Proceedings Paper:

Yin, M, Li, K and Zheng, M (2018) Spectrum Utilization of Cognitive Radio in Industrial Wireless Sensor Networks - A Review. In: ICSEE 2018, IMIOT 2018: Intelligent Computing and Internet of Things. 2018 International Conference on Intelligent Manufacturing and Internet of Things & International Conference on Intelligent Computing for Sustainable Energy and Environment, 21-23 Sep 2018, Eilat, Israel. Springer, Singapore , pp. 419-428. ISBN 978-981-13-2384-3

https://doi.org/10.1007/978-981-13-2384-3_39

Spectrum Utilization of Cognitive Radio in Industrial Wireless Sensor Networks - A Review

Mingjia Yin[1], Kang Li[1], and Min Zheng[2]

[1] School of Electronic and Electrical Engineering,
University of Leeds, Leeds LS2 9 JT, UK
{elmyi,k.li1}@leeds.ac.uk
[2] School of Mechatronic Engineering and Automation,
Shanghai University, China
zhengmin203@shu.edu.cn

Abstract. The increasing demand for intelligent control and automation in industry requires better use of the radio spectrum due to the use of industrial wireless sensor networks (IWSNs). Cognitive Radio (CR) is a promising technology to improve the spectrum utilization by sensing spectrum holes. Research in this area is still in its infancy, but it is progressing rapidly. In this paper, industrial environment with different wireless technology, such as WirelessHART and ISA 100.11a is investigated. Various sensing schemes and the challenges associated for the cognitive radio are reviewed. In addition, the paper discussed the methods relevant to industrial applications, covering architecture, spectrum access, interference management, spectrum sensing and spectrum sharing.

Keywords: IWSN, cognitive radio, spectrum sensing, spectrum utilization

1 Introduction

In the current information-intensive society, the development of distributed monitoring and control system and industrial and factory automation is featured by the characteristics of flexibility, integration, robotization and intelligentization. Industrial applications have no longer been confined to closed plant environment, the networks tend to coexist with other industrial wireless systems and existing commercial wireless systems [1]. Given the growing number of interconnected industrial systems and devices for agile industrial manufacturing, industrial wireless sensor networks (IWSNs) are playing an increasingly more important role. In an industrial environment, wireless sensor nodes are installed on on-site equipment and used to monitor diverse parameters such as temperature, pressure, humidity, location and vibration [2]. The advantage of IWSNs are appealing over traditional wired communication systems such as cost-efficiency, self-organization, scalability and mobility [3]. It has been seen as a vital component in the Industry 4.0 framework, and can be used for smart factories, networked manufacturing and industrial internet of things.

Current spectrum allocation mechanism assigns wireless spectrum to licensed operators based on the static spectrum allocation policy. The cost of the license is very high, however, only parts of the spectrum is utilized effectively. Most of the distributive spectrum is utilized intermittently. According to report of Federal Communications Commission (FCC), the current utilization of a licensed spectrum varies from 15% to 85% [4]. The inefficient use and spectrum scarcity definitely hinder the development of wireless communication systems. The rest of industrial and home applications have to compete for the even more crowded free Industrial Scientific Medical (ISM) bands not only with each other but also with other wireless communication devices in the same area.

Cognitive Radio (CR) technology is recognized as an emerging technology to solve the dilemma spectrum utilization is facing: the contradiction between rapid-growing number of wireless devices and the scarcity of available spectrum resources. The definition of CR by FCC is "*Cognitive radio: A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets* [5]." In this paradigm, sensor nodes can sense the idle frequency bands (namely, the spectrum holes) and transmit data by re-using the frequency bands occupied by the authorized users. Thus, the utilization of existing spectrum resources is enhanced. The authorized users are recognized as primary users(PUs) while sensors nodes are secondary users(SUs). SUs carry radio devices that have the ability of scan and sense of the surrounding spectrum utilization. Once spectrum holes found, SUs can access the idle spectrum opportunistically by altering their spectrum bands subsequently [6].

In this paper, we start with a discussion on the challenges of industrial environments, focusing on different interference sources, coexistence, and heterogeneous environment. Next, an overview of spectrum sensing techniques is given. This is then followed by a presentation on a range of methods relative to spectrum utilization. Finally, we discuss some open problems and future trends of IWSNs.

