has been compared in [5]. In [6], infrastructure based and ad-hoc cognitive MAC protocols are classified according to the exploited medium access scheme. In [7], a general review in CRN spectrum management has been provided. MAC functionalities and current research challenges of Cognitive Radio Ad Hoc Networks (CRAHNs) are discussed in [8]. In [9] opportunistic networks are divided according to the infrastructure, in centralized and distributed networks. Moreover, several MAC protocols have been reviewed according to their classification. A comprehensive overview of state of art for cognitive radio network has been presented in [10]. In [11], route selection strategy combined with spectrum characteristic in decentralized cognitive radio network has been studied. In [12], signal feature detection method using SCF (Spectral Correlation Function) is discussed. It analyzed main signal patterns using the SCF method and compared main special points of several signal types by simulation factors as follows: center carrier frequency, modulation type, signal pattern, and so on. In [13], an improved version of cyclostationary feature detection spectrum sensing technique is proposed and it shows better performance even in low SNR environment.

It is promising and challenging for WSNs to adopt the CR technology to sense spectrum hole and utilize the vacant frequencies to improve the spectrum utilization. However, the existing protocols and algorithms developed for CRNs and WSNs are not perfectly fit for CRSN. In this study, we discuss the major cause of extra energy expenditure in Section 2 followed by dynamic spectrum management issues in terms of spectrum sensing, spectrum decision and spectrum handoff are discussed in Section 3 and later the major MAC layer issues and some open research issues in incorporating CR capabilities into CRSN in Section 4. Finally Section 5 draws the conclusion.

2. Extra Energy Expenditure

In WSN, neighbor nodes may be close to each other. One of the most important constraints on sensor is the low power consumption requirement. It is obvious that sensor nodes carry limited power sources. Hence, multihop communication in sensor networks is expected to consume less power than the traditional single hop communication. Multihop communication can also effectively overcome some of the signal propagation effects experienced in long-distance wireless communication [1]. In [14], it was proposed that by adjusting the constellation size, different data rate can be achieved. This will directly influence the power consumption of each node and, in turn, will affect the lifetime of the whole sensor network. Furthermore, a distributed spectrum allocation strategy was adopted with the assumption that each sensor node had a fully functional cognitive radio – *i.e.*, detection, identification and exploitation of spectrum opportunities. The authors applied the dynamic spectrum access in the time domain by exploiting white space between bursty transmissions of multi-access communication channels [15]. It was mentioned that, if sensors communicate sporadically or perhaps at a low rate, the system can efficiently reuse remaining white space.

Typically, a large number of sensor nodes are deployed in a specific monitor area. In [16], it has been assumed a base station which provides broadcasting service for the primary users, and most of the sensor nodes are within its coverage region. The nodes organize themselves into local clusters, with one node acting as the cluster head. All non-cluster-head nodes in a cluster transmit their data to the cluster head at given time slots according to TDMA scheme, while the cluster head receives data from its members, performs signal processing functions on the data, and transmits the data to the dedicated sink. To prolong the network lifetime, a cluster head rotation mechanism is taken and consequently the energy load of network is evenly distributed among all the sensor nodes. The sensor nodes cooperatively detect potentially vacant bands and transmit the detection results to the sink. The spectrum decision is ultimately determined by the sink. Depending on the spectrum availability, sensor nodes transmit their readings in an opportunistic manner to the next hops and finally to the sink. Here, we summarize some important cause of extra energy expenditure:

- *Spectrum sensing*: Spectrum sensing is the one of the major functionalities that differentiates CRSN with the traditional WSN. There are various sensing methods proposed in this literature and they have been summarized in [17]. This sensing is abstracted in the MAC layer to identify whether the channel is occupied by PUs or not. However, it is not feasible to equip CRSN nodes with highly capable processors and A/D units. Thus, complex detection algorithm cannot be feasible in CRSN. Spectrum sensing must be performed with limited node hardware. Moreover, spectrum sensing duration should minimize although sensing accuracy increases with duration. However, due to limitations of the cognitive radio sensor node, techniques developed for cognitive radio networks cannot be directly applied to CRSN. Therefore, additional research must be conducted on spectrum sensing for CRSN.

