IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 3 Issue 11, November 2016
ISSN (Online) 2348 – 7968 | Impact Factor (2015) - 4.332
www.ijiset.com

Survey on Energy Efficient Low power Spectrum Sensing Techniques in Cognitive Radio

Yogendra Yadav
Electronics and Communication Department
MPCT, Gwalior (M.P.)

Pankaj Singh Tomar
Electronics and Communication Department
MPCT, Gwalior (M.P.)

Abstract— Due to scarcity of spectrum Cognitive Radio (CR) is one of the most challenging recently emerged fields of Wireless Networks. Spectrum decision is the capability of a cognitive radio (CR) to select the best accessible spectrum band to satisfy secondary users' (SUs'), quality of service (QoS) requirements, without causing harmful interference to licensed or primary users (PUs). It's solved the problem by using its sharp sensing and adaptation to the surroundings. It locates the vacant radio spectrum which is allocated to the Primary users and helps to reorganize the unused spectrum to Secondary users thereby recovering the deployment of the spectrum. In this paper we focus on various low power energy efficient techniques in spectrum detection and boundaries faced by areas such as wireless sensor networks, vehicular networks, smart grid, healthcare, and public safety networks and placed interest in the improvements made to the consumption of the spectrum as well as the quality of communication, which makes these networks more competent. An review paper on CR along with its various research techniques are presented in the paper. Cognitive Radio technique like Energy Detection, Cyclostationary Feature Detection, Matched Filter, Wavelet Transform, Multiple antenna, etc. available in literature.

Keywords—cognitive radio, spectrum sensing, low power

I. INTRODUCTION

Cognitive radio (CR) network is competent of healing the wireless access networks from spectral point of view. The restriction of the spectrum is relieved by exploiting cognitive networking in which wireless nodes intelligently sense and operate on the unused spectrum for communications. CR increases the network accessibility and thus extends rising network vigilances. Manipulating CR networks is challenging. It requires not only the modeling of dynamic spectrum access but also the efficient power. This paper surveys the cognitive radio techniques and the modeling of wireless networks. Recent works on spectrum sensing, supervision, and sharing are investigated in brief.

The CR wireless access network is studied in diverse aspects such as smart cell, cooperative radio and relay. Network of CR highly depends on the nature of the existing spectrum. To optimize and acclimatize the convention of Spectrum according to the prospect of spectrum accessibility, we converse research concurrences in designing cognitive radio networks.

