ISSN: 2278 – 909X
International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE)
Volume 5, Issue 10, October 2016

A novel scheme for Joint Spectrum Sensing and Power Allocation for Cognitive Radio Networks

Ms.Preeti singh,MIT Ujjain

Prof.sandeep agrawal,Asst. Prof., MIT Ujjain

Abstract**—**Fifth-generation (5G) wireless networks are expected to achieve 1000 times higher capacity compared with fourthgeneration wireless networks. Thus, improving the spectrum efficiency (SE) is a crucial problem, which must be considered. Cognitive radio (CR) is considered an effective approach to alleviate the spectrum scarcity problem. In this paper, based on the location information of the primary transmitter (PT) and the CR network, we estimate the distance between the PT and the secondary transmitter (ST) and then propose a joint spectrum sensing and power allocation (JSS-PA) scheme to improve the SE of the CR network. In the JSS-PA scheme, we focus on jointly optimizing the sensing parameters and the transmit power of the secondary user (SU) such that the SE is maximized, whereas the primary user (PU) outage constraint is satisfied.When cooperative spectrum sensing is employed to detect the PU's status, we analyze two cooperative strategies, i.e., soft information fusion (SIF) and hard information fusion (HIF). Under the SIF strategy, the optimization of sensing and power (S-OSP) algorithm is proposed to maximize the SE. Under the HIF strategy, the optimization of thresholds (H-OT) algorithm is proposed, and then, the optimization of sensing and power (H-OSP) algorithm is proposed to find the optimal duration of local sensing, the optimal transmit power of the SU, and the optimal final decision threshold. Finally, we present the simulation results to evaluate the performance of the proposed JSS-PA scheme and discuss the effects of the optimal parameters on different schemes under SIF and HIF strategies.

Index Terms**—**Cognitive radio (CR), hard information fusion (HIF), location information, power allocation, soft information fusion (SIF), spectrum sensing.

I. INTRODUCTION

FUTURE wireless networks will face several challenges, such as higher data rates, lower energy consumption, higher spectrum efficiency (SE), and so on [1]. Fifth-generation (5G) wireless systems, which are expected to solve these challenges, have attracted much attention in recent years [2]–[4]. It is widely agreed that the system capacity of the 5G network is 1000 times higher than that of the fourth-generation network [5]. To achieve this goal, we need more bandwidth, higher area capacity, higher SE, etc. Improving the SE is an important task since the current spectrum utilization is not quite efficient [6]. Cognitive radio (CR), with the aim of increasing the SE, has been proposed [7]. It enables dynamic spectrum access by allowing the secondary users (SUs) to access the spectrum bands that are allocated to the primary users (PUs) [8]. Accordingly, the CR technology has attracted a lot of attention from academia and industry [9]. The aim of the IEEE 802.22 wireless regional area network (WRAN) standard is to allow sharing of geographically unused spectrum bands allocated to the TV broadcast service. It is required that no harmful interference is caused to the incumbent operation (i.e., TV users) and low-power licensed devices [10]. To utilize the licensed spectrum bands without causing interference to the PUs, theWRAN system should be cognizant of all the incumbent operations nearby. The SUs can utilize the licensed spectrum bands via spectrum sensing or power allocation. In the former scheme, the SUs need to perform spectrum sensing to detect the PU's status. Only when the PU is absent that the SUs are allowed to transmit data. However, when the PU is present, the CR network will not be able to utilize the spectrum. We call it *only spectrum sensing* (OSS) scheme in this paper. In the latter scheme, the SUs do not need to perform spectrum sensing and are allowed to transmit data simultaneously with the PU, as long as the interference power is constrained to below a tolerable level. However, the SU needs to estimate the interference power caused to the PU [11]. We call it *only power allocation* (OPA) scheme in this paper. No matter which scheme is used, the QoS of the PU should be guaranteed. However, under the condition of PU outage constraint, which scheme performs better on improving the SE? In this paper, we investigate the effects of the SUs' locations on the scheme selection. When the distance between the primary network and the secondary network is very short, the transmission of the secondary transmitter (ST), even with a small value of transmit power, may make the primary receiver (PR) in outage. In this scenario, the SE of the OPA scheme will be low due to the PU outage constraint. The SUs may employ the OSS scheme because the SNR of the received signal is high and the SUs can easily detect the primary transmitter (PT)'s status. Thus, the SE can be improved. When the distance between the primary

