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TECHNICALLY SPEAKING

ENERGY-AWARE APPROACHES IN COGNITIVE RADIO SENSOR NETWORKS

Karel Toledo de la Garza[1]

[1]Department of Electronics, Federico Santa María Technical University, UTFSM, Valparaiso, Chile
[1]e-mail: karel.tdlg@gmail.com

1. COGNITIVE RADIO IN WIRELESS SENSOR NETWORKS

Wireless Sensor Networks (WSN) constitute a new application field that has attracted great interest among researchers in recent years [1]. Due to the expansion of WSN scenarios running in Industrial, Scientific, and Medical (ISM) bands, a new challenge associated with spectral efficiency has arisen. To overcome this issue, Mitola [2] has introduced the concept of Cognitive Radio (CR) which empowers nodes by increasing the radio unit's awareness of its environment. This technology allows each CR node to access the unused frequency bands under certain interference constraints with the primary user (PU) signal.

The introduction of CR to WSN encourages the development of Cognitive Radio Sensor Networks (CRSN) [3]. Better use of the network bandwidth is achieved but at the same time, the task of sensing the spectrum holes to determine idle frequency bands is added to each node. The cooperation between nodes represents the most suitable alternative to improve the spectrum management mechanisms. This compromises the energy efficiency and therefore, it is required to establish mechanisms to extend the network lifetime. Fig. 1 illustrates a scenario where a WSN (green cloud) with cognitive radio capabilities coexists with a primary network (base stations, laptops, etc.) that is licensed to use certain frequency bands. The secondary network should perform energy-efficient operations to sense and access the spectrum when the PU is idle.

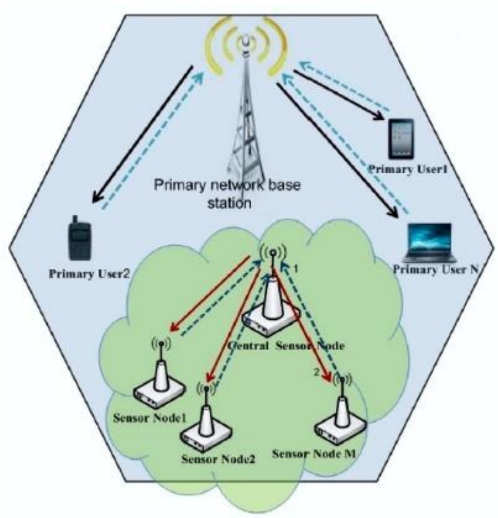

Figure 1: Cognitive Radio Sensor Network.

2. ENERGY-EFFICIENT TECHNIQUES IN CRSN

The nodes in WSNs are equipped with limited power supplies which are usually non-rechargeable batteries. Therefore, this is a critical point provided these networks are designed to operate in an unattended manner for as long as possible. One strategy to compensate for energy consumption is the use of energy harvesting techniques [4]. However, the energy harvested from natural sources can be unstable over time, such as the solar energy. Consequently, WSN must be able to know and manage their energy consumption to extend the network lifespan.

The energy efficiency in CRSN can be analyzed from different approaches considering the protection of PU in spectrum management. A lot of reported solutions addresses this concern from different points of view as follows:

- Cooperative spectrum sensing.
- Sensor selection.
- Spectrum management.
- Resource allocation.
- Packet size optimization.
- Primary user activity.

2.1. COOPERATIVE SPECTRUM SENSING

Regarding the spectrum sensing, reported solutions expose that signal processing techniques (non-cooperative) [5] are affected by undesirable channel effects such as the hidden terminal problem. Therefore, collaborative methods are desired because they achieve greater performance in spectrum sensing operations [6]. As a result, main contributions are associated with cooperative spectrum sensing (CSS).