Wireless access networks are surrounded by diverse behavior of spectrum in the telecommunications transportation, and their existing rate of power utilization is swelling because of the unstable pitch of mobile data traffic [1], [2]. Wireless access networks can exploit on the wide hypothesis of cognitive radio (CR). Haykin [3] has correctly defined CR as "A cognitive radio transmitter is smart enough that it will learn from the surroundings and adjust its states to variations in the existing radio frequency (RF) stimuli by adjusting the broadcast parameters (e.g., transmission power, frequency band and modulation mode) in instantaneous manner". With the cognitive potential to sense the vacant spectrum and the modification to vigorously change spectrum in order to less fading and intrusion is experienced, the smart CR communication system modeled the spectrum alertness and energy competence [4].Different areas of wireless systems can be smart and better via CR, existing research focuses on spectrum efficiency and allocation to secondary user (SU). Zhao and Sadler [5] offered an overview of the dynamic spectrum access (DSA), which compare the CR wireless system from inheritance wireless systems, which are accredited to operate in a committed effective frequency band. Diverse activity of CR is introduced in [6], [7]. Whereas researchers in [8] - [10] elaborate spectrum sensing in brief which enables CR to search and access the spectrum availability, Wang et al. [11] demonstrate a range of attention in CR which can take benefit of the DSA quality of CR, and Akyildiz et al. [12] pay attention on the CR-based wireless access network structural design. Cooperative sensing (CS) with compound Secondary user sense the common signal in a synchronized manner, has been more better than sole Secondary User sensing [4]-[13] in the realistic noisy atmosphere. For its simple and low cost realization, energy detection based cooperative and non-cooperative spectrum sensing has been broadly examined in latest. Generally, the maximum ratio combing and the square-law combining have been deliberate in [9], [12]. However, the maximum ratio combing (MRC) method requires the information of channel from the primary user to the Secondary User and from each Secondary user to the fusion center. If the Square Law Combing method is applied with a changeable amplification factor at each Secondary User, are also required. As a result, both Maximum Ratio Combing and Square Law Combing method have significantly high complication. Cooperative energy detection with equal gain combination is also measured in practical operation due to its less operational difficulty [9], [13]. By allowing diverse arriving SNRs of Secondary User, [8] elaborate a cooperative sensing scheme based on normalized Energy detection when Secondary User are capable of sole receive antenna. The maximum normalized energy method is also explained in [13]. In some realistic application atmosphere, each Secondary User in a Cognitive Radio network have diverse hardware configuration with different SNR signals, such as multiple antennas and the accuracy of analog to digital converter. These diverse requirements of hardware lead to different sensing dependability for each Secondary User. For such a mixed environment CR network composed of Secondary Users with diverse analyzing capabilities and consistency, no efficient method has been modeled yet, to the best of our known information, to recognize the cooperative sensing of Secondary Users with different capabilities. In general, Secondary Users need to sample their analyzing data before transport them to the Fusion Center due to the scarcity of the bandwidth. Quantization and quantization noise method for Cognitive Radio spectrum sensing systems have been demonstrated in [14]-[17] there is lot of things is yet to be done. In[8], the arriving error is modeled as Gaussian random variable, based on which the impact of the reporting errors on the sensing performances have been elaborated for the case of Energy Detection based linear combining cooperative spectrum sensing. Moreover, [18] analyze the decision making power of cognitive radio under hard situation. Space-time coding has also been proposed to expose the reporting error of cooperative spectrum sensing in [18].

The survey gives the summary of the energy efficient cognitive radio systems from three aspects:

1) Achieving power aware functionality in the CR systems,
2) Designing energy efficient wireless access systems via cognitive radio, and
3) Optimizing CR networks.

II. ENERGY EFFICIENCY IN CR

Conventional spectrum allotting schemes use the control and command model, in which they have certain protocol for allotting spectrum [15]. Static licensed spectrum presents great challenges for the wireless network to handle the growing status of new wireless devices and applications. To get the spectrum access easily, dynamic spectrum access techniques have been proposed to solve this spectrum inefficiency problem, by allowing secondary users to access the radio spectrum under certain restrictions but in this problem of switching of SC in the spectrum again and again energy lost is must. Dynamic spectrum access network categorized in three different models (based on [5], [15]) shown in Fig. 1 are commonly used. Cognitive radio technology has emerged as a key for dynamic spectrum access. In a CR-based

Dynamic Spectrum Access network, the primary system owns the spectrum rights, while unlicensed users can dynamically share the licensed spectrum in an opportunistic manner. This capability is provided by the following cognitive functionalities [6].

A. Spectrum Sensing and Analysis

Spectrum sensing is defined as the task of finding spectrum opportunities, i.e., spectrum holes, in the local neighborhood of the overlay CR receiver [16]. Once the spectrum hole is utilized by a secondary (unlicensed) transmitter, no primary receiver will be affected by this secondary transmitter, and no primary transmitter will interfere with the intended secondary receiver either [17]. Spectrum analysis uses the information obtained from spectrum sensing to schedule and make a decision to access the spectrum by SUs. The primary goal of CR is to access the spectrum. As much as the spectrum accessing is easier the allocation is as simple as possible. The categories of spectrum sensing, energy related advantages and drawbacks, and the research problems concerning energy efficiency are presented in block diagram.