2 Challenges of Wireless Industrial Network

2.1 Interferences in Wireless Industrial networks

Industrial environment is often more complicated than public and private environments. It has higher quality of service (QoS) requirements than that applications at homes and offices. Reliability, latency, and availability are some major aspects and they can be quite specific for different applications. For example, monitoring system is usually time-sensitive. Data with long latency may lead to wrong decisions.

The signal strength in the industrial environment is heavily affected by multipath fading (e.g., the reflections from floors and walls), the interferences from other devices(e.g., motors), and noise. Specifically, interference signals can be divided into two classes: broadband or narrowband [7]. Broadband interferences usually come from unintentional radiating sources. They have high energy and constant energy spectrum across a large range of frequencies whereas narrowband interference signals have lower energy at specific frequencies.

In a typical industrial site, there are sufficient wireless communication systems and networks that might generate interference against the radio signals [8]. The co-existence issues between various wireless networks also need to be considered. The deployed networks include wireless local area networks (WLANs) and wireless personal area networks (WPANs) which are short range networks. The common protocols used in industrial environment like Zigbee, bluetooth, Wi-Fi (Wi-Fi also works in the 5GHz band), WirelessHART, ISA 100.11a and wireless interface for sensors and actuators (WISA) are operating at 2.4GHz band. The emerging low power wide area network (LPWAN) allows small amounts of data to be transmitted within a long distance at lower frequencies. Table 1 presents the key characteristics and make a comparison among different platforms. Zigbee, WirelessHART and ISA 100.11a use the same physical layer and media access control protocol (IEEE 802.15.4). The frequency spectrum is divided into 16 channels at 2.4GHz with each channel having a bandwidth of 2MHz. IEEE 802.11 is adopted by Wi-Fi which also works at 2.4GHz and normally has 13 channels. The bandwidth of each channel is 20 MHz and most routers choose channel 1,6 and 11 because they hardly overlap.

Table 1. Wireless Industrial Communication Protocols

	Zigbee	**Wi-Fi**	**WirelessHART**	**ISA 100.11a**	**LoRa**
Bandwidth	2MHz	40MHz,20MHZ	2MHz	2MHz	125KHz
Frequency	2.4GHz	2.4GHz	2.4Ghz	2.4GHz	433,915MHz
Channels	16	13	16	16	32
Radio	802.15.4	802.11a,b,g	802.15.4	802.15.4	Proprietary
Data Rate	250kbps	11-54Mbps	250kbps	250kbps	10kbps
Range	10-100m	1-100m	50-100m	50-100m	50m-10km

In order to reduce the effect of interference, spectrum allocation without CR technology chooses non-overlapping channels. Figure 1 illustrates the channel distribution and highlight the non-overlapping bands between IEEE 802.15.4 and IEEE 802.11. In [9], a multi-dimensional resource allocation strategy (MRAS) is used to meet the different industrial requirements. It can improve the utilization of available wireless network resources, but the improvement is not significant enough compared to its complexity.

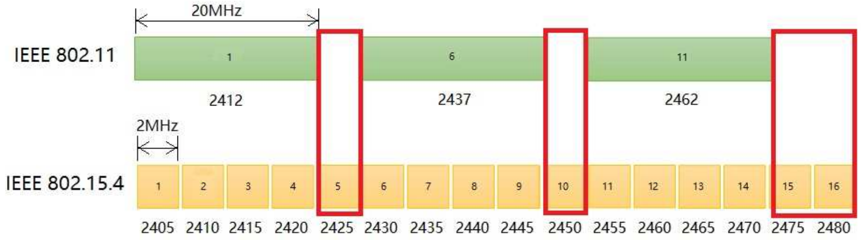

Fig. 1. The Channel Distribution of IEEE 802.15.4 and IEEE 802.11

2.2 Complex Heterogeneous Environment

Traditionally, the applications of the IWSN systems can be classified into three categories: safety systems, control systems, and monitoring systems [10]. In these systems, a wide range of data are collected or processed over a given region for a long duration and the data are exploited thoroughly to make certain conclusions. In recent years, the data sources are more abundant which may include on-demand or live video streaming, audio, and still images. These multimedia applications set high demands for transmission rate and bandwidth. Moreover, in a dense network environment such as indoor plants, the media control access mechanism should be carefully designed because different sensor nodes in the area are likely to access a channel simultaneously. In addition, the topology of the network and connection of the nodes change over time due to the link failures and battery depletion. The idea of heterogeneous sensor networks thus come naturally with two of more nodes working with different energy and hardware complexity.