network and the secondary network is very long, the data transmission between the SUs will have little interference on the PU transmission. Because of the effect of path loss, the PU outage constraint may be satisfied, even when the ST transmits data with its maximum power. In this scenario, the spectrum sensing is unnecessary because it introduces additional overhead. Hence, the OSS scheme may perform worse than the
OPA scheme. In other scenarios, joint spectrum sensing and power control can be used to protect the PRs. In previous works
[12], a joint spectrum sensing, access, and power allocation
scheme was proposed to improve the SUs' throughput.

II. SYSTEM MODEL AND PROBLEM FORMULATION

Our system model is shown in Fig. 1. In the primary network, PT denotes the PU transmitter, and PR represents the PU receiver. We suppose that the location of the PT and the transmit power of the PT are known to the SUs. This assumption is reasonable. When the PT is TV transmitter, its location and transmit power are possibly known because these parameters are fixed. In [23], the FC can use the energy levels sent by the SUs to construct channel gain (CG) maps and estimates the PU locations and the transmit power levels. However, the SUs are unable to access the database and hence do not have the knowledge of operation time of the PT. Thus, spectrum sensing is required to decide whether the PT is present. Since the PRs should be protected, a PT-centered boundary will be determined by the minimum SNR of received PT signal. Without loss of generality, the PT is assumed located at coordinate (0, 0). The protected area is a circular field, and the radius of the protected boundary is denoted L.

The CR network consists of a number of SUs and an FC. We consider that the SUs are uniformly distributed in a circular field with a radius of r, and the FC is assumed located in the center. To obtain the location information, the devices in the CR network are equipped with satellite-based geolocation technology (e.g., GPS). The SUs detect the PT's status in the local sensing phase. In the reporting phase, all the sensing results are reported to the FC via a common control channel. Then, the FC makes a final decision to indicate that the PT is present or absent. If the PT is absent, one of the SUs is allowed to conduct data transmission.

A. OSS Scheme

The transmit power of the ST is denoted P_{ST}, and the distance between the ST and the secondary receiver (SR) is assumed to be l_{SS}. The received power of SR from ST can be calculated as $P_{lSS} = \left(P_{ST} \cdot g_S \cdot h_{SS}^2\right) / l_{SS}^{\in}$, where g_s is the CG between the ST and the SR, and h_{SS} is the channel response of the ST to SR. When the PT is absent, the transmission rate of the CR network can be computed by

$$\Upsilon_1 = \log_2(1+\gamma_S) = \log_2\left(1+\frac{P_{lSS}}{\sigma_2^2}\right) = \log_2\left(1+\frac{P_{ST} \cdot g_S \cdot h_{SS}^2}{l_{SS}^{\in} \cdot \sigma_2^2}\right) \quad (1)$$

where γ_S denotes the SNR of the secondary link, and σ_2^2 is the variance of the noise at the SR. However, in a realistic scenario, perfect spectrum sensing without sensing error is not achievable, and the PT's true status may be incorrectly detected. This distance between the PT and the SR is assumed to be l_{PS}, and the received power of SR from PT can be calculated as $P_{lPS} = \left(P_{PT} \cdot g_P \cdot E\left[h_P^2\right]\right) / l_{PS}^{\in}$. When the PT is incorrectly detected to be absent, although its true status is present, the transmission rate of the CR network can be calculated as

$$\Upsilon_2 = \log_2(1+\gamma_{SI}) = \log_2\left(1+\frac{P_{lSS}}{\sigma_2^2}\right) = \log_2\left(1+\frac{P_{ST} \cdot g_S \cdot h_{SS}^2 \cdot l_{PS}^{\in}}{\left\{\sigma_2^2 \cdot l_{PS}^{\in} + P_{PT} \cdot g_P \cdot E\left[h_P^2\right]\right\} \cdot l_{SS}^{\in}}\right) \quad (2)$$

where γ_{SI} denotes the signal-to-interference-plus-noise ratio of the secondary link.