Some solutions have a common formulation based upon mathematical optimization to maximize or minimize an energy metric in the context of CSS. For instance, in [7] the authors maximize the ratio between throughput and average energy consumption in network subject to constraints in detection performance. Also, some methods focus on how to effectively collaborate between CR nodes as well as maximize energy savings via an evolutionary game model. To let CR nodes sense the spectrum, a contribution-punishment mechanism which can stimulate high signal-to-noise (SNR) nodes to participate in spectrum sensing is described in [8]. Cluster formation is investigated in [9] to improve cooperative sensing. In that work, they determine the optimal number of clusters in the network and demonstrate that the spectrum sensing stage consumes more energy than communication inside the clusters. Finally, the integrity of the information during CSS is discussed in a few papers. Some nodes can send false sensing reports to mislead the spectrum sensing decision, making CRSN vulnerable to spectrum sensing data falsification (SSDF) attacks. Meanwhile, SSDF attack countermeasures should be carefully devised with the consideration of energy efficiency. To this end, an energy-efficient collaborative spectrum sensing scheme to resist SSDF attacks and enhance the energy efficiency in CRSN is presented in [10].

2.2. SENSOR SELECTION

The disadvantage of cooperative spectrum sensing is the increase in the amount of energy consumed by each node due to the information exchange. Therefore, minimizing the number of cooperating nodes becomes an essential issue. Most common solutions are based on optimization problems with different objective functions, constraints, and solution methods.

In specifics, regarding the sensor selection strategies for CSS, several solutions are reported to specify which nodes will participate in CSS, remaining nodes will be on sleep mode to reduce energy consumption and extend the network lifetime. These strategies determine the total minimum number of awake nodes while satisfying detection performance, simultaneously. Early works on sensor selection over centralized CRSN have been presented in [11], where awake nodes are selected for solving a convex optimization problem. More comprehensive analyses focused on balancing the energy consumption process among sensor nodes, taking into account the remaining energy of nodes, and also exploiting diversity advantages in multi-antenna sensors, are discussed in [12]. Another approach presented in [13] considers the problem of joint sensing node selection, detection threshold, and decision node selection with the knowledge of instantaneous or average SNR for each node. In addition, a solution that assumes partial information about some network parameters and multiple PUs located on a given simulation field is proposed in [14].

2.3. SPECTRUM MANAGEMENT

To analyze spectrum management, two scenarios are described: cognitive radio features integrated into sensors or a cognitive radio network as a service to WSN [15]. A solution for energy-efficient spectrum sensing is analyzed in [16] where sensors with cognitive radio capabilities are implemented as a standalone network. The authors formulate an optimization problem for the periodical sensor planning considering the protection of the PU, the throughput of the SU, and the battery life. Dynamic spectrum access is a main concern to achieve a balance between interference to the PU and energy efficiency in network. A set of solutions addresses this problem through mathematical optimization. For instance, a new concept is proposed by Ren [17] by accessing the licensed frequency bands only when the packet loss on free channels increases. Besides, Lin [18] deal with the process of spectrum sensing by considering the selection of the optimal number of SUs, fair competition, and efficient utilization of spectrum access. They employ a greedy algorithm based on a non-cooperative game model to select the most competitive SUs according to the amount of data, residual energy, and privacy metric.

2.4. RESOURCE ALLOCATION

Network resource allocation makes it possible to optimize the energy consumption of each node in CRSN. Regarding the modulation, Gao [19] proposes the design of cognitive radio and multi-carrier modulation scheme that achieves high energy and bandwidth efficiency. The main contribution is the implementation of an adaptive Quadrature Amplitude Modulation (QAM) strategy that selects the optimal constellation size to maximize the network lifetime. A variety of solutions focus on optimizing the transmission power through mathematical optimization. A solution for scenarios composed by one transmitter and multiple receivers subject to constraints in transmission rate and interference with the PU is discussed in [20]. Another application is found in [21] where the best data retransmission path is selected based on the knapsack problem. It is important to note that the choice of the best information path depends on the restrictions on the energy consumed and the residual energy. Finally, energy harvesting allows extending the battery life of nodes, and therefore several strategies include this concept in their CRSN applications. A novel optimization variant is addressed in [22] where stochastic programming is used for resource allocation in Energy Harvesting Cognitive Radio Sensor Network (EHCRSN).