To design energy efficient low power spectrum sensing methods, the Performance of cognitive radio shown by following parameters: the detection probability P_d and the false alarm probability P_f. it is good for the spectrum the P_d should be as higher as possible. The lower the P_f, the more spectrum opportunities are explored by Secondary User [19]. Note that the opposite of the probability of P_f, is called miss-detection probability P_m, and sometimes called as collision probability [5]. To improve the quality of spectrum sensing under various conditions, such as whether prior information about the probability of the primary user's presence on the target channel, defined in Eq. (2), is available or not, and the target channel is narrow or wide, a collection of spectrum sensing methods have been proposed [8].

$$\pi_0 = Prob\{H_0\} \quad (1)$$
$$\pi_1 = Prob\{H_1\} \quad (2)$$

Where H_1 is the hypothesis that PU is active, while H_0 means the spectrum is idle. Although the aforementioned algorithms yield different sensing performance and power consumption, the relationship in Eq. (3) holds in general, based on the binary hypothesis testing.

$$p_d = Prob\{f(T_s, \gamma) > \lambda_d / H_1\} \quad (3)$$
$$p_f = Prob\{f(T_s, \gamma) > \lambda_f / H_0\} \quad (4)$$

Where f is related to signal detection and processing in the physical layer (PHY) [8], [12]. P_d is increasing with the sensing time and SNR, but is decreasing with the detection threshold. p_f is decreasing with sensing time and as well as the false alarm threshold. In addition to sensing performance, the energy efficiency of the spectrum sensing algorithms depends on the power consumption, as shown in Eq. (4), which involves the scheduling of a spectrum sensing activity in the time and spatial domains by the media access control (MAC) layer.

$$Ps = Fs(Ts) = Fs(Ns) \quad (5)$$
$$Pr = Fr(Nc, D) \quad (6)$$

Where F_S and Fr are the sensing and reporting power functions, respectively. The sensing power P_S is increasing with the sensing time T_S, which is further proportional to N_S, the number of collected samples. P_R, the power consumed by reporting the sensing result, is increasing with the transmission distance D and the number of nodes participating in the sensing N_C. Besides the energy consumed to obtain the sensing result, the major energy waste of CRNs is due to the miss-detection of PU, which can lead to collision and retransmission. As a result, the power consumed for data transmission, P_T, is related to the detection probability P_d and SNR, according to a decreasing function F_T defined as follows.