It is assumed that the distance between the PT and the ST is d_{PS}, the coordinate of the ST is (x_{ST}, y_{ST}), and, and the coordinate of the SR is (x_{SR}, y_{SR}). Then, we can obtain that $d_{PS} = \sqrt{x_{ST}^2 + y_{ST}^2}$, $l_{PS} = \sqrt{x_{SR}^2 + y_{SR}^2}$, and $l_{SS} = \sqrt{(x_{ST} - x_{SR})^2 + (y_{ST} - y_{SR})^2}$.

The ST will conduct data transmission in the following two cases.

1) The PT's true status is absent, and the final decision of the FC indicates that the PT is absent. The probability of this case happening is α (1 - Q_{FA}), where α represents the probability that the PT's true status is absent.

2) The PT's true status is present, and the final decision of the FC indicates that the PT is absent, i.e., missed detection occurs. The probability of this case happening is (1 - α) Q_{MD}, where 1 - α represents the probability that the PT's true status is present.

B. OPA Scheme

When the location of the ST is outside the protected area (e.g., CNR 2 in Fig. 1), the SUs may employ the OSS, OPA, or JSS-PA scheme. The OSS scheme has been analyzed in Section II-A. For the OPA scheme, the SUs do not need to perform spectrum sensing; however, the ST should control its transmit power to avoid interference to the PRs. Since the locations of the PRs, the SUs should suppose that one PR is located on the protected boundary, and this PR is also located on the line between the PT and ST. Thus, the distance between the PT and the PR is L, and the received power of the PR from the PT is $P_L = (P_{PT} \cdot g_P \cdot E[h_P^2])/L^{\in}$. The distance between the ST and the PR is assumed to be l_{SP}, and the received power of the PRfrom the ST can be calculated as $P_{lSP} = (P_{ST} \cdot g_S \cdot h_{SP}^2)/l_{SP}^{\in}$, where h_{SP} is the channel response of the ST to the PR, and h_{SP}^2 is assumed exponentially distributed with $E[h_{SP}^2] = 1$. If the ratio of SU signal over PU signal is larger than a present value θ, the PR will be in outage. In the OPA scheme, the outage probability of the PR is given as follows:

$$p_{out} = P_{rob}\left\{\frac{P_{lSP}}{P_L} > \theta\right\} = P_{rob}\left\{\frac{P_{ST} \cdot g_S \cdot L^{\in} \cdot h_{SP}^2}{P_{PT} \cdot g_P \cdot l_{SP}^{\in} \cdot E[h_P^2]} > \theta\right\} \quad (14)$$

$$= e^{-\frac{\theta \cdot P_{pt} \cdot g_P \cdot l_{SP}^{\in} \cdot E[h_P^2]}{P_{ST} \cdot g_s \cdot L^{\in}}}$$

To sufficiently protect the PRs, p_{out} must be equal to or less than p_{out}^{th}, i.e., $p_{out} \le p_{out}^{th}$. Then, we can obtain that

$$P_{ST} \le -\frac{\theta \cdot P_{PT} \cdot g_P \cdot l_{SP}^{\in} \cdot E[h_P^2]}{\ln(p_{out}^{th}) \cdot g_s \cdot L^{\in}} = P_{ST}^{\circ} \quad (3)$$

To maximize the SE of the CR network, the transmit power of the ST should be equal to P_{ST}°. In this case, the average SE of the CR network can be presented as

$$\Phi = \Phi_1 + \Phi_2 = \alpha \cdot \log_2\left(1 + \frac{P_{ST}^{\circ} \cdot g_S \cdot h_{SS}^2}{l_{SS}^{\in} \cdot \sigma_2^2}\right) + (1 - \alpha) \cdot \log_2\left(1 + \frac{P_{ST}^{\circ} \cdot g_S \cdot h_{SS}^2 \cdot l_{PS}^{\in}}{\left(\sigma_2^2 \cdot l_{PS}^{\in} + P_{PT} \cdot g_P \cdot E[h_P^2]\right) l_{SS}^{\in}}\right). \quad (4)$$