2.5. PACKET SIZE OPTIMIZATION

Packet size optimization improves the energy efficiency in CRSN provided short packets enhance the network performance in varying channel conditions and reduce interference to PUs. However, nodes increase power consumption due to the overload caused by transmitting more packet headers and tails. On the other hand, long packets allow a large amount of transmitted data in a short time, but these advantages are achieved at the expense of increasing interference with the PUs and packet loss probability [23]. Oto and Akan [24] are the first to determine the optimal packet size subject to interference and signal distortion constraints. A remarkable conclusion is that the behavior of the PU and the bit error rate (BER) are the most critical parameters to derive the optimal solution provided their variations result in packet sizes between 100 bits and 600 bits. A new paradigm for packet size optimization via a variable rate QAM modulation is presented in [25] applicable to the Internet of Things. This paper proposes a heuristic exhaustive search-based algorithm and a computationally efficient suboptimal low complexity Karuh-Kuhn-Tucker (KKT) condition-based algorithm to compute the optimal packet size.

2.6. PRIMARY USER ACTIVITY

Primary user activity is analyzed independently for each wireless network. However, Rehmani [26] contributes significantly to develop adaptive schemes that detect and classify the PU activity based on the kind of network. A comprehensive summary of PU activity models for CRSN is presented for the first time by Saleem and Rehmani [27]. In that work, a taxonomy of the different models reported in the state of the art to analyze the behavior of PU is introduced. Those models are classified as: Markov processes, queuing theory, on/off states -based, time series, among others, which provide a starting point to choose the most suitable method for each specific application.

3. CHALLENGES AND OPEN PROBLEMS

The cognitive radio paradigm addresses the spectrum scarcity concern in WSN. However, there are several challenges to improve network performance in various scenarios. Regarding the selection of nodes, many proposed methods involve a free space loss model to analyze the path loss between the nodes and the PU. Therefore, fading effects are considered a future study problem. In addition, adaptive transmission power has not been addressed in CRSNs using energy harvesting techniques. Analysis of dynamic routing protocols under adaptative channel access and sampling rate control to dynamically varying routing paths is an open problem too. In general, the spectrum sensing is assumed to be error-free and thus, the problem of imperfect sensing for real applications arises as a problem to be investigated. The new approach for packet size optimization presented in [25] can be applied to other channel access strategies. Furthermore, they introduce time variable spectrum sensing as future work. Mobility in current networks has begun to be studied by many authors provided the application in 5G and beyond-5G networks. Two important aspects state in these environments, the first one is the dynamic of network participants and the other one is the deployment and the most appropriate trajectory for the base stations. Finally, predictions about massive capacity and connectivity in next-generation networks will require energy-aware solutions involved in all layers of wireless communications standards, that is, green communications will remain a big challenge.

