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Cooperative Spectrum Sensing Optimization in Cognitive Radio Networks

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***Abstract*—Cognitive radio is being recognized as an intelligent technology due to its ability to rapidly and autonomously adapt operating parameters to changing environments and conditions. In order to reliably and swiftly detect spectrum holes in cognitive radios, spectrum sensing must be used. In this paper, we consider cooperative spectrum sensing in order to optimize the sensing performance. We focus on energy detection for spectrum sensing and find that the optimal fusion rule is the half-voting rule. Next, the optimal detection threshold of energy detection is determined numerically. Finally, we propose a fast spectrum sensing algorithm for a large network which requires fewer than the total number of cognitive radios to perform cooperative spectrum sensing while satisfying a given error bound.**

I. Introduction

Over the last decade, wireless technologies have grown rapidly and more and more spectrum resources are needed to support numerous emerging wireless services. Within the current spectrum regulatory framework, however, all of the frequency bands are exclusively allocated to specific services and no violation from unlicensed users is allowed. The issue of spectrum scarcity becomes more obvious and worries the wireless system designers and telecommunications policy makers. Interestingly, a recent survey of the spectrum utilization made by the Federal Communications Commission (FCC) has indicated that the actual licensed spectrum is largely under-utilized in vast temporal and geographic dimensions [1].

In order to solve the conflicts between spectrum scarcity and spectrum under-utilization, cognitive radio technology was recently proposed [2], [3]. It can improve the spectrum utilization by allowing secondary networks (users) to borrow unused radio spectrum from primary licensed networks (users) or to share the spectrum with the primary networks (users). As an intelligent wireless communication system, a cognitive radio is aware of the radio frequency environment. It selects the communication parameters (such as carrier frequency, bandwidth, and transmission power) to optimize the spectrum usage and adapts its transmission and reception accordingly. One of the most critical components of cognitive radio technology is spectrum sensing. By sensing and adapting to the environment, a cognitive radio is able to fill in spectrum holes and serve its users without causing harmful interference to the licensed user.

One of the great challenges of implementing spectrum sensing is the hidden terminal problem, which occurs when the cognitive radio is shadowed, in severe multipath fading or inside buildings with high penetration loss, while a primary user (PU) is operating in the vicinity [4]. Due to the hidden terminal problem, a cognitive radio may fail to notice the presence of the PU and then will access the licensed channel and cause interference to the licensed system. In order to deal with the hidden terminal problem in cognitive radio networks, multiple cognitive users can cooperate to conduct spectrum sensing. It has been shown that the spectrum sensing performance can be greatly improved with an increase of the number of cooperative partners [5]–[9].

In this paper, we consider the optimization of cooperative spectrum sensing with energy detection to minimize the total error rate. In particular, we find the optimal decision fusion rule which demonstrates that the OR rule and the AND rule are optimal in rare cases whereas the half-voting rule is optimal or near-optimal for most cases. We also determine the optimal detection threshold to minimize the error rate. We further propose a fast spectrum sensing algorithm for large cognitive networks which requires only a few, not all, cognitive radios in cooperative spectrum sensing to get a target error bound. We note that the optimum number of cognitive radios in cooperative spectrum sensing was investigated in [10] for a fixed detection rate or a fixed false alarm rate when AND or OR rule was applied. Here, our focus on the number of cooperating nodes is based on a general fusion rule.

The rest of this paper is organized as follows. In Section II, the system model and spectrum sensing are briefly introduced. Cooperative spectrum sensing and performance metrics are derived in Section III. In Section IV, the optimization of cooperative spectrum sensing is presented. In particular, the optimal fusion rule, the optimal threshold, and a fast spectrum sensing method are proposed. Finally, we draw our conclusions in Section V.