When the location of the ST is quite far away from the PT and l_{SP} is a very large value (e.g., CNR 4 in Fig. 1), the data transmission between the SUs will have little interference on the PU transmission. Due to the effect of path loss, p_{out} may be equal to or less than p_{out}^{th} even when the ST transmits data with its maximum power $P_{ST,\,max}$. In this case, the spectrum sensing is unnecessary because it introduces additional overhead, and the OPA scheme is better compared with the OSS scheme. It is assumed that, when $l_{SP} \ge l_{SP}^{th}$, the ST can transmit data with its maximum power $P_{ST,\,max}$, and $p_{out} \le p_{out}^{th}$ is also guaranteed. When the distance between the ST and the PR is l_{SP}^{th} and the ST transmits data with $P_{ST,\,max}$, the received power of PR from ST can be calculated as $P_{lSP}^{th} = Pl_{SP}^{th} = (P_{ST,\max} \cdot g_S \cdot h_{SP}^2)/(l_{SP}^{th})^{\in}$. Then, the outage probability of PR is given by

$$p_{out} = P_{rob}\left\{\frac{P_{lSP}^{th}}{P_L} > \theta\right\} = e^{-\frac{\theta \cdot P_{PT} \cdot g_P \cdot (l_{SP}^{th})^{\in} \cdot E[h_P^2]}{P_{ST,\max} \cdot g_S \cdot L^{\in}}} = p_{out}^{th} \quad (5)$$

Solving the given equation, it is derived that

$$l_{SP}^{th} = L \cdot \left[-\frac{P_{ST,\max} \cdot g_S \cdot \ln\left(p_{out}^{th}\right)}{\theta \cdot P_{PT} \cdot g_P \cdot E\left[h_P^2\right]} \right]^{\frac{1}{\in}} \quad (6)$$

Let $L^+ = L + l_{SP}^{th}$. When $d_{PS} \geq L^+$, the ST can transmit data with its maximum power $P_{ST,\max}$ to maximize the SE of the CR network.

C. JSS-PA Scheme

When the location of the ST is outside the protected area and $L < d_{PS} < L^+$ (e.g., CNR 3 in Fig. 1), joint spectrum sensing and power control can be used to protect the PRs, i.e., the JSS-PA scheme. In this case, when missed detection occurs, the SUs coexist with PUs in the same frequency band. If the ratio of SU signal over PU signal is larger than a present value θ, the PR will be in outage. Thus, in the JSS-PA scheme, the outage probability of PR can be presented as

$$p_{out} = Q_{MD} \cdot P_{rob}\left\{\frac{P_{lSP}}{P_L} > \theta\right\} = Q_{MD} \cdot P_{rob}\left\{h_{SP}^2 > \frac{\theta \cdot P_{PT} \cdot g_P \cdot l_{SP}^{\in} \cdot E\left[h_P^2\right]}{P_{ST} \cdot g_S \cdot L^{\in}}\right\} = e^{-\frac{\theta \cdot P_{PT} \cdot g_P \cdot l_{SP}^{\in} \cdot E\left[h_P^2\right]}{P_{ST} \cdot g_S \cdot L^{\in}}} \quad (7)$$

In (19), it can be seen that both the missed-detection probability Q_{MD} and ST transmit power P_{ST} can be adjusted to guarantee that $p_{out} \leq p_{out}^{th}$. If the transmit power of the ST is increased with the aim of improving the SE of the CR network, the interference to the PR will be larger; hence, more accurate spectrum sensing technology should be employed to make the missed-detection probability smaller. If the SUs have limited sensing abilities and Q_{MD} is a large value, the ST must control its transmit power to protect the PR sufficiently.

