Double Threshold Energy Detection of Cooperative Spectrum Sensing in Cognitive Radio

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***Abstract*—Cognitive radio has become an effective theory to solve the inefficiency of the spectrum usage, and cooperative spectrum sensing among the secondary users to detect the primary user accurately is broadly studied before. In this paper, we employ a double threshold method in energy detector to perform spectrum sensing, while a fusion center in the cognitive radio network collects the local decisions and observational values of the secondary users, and then makes the final decision to determine whether the primary user is absence or not. Simulation results will show that the spectrum sensing performance in AWGN channels is improved significantly under the proposed scheme as opposed to the conventional method.**

Keywords—double threshold, energy detect, cooperative sensing, cognitive radio

I. INTRODUCTION

In nowadays, cognitive radio (CR) has become a better way to solve the inefficiency of spectrum usage rather than the fixed spectrum assignment. The concept of CR is first introduced in [1], where secondary (unlicensed) users utilize the licensed frequencies while the primary (licensed) user is absence. To achieve this, secondary users require sensing the spectrum environment in its surroundings to decide the absence and presence of the primary user. In another word, the secondary user needs to sense the spectrum holes while the primary is absent, and vacate the band when the primary user represents. Generally, the spectrum sensing techniques can be classified as transmitter detection (non-cooperative detection), cooperative detection, and interference-based detection. While in most cases, the secondary user is lack of the information of primary user, and interference-based detection is typically utilized in a transmitter-centric way, cooperative detection among secondary users is theoretically more accurate and convenient since the uncertainty and the detection time in a single user's detection can be minimized [2].

In cooperative detection, the optimal detector in stationary Gaussian noise channels is match filter detector, which requires the prior knowledge of primary user, since it maximizes the received signal-to-noise ratio (SNR) [3]. However, this knowledge is not always available, and the implementing of match filter coherent detector is difficult in reality. A common method for detection of unknown signals in noise is energy detection. It is an optimal detector in random Gaussian noise channel. Further more, it simplifies the implementation of the receiver compare to the match filter.

In [4], a censoring method using double threshold in energy detection was proposed to reduce the communication traffic. In contrast, we use this method to improve the macro detection capability of cognitive radio networks: assuming that the energy detector has two threshold values; each secondary user performs energy detection to sensing spectrum individually, and then report their local decisions or observational values to a fusion center, and the latter one will make a final decision to determine whether the primary user is absence. Simulation results will show that the spectrum sensing performance under AWGN channels is improved significantly as opposed to the conventional method introduced later.

The rest of the paper is organized as follows, in Section Ⅱ; the conventional cooperative spectrum sensing is introduced. In SectionⅢ, the theory of double threshold energy detection is derived and the detection performance is analyzed. Then the simulation results are shown in Section Ⅳ. Finally, we draw our conclusions in Section Ⅴ.

II. CONVENTIONAL COOPERATIVE SPECTRUM SENSING

The primary objective of cognitive radio is to maximize the spectrum efficiency. There are three main detection methods that are used in traditional systems: matched filter is optimal but it requires the prior knowledge of the primary user. Energy detector is suboptimal but simple to implement. Cyclostationary feature detection can detect the signals with low SNR but still needs some prior knowledge of the primary user, such as modulation types, symbol rates and presence of interferers. In reality, the prior knowledge of the primary user may probably unknown, furthermore, energy detector has the simplest implementation, so many researchers focus on energy detection in the spectrum sensing.

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For spectrum sensing, our goal is to distinguish between the following two hypotheses [5],

$$x(t) = \begin{cases} n(t) & H_0 \\ h(t) \bullet s(t) + n(t) & H_1 \end{cases}$$

where $x(t)$ is the signal received by secondary user, and $s(t)$ is primary user's transmitted signal, $n(t)$ is stochastic noise, for simplicity, we assume $n(t)$ is AWGN, and $h(t)$ is the temporary amplitude gain of the channel. Hypothesis H_0 and H_1 represent the absence and presence of the primary user, respectively.