II. Spectrum Sensing

Spectrum sensing is a key element in cognitive radio communications as it should be firstly performed before allowing unlicensed users to access a vacant licensed channel. The

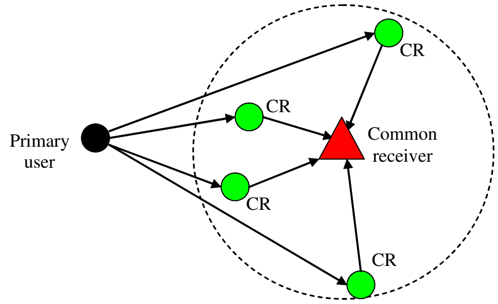

Fig. 1. Spectrum sensing structure in a cognitive radio network.

essence of spectrum sensing is a binary hypothesis-testing problem:

$$\begin{array}{ll} H_0: & \text{primary user is absent;} \\ H_1: & \text{primary user is in operation.} \end{array}$$

To enhance the detection probability, many signal detection techniques can be used in spectrum sensing [11]–[14]. The energy detection method is optimal for detecting any unknown zero-mean constellation signals [14]. In the energy detection approach, the radio frequency energy in the channel or the received signal strength indicator (RSSI) is measured in a fixed bandwidth W over an observation time window T to determine whether the channel is occupied or not.

We consider a cognitive radio network composed of K cognitive radios (secondary users) and a common receiver, as shown in Fig. 1. The common receiver functions as a base station (BS) which manages the cognitive radio network and all associated K cognitive radios. We assume that each cognitive radio performs local spectrum sensing independently. In order to see how the energy detector works, in the following we only consider the ith cognitive radio. The local spectrum sensing is to decide between the following two hypotheses,

$$x_i(t) = \begin{cases} n_i(t)\,, & H_0, \\ h_i s(t) + n_i(t)\,, & H_1, \end{cases} \tag{1}$$

where $x_i(t)$ is the observed signal at the ith cognitive radio, $s(t)$ is the PU signal, $n_i(t)$ is the additive white Gaussian noise (AWGN), and h_i is the complex channel gain of the sensing channel between the PU and the ith cognitive radio. We assume that the sensing channel is time-invariant during the sensing process.

The energy collected in the frequency domain is denoted by E_i which serves as a decision statistic and has the following distribution [15], [16]

$$E_i \sim \begin{cases} \chi^2_{2u}\,, & H_0, \\ \chi^2_{2u}(2\gamma_i)\,, & H_1, \end{cases} \tag{2}$$

where χ^2_{2u} denotes a central chi-square distribution with $2u$ degrees of freedom and $\chi^2_{2u}(2\gamma_i)$ denotes a noncentral chi-square distribution with $2u$ degrees of freedom and a non-centrality parameter $2\gamma_i$, respectively. The instantaneous signal-to-noise ratio (SNR) of the received signal at the ith cognitive radio is γ_i and $u = TW$ is the time-bandwidth product.

For the ith cognitive radio with the energy detector, the average probability of false alarm, the average probability of detection, and the average probability of missed detection over AWGN channels are given, respectively, by [16]

$$\begin{aligned} P_{f,i} &= \text{Prob}\{E_i > \lambda_i | H_0\} \\ &= \frac{\Gamma(u, \frac{\lambda_i}{2})}{\Gamma(u)}\,, \end{aligned} \tag{3}$$

$$\begin{aligned} P_{d,i} &= \text{Prob}\{E_i > \lambda_i | H_1\} \\ &= Q_u\left(\sqrt{2\gamma_i}, \sqrt{\lambda_i}\right), \end{aligned} \tag{4}$$

and

$$P_{m,i} = 1 - P_{d,i}\,, \tag{5}$$

where λ_i and γ_i denote the energy threshold and the instantaneous SNR at the ith cognitive radio, respectively, $\Gamma(a,x)$ is the incomplete gamma function given by $\Gamma(a,x) = \int_x^\infty t^{a-1}e^{-t}dt$, $\Gamma(a)$ is the gamma function, and $Q_u(a,b)$ is the generalized Marcum Q-function given by $Q_u(a,x) = \frac{1}{a^{u-1}}\int_x^\infty t^u e^{-\frac{t^2+a^2}{2}} I_{u-1}(at)dt$, $I_{u-1}(\cdot)$ being the modified Bessel function of the first kind and order $u-1$.

III. Cooperative Spectrum Sensing

One of the most challenging issues of spectrum sensing is the hidden terminal problem, which happens when the cognitive radio is shadowed or in deep fade. To address this issue, multiple cognitive radios can be coordinated to perform spectrum sensing. Several recent works have shown that cooperative spectrum sensing can greatly increase the probability of detection in fading channels [5]–[9].