REFERENCES

[1] S. Aslam, W. Ejaz, y M. Ibnkahla, «Energy and Spectral Efficient Cognitive Radio Sensor Networks for Internet of Things», *IEEE Internet of Things Journal*, vol. 5, n.º 4, pp. 3220-3233, ago. 2018, doi: 10.1109/JIOT.2018.2837354.
[2] J. Mitola y G. Q. Maguire, «Cognitive radio: making software radios more personal», *IEEE Personal Communications*, vol. 6, n.º 4, pp. 13-18, ago. 1999, doi: 10.1109/98.788210.
[3] M. Ibnkahla, *Wireless Sensor Networks: A Cognitive Perspective*. CRC Press, 2016.
[4] R. Deng, Y. Zhang, S. He, J. Chen, y X. Shen, «Maximizing Network Utility of Rechargeable Sensor Networks With Spatiotemporally Coupled Constraints», *IEEE Journal on Selected Areas in Communications*, vol. 34, n.º 5, pp. 1307-1319, may 2016, doi: 10.1109/JSAC.2016.2520181.
[5] R. Husain Mubashir, *Cognitive Radio Sensor Networks: Applications, Architectures, and Challenges*. IGI Global, 2014.
[6] A. Ghasemi y E. S. Sousa, «Collaborative spectrum sensing for opportunistic access in fading environments», en *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, nov. 2005, pp. 131-136, doi: 10.1109/DYSPAN.2005.1542627.
[7] M. Zheng, L. Chen, W. Liang, H. Yu, y J. Wu, «Energy-Efficiency Maximization for Cooperative Spectrum Sensing in Cognitive Sensor Networks», *IEEE Transactions on Green Communications and Networking*, vol. 1, n.º 1, pp. 29-39, mar. 2017, doi: 10.1109/TGCN.2016.2646819.
[8] X. Ma, F. Zeng, y J. Xu, «A novel energy efficient cooperative spectrum sensing scheme for cognitive radio sensor network based on evolutionary game», en *The 21st IEEE International Workshop on Local and Metropolitan Area Networks*, abr. 2015, pp. 1-6, doi: 10.1109/LANMAN.2015.7114726.
[9] I. Mustapha, B. M. Ali, A. Sali, M. F. A. Rasid, y H. Mohamad, «Energy-aware cluster based cooperative spectrum sensing for cognitive radio sensor networks», en *2014 IEEE 2nd International Symposium on Telecommunication Technologies (ISTT)*, nov. 2014, pp. 45-50, doi: 10.1109/ISTT.2014.7238174.
[10] J. Ren, Y. Zhang, Q. Ye, K. Yang, K. Zhang, y X. S. Shen, «Exploiting Secure and Energy-Efficient Collaborative Spectrum Sensing for Cognitive Radio Sensor Networks», *IEEE Transactions on Wireless Communications*, vol. 15, n.º 10, pp. 6813-6827, oct. 2016, doi: 10.1109/TWC.2016.2591006.
[11] M. Najimi, A. Ebrahimzadeh, S. M. H. Andargoli, y A. Fallahi, «A Novel Sensing Nodes and Decision Node Selection Method for Energy Efficiency of Cooperative Spectrum Sensing in Cognitive Sensor Networks», *IEEE Sensors Journal*, vol. 13, n.º 5, pp. 1610-1621, may 2013, doi: 10.1109/JSEN.2013.2240900.
[12] S. H. Hojjati, A. Ebrahimzadeh, S. M. H. Andargoli, y M. Najimi, «Energy efficient cooperative spectrum sensing in wireless multi-antenna sensor network», *Wireless Netw*, vol. 23, n.º 2, pp. 567-578, ene. 2016, doi: 10.1007/s11276-015-1175-x.
[13] A. Ebrahimzadeh, M. Najimi, S. M. H. Andargoli, y A. Fallahi, «Sensor Selection and Optimal Energy Detection Threshold for Efficient Cooperative Spectrum Sensing», *IEEE Transactions on Vehicular Technology*, vol. 64, n.º 4, pp. 1565-1577, abr. 2015, doi: 10.1109/TVT.2014.2331681.
[14] A. Bagheri, A. Ebrahimzadeh, y M. Najimi, «Sensor selection for extending lifetime of multi-channel cooperative sensing in cognitive sensor networks», *Physical Communication*, vol. 26, pp. 96-105, feb. 2018, doi: 10.1016/j.phycom.2017.11.003.
[15] M. B. H. Weiss, S. Delaere, y W. H. Lehr, «Sensing as a Service: An Exploration into Practical Implementations of DSA», en *2010 IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN)*, abr. 2010, pp. 1-8, doi: 10.1109/DYSPAN.2010.5457829.
[16] R. Deng, S. He, J. Chen, J. Jia, W. Zhuang, y Y. Sun, «Energy-efficient spectrum sensing by optimal periodic scheduling in cognitive radio networks», *IET Communications*, vol. 6, n.º 6, pp. 676-684, abr. 2012, doi: 10.1049/iet-com.2011.0565.
[17] J. Ren, Y. Zhang, N. Zhang, D. Zhang, y X. Shen, «Dynamic Channel Access to Improve Energy Efficiency in Cognitive Radio Sensor Networks», *IEEE Transactions on Wireless Communications*, vol. 15, n.º 5, pp. 3143-3156, may 2016, doi: 10.1109/TWC.2016.2517618.
[18] K. Lin, H. Si, L. Kang, X. Li, y Y. Zhang, «Energy Efficient Spectrum Access for Cognitive Radio Sensor Networks», en *2014 International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery (CyberC)*, oct. 2014, pp. 464-469, doi: 10.1109/CyberC.2014.86.
[19] S. Gao, L. Qian, D. R. Vaman, y Q. Qu, «Energy Efficient Adaptive Modulation in Wireless Cognitive Radio Sensor Networks», en *2007 IEEE International Conference on Communications*, jun. 2007, pp. 3980-3986, doi: 10.1109/ICC.2007.655.