- *Bursty traffic*: If there is large number of sensor nodes, the generated packet traffic is high. So it may increase the probability of collision, decrease the communication reliability, excessive power consumption and packet delay. So this opportunistic spectrum access to multiple choice channels, this challenge may be overcome.
- Some nodes sometimes may receive and process the data that do not belong to them. This makes wireless receiver module suffer from a large amount of energy dissipation.
- When nodes have no data to send, they will remain idle listening to the radio channel. This excessive idle listening will cause waste of energy.
- If there will be multiple nodes that want to access or participate in competition for the same channel, and it consequently lead to data collision. As a result there will be the packet data loss and it will incur extra energy consumption in retransmission.
- *Spectrum handoff*: CRSN node must detect the primary user activity and they should immediately vacate the channel even if they have ongoing transmission. However, they should move to another available channel decided by an effective spectrum decision mechanism. This fundamental mechanism of cognitive radio is called spectrum handoff. When spectrum handoff is necessary, first another best channel available must be find out. Handshake between receiver and transmitter on the new channel is also needed. For this, it takes long delays and hence, buffer overflows which may result to packet losses, degradation in reliability and ultimately resource waste in CRSN. Thus, unnecessary spectrum handoff should be eliminated. In [18], a central spectrum allocation scheme, which tries to minimize spectrum handoff, has been proposed for CRSN. First, minimizing the effect of spectrum handoff on various communication layers must be analyzed.

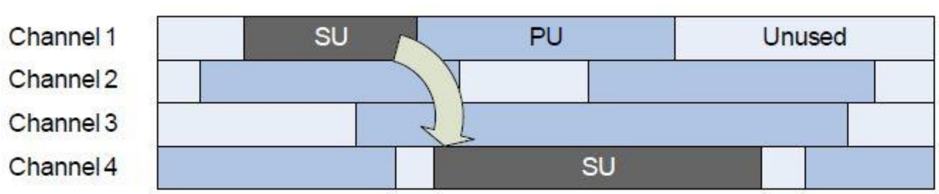

Figure 2. Spectrum handoff in CRSN

3. Spectrum management in CRSN

An efficient spectrum management framework is primarily required to realize the cognitive radio sensor networks. In this section, some major challenges and major issues regarding such dynamic spectrum management framework is discussed in this section.

Among these, *spectrum sensing* is one of the key functionalities distinguishing CRSN from traditional WSN. Several techniques for channel sensing in the physical layer have been proposed in this literature. Matched filter, energy detection, feature detection, interference temperature are the most common spectrum sensing techniques. Available channels are assigned to cognitive users opportunistically by resource allocation. There may be multiple cognitive users trying to access the spectrum. SUs should coordinate their access to the available spectrum channel. Now, we will discuss some of the well known spectrum sensing techniques and examine in terms of how they can apply to CRSN.

- *Matched filter*: It has been shown that the optimal spectrum sensing method for the cognitive radio with the presence of Gaussian noise is the matched filter method [19]. However, this approach requires a priori knowledge about the transmission of the primary user. Since it is a coherent detection method, it requires synchronization with the primary user. In cases, where PU transmission characteristics are available, matched filter-based detection may be employed. However, most of the time, such assumption is unrealistic. Furthermore, CRSN nodes need additional dedicated circuitry for each encountered primary user type. This considerably increases the cost and complexity for low-end sensor nodes.

- *Energy detection*: CRSN nodes needs for a simpler spectrum sensing technique such as energy detection method. This method is popular even in cognitive radio networks, where nodes are typically less power constrained and have more computational power [20]. It measures the received energy on the specific portion of the spectrum, *i.e.*, channel, for a certain period of time. If the measured energy is below a threshold value, the channel is considered available. Its simplicity and low signal processing requirement make this method very attractive for CRSN. However, it has a number of drawbacks. Energy detection requires longer measurement duration to achieve a certain performance level compared to matched filter method. Furthermore, the performance of this method highly depends on variations of the noise power level. Therefore, in case of a small increase in detected energy, it is impossible to understand whether the reason is a primary user activity or an increase noise power level.