In general, cooperative spectrum sensing is performed as follows:

- *Step 1*: Every cognitive radio i performs local spectrum measurements independently and then makes a binary decision $D_i \in \{0,1\}$ for all $i = 1, \cdots, K$;
- *Step 2*: All of the cognitive radios forward their binary decisions to a common receiver which is an AP in a wireless LAN or a BS in a cellular network;
- *Step 3*: The common receiver combines those binary decisions and makes a final decision $\mathcal{H}_0$ or $\mathcal{H}_1$ to infer the absence or presence of the PU in the observed frequency band.

In the above cooperative spectrum sensing algorithm, each cooperative partner makes a binary decision based on its local observation and then forwards one bit of the decision to the common receiver. At the common receiver, all 1-bit decisions are fused together according to following logic rule

$$Z = \sum_{i=1}^{K} D_i \begin{cases} \geq n\,, & \mathcal{H}_1, \\ < n\,, & \mathcal{H}_0, \end{cases} \tag{6}$$

where $\mathcal{H}_0$ and $\mathcal{H}_1$ denote the inferences drawn by the BS that the PU signal is *not* transmitted or transmitted, respectively.

The expression (6) demonstrates that the BS infers the PU signal being transmitted, i.e., $\mathcal{H}_1$, when there exists *at least n out of K cognitive radios inferring H_1*. Otherwise, the BS decides the PU signal not being transmitted, i.e., $\mathcal{H}_0$. It can be seen that the OR rule corresponds to the case of $n = 1$ and the AND rule corresponds to the case of $n = K$.

We assume that, compared with the distance from any cognitive radio to the primary transmitter, the distance between any two cognitive radios is small, so that the received signal at each cognitive radio experiences almost identical path loss. Therefore, it is reasonable to assume that we have independent and identically distributed (i.i.d.) Rayleigh fading with the instantaneous SNRs $\gamma_1, \ldots, \gamma_K$ being i.i.d. exponentially distributed random variables with the same mean $\bar{\gamma}$. Furthermore, we assume that all cognitive radios use the same threshold λ. This results in $P_{f,i}$ being independent of i, and we denote it as P_f. In the case of an AWGN channel, $P_{d,i}$ is independent of i (we denote this as P_d). In the case of a Rayleigh fading channel, let P_d be $P_{d,i}$ averaged over the statistics of γ_i. For both kinds of channels, we have $P_m = 1 - P_d$.

The false alarm probability of cooperative spectrum sensing is then given by

$$\begin{aligned} Q_f &= \mathrm{Prob}\{\mathcal{H}_1|H_0\} \\ &= \sum_{l=n}^{K} \binom{K}{l} [\mathrm{Prob}\{H_1|H_0\}]^l [\mathrm{Prob}\{H_0|H_0\}]^{K-l} \\ &= \sum_{l=n}^{K} \binom{K}{l} P_f^l (1-P_f)^{K-l}, \end{aligned} \tag{7}$$

The missed detection probability of cooperative spectrum sensing is given by

$$\begin{aligned} Q_m &= \mathrm{Prob}\{\mathcal{H}_0|H_1\} \\ &= 1 - \mathrm{Prob}\{\mathcal{H}_1|H_1\} \\ &= 1 - \sum_{l=n}^{K} \binom{K}{l} [\mathrm{Prob}\{H_1|H_1\}]^l [\mathrm{Prob}\{H_0|H_1\}]^{K-l} \\ &= 1 - \sum_{l=n}^{K} \binom{K}{l} P_d^l (1-P_d)^{K-l}. \end{aligned} \tag{8}$$

IV. Optimization of Cooperative Spectrum Sensing

For a cooperative spectrum sensing algorithm, the main metric of sensing performance is either minimizing the miss probability for a target false alarm probability or minimizing the false alarm probability for a target miss probability. In this paper, we investigate the minimization of the total error probability $Q_f + Q_m$ in terms of the various parameters.