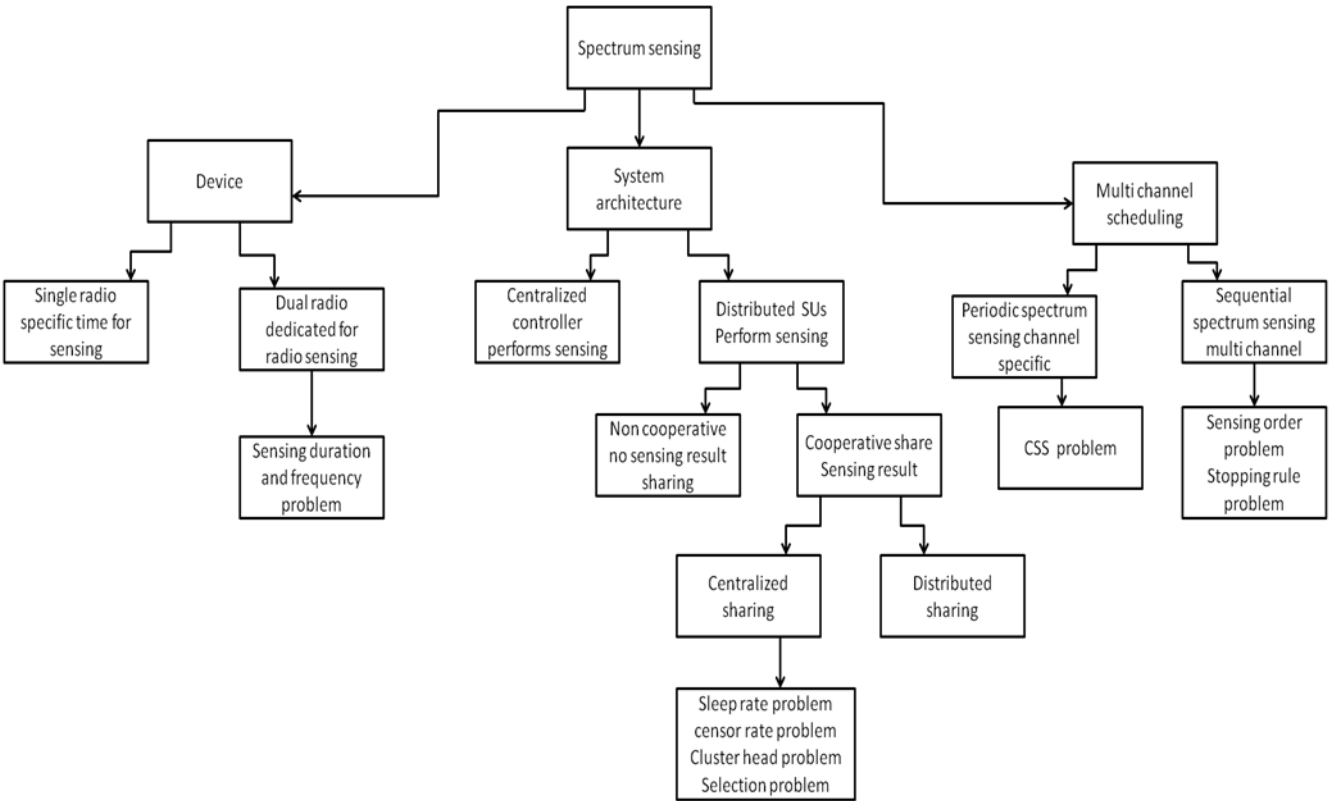
$$P_T = F_T(\gamma, p_d) \quad (7)$$

1.) *Sensing Duration and Frequency Problem:*

To poise the energy-stability of continuous spectrum sensing (high P_S) and the irregularity of periodic spectrum sensing (low P_d and high P_f), Gan et al. [20] optimized the sampling rate (N_S/T_S) and sensing time to minimize the total sensing power in multiple potential channels, within the constraints of detection performance.

2.) *Sensing Architecture Design Problem:*

With various Secondary Users sensing and sharing information, power used by sensing P_S and reporting P_R can both be decreased when every cognitive radio will randomly turn off its sensing device, this energy saving approach is referred to as sleeping or on-off sensing.



Fiq.1) Categories of spectrum sensing [12].

With various secondary user waiting for sensing and sharing information , consumed by sensing power and reporting the sensing result both decreased when cognitive radio randomly turn off its sensing and sharing device this scheme referred as sleeping or on-off sensing. Two more approach to reduce power consumed by reporting the sensing result is censoring and clustering [21], where in clustering, we sent local data to the cluster head instead of fusion center, which make sent decision to the fusion center and in censoring the result is sent only if it is informative in this way energy induction is reduced.

Algorithms for performance optimization of Extensive centralized detection and overhead minimization can be found in [22] - [24]. Here three different schemes are there. Each secondary users have the authority to decide whether to sleep or share. This kind of nature is generalized by spatial diversity scheduling.

With the introduction of scheduling in the frequency domain, spectrum opportunity can be further exploited from a new degree of freedom. There are many scheduling problems existing in the frequency domain which are further discussed in the new era of wireless communication.

The problem of cooperative sensing scheduling is automatically generated when the multiple channels exist; it is very difficult to allot the spectrum vacant node to the secondary user in multiple channels. So

a tradeoff between energy-performance should be maintained [28].

3)*.Sequential Channel Scheduling:*

For the perfect fencing and allocation of a spectrum the first step is that the secondary users should be able to sense whether the channel is free or occupied. Once the channel is sensed secondary user can switch to the vacant slot or wait for the sloth to be empty. Using these sensing results quality estimation can be done [29].

More research has to be done in the area of sensing and efficiently allocating the ideal slot. A protocol has to be designed for channel selection.

The performance parameters to detect the spectral efficiency are delay time and power.

These two parameters can be analyzed to detect the efficiency of the spectrum sensing.