- Feature detection: When certain features of the primary user transmission such as carrier frequency and cyclic prefixes are known, this method can be used [21]. Feature detection method takes advantage of the cyclo-stationary features of the PU signal. Unlike noise, the PU signal has spectrum correlation due to its inherent cyclo-stationarity. By making use of this correlation, the PU signal inside the noise can be detected. Thus, feature detection method is very robust against variations of noise. However, this additional capability comes with the cost of increased complexity, which typical CRSN nodes may not be able to provide. Hence, feature detection is more suitable to special CRSN cases where the network includes nodes with greater computational power.

- *Interference temperature*: The sensing method introduced by the FCC is the interference temperature measurement method [22]. An interference temperature level above the noise floor is determined. CRSN nodes calculate how much interference they would cause at the primary user receiver. Then, they adjust their power such that their interference plus the noise floor is not greater than the interference temperature level. This method requires CRSN nodes to know the locations of the primary users for precise interference measurement. Furthermore, it may be too computationally intense for a low-end sensor node.

There is enough amount of work on spectrum sensing methods. Clearly, most of these methods are not suitable for CRSN as they are designed by without considering the unique challenges posed by the resource constraints of wireless sensor nodes. Spectrum sharing is employed to prevent multiple users colliding. Due to limitation of the cognitive radio sensor nodes, techniques developed for cognitive radio networks can not directly applied to CRSN. Therefore, additional research must be conducted on spectrum sensing for CRSN.

However, a hybrid technique to obtain spectrum information with minimum sensing duration and low computational complexity is to be developed. When nodes rely only on their own spectrum sensing results, they may not be able to detect the primary user due to shadowing. Therefore, cooperative sensing technique may be employed for increasing sensing accuracy. While cooperative sensing yields better sensing results, it also imposes additional complexity and communication overhead. New cooperative sensing method, requiring minimum amount of extra packet transmission and having minimum impact on the sleep cycles of the node, is an open research issue.

CRSN nodes must analyze the sensing data and make a decision about channel and the transmission parameters, *e.g.*, transmission power and modulation. *Spectrum decision* methods proposed for cognitive radio networks consider power consumption as a secondary issue and the amount of extra control packets to transmit is almost never taken into account [3]. Furthermore, nodes in a cognitive radio network have more memory and computational power. More complicated schemes for coordination of spectrum decision, which incur higher communication overhead, may be used in cognitive radio networks. However, these solutions are not feasible for CRSN due to additional challenges posed by the ad hoc multi-hop nature as well as the inherent constraints of sensor nodes.

When PU starts using a previously available channel, CRSN nodes must detect primary user activity within a certain time through spectrum sensing methods and it has to switch the next available channel immediately without causing the interference to the PU as illustrated in Figure 2. This activity is called *spectrum handoff*. When a necessity of spectrum handoff is felt, initially an alternative channel must be determined. For this, a handshake mechanism between transmitter and receiver must be performed on the new channel. Only then nodes can continue their transmissions. All of these additional operations may take long delays, and hence, buffer overflows which lead to packet losses, degradation in reliability, and ultimately resource waste in CRSN. Various spectrum handoff methods have been proposed in literature for cognitive radio [23], [24]. However, none of these works consider the challenges posed by the inherent limitations of CRSN. Therefore, minimizing the effect of spectrum handoff is very important issue to increase the communication reliability.

4. Discussion and Open Research Issues

The performance of communication in CRSN is closely tied with how effectively dynamic spectrum management issues discussed in Section 3. We have to investigate the specific design considerations of each communication layer, and explore the existing networking solutions of cognitive radio and wireless sensor networks for effective communications in CRSN.

While designing CR MAC protocol for dynamic spectrum access, we must have to consider some communication challenges. While deploying cognitive networks, there will be both PUs and SUs. Each CR MAC protocol should maintain the coexistence between them in order to avoid interference. It is one of the important functions of a CR MAC protocol. Also, coexistence among SUs is important to avoid collisions due to simultaneous channel access. Since the channel occupancy time of PUs is varying, CR MAC protocol must be able to detect time-varying activity of PUs and adjust the channel access strategies dynamically. Moreover, two major challenges arise in a multichannel cognitive radio network. First, if the cognitive radio is hardware-limited (*e.g.*, the number of channels which can be sensed and accessed is limited), an optimal scheme is required for selection of the sets of channels to sense and to access. Second, synchronization between transmitter and receiver is necessary so that transmitter and receiver can communicate in the same channel and at the same time slot [4]. Transmission of secondary users can span multiple hops to extend the transmission range (*e.g.*, cognitive mesh networks). However, in different locations, secondary nodes can experience different channel conditions (*i.e.*, different sets of primary users with different channel activity). Also, the hidden and exposed terminal problems have to be solved to avoid collision and underutilization of the available channels.