A. Optimal Fusion Rule

The first question we are concerned about is as follows:

Q1: *Suppose that K and SNR are known, then what is the optimal fusion rule, i.e., what is the optimal n, which we denote as n_{opt}, that minimizes the total error rate $Q_f + Q_m$?*

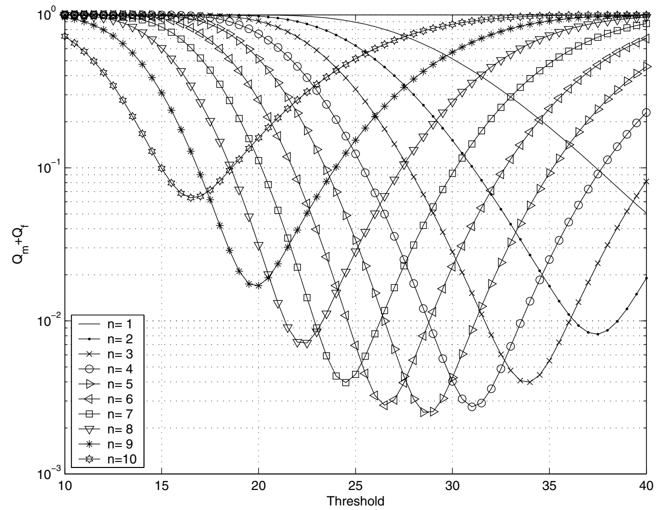

Fig. 2. Total error probability versus detection threshold for various fusion rules when $n = 1, 2, \cdots, 10$, $K = 10$, and SNR = 10 dB.

Before we delve into pursuing the exact optimal solution of n, let us get some intuitive results from Fig. 2 which shows the total error rate in terms of the detection threshold for various fusion rules from $n = 1$ to $n = 10$ in a cognitive network with 10 users. It can be observed from Fig. 2 that the optimal fusion rule over all the examined range of detection threshold is $n = 5$. However, for a fixed very small threshold, the optimal rule is the AND rule, i.e., $n = 10$. Meanwhile, for a fixed very large threshold, the OR rule, i.e., $n = 1$, tends to be optimal.

Next, we give the exact solution of the optimal n in the following theorem.

Theorem 1: Given K and $\bar{\gamma}$, the optimal fusion rule for cooperative spectrum sensing that minimizes $Q_f + Q_m$ is

$$n_{opt} = \min\left(K, \left\lceil \frac{K}{1+\alpha} \right\rceil\right), \tag{9}$$

where $\alpha = \frac{\ln \frac{P_f}{1-P_m}}{\ln \frac{P_m}{1-P_f}}$ and $\lceil \cdot \rceil$ denotes the ceiling function.

Proof: Define $F = Q_f + Q_m$. From (7) and (8), we get

$$F = 1 + \sum_{l=n}^{K} \binom{K}{l} \left[P_f^l (1-P_f)^{K-l} - (1-P_m)^l P_m^{K-l}\right].$$

Further, we let

$$G(n) = \sum_{l=n}^{K} \binom{K}{l} \left[P_f^l (1-P_f)^{K-l} - (1-P_m)^l P_m^{K-l}\right].$$

Then, we have

$$\begin{aligned} \frac{\partial G(n)}{\partial n} &\approx G(n+1) - G(n) \\ &= \binom{K}{n} \left[(1-P_m)^n P_m^{K-n} - P_f^n (1-P_f)^{K-n}\right]. \end{aligned}$$

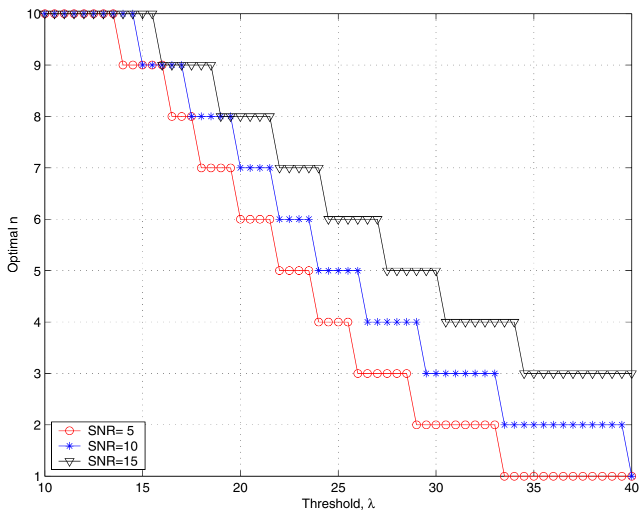

Fig. 3. Optimal fusion rule versus detection threshold at SNR of 5, 10, and 15 dB, and $K = 10$.