III. SOLUTIONS FORMULATION UNDER SOFT INFORMATION FUSION STRATEGY

In the CR networks, cooperative spectrum sensing requires cooperation among multiple SUs from different locations. When the SIF strategy is employed, the received signal of each SU is amplified and sent to the FC. After the FC collects all the local sensing information, the energy detection technique is used to decide if the PT is present or absent.

For the jth SU, the decision statistic of energy detection is denoted V_j. The FC receives V_1, V_2, …, V_K from the SUs, where K is the number of SUs in the CR network, and V_j are assumed independent and identically distributed. According to [24], when the PT signal is a BPSK signal, the noise is real-valued Gaussian variable with zero mean and variance σ^2; thus, we have

$$V_j \sim N\left(\sigma^2, \frac{2\sigma^4}{t_{se} f_S}\right) \quad H_0$$

$$V_j \sim N\left(\sigma^2(\gamma_j+1), \frac{2\sigma^4(2\gamma_j+1)}{t_{se} f_S}\right) \quad H_1 \quad (8)$$

In the FC, the test statistic for cooperative spectrum sensing with SIF is $V_S = \phi_1 V_1 + \phi_2 V_2 + \ldots + \phi_K V_K = \sum_{j=1}^{K} \phi_j V_j$ [20], where ϕ_j is the weight coefficient of the jth SU. Since V_j are independent and identically distributed, it is derived that

$$V_j \sim N\left(\sigma^2 \sum_{j=1}^{K} \phi_j, \frac{2\sigma^4}{t_{se} f_S} \sum_{j=1}^{K} \phi_j^2\right) \quad H_0$$

$$V_j \sim N\left(\sigma^2 \sum_{j=1}^{K} \phi_j(\gamma_j+1), \frac{2\sigma^4}{t_{se} f_S} \sum_{j=1}^{K} \phi_j^2(2\gamma_j+1)\right) \quad H_1 \quad (27)$$

The probability density functions of V_S under H_0 and H_1 can be, respectively, written as

$$f_{V_S|H_0}(v) = \frac{1}{2\sigma^2}\sqrt{\frac{t_{Se} f_S}{\pi \sum_{j=1}^{K} \phi_j^2}}\, e^{-\frac{t_{Se} f_S \left(v - \alpha^2 \sum_{j=1}^{K} \phi_j\right)^2}{4\sigma^4 \sum_{j=1}^{K} \phi_j^2}} \quad (9)$$

$$f_{V_S|H_1}(v) = \frac{1}{2\sigma^2}\sqrt{\frac{t_{Se} f_S}{\pi \sum_{j=1}^{K} \phi_j^2 (2\gamma_j + 1)}} \times e^{-\frac{t_{Se} f_S \left[v - \alpha^2 \sum_{j=1}^{K} \phi_j (2\gamma_j + 1)\right]^2}{4\sigma^4 \sum_{j=1}^{K} \phi_j^2 (2\gamma_j + 1)}} \quad (10)$$

IV. SOLUTIONS OF FORMULATION UNDER THE HARD INFORMATION FUSION STRATEGY

For cooperative spectrum sensing with HIF, each SU makes a "one bit" decision R_j to indicate the PT's status ($R_j = 0$ represents that the PT is absent, and $R_j = 1$ represents that the PT is present) in the local sensing phase. All the "one bit" decisions are reported to the FC in the reporting phase. Then, according to some fusion rules, the FC makes a final decision on the PT's status.