B.Spectrum management and handoff:
This provide you the capability of detecting the vacant position in spectrum and allocate the frequency to secondary user [12], by this major challenges come through , as well as the diverse quality of service (QoS) requirements of various applications [7]. The spectrum management mechanism is further subdivided into two major components which are spectrum analysis and Spectrum access. The first strategy specifies whether to send and where to send. Then according to these results spectrum holes are identified. After this, decision will be made by the access strategy, whether to access or not according to best available channel. Data transmission power level according to the user requirement can be determined with the help of channel characteristics. Thus in order to design spectrum management mechanism Energy Efficiency is an important parameter.

1) Spectrum Access: With the help of sequential Decision Process secondary users come up with one more option: whether to use the vacant slot or not if energy consumption is an important parameter to be taken care of. So in the case of poor fading signal, it is better for secondary user to be idle.

The partially observable Markov decision process the POMDP framework [30] indicates that the optimal sensing decision and access strategy uses a threshold structure in terms of channel free probability and channel fading condition, i.e., SU with un-rechargeable battery and limited power should sense the channel when the conditional probability that the channel is idle in the current slot is above a certain threshold, and it will access the channel if the fading condition of this idle channel is better than a certain threshold.

2) *Spectrum Mobility:* As the problem mentioned, listed in the above section there are lot of time variation in spectrum, sometimes it is impossible to get the empty hole for the secondary user or it continuously switching the spectrum one place to other due to arrival of primary user [31],by using spectrum mobility secondary user does not interfere to primary user under any circumstances. CR works on the mobility management adaptively and should gone through heterogeneous spectrum availability. In general, spectrum handoff is divided into two parts. One is the reactive-sensing spectrum handoff, in which the target channel is sensed or selected only after the spectrum handoff request is made. The second is the proactive-sensing spectrum handoff, where the object channel for spectrum handoff is prearranged [32]. The reactive spectrum handoff gives accuracy but time taken is more. By pre-determining the target channel, the proactive spectrum handoff is vice versa. Extensive performance analysis of spectrum handoff can be found in [32] - [35]. As shown in Eq. (8), tuning the radio frequency of the cognitive device will result in additional power consumption

$$P_{HO} = F_{HO}(f_t - f_c) \ldots\ldots\ldots\ldots\ldots.. (8)$$

Where FHO is an increasing function and the handing off power PHO is related to the frequency difference between the target channel ft and the current channel fc. In order, to reduce the energy consumption which occurred during the process of handoff, the secondary user gets an option to wait for the current channel. In this way energy can be conserved and quality of service can be maintained.
Because of this, a decision should have to be made whether to request handoff should be requested or not.
Now in next section coordination among secondary users for spectrum access, effective usage of spectrum resource will be studied.

C). Spectrum allocation and sharing: Here in order to maintain the collisions and interference caused by secondary users to an acceptable level, the access to the available channel with other primary as well secondary users should be coordinated properly. Based on these coordination results three different spectrum sharing process are there [36]. First is Spatial spectrum sharing, for example spectrum underlay, in which secondary users can access the spectrum subject to interference temperature (IT) [37]. Second is Temporal spectrum sharing, e.g., spectrum overlay, in which secondary users can utilize the spectrum only when it is idle. Third one is Hybrid spectrum sharing, in which SUs initially sense for the status (active/idle) of a frequency band (as in the temporal spectrum sharing) and adapt their transmit power based on the decision made by spectrum sensing, to avoid causing heavy interference (as in spatial spectrum sharing) [38].

Inorder to improve efficiency and fairness of resource sharing [39], [40], [41], spectrum sharing is further subdivided in two categories: cooperative and non-cooperative, which depends on the behavior of SU in the network. The energy consumption and performance of each secondary user and the complete network can be improved by proper choice of spectrum sharing model and proper choice of spectrum allocation mechanisms. As a result efficient designs in terms of energy, power budget, quality of service and channel conditions can be maintained.