According to energy detection theory [6], we have the following distribution,

$$O \sim \begin{cases} \chi^2_{2TW} & H_0 \\ \chi^2_{2TW}(2\gamma) & H_1 \end{cases}$$

where O and γ denote the energy value the secondary user received and the SNR respectively, χ^2_{2TW} and $\chi^2_{2TW}(2\gamma)$ are central and non-central chi-square distributions respectively, each with $2TW$ degrees of freedom and a non-centrality parameter of 2γ for the latter one. For statement simplicity, we use u to denote the time-bandwidth product TW, i.e. χ^2_{2u} and $\chi^2_{2u}(2\gamma)$.

In a non-fading environment where $h(t)$ is deterministic, probabilities of detection, missing and false alarm are as follows [6],

$$P_d = P\{O > \lambda / H_1\} = Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) \tag{1}$$

$$P_m = P\{O \le \lambda / H_1\} = 1 - P_d \tag{2}$$

$$P_f = P\{O > \lambda / H_0\} = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)} \tag{3}$$

where P_d, P_m, P_f are the detection probability, missing probability and false alarm probability of the secondary user respectively, and λ is the threshold value. $\Gamma(a)$, $\Gamma(a,b)$ are complete and incomplete gamma function, respectively and $Q_u(a,b)$ is the generalized Marcum function [7].

The missing probability P_m (also the detection probability P_d) and the false alarm probability P_f describe the detection capability of the secondary user. A high P_m (low P_d) would result in missing the presence of the primary user with high probability which interferes the primary user. On the contrast, a high P_f means that the secondary user observes the primary user while it does not exist in fact, which turns out to be low spectrum utilization.

In real communication environments, the hidden node problem, fading and shadowing, etc, would deteriorate the spectrum sensing performance of secondary users. To solve this problem, cooperative sensing method is introduced [5]. In many papers, it often assume that there are N secondary users and a fusion center in a cognitive radio network, each secondary user experiences independent and identically distributed fading and shadowing with the same average SNR, and each user has the same threshold value λ. The fusion center receives the information of each secondary user and makes a final decision whether the primary is presence or not. In conventional fusion method, OR-rule is used. For example, if one secondary user observes the primary user, then the fusion center determines that it really exists [8]. Probabilities of detection, missing and false alarm for this cooperative sensing method are as follows,

$$Q_d = 1 - \prod_{i=1}^{N}(1 - P_{d,i}) \tag{4}$$

$$Q_m = \prod_{i=1}^{N} P_{m,i} \tag{5}$$

$$Q_f = 1 - \prod_{i=1}^{N}(1 - P_{f,i}) \tag{6}$$

where Q_d, Q_m, Q_f denote the cooperative probabilities of detection, missing and false alarm respectively, and $P_{d,i}$, $P_{m,i}$, $P_{f,i}$ are the detection probability, missing probability and false alarm probability of the i th secondary user respectively, and each has the same formulas as described above.

III. DOUBLE THRESHOLD ENERGY DETECTION OF COOPERATIVE SPECTRUM SENSING

In conventional energy detections, each secondary user makes their local decisions by comparing its observational value with a pre-fixed threshold, as illustrated in figure 1 (a).

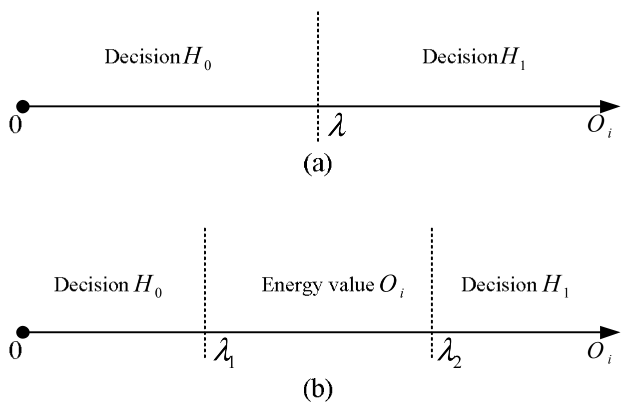

Figure 1 (a) Conventional detection method with one threshold

(b) Double threshold energy detection method

where O_i denotes the collected energy value of the i th secondary user. Decision H_0 and H_1 will be made when O_i is greater or less than the threshold value λ, respectively. [4] introduced a two thresholds method as shown in figure 1 (b). In this model, two thresholds λ_1 and λ_2 are used to help the decision of the secondary user. If energy value exceeds λ_2, then this user reports H_1, which means that it 'sees' the primary user. If O_i is less than λ_1, decision H_0 will be made.