In CRSN also, MAC protocols provides the sensor nodes the means to access the medium in fair and efficient manner. The existing MAC solutions for WSN are not designed for dynamic spectrum access, and simply they cannot address the requirement for CRSN. This is a challenging task by considering the resource limitation, dense deployment of sensor nodes. In CRSN, handshaking mechanism may require to negotiate the channel by exchanging some control packets. Thus, MAC layer of CRSN has to handle additional challenges as compared to the traditional WSN. On-demand negotiation is one of the channel reservation mechanisms. In this reservation approach, a channel, *i.e.*, control channel is used to exchange the information about the channel reservation on demand and the nodes switch to the negotiated channel for transmission. The main problem with this approach is that if large number of nodes attempt to transmit in a short amount of time, it cannot handle the cases. It will get congested very quickly. It is due to the bursty traffic due to the dense deployment of sensor networks. Having multiple control channels can also improve the performance of the cases such that the other control channels can be used until a new vacant band is found. On the other hand, those approaches which have multiple transceiver assumption are also not so practical for CRSN. Another approach is based on the use of time division techniques which divides the time into frame and nodes transmit their data in a round-robin fashion [25]. Channel reservation is made at the beginning of each frame and nodes perform their transmission in their reserved slots. Due to the network wide strict synchronization requirement, this approach is also cannot be directly implemented in CRSN. Moreover, as the number of nodes increase, the reservation time at the beginning of each frame increases, leading to overall performance degradation. Thus, none of these existing approaches can be directly employed in CRSN.

In MAC layer, the means of lessening energy dissipation mainly include reducing traffic, prolonging sleep time of RF module and taking collision avoidance mechanism etc. Among them, reducing traffic is a fundamental method, and is achieved generally by adding a data fusion layer over the MAC layer or network layer [16]. However, the mature research results about data fusion in MAC layer have not been reported. Even though reducing duty cycle is an efficient energy-saving method, it probably introduces a large amount of communication delay and decreases the system throughput. MAC protocols need to be designed according to specific applications.

A CRSN node can reconfigure its operating frequency, modulation, channel coding and output power without hardware replacement. This is the most significant difference between cognitive radio sensor network and wireless sensor network physical layer. Software defined radio (SDR) based RF front-end transmitters and receivers [26] are required for reconfigurability of cognitive radio sensor nodes. However, implementing

RF front-end for cognitive radio sensor node is a significant challenge due to low cost and resource-constrained nature of sensor nodes.

Data link layer is responsible for reliable transmission and reception of frames between sensor nodes. In general, efficient medium access control (MAC), and error control and correction are the main functionalities of link layer to achieve its goals. In CRSN, these objectives must be achieved in accord with the principles of dynamic spectrum management and in an energy-efficient manner.

Existing ad hoc cognitive radio routing schemes [27, 28, 29] aim to provide joint spectrum and routing decisions, however, do not consider the inherent resource constraints of CRSN. At the same time, routing schemes developed for WSN mainly aim to minimize energy consumption [30] and do not handle dynamic spectrum access. In fact, there are various energy efficient routing algorithms proposed for WSN with fixed allocation scheme [30]. However, predetermined routing is not suitable for dynamic topology caused by opportunistic channel access. Hence, on-demand routing is advised for cognitive radio networks [28]. Despite the communication overhead and increased contention, dynamic spectrum-aware on-demand routing can be investigated for CRSN.

In sensor networks, transport layer is mainly responsible for end-to-end reliable delivery of event readings and congestion control to preserve scarce network resources while considering application-based QoS requirements. With the detection of an event, sensor nodes inject high and bursty traffic into the network. To achieve successful detection and tracking of an event signal, sufficient number of event readings must be reliably delivered to the sink. At the same time, if the capacity of multi-hop network is exceeded, this would lead to congestion which wastes power and communication resources in sensor networks.