1) Spatial Spectrum Sharing: In order to build an energy efficient underlay cognitive radios it is very important to consider the parameters light spectrum sharing, power control, bit rate and antenna beam location. These parameters are implemented by dynamic resource allocation (DRA) [42]. The result of efficient spectrum sharing and allocation can build more revenue which is beneficial for the spectrum owner. Thus satisfaction of primary users can also be enhanced. Here inspite of using centralized DRA in which full knowledge of network is required, Distributed DRA can be used if no such information is available. Also we can use auction based energy spectrum trading scheme in order to minimize the primary energy consumption along with the power budget and rate using distributed spectrum allocation scheme.

2) Temporal Spectrum Sharing: Spectrum exploitation is another issue for transmission of signal efficiently. In this how secondary user manage the spectrum allocation efficiently can be studied. Interference of secondary user for the vacant node of primary user is being easily detected in spectrum exploitation. The reuse of frequency again and again is becoming a disadvantage in today's scenario to achieve quality of service in the undeterministic spectrum condition energy requirement is the challenge [46].

Hasan et al. [46] Measured Limited transmission power budget and centralized power allocation in multiple OFDM careers along with IT constraint. Also few more schemes proposed in order to increase the utility which considers the parameter data rate and rate loss because of sensing error reoccupation buy a primary user [47].

VI. CONCLUSION

This paper surveys different area of low power and energy efficient cognitive radio functionality from spectrum sensing and analysis, spectrum management and handoff, to spectrum sharing and allocation. The state of the art of the energy efficient CR based wireless access network, such as relay and cooperative radio and small cells, is reviewed from each aspect. Recent advances and challenges in research related to energy harvesting based green cognitive radios are elicited. Yet, many challenging problems remain to be tackled. This article will hopefully help readers to jump start further research in provisioning green energy powered cognitive radio networks.

REFERENCES

[1] T. Han and N. Ansari, "On greening cellular networks via multicell cooperation," Wireless Communications, IEEE, vol. 20, no. 1, pp. 82–89, 2013.
[2] A. D. Domenico, E. C. Strinati, and A. Capone, "Enabling green cellular networks: A survey and outlook," Computer Communications, vol. 37, no. 0, pp. 5 – 24, 2014.
[3] S. Haykin, "Cognitive radio: brain-empowered wireless communications," Selected Areas in Communications, IEEE Journal on, vol. 23, no. 2, pp. 201–220, 2005.
[4] J. Mitola, "Cognitive Radio," Licentiate proposal, KTH, Stockholm, Sweden.
[5] Q. Zhao and B. Sadler, "A Survey of Dynamic Spectrum Access," Signal Processing Magazine, IEEE, vol. 24, no. 3, pp. 79–89, 2007.
[6] B. Wang and K. Liu, "Advances in cognitive radio networks: A survey," Selected Topics in Signal Processing, IEEE Journal of, vol. 5, no. 1, pp. 5–23, 2011.
[7] I. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," Communications Magazine, IEEE, vol. 46, no. 4, pp. 40–48, 2008.
[8] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," Communications Surveys Tutorials, IEEE, vol. 11, no. 1, pp. 116–130, 2009.
[9] H. Sun, A. Nallanathan, C.-X. Wang, and Y. Chen, "Wideband spectrum sensing for cognitive radio networks: a survey," Wireless Communications, IEEE, vol. 20, no. 2, pp. 74–81, 2013.
[10] S. Atapattu, C. Tellambura, and H. Jiang, "Energy Detection Based Cooperative Spectrum Sensing in Cognitive Radio Networks," Wireless Communications, IEEE Transactions on, vol. 10, no. 4, pp. 1232–1241, 2011.