3 Spectrum Sensing Technologies

In section 2, the difficulty of spectrum scarcity is discussed and the deployment problem of several objects connected to infrastructure through radio links is introduced. Recently, integration of CR technology in wireless sensor nodes has gained much attention as it enables sensors transmit data packets over the licensed spectrum bands as well as the free ISM bands. Spectrum sensing is a critical component for CR. Through spectrum sensing, CR can obtain necessary observations about its surrounding radio environment, such as the presence of PUs and appearance of spectrum holes. Basically, there are two types of sensing techniques: signal processing techniques and cooperative sensing techniques. Figure 2 shows the classification of spectrum-sensing techniques.

3.1 Signal Processing Techniques

1) *Matched Filter Detection*: The matched filter (also known as coherent detector), is considered as the optimum method because of its accuracy. As the parameters of the transmitted signals are known, the matched filter accordingly

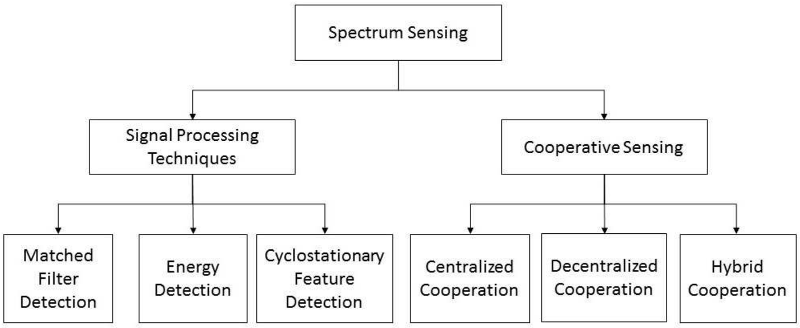

Fig. 2. Classification of Spectrum-sensing Techniques

maximizes the received signal-to-noise ratio (SNR). The presence or absence of PU is determined by the comparison between the result of correlation and a predetermined threshold. However, matched-filtering also has limitations. It requests the features of PU signal in advance, which include bandwidth, operating frequency, modulation type and order, pulse shaping, and frame format [11]. Also, the computational complexity and power consumption are very high.

2) *Energy Detection*: Energy detection is performed in both time and frequency domain. It compares the energy received by PU signal with a threshold based on the noise estimation. The method is simple and has low computational cost because it does not need a *priori* information of PUs signal. But, the drawback of the method is obvious as well. The noise needs to be accurate which is difficult to estimate [12]. It is also not suitable to use the method in low SNR environment and for detecting spread spectrum signals.
3) *Cyclostationary Feature Detection*: The cyclostationary feature detector differentiates the PU signal from the additive noise since the method deals with the inherent cyclostationary properties or features of a signal. A cyclostationary signal is said to be periodic when considering the mean and autocorrelation [13]. The technique is simple and effective. Only one or two periodic features of the PU signal are needed. It can be used to detect at very low SNR condition. The robustness to noise of the method performs better than energy detector, nevertheless, the computational complexity is higher than that of energy detector.

3.2 Cooperative Sensing

Cooperative sensing literally means that the sensor nodes with CR can cooperate and exchange their sensed information in different manners. It can improve sensing accuracy by exploiting spatial diversity.

1) *Centralized Cooperation*: In centralized cooperation, a central cooperator, which can be a collector, or server, is used to manage the information from

distributed CR sensor nodes and determine the absence or presence of the PU. Firstly, each sensor node with CR senses the surrounding spectrum by themselves and distinguish the presence of the PU from the absence at a specific frequency. Secondly, the nodes forward the results to the central cooperator. At last, the central cooperator aggregates and organizes data together. Once a sensor node requests for channel information, the cooperator can transmit the final decision after data fusion.

2) *Decentralized Cooperation*: The decentralized cooperation works in a decentralized manner with no central cooperator. Instead, it uses a spectrum information table to record the sensing results. Each node performs local spectrum sensing and make a decision as to the presence or absence of the PU. Then the nodes spread the information to neighbouring ones and create spectrum information table in a predicted period. The scheme is more flexible, but the storage and computation cost are high due to the updated table [14].
3) *Hybrid Cooperation*: The hybrid cooperation combines the advantages of centralized cooperation and decentralized cooperation. Each sensor node sense and transmit information in the same way as decentralized manner and it may share channel information with centralized cooperator as requested.