In the FC, it is assumed that $R = [R_1, R_2 \ldots R_K]$ represents the "one bit" local decisions from the K SUs. Let Ω_0 represents the set of R values that the PT is regarded as absent, and Ω_1 represents the set of R values that the PT is regarded as present. The final decision threshold M in the FC is an integer, and its optimal value is determined by Ω_0 and Ω_1. Since Ω_0 and Ω_1 are complementary, we will only analyze Ω_1 here. The final false-alarm probability, the final detection probability, and the final missed-detection probability of cooperative spectrum sensing with HIF are computed, respectively, as follows :

$$Q_{FA,h} = \sum_{R \in \Omega_1} \left[\prod_{j=1}^{K} \left(1 - p_{fa,j}\right)^{1-R_j} p_{fa,j}^{R_j} \right] \quad (44)$$

$$Q_{DE,h} = \sum_{R \in \Omega_1} \left[\prod_{j=1}^{K} \left(1 - p_{de,j}\right)^{1-R_j} p_{de,j}^{R_j} \right] \quad (45)$$

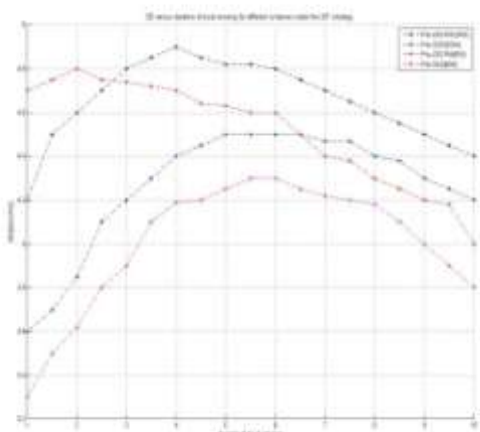
$$Q_{MD,h} = 1 - Q_{DE,h} \quad (46)$$

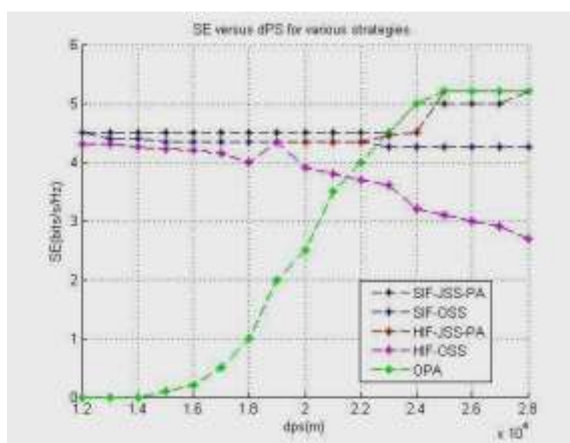
According to (10), for cooperative spectrum sensing with HIF, the average achievable SE of the CR network is given by

$$\Phi_h = [\, \alpha (1 - Q_{FA,h}) \cdot \Upsilon_1 + (1 - \alpha) Q_{MD,h} \cdot \Upsilon_2] \cdot \frac{T - t_{Se} - K t_{re}}{T}. \quad (47)$$

V. SIMULATION RESULTS

Here, computer simulations are conducted to evaluate the performance of the proposed JSS-PA scheme under SIF and HIF strategies. In the simulations, the PT is assumed located at coordinate (0,0). The SUs are uniformly distributed in a circular field with a radius of r = 800 m, the FC is located in the center. The number of SUs is K = 20. If the PT is detected to be absent, one of the SUs is allowed to conduct data transmission, and there is no collision among the SUs. The frame duration is T = 40 ms, and the individual reporting time is much smaller than T and is set as t_{re} = 10 μs [25]. f_s = 10 kHz, and α = 0.85. To sufficiently protect the PR, $p_{th\,out}$ = 0.1, unless otherwise stated. The transmit power of the PT is P_{PT} = 30 kW [29]. Because of the hardware limitation or other regulations, the maximum transmit power of the ST is
assumed 6W, unless otherwise stated.





VI. **CONCLUSION**

With the assistance of the location information of the PT and the CR network, a JSS-PA scheme is proposed to improve the SE. Under SIF and HIF strategies, the sensing parameters and the ST transmit power are jointly optimized to maximize the SE of the CR network. Then, efficient algorithms are proposed to obtain the optimal values. It has been shown that the JSSPA scheme outperforms both the OSS scheme and the OPA scheme, and the SE of the SIF strategy is higher than that of the HIF strategy. To maximize the SE of the CR network, the duration of local sensing, the ST transmit power, and the final decision threshold in FC are important parameters that should be optimized. In addition, relaxing the constraint on the protection to the PR will result in a higher SE of the CR network. Based on the system model in this paper, the protected area cannot be estimated accurately by using the PT location and its transmit power. Hence, the PRs may be interfered by the secondary transmission. Therefore, more accurate estimation of the protected area will be investigated in our future work. In addition, we will investigate the energy efficiency (EE) of the CR network due to user device requirements and environment concerns.Which scheme performs better on improving the EE? We will study this problem and consider the tradeoff between the SE and the EE.