The optimal value of n is obtained when $\frac{\partial G(n)}{\partial n} = 0$, i.e.,

$$(1-P_m)^n P_m^{K-n} = P_f^n (1-P_f)^{K-n}.$$

This implies that

$$\left(\frac{P_f}{1-P_m}\right)^n = \left(\frac{P_m}{1-P_f}\right)^{K-n} \quad (10)$$

$$\Longleftrightarrow \frac{K-n}{n} = \frac{\ln \frac{P_f}{1-P_m}}{\ln \frac{P_m}{1-P_f}}. \quad (11)$$

Let

$$\alpha = \frac{\ln \frac{P_f}{1-P_m}}{\ln \frac{P_m}{1-P_f}}.$$

Then, we get

$$n \approx \left\lceil \frac{K}{1+\alpha} \right\rceil .$$

■

From Theorem 1, the following observations can be made:

- Usually, P_f and P_m have the same order, i.e., $\alpha \approx 1$. Thus, the optimal choice of n is $K/2$.
- The OR rule is optimal when $\alpha \geq K-1$. This means that $P_f \leq P_m^{K-1}$. This implies that $P_f << P_m$ for large K. It can be achieved when the detection threshold λ is very large.
- The AND rule is optimal when $\alpha \to 0$. This is achieved when $P_m << P_f$, i.e., for a very small λ.

Fig. 3 shows the exact solution of n in terms of detection threshold evaluated from (9). The analytical results validate the intuitive results and remarks that we have made above.

B. Optimal Threshold

The second question we are interested in is as follows:

Q2: *Suppose that K, n and SNR are known, then what is the optimal threshold λ^* such that $\lambda^* = \arg\min_\lambda (Q_f + Q_m)$?*

We have observed from Fig. 2 that the total error rate curve is a convex function of λ for any given n. This implies that there exists one and only one value of λ which minimizes $Q_f + Q_m$. The optimal threshold λ^* is given by

$$\lambda^* = \arg\min_\lambda (Q_f + Q_m).$$

It can be achieved when $\frac{\partial Q_m}{\partial \lambda} + \frac{\partial Q_f}{\partial \lambda} = 0$. From (7), we obtain

$$\begin{aligned}
\frac{\partial Q_f}{\partial \lambda} &= \sum_{l=n}^{K} \binom{K}{l} l \cdot P_f^{l-1} \cdot \frac{\partial P_f}{\partial \lambda}(1-P_f)^{K-l} \\
&\quad - \sum_{l=n}^{K} \binom{K}{l} P_f^l (K-l)(1-P_f)^{K-l-1} \frac{\partial P_f}{\partial \lambda} \\
&= \frac{\partial P_f}{\partial \lambda} \sum_{l=n}^{K} \binom{K}{l} P_f^{l-1}(1-P_f)^{K-l} \\
&\quad \times \left[l - (K-l)\frac{P_f}{1-P_f} \right], \qquad (12)
\end{aligned}$$

where P_f is given by

$$P_f = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)}. \quad (13)$$

From (8), we get

$$\begin{aligned}
\frac{\partial Q_m}{\partial \lambda} &= -\sum_{l=n}^{K} \binom{K}{l} l P_d^{l-1}(1-P_d)^{K-l} \frac{\partial P_d}{\partial \lambda} \\
&\quad + \sum_{l=n}^{K} \binom{K}{l} P_d^l (K-l)(1-P_d)^{K-l-1} \frac{\partial P_d}{\partial \lambda} \\
&= -\frac{\partial P_d}{\partial \lambda} \sum_{l=n}^{K} \binom{K}{l} P_d^{l-1}(1-P_d)^{K-l} \\
&\quad \times \left[l - (K-l)\frac{P_d}{1-P_d} \right]. \qquad (14)
\end{aligned}$$