4 Spectrum Utilization

The cognitive capability is a promising solution to enhance the spectrum sensing of dynamic environment by adjusting the parameters used to determine the transmitted signal. Meanwhile, it provides an elastic feature, known as reconfigurability, that is suited to the changing parameters in a dynamic radio environment without modifying the hardware structure. In this section, many techniques that can be used to improve the spectrum efficiency are introduced. The network architecture, spectrum access, interference management, spectrum sensing and spectrum sharing should always be considered together.

4.1 Clustering

The complexity of the architecture can be reduced by forming clusters with neighbouring nodes. The physically nearby sensor nodes are grouped into single-hop clusters with a star topology. Each cluster elects a cluster head (CH) to perform the intra- and inter-cluster management and data processing. CHs then forward their data to sinks or base stations (BS) which are supposed to have higher energy and stronger processing capabilities.

The existing clustering algorithms [15–18] consider homogeneous sensor nodes, and in [19] a cluster-based approached is formed for a meshed network. Within the cluster, the CH is responsible for the spectrum management. In [20], a distributed spectrum-aware clustering (DSAC) protocol is proposed. The simulation results show the preferable scalability and stability under dynamic spectrum access.

4.2 Hierarchical Topology

A hierarchical network allows nodes at different tiers to perform different tasks. Among them, a typical example is the two-tier structure. The lower tier is responsible for sophiscated task such as monitoring nodes without CR. In the upper tier, it comprises a set of SUs opportunistically access the spectrum to send the detection results to the sink node. In [21], the author incorporated two constrained Markov Decision Processes (MDP) with the two-tier network for event detection and channel allocation. One MDP is used to adjust the detection criterion for the delay constraint. Meanwhile, the other MDP is used for optimum spectrum allocation of SUs.

4.3 Fuzzy Cognitive Map

When multiple objectives, environment variables, and processes are considered, fuzzy cognitive map (FCM) is a simple way to present the system in a parameterized and directed form. The goals can be expressed as causal relationships which are in low complexity under conflicting constraints [22]. FCM is an unsupervised model which can be viewed as a intelligent tool. The authors of [23] present a cognitive sensor network framework for highway safety applications. FCM is used to address the challenges of highway safety, network lifetime and throughput. The Q-learning algorithm is also incorporated in the system so as to enhance the learning ability of the FCM after evaluation and improve the system performance by a well-designed reward system.

4.4 Optimization

The challenges of power and hardware limitations of sensor nodes should be overlooked as its inherent characteristics. Combining CR functionalities with sensor nodes is a self-evident choice when energy and network lifetime is co-considered. The existing networks and protocols are seldom aware of cognitive capability, many open optimization issues are left for research. For example, authors in [24] investigated the optimal packet size for a cognitive wireless sensor network. It defines the system and gives the simulation result of the optimal packet size for the proposed system with maximum energy efficiency while maintaining reasonable interference level for the licensed PU. In [25], a multi-objective optimization framework is proposed for reducing CO_2 emissions. The cooperative cognitive system jointly optimizes the relay assignment and power allocation with two conflicting objectives which are to maximize the sum-capacity and to minimize the CO_2 emissions. Although a hybrid evolutionary scheme of EDA is proposed, the real-time performance is poor due to the priori knowledge of the distribution of relay nodes and the constraints of greedy algorithm.

4.5 Random Processes

A random process is often referred to a whole set of random variables that depend on the parameters. One of the parameters is usually time. Random variables are the mathematical models of random phenomena, and their values will change with the affecting factors. [26] proposes a hybrid sensing method using a continuous time Markov chain model to adjust the parameters in avoid of contradictory factors. According to the characteristics of PU and SUs, the best sensing period is found. Considering that sensing results are affected by uncertain noise and contradictory factors, [27] introduces the partially observable Markov decision processes to build the channel model. It enables the cognitive nodes with the ability of channel sensing, channel switching, and data transmission.

4.6 Game Theory

Game theory mainly studies the interaction between the formulated incentive structure, which is a mathematical theory and method for studying the phenomena of competition. It considers the predicted behavior and actual behavior of individuals and studies their optimization strategies [28]. Cognitive radio network is a good instance of game theory as the SUs are competing for spectrum usage based on the sensed spectrum and actions of other users. Non-cooperative game theory can be used for spectrum sharing schemes since the SUs are assumed to be selfish who only care about their own spectrum. [29] analyzes how to maximize the benefits of cognitive users (i.e., maximize spectrum utilization). In the premise of maintaining the benefits of the authorized users, the choice of cognitive nodes are evaluated by the revenue function. On this basis, the decision-making interactions among cognitive nodes are formulated as a non-cooperative game process and Nash equilibrium (NE) corresponding to a stable decision is obtained. The proposed mechanism shows that the complexity is relatively low. Auction mechanisms are also widely used for spectrum sharing. In [30], the spectrum usage is defined as a function of SNR. [31] proposes a real-time spectrum auction framework. In the mechanism, spectrum channels are assigned to proper SUs under interference constraints.