Application layer algorithms in sensor networks mainly deal with the generation of information and extracting the features of event signal being monitored to be communicated to the sink. Other services provided by the application layer include methods to query sensors, interest and data dissemination, data aggregation and fusion [2]. Clearly, each of these services must utilize the capabilities of cognitive radio sensor network while conforming to its limitations. Therefore, existing application layer protocols must be revisited with these capabilities and limitations in mind.

Clearly none of the existing approaches can be directly employed in CRSN. Here, we discuss the main open research issues. If the channel condition is degraded, forward error correction (FEC) schemes with more redundancy may be used to decrease the error rate. Therefore, dynamic spectrum FEC schemes with minimum energy consumption must be developed. Moreover, impact of packet size on transmission efficiency is one of the crucial factors and hence, optimal packet size for CRSN must be analyzed under varying channel characteristics [3]. New MAC solutions must be developed that can make full use of the multiple alternative channel availability. Home channel-based MAC seems to be promising as it requires minimum communication overhead for channel negotiation. However, it is not feasible for CRSN since it requires two transceivers [3]. Methods to adopt home channel idea with a single transceiver in CRSN must be studied.

5. Conclusion

In the past few years, even though significant progress has been made in the field of dynamically spectrum access in cognitive radio networks, it is still at immature stage. Many important and complex issues need to be addressed and solved in future. In this paper, we discussed cognitive radio sensor network which is a new paradigm formed by incorporating the cognitive capability into wireless sensor networks, *i.e.*, CRSN. As we know that the energy is the most important constraint while realization of CRSN, initially we tried to exploit some important cause of extra energy expenditure. Later, we focused on the issues in the context of dynamic spectrum management while realizing the cognitive radio sensor networks and came to know that no complete spectrum sensing algorithm is available. Therefore, we must have to make many improvements in the existing CR sensing algorithms to implement in CRSN. Further, we discussed the importance of CRSN and the basic functionalities and role of CR MAC layer. We definitely must have to modify and enhance to the existing CR MAC protocols since there exists no complete MAC solution which can address the requirements of CRSN. Moreover, we explained some key points and discussed on them that we have to consider while realization of CRSN on the basis of the effects on each communication layer and discussed some open research issues. Even though cognitive radio and wireless sensor networks have individually been studied extensively, it is obvious that it is promising and challenging for WSNs to incorporate the CR principle to sense the vacant spectrum bands and utilize to improve spectrum utilization to deliver the sensed data to the sink. We expect that this paper will provide better understanding of the CRSN and motivate research community to further explore this paradigm.

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References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, “Wireless Sensor Networks: A Survey”, Elsevier Computer Networks, vol. 38, no. 4, **(2002)**.
[2] I. F. Akyildiz, W. Y. Lee, M. C. Vuran and S. Mohanty, “Next Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey”, Elsevier Computer Networks, vol. 50, no. 13, **(2006)**.
[3] O. Akan, O. Karli and O. Ergul, “Cognitive Radio Sensor Networks”, IEEE Network, vol. 23, no. 4, **(2009)**.
[4] X. Yang and F. Hu, “Cognitive Radio Networks”, CRC Press, **(2008)**.
[5] D. Cavalcanti, S. Das, J. Wang and K. Challapali, “Cognitive Radio Based Wireless Sensor Networks”, ICCCN, **(2008)**.
[6] C. Cormio and K. R. Chowdhury, “A Survey on MAC Protocols for Cognitive Radio Networks”, Elsevier Ad Hoc Networks, vol. 7, no. 7, **(2009)**.
[7] I. F. Akyildiz, W. Y. Lee, M. C. Vuran and S. Mohanty, “A Survey on Spectrum Management in Cognitive Radio Networks”, IEEE Communication Magazine, vol. 46, no. 4, **(2008)**.
[8] I. F. Akyildiz, W. Y. Lee and K. R. Chowdhury, “CRAHNs: Cognitive Radio Ad Hoc Networks”, Elsevier Ad Hoc Networks Journal, vol. 7, no. 5, **(2009)**.
[9] T. V. Krishna and A. Das, “A Survey on MAC Protocols in OSA Networks”, Elsevier Computer Networks Journal, vol. 53, no. 9, **(2009)**.
[10] A. De Domenico, E. C. Strinati and M. -G. Di Benedetto, “A Survey on MAC Strategies for Cognitive Radio Networks”, IEEE Communications Surveys & Tutorials, vol. 14, no. 1, **(2012)**.
[11] J. Chen, S. Li and S. Deng, “Route Selection Strategy Combined with Spectrum Characteristic in Cognitive Radio Networks”, IJSEIA, vol. 2, no. 2, **(2008)**.
[12] C. Song, K. Kim, W. Park and J. Kim, “Performance Analysis of Signal feature detection using Spectral Correlation Function for Cognitive Radio Environments”, IJMUE, vol. 1, no. 3, **(2006)**.
[13] J. Lee, “Blind Spectrum Sensing Techniques for Cognitive Radio System”, IJMUE, vol. 3, no. 2, **(2008)**.
[14] S. Gao, L. Qian, D. Vaman and Q. Qu, “Energy Efficient Adaptive Modulation in Wireless Cognitive Radio Sensor Networks”, IEEE ICC, **(2007)**.
[15] S. Geirhofer, L. Tong and B. Sadler, “A Measurement-based Model for Dynamic Spectrum Access”, IEEE MILCOM, **(2006)**.