In an AWGN channel, the detection probability is [16]

$$\begin{aligned}
P_d &= Q_u\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \\
&= \frac{1}{(\sqrt{2\gamma})^{u-1}} \int_{\sqrt{\lambda}}^{\infty} x^u \exp\left(-\frac{x^2+2\gamma}{2}\right) I_{u-1}(\sqrt{2\gamma}x)dx.
\end{aligned}$$

Then,

$$\frac{\partial P_d}{\partial \lambda} = -\frac{\lambda^{\frac{u-1}{2}}}{2(2\gamma)^{\frac{u-1}{2}}} \exp\left(-\frac{\lambda+2\gamma}{2}\right) I_{u-1}(\sqrt{2\gamma\lambda}). \quad (15)$$

An expression in the case of Rayleigh fading channel can be obtained in a similar way.

Using (12) and (14), the solution to $\frac{\partial Q_m}{\partial \lambda} + \frac{\partial Q_f}{\partial \lambda} = 0$ can be evaluated numerically. The solution is exactly the optimal detection threshold.

C. Optimal Number of Cognitive Radios

In a cognitive radio network with a large number of cognitive radios, cooperative spectrum sensing may become impractical because in a time slot only one cognitive radio should send its local decision to the common receiver so as to separate decisions easily at the receiver end. Hence, it may make the whole sensing time intolerantly long. This issue can be addressed by allowing the cognitive radios to send the decisions concurrently. But it may complicate the receiver design when separating the decisions from different cognitive radios. Another potential solution is to send the decisions on orthogonal frequency bands, but it costs a large portion of available bandwidth. Next, we shall propose an efficient sensing algorithm which relies on the transmission of decision in one time slot for one cognitive radio but guarantees a target error bound by requiring a few cognitive radios in cooperative spectrum sensing instead of all of them. The optimal number of cognitive radios in cooperative spectrum sensing was investigated in [10] when AND or OR rule was applied. However, an optimal number of cooperative nodes in spectrum sensing for a general fusion rule has not been well addressed. In the following, we should answer the following question:

Q3: *Suppose that SNR and λ are known, then what is the least number of cooperative cognitive radios in cooperative spectrum sensing to achieve a target error bound $(Q_f+Q_m) \leq \epsilon$?*

First we assume that k^* $(1 \leq k^* \leq K)$ is the least number of cognitive radios required in cooperative spectrum sensing so as to satisfy $(Q_f + Q_m) \leq \epsilon$. Then, from Theorem 1, we can see that the optimal fusion rule for cooperative spectrum sensing with k^* cognitive radios is $n_{k^*}^{opt} = \min\left(k^*, \lceil \frac{k^*}{1+\alpha} \rceil\right)$ where α is related to P_f and P_m and can be evaluated from the known λ and SNR.

Define the function $F(\cdot,\cdot)$ in terms of variable k as

$$F(k, n_k^{opt}) = Q_f + Q_m - \epsilon \,,$$

where k denotes the number of cooperative cognitive radios in cooperative spectrum sensing and $n_k^{opt} = \min\left(k, \lceil \frac{k}{1+\alpha} \rceil\right)$. The probabilities Q_f and Q_m are functions of k and n_k^{opt} given by (7) and (8), respectively. Then, we have

$$F(k^*, n_{k^*}^{opt}) \leq 0 \,, \quad (16)$$

$$F(k^*-1, n_{k^*-1}^{opt}) > 0 \,, \quad (17)$$

because k^* is the least number of cognitive radios to satisfy $(Q_f + Q_m) \leq \epsilon$. Using the properties (16) and (17), we can easily get $k^* = \lceil k_0 \rceil$ where k_0 is the first zero-crossing point of the curve $F(k, n_k^{opt})$ in terms of k. Therefore, a fast spectrum sensing algorithm can be formulated by considering only k^* cognitive radios in cooperative spectrum sensing instead of K. Consequently, the sensing duration (in which the decisions are sent to the common center for decision fusion) can be reduced from K time slots to k^* time slots. Meanwhile, the given error bound ϵ is guaranteed.

V. Conclusion

We have studied the performance of cooperative spectrum sensing in cognitive radio networks. It has been found that the optimal decision fusion rule to minimize the total error probability is the half-voting rule. Moreover, the optimal detection threshold of energy detection is determined numerically. In particular, an efficient spectrum sensing algorithm has been proposed which requires fewer than the total number of cognitive radios in cooperative spectrum sensing while satisfying a given error bound.