5 Conclusion

In this paper, the potential benefits and current studies of using CR technology to improve the spectrum utilization in IWSN have been discussed. We give a brief introduction of the CR technology and its different sensing techniques, namely signal processing and cooperative sensing techniques. Further, the potential techniques from the aspects of network architecture, spectrum access, interference management, spectrum sensing and spectrum sharing are presented. However, there are still some open problems in this area. One thing should be noted is that there is no universal test platform and test environment to implement the approaches, evaluate the cooperation mechanism and verify the accuracy. Hence, standardized protocols and practical methods need to be proposed.

Acknowledgments. This work was financially supported by UK EPSRC under the Optimising Energy Management in Industry - 'OPTEMIN' project EP/P0046

-36/1. Mingjia Yin would like to thank the EPSRC for sponsoring her research (project reference 1951147).

References

1. Chiwewe, T.M., Mbuya, C.F., Hancke, G.P.: Using cognitive radio for interference-resistant industrial wireless sensor networks: An overview. IEEE Transactions on Industrial Informatics 11(6), 1466–1481 (Dec 2015)
2. Gungor, V.C., Hancke, G.P.: Industrial wireless sensor networks: Challenges, design principles, and technical approaches. IEEE Transactions on Industrial Electronics 56(10), 4258–4265 (Oct 2009)
3. Cena, G., Seno, L., Valenzano, A., Zunino, C.: On the performance of ieee 802.11e wireless infrastructures for soft-real-time industrial applications. IEEE Transactions on Industrial Informatics 6(3), 425–437 (Aug 2010)
4. Akyildiz, I.F., y. Lee, W., Vuran, M.C., Mohanty, S.: A survey on spectrum management in cognitive radio networks. IEEE Communications Magazine 46(4), 40–48 (April 2008)
5. Commission, F.C.: Notice of proposed rule making and order: Facilitating opportunities for exible, efcient, and reliable spectrum use employing cognitive radio technologies. ET Docket (Feb 2005)
6. Joshi, G.P., Nam, S.Y., Kim, S.W.: Cognitive radio wireless sensor networks: Applications, challenges and research trends. Sensors 13(9), 11196–11228 (2013), `http://www.mdpi.com/1424-8220/13/9/11196`
7. Low, K.S., Win, W.N.N., Er, M.J.: Wireless sensor networks for industrial environments. In: International Conference on Computational Intelligence for Modelling, Control and Automation and International Conference on Intelligent Agents, Web Technologies and Internet Commerce (CIMCA-IAWTIC'06). vol. 2, pp. 271–276 (Nov 2005)
8. Werb, J., Newman, M., Berry, V., Lamb, S., Sexton, D., Lapinski, M.: Improved quality of service in ieee 802.15.4 mesh networks. In: Proceedings of International Workshop on Wireless and Industrial Automation. pp. 1–4 (2005)
9. Qu, F., Zhang, J., Shao, Z., Qi, S.: Research on resource allocation strategy of industrial wireless heterogeneous network based on ieee 802.11 and ieee 802.15.4 protocol. In: 2017 3rd IEEE International Conference on Computer and Communications (ICCC). pp. 589–594 (Dec 2017)
10. S., A.A.K., Ovsthus, K., Kristensen., L.M.: An industrial perspective on wireless sensor networks x2014; a survey of requirements, protocols, and challenges. IEEE Communications Surveys Tutorials 16(3), 1391–1412 (Third 2014)
11. Zhang, X., Chai, R., Gao, F.: Matched filter based spectrum sensing and power level detection for cognitive radio network. In: 2014 IEEE Global Conference on Signal and Information Processing (GlobalSIP). pp. 1267–1270 (Dec 2014)
12. Xuping, Z., Jianguo, P.: Energy-detection based spectrum sensing for cognitive radio. In: 2007 IET Conference on Wireless, Mobile and Sensor Networks (CCWMSN07). pp. 944–947 (Dec 2007)
13. P.S, A., Jayasheela, M.: Cyclostationary feature detection in cognitive radio using different modulation schemes (2012)
14. Bera, D., Maheshwari, S., Chakrabarti, I., Pathak, S.S.: Decentralized cooperative spectrum sensing in cognitive radio without fusion centre. In: 2014 Twentieth National Conference on Communications (NCC). pp. 1–5 (Feb 2014)