[16] J. G. Jia, Z. W. He, J. M. Kuang and H. F. Wang, "Analysis of Key Technologies for Cognitive Radio Based Wireless Sensor Networks", IEEE WiCOM, **(2010)**.
[17] T. Yucek and H. Arslan, "A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications", Communications Surveys & Tutorials, IEEE, vol. 11, no. 1, **(2009)**.
[18] S. -S. Byun, I. Balasingham and X. Liang, "Dynamic Spectrum Allocation in Wireless Cognitive Sensor Networks: Improving Fairness and Energy Efficiency", IEEE Vehicular Technology Conference, **(2008)**.
[19] A. Sahai, N. Hoven and R. Tandra, "Some Fundamental Limits in Cognitive Radio", in Proc. Forty-second Allerton Conference on Communication, Control, and Computing, **(2004)**.
[20] A. Ghasemi and E. S. Sousa, "Collaborative Spectrum Sensing for Opportunistic Access in Fading Environment", in Proc. IEEE DySPAN, **(2005)**.
[21] A. Fehske, J. D. Gaeddert and J. H. Reed, "A New Approach to Signal Classification Using Spectral Correlation and Neural Networks", in Proc. IEEE DySPAN, **(2005)**.
[22] FCC, ET Docket No 03-237 Notice of Inquiry and Notice of Proposed, ET Docket No. 03-237, **(2003)**.
[23] B. Atakan and O. B. Akan, "BIOlogically-inspired Spectrum Sharing in Cognitive Radio Networks", IEEE WCNC, **(2007)**.
[24] L. Giupponi and A. I. Prez-Neira, "Fuzzy-based Spectrum Handoff in Cognitive Radio Networks", 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications, **(2008)**.
[25] J. So and N. Vaidya, "Multi-Channel MAC for AD-Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver", ACM MOBIHOC, **(2004)**.
[26] V. Blaschke, S. Nagel and F. K. Jondral, "Mechanisms for the Adaptation of the Physical Layer in a Cognitive Radio", in Proc. 9th European Conference on Wireless Technology, **(2006)**.
[27] C. Xin, "A Novel Layered Graph Model for Topology Formation and Routing in Dynamic Spectrum Access Networks", in Proc. IEEE DySPAN, **(2005)**.
[28] G. Cheng, W. Liu, Y. Li and W. Cheng, "Spectrum Aware On-Demand Routing in Cognitive Radio Networks", in Proc. DySPAN, **(2007)**.
[29] S. Krishnamurthy, M. Thoppian, S. Venkatesan and R. Prakash, "Control Channel based MAC Layer Configuration, Routing and Situation Awareness for Cognitive Radio Networks", in Proc. IEEE MILCOM **(2005)**.
[30] J. N. Al-Karaki and A. E. Kamal, "Routing Techniques in Wireless Sensor Networks: a Survey", IEEE Wireless Communications, vol. 11, no. 6, **(2004)**.

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