[20] J. R. A. Solares, Z. Rezki, y M. S. Alouini, «Optimal power allocation of a single transmitter-multiple receivers channel in a cognitive sensor network», en *2012 International Conference on Wireless Communications in Unusual and Confined Areas (ICWCUCA)*, ago. 2012, pp. 1-6, doi: 10.1109/ICWCUCA.2012.6402479.

[21] A. Y. Elnakeeb, H. M. Elsayed, y M. M. Khairy, «Energy minimization and lifetime enhancement in Cognitive Radio Sensor Networks via relaying under interference constraints», en *2014 Euro Med Telco Conference (EMTC)*, nov. 2014, pp. 1-6, doi: 10.1109/EMTC.2014.6996629.

[22] D. Zhang, Z. Chen, M. K. Awad, N. Zhang, H. Zhou, y X. S. Shen, «Utility-Optimal Resource Management and Allocation Algorithm for Energy Harvesting Cognitive Radio Sensor Networks», *IEEE Journal on Selected Areas in Communications*, vol. 34, n.º 12, pp. 3552-3565, dic. 2016, doi: 10.1109/JSAC.2016.2611960.

[23] A. Jamal, C. K. Tham, y W. C. Wong, «Dynamic Packet Size Optimization and Channel Selection for Cognitive Radio Sensor Networks», *IEEE Transactions on Cognitive Communications and Networking*, vol. 1, n.º 4, pp. 394-405, dic. 2015, doi: 10.1109/TCCN.2016.2531082.

[24] M. C. Oto y O. B. Akan, «Energy-Efficient Packet Size Optimization for Cognitive Radio Sensor Networks», *IEEE Transactions on Wireless Communications*, vol. 11, n.º 4, pp. 1544-1553, abr. 2012, doi: 10.1109/TWC.2012.021412.021512.111398.

[25] C. Majumdar, D. Lee, A. A. Patel, S. N. Merchant, y U. B. Desai, «Packet Size Optimization for Cognitive Radio Sensor Networks Aided Internet of Things», *IEEE Access*, vol. 5, pp. 6325-6344, 2016, doi: 10.1109/ACCESS.2016.2619358.

[26] M. H. Rehmani, «Opportunistic Data Dissemination in Ad-Hoc Cognitive Radio Networks», phdthesis, Université Pierre et Marie Curie - Paris VI, 2011.

[27] Y. Saleem y M. H. Rehmani, «Primary radio user activity models for cognitive radio networks: A survey», *Journal of Network and Computer Applications*, vol. 43, pp. 1-16, ago. 2014, doi: 10.1016/j.jnca.2014.04.001.

ABOUT THE AUTHOR

Karel Toledo received a B.Sc. degree in Telecommunication Engineering and an M.Sc. degree in Digital Systems from the Technological University of Havana, Cuba, in 2012 and 2015, respectively. Also, he received a Ph.D. degree in Engineering Sciences, mention in Automation from the University of Santiago de Chile, Chile, in 2020. He is currently with the Department of Electronics, Federico Santa María Technical University, as a postdoc. He has been with the Department of Telecommunications and Telematics, Technological University of Havana, CUJAE, Cuba, as a professor, from 2013 to 2015. In addition, he has been with the Department of Electrical Engineering, University of Santiago de Chile, Chile, as a lecturer, from 2019 to 2020. His research interests include wireless communication systems, energy-efficient spectrum management, optimization, and digital signal processing.