15. Pritom, M.M.A., Sarker, S., Razzaque, M.A., Hassan, M.M., Hossain, M.A., Alelaiwi, A.: A multiconstrained qos aware mac protocol for cluster-based cognitive radio sensor networks. International Journal of Distributed Sensor Networks 11(5), 262871 (2015), `https://doi.org/10.1155/2015/262871`
16. Rauniyar, A., Shin, S.Y.: A novel energy-efficient clustering based cooperative spectrum sensing for cognitive radio sensor networks. International Journal of Distributed Sensor Networks 11(6), 198456 (2015), `https://doi.org/10.1155/2015/198456`
17. Singhal, D., Barjatiya, S., Ramamurthy, G.: A novel network architecture for cognitive wireless sensor network. In: 2011 International Conference on Signal Processing, Communication, Computing and Networking Technologies. pp. 76–80 (July 2011)
18. Li, X., Wang, D., McNair, J., Chen, J.: Residual energy aware channel assignment in cognitive radio sensor networks. In: 2011 IEEE Wireless Communications and Networking Conference. pp. 398–403 (March 2011)
19. Chen, T., Zhang, H., Maggio, G.M., Chlamtac, I.: Topology management in cogmesh: A cluster-based cognitive radio mesh network. In: 2007 IEEE International Conference on Communications. pp. 6516–6521 (June 2007)
20. Zhang, H., Zhang, Z., Dai, H., Yin, R., Chen, X.: Distributed spectrum-aware clustering in cognitive radio sensor networks. In: 2011 IEEE Global Telecommunications Conference - GLOBECOM 2011. pp. 1–6 (Dec 2011)
21. Jamal, A., Tham, C.K., Wong, W.C.: Event detection and channel allocation in cognitive radio sensor networks. In: 2012 IEEE International Conference on Communication Systems (ICCS). pp. 157–161 (Nov 2012)
22. Mougy, A.E., Ibnkahla, M.: Achieving end-to-end goals of wsn using weighted cognitive maps. In: 37th Annual IEEE Conference on Local Computer Networks. pp. 328–331 (Oct 2012)
23. El Mougy, A., Ibnkahla, M.: A cognitive wsn framework for highway safety based on weighted cognitive maps and q-learning. In: Proceedings of the Second ACM International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications. pp. 55–62. DIVANet '12, ACM, New York, NY, USA (2012), `http://doi.acm.org/10.1145/2386958.2386967`
24. Oto, M.C., Akan, O.B.: Energy-efficient packet size optimization for cognitive radio sensor networks. IEEE Transactions on Wireless Communications 11(4), 1544–1553 (April 2012)
25. Naeem, M., Ashrafinia, S., Lee, D.: Estimation of distribution algorithm for green resource allocation in cognitive radio systems. In: 2012 6th International Conference on Signal Processing and Communication Systems. pp. 1–7 (Dec 2012)
26. Khattab, A., Perkins, D., Bayoumi, M.A.: Opportunistic spectrum access: From theory to practice. IEEE Vehicular Technology Magazine 7(2), 62–68 (June 2012)
27. Han, J.A., Jeon, W.S., Jeong, D.G.: Energy-efficient channel management scheme for cognitive radio sensor networks. IEEE Transactions on Vehicular Technology 60(4), 1905–1910 (May 2011)
28. Wang, B., Wu, Y., Liu, K.R.: Game theory for cognitive radio networks: An overview. Computer Networks 54(14), 2537 – 2561 (2010), `http://www.sciencedirect.com/science/article/pii/S1389128610001064`
29. Yuan, W., Leung, H., Chen, S., Cheng, W.: A distributed sensor selection mechanism for cooperative spectrum sensing. IEEE Transactions on Signal Processing 59(12), 6033–6044 (Dec 2011)

30. Huang, J., Berry, R.A., Honig, M.L.: Auction-based spectrum sharing. Mob. Netw. Appl. 11(3), 405–418 (Jun 2006), `http://dx.doi.org/10.1007/s11036-006-5192-y`
31. Gandhi, S., Buragohain, C., Cao, L., Zheng, H., Suri, S.: A general framework for wireless spectrum auctions. In: 2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks. pp. 22–33 (April 2007)