Otherwise, if O_i is between λ_1 and λ_2, then we also allow the secondary user reporting its observational energy value, i.e., O_i, while the secondary user is forbidden to report anything in [4] to achieve the bandwidth constraints, or, to reduce the communication traffic. So in our model, the fusion center receives two kinds of information: local decisions and observational values of the secondary users, i.e. local energy values. Following are the performing schemes of the double threshold energy detection cooperative spectrum sensing method:

1. Each secondary user i, for $i = 1,\cdots,N$, performs spectrum sensing individually, i.e., energy detection with a result of O_i. Furthermore, we assume that each secondary user has identical threshold values for simplicity. If O_i satisfies $\lambda_1 < O_i \le \lambda_2$, then the i th secondary user sends the energy detection value O_i to the fusion center. Otherwise, it will report its local decision L_i according to O_i. We use R_i to denote the information that the fusion center receives from the i th secondary user, then it can be given by

$$R_i = \begin{cases} O_i & \lambda_1 < O_i \le \lambda_2 \\ L_i & Otherwise \end{cases}$$

and

$$L_i = \begin{cases} 0 & 0 \le O_i \le \lambda_1 \\ 1 & O_i > \lambda_2 \end{cases}$$

2. Without loss of generality, we assume that the fusion center receives K local decisions and $N-K$ energy detection values among N secondary users. Then the fusion center makes an upper decision according to $N-K$ energy detection values, which is given by

$$D = \begin{cases} 0 & 0 \le \sum_{i=1}^{N-K} O_i \le \lambda \\ 1 & \sum_{i=1}^{N-K} O_i > \lambda \end{cases}$$

where λ is the energy detection threshold value of the fusion center according to appropriate false alarm probability.(See eq. (3)) It shows that these $N-K$ secondary users couldn't distinguish between the absence and the presence of the primary user, so the fusion center collects their observational values and makes an upper decision instead of the local decision of themselves, i.e., the fusion center performs energy fusion [9] according to $N-K$ secondary users. From [10], it is shown that $\sum_{i=1}^{N-K} O_i$ follows the distribution as given below:

$$\sum_{i=1}^{N-K} O_i \sim \begin{cases} \chi^2_{2(N-K)u} & H_0 \\ \chi^2_{2(N-K)u}(2\gamma_0) & H_1 \end{cases}$$

where $\gamma_0 = \sum_{i=1}^{N-K} \gamma_i$ represents the sum of SNR for $N-K$ secondary users, and the other parameters are the same as before.

3. The fusion center makes a final decision according to decision fusion [9], as defined as follows:

$$F = \begin{cases} 1 & D + \sum_{i=1}^{K} L_i > 1 \\ 0 & Otherwise \end{cases}$$

Based on the double threshold energy detection method discussed above, we now analyze the spectrum sensing performances of the proposed method. As before, $P_{d,i}$, $P_{m,i}$, $P_{f,i}$ are the detection probability, missing probability and false alarm probability of the i th secondary user respectively. For analyzing simplicity, adding two parameters $\Delta_{0,i}$ and $\Delta_{1,i}$ to represent the probability of $\lambda_1 < O_i \le \lambda_2$ for the i th secondary user under hypothesis H_0 and H_1 respectively, then we have [4]:

$$\Delta_{0,i} = P\{\lambda_1 < O_i \le \lambda_2 / H_0\} \tag{7}$$

$$\Delta_{1,i} = P\{\lambda_1 < O_i \le \lambda_2 / H_1\} \tag{8}$$

So it can be derived that:

$$P_{d,i} = P\{O_i > \lambda_2 / H_1\} = Q_u(\sqrt{2\