[11] J. Wang, M. Ghosh, and K. Challapali, “Emerging cognitive radio applications: A survey,” Communications Magazine, IEEE, vol. 49, no. 3, pp. 74–81, March 2011.
[12] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, “NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey,” Comput. Netw., vol. 50, no. 13, pp. 2127–2159, Sep. 2006.
[13] T. Le, K. Mayaram, and T. Fiez, “Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks,” Solid- State Circuits, IEEE Journal of, vol. 43, no. 5, pp. 1287–1302, 2008.
[14] H. Jabbar, Y. Song, and T. Jeong, “RF energy harvesting system and circuits for charging of mobile devices,” Consumer Electronics, IEEE Transactions on, vol. 56, no. 1, pp. 247–253, 2010.
[15] M. Buddhikot, “Understanding Dynamic Spectrum Access: Models, Taxonomy and Challenges,” in New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on, April 2007, pp. 649–663.
[16] S. Haykin, D. Thomson, and J. Reed, “Spectrum Sensing for Cognitive Radio,” Proceedings of the IEEE, vol. 97, no. 5, pp. 849–877, 2009.
[17] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” Selected Areas in Communications, IEEE Journal on, vol. 23, no. 2, pp. 201–220, 2005.
[18] G. Gur and F. Alagoz, “Green wireless communications via cognitive dimension: an overview,” Network, IEEE, vol. 25, no. 2, pp. 50–56, 2011.
[19] R. Deng, S. He, J. Chen, J. Jia, W. Zhuang, and Y. Sun, “Energy efficient spectrum sensing by optimal periodic scheduling in cognitive radio networks,” Communications, IET, vol. 6, no. 6, pp. 676–684, 2012.
[20] X. Gan, M. Xu, and H. Li, “Energy efficient sequential sensing in multiuser cognitive ad hoc networks: A consideration of an ADC device,” Communications and Networks, Journal of, vol. 14, no. 2, pp. 188–194, 2012.
[21] E. Axell, G. Leus, and E. Larsson, “Overview of spectrum sensing for cognitive radio,” in Cognitive Information Processing (CIP), 2010 2nd International Workshop on, 2010, pp. 322–327.
[22] L. Wang, J. Wang, G. Ding, F. Song, and Q. Wu, “A survey of clusterbased cooperative spectrum sensing in cognitive radio networks,” in Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC), 2011, vol. 1, 2011, pp. 247–251.
[23] N. Nguyen-Thanh and I. Koo, “A cluster-based selective cooperative spectrum sensing scheme in cognitive radio,” EURASIP Journal on Wireless Communications,and,Networking,vol.,2013no.1,p.176, 2013.
[24] J. Wei and X. Zhang, “Energy-Efficient Distributed Spectrum Sensing for Wireless Cognitive Radio Networks,” in INFOCOM IEEE Conference on Computer Communications Workshops , 2010, 2010, pp. 1–6.
[25] B. Wang, K. Liu, and T. Clancy, “Evolutionary cooperative spectrum sensing game: how to collaborate?” Communications, IEEE Transactions on, vol. 58, no. 3, pp. 890–900, 2010.
[26] J. Lai, E. Dutkiewicz, R. P. Liu, and R. Vesilo, “Comparison of cooperative spectrum sensing strategies in distributed cognitive radio networks,” in Global Communications Conference (GLOBECOM), 2012 IEEE, 2012, pp. 1513–1518.
[27] W.-B. Chien, C.-K. Yang, and Y.-H. Huang, “Energy-Saving Cooperative Spectrum Sensing Processor for Cognitive Radio System,” Circuits and Systems I: Regular Papers, IEEE Transactions on, vol. 58, no. 4, pp. 711–723, 2011.
[28] X. Sun and D. Tsang, “Energy-Efficient Cooperative Sensing Schedul 1553- 877X (c) 2013 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
[29] H. Jiang, L. Lai, R. Fan, and H. Poor, “Optimal selection of channel sensing order in cognitive radio,” Wireless Communications, IEEE Transactions on, vol. 8, no. 1, pp. 297–307, 2009.