REFERENCES

[1] S. Chen and J. Zhao, "The requirements, challenges, and technologies for 5G of terrestrial mobile telecommunication," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 36–43, May 2014.

[2] J. Mitola, III, *et al.*, "Accelerating 5G QoE via public-private spectrum sharing," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 77–85, May 2014.

[3] P. Demestichas *et al.*, "5G on the horizon: Key challenges for the radioaccess network," *IEEE Veh. Technol. Mag.*, vol. 8, no. 3, pp. 47–53, Sep. 2013.

[4] Q. Li, H. Niu, A. T. Papathanassiou, and G. Wu, "5G network capacity: Key elements and technologies," *IEEE Veh. Technol. Mag.*, vol. 9, no. 1, pp. 71–78, Mar. 2014.

[5] C.-X. Wang *et al.*, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[6] R. Q. Hu and Y. Qian, "An energy efficient and spectrum efficient wireless heterogeneous network framework for 5G systems," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 94–101, May 2014.

[7] Y.-C. Liang, K.-C. Chen, G. Y. Li, and P. Mahonen, "Cognitive radio networking and communications: An overview," *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 3386–3407, Sep. 2011.

[8] S. Eryigit, S. Bayhan, and T. Tugcu, "Energy-efficient multichannel cooperative sensing scheduling with heterogeneous channel conditions for cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 6, 2690–2699, Jul. 2013.

[9] L. Wang, K. Wu, J. Xiao, and M. Hamdi, "Harnessing frequency domain for cooperative sensing and multi-channel contention in CRAHNs," *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 440–449, Jan. 2014. [10] C. R. Stevenson *et al.*, "IEEE 802.22: The first cognitive radio wireless regional area network standard," *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 130–138, Jan. 2009.

[11] E. Peh, Y.-C. Liang, and Y. Zeng, "Sensing and power control in cognitive radio with location information," in *Proc. IEEE Int. Conf. Commun. Syst.*, 2012, pp. 255–259.

[12] H. Mu and J. K. Tugnait, "Joint soft-decision cooperative spectrum sensing and power control in multiband cognitive radios," *IEEE Trans. Signal Process.*, vol. 60, no. 10, pp. 5334–5346, Oct. 2012.

[13] Y. Wang, P. Ren, F. Gao, and Z. Su, "A hybrid underlay/overlay transmission mode for cognitive radio networks with statistical quality-ofservice provisioning," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1482–1497, Mar. 2014.

[14] P. Chen, Q. Zhang, J. Yu, Y. Zhang, and B. Cao, "Sensing-throughput tradeoff in joint spatial-temporal sensing based cognitive radio networks," in *Proc. IEEE/CIC Int. Conf. Commun. China*, Aug. 2013, pp. 727–732.

[15] Q. Wu, G. Ding, J. Wang, and Y.-D. Yao, "Spatial-temporal opportunity detection for spectrum-heterogeneous cognitive radio networks: Twodimensional sensing," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 516–526, Feb. 2013.

[16] T. Xue, Y. Shi, and X. Dong, "A framework for location-aware strategies in cognitive radio systems," *IEEE Wireless Commun. Lett.*, vol. 1, no. 1, pp. 30–33, Feb. 2012.

[17] B. Cao, Q. Zhang, J. W. Mark, L. X. Cai, and H. V. Poor, "Toward efficient radio spectrum utilization: User cooperation in cognitive radio networking," *IEEE Netw.*, vol. 26, no. 4, pp. 46–52, Jul./Aug. 2012.