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References

[1] Federal Communications Commission, “Spectrum Policy Task Force,” Rep. ET Docket no. 02-135, Nov. 2002.

[2] J. Mitola and G. Q. Maguire, “Cognitive radio: Making software radios more personal,” *IEEE Personal Commun.*, vol. 6, pp. 13–18, Aug. 1999.

[3] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE J. Sel. Areas Commun.*, vol. 23, pp. 201–220, Feb. 2005.

[4] D. Cabric, S. M. Mishra, and R. W. Brodersen, “Implementation issues in spectrum sensing for cognitive radios,” in *Proc. Asilomar Conf. on Signals, Systems, and Computers*, Nov. 7-10, 2004, vol. 1, pp. 772–776.

[5] C. Sun, W. Zhang, and K. B. Letaief, “Cooperative spectrum sensing for cognitive radios under bandwidth constraints,” in *Proc. IEEE Int. Wireless Commun. Networking Conf.*, Hong Kong, Mar. 11-15, 2007, pp. 1–5.

[6] C. Sun, W. Zhang, and K. B. Letaief, “Cluster-based cooperative spectrum sensing for cognitive radio systems,” in *Proc. IEEE Int. Conf. Commun.*, Glasgow, Scotland, UK, June 24-28, 2007, pp. 2511–2515.

[7] G. Ganesan and Y. G. Li, “Cooperative spectrum sensing in cognitive radio networks,” in *Proc. IEEE Symp. New Frontiers in Dynamic Spectrum Access Networks* (DySPAN’05), Baltimore, USA, Nov. 8-11, 2005, pp. 137–143.

[8] A. Ghasemi and E. S. Sousa, “Collaborative spectrum sensing for opportunistic access in fading environments,” in *Proc. IEEE Symp. New Frontiers in Dynamic Spectrum Access Networks* (DySPAN’05), Baltimore, USA, Nov. 8–11, 2005, pp. 131–136.

[9] S. M. Mishra, A. Sahai, and R. Brodersen, “Cooperative sensing among cognitive radios,” in *Proc. IEEE Int. Conf. Commun.*, Turkey, June 2006, vol. 4, pp. 1658–1663.

[10] E. Peh and Y.-C. Liang, “Optimization for cooperative sensing in cognitive radio networks,” in *Proc. IEEE Int. Wireless Commun. Networking Conf.*, Hong Kong, Mar. 11-15, 2007, pp. 27–32.

[11] Z. Tian and G. B. Giannakis, “A wavelet approach to wideband spectrum sensing for cognitive radios,” in *Proc. Int. Conf. on Cognitive Radio Oriented Wireless Networks and Communications*, Greece, June 8-10, 2006, pp. 1–5.

[12] J. Lunden, V. Koivunen, A. Huttunen, and H. V. Poor, “Spectrum sensing in cognitive radios based on multiple cyclic frequencies,” in *Proc. of the Second Int. Conf. on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom)*, Orlando, FL, USA, July 31-August 3, 2007.

[13] Y. Hur, J. Park, W. Woo, K. Lim, C.-H. Lee, H. S. Kim, and J. Laskar, “A wideband analog multi-resolution spectrum sensing (MRSS) technique for cognitive radio (CR) systems,” in *Proc. IEEE Int. Symp. Circuit and System*, Greece, May 21-24, 2006, pp. 4090–4093.

[14] A. Sahai, N. Hoven, and R. Tandra, “Some fundamental limits on cognitive radio,” in *Proc. Allerton Conf. on Commununictions, control, and computing*, Monticello, Oct. 2004.

[15] V. I. Kostylev, “Energy detection of a signal with random amplitude,” in *Proc. IEEE Int. Conf. Commun.*, New York, Apr. 28 - May 2, 2002, pp. 1606–1610.

[16] F. F. Digham, M.-S. Alouini, and M. K. Simon, “On the energy detection of unknown signals over fading channels,” in *Proc. IEEE Int. Conf. Commun.*, Anchorage, AK, USA, May 11-15, 2003, pp. 3575–3579.