[30] Y. Chen, Q. Zhao, and A. Swami, “Distributed Spectrum Sensing and Access in Cognitive Radio Networks With Energy Constraint,” Signal Processing, IEEE Transactions on, vol. 57, no. 2, pp. 783–797, 2009.
[31] W.-Y. Lee and I. Akyildiz, “Spectrum-Aware Mobility Management in Cognitive Radio Cellular Networks,” Mobile Computing, IEEE Transactions on, vol. 11, no. 4, pp. 529–542, 2012.
[32] L.-C. Wang and C.-W. Wang, “Spectrum Handoff for Cognitive Radio Networks: Reactive-Sensing or Proactive-Sensins?” in Performance, Computing and Communications Conference, 2008. IPCCC 2008. IEEE International, 2008, pp. 343–348.
[33] C.-W. Wang and L.-C. Wang, “Analysis of reactive spectrum handoff in cognitive radio networks,” Selected Areas in Communications, IEEE Journal on, vol. 30, no. 10, pp. 2016–2028, November 2012.
[34] C. Wu, C. He, L. Jiang, and Y. Chen, “A Novel Spectrum Handoff Scheme with Spectrum Admission Control in Cognitive Radio Networks,” in Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE, Dec 2011, pp. 1–5.
[35] W. Ahmed, J. Gao, H. Suraweera, and M. Faulkner, “Comments on ”Analysis of cognitive radio spectrum access with optimal channelreservation,” Wireless Communications, IEEE Transactions on, vol. 8, no. 9, pp. 4488–4491, September 2009.

[36] Q. Li, Z. Feng, W. Li, and T. Gulliver, "Joint temporal and spatial spectrum sharing in cognitive radio networks: A region-based approach with cooperative spectrum sensing," in Wireless Communications and Networking Conference (WCNC), 2013 IEEE, 2013, pp. 620–625.

[37] J. Huang, R. A. Berry, and M. L. Honig, "Auction-based spectrum sharing," Mob. Netw. Appl., vol. 11, no. 3, pp. 405–418, Jun. 2006.

[38] S. Stotas and A. Nallanathan, "Enhancing the Capacity of Spectrum Sharing Cognitive Radio Networks," Vehicular Technology, IEEE Transactions on, vol. 60, no. 8, pp. 3768–3779, 2011.

[39] Q. Zhang, J. Jia, and J. Zhang, "Cooperative relay to improve diversity in cognitive radio networks," Communications Magazine, IEEE, vol. 47, no. 2, pp. 111–117, 2009.

[40] R. Etkin, A. Parekh, and D. Tse, "Spectrum sharing for unlicensed bands," Selected Areas in Communications, IEEE Journal on, vol. 25, no. 3, pp. 517–528, 2007.

[41] D. Niyato and E. Hossain, "Spectrum trading in cognitive radio networks: A market-equilibrium-based approach," Wireless Communications, IEEE, vol. 15, no. 6, pp. 71–80, 2008.

[42] R. Zhang, Y.-C. Liang, and S. Cui, "Dynamic Resource Allocation in Cognitive Radio Networks," Signal Processing Magazine, IEEE, vol. 27, no. 3, pp. 102–114, 2010.

[43] K. Illanko, M. Naeem, A. Anpalagan, and D. Androutsos, "Low complexity energy efficient power allocation for green cognitive radio with rate constraints," in Global Communications Conference (GLOBECOM), 2012 IEEE, 2012, pp. 3377–3382.

[44] S. Buzzi and D. Saturnino, "A Game-Theoretic Approach to Energy- Efficient Power Control and Receiver Design in Cognitive CDMA Wireless Networks," Selected Topics in Signal Processing, IEEE Journal of, vol. 5, no. 1, pp. 137–150, 2011.

[45] T. Han and N. Ansari, "Auction-based Energy-Spectrum Trading in Green Cognitive Cellular Networks," Communications (ICC), 2013 IEEE International Conference on, 2013.

[46] Z. Hasan, G. Bansal, E. Hossain, and V. Bhargava, "Energy-efficient power allocation in OFDM-based cognitive radio systems: A riskreturn model," Wireless Communications, IEEE Transactions on, vol. 8, no. 12, pp. 6078–6088, 2009.

[47] S. Gao, L. Qian, and D. Vaman, "Distributed energy efficient spectrum access in cognitive radio wireless ad hoc networks," Wireless Communications, IEEE Transactions on, vol. 8, no. 10, pp. 5202–5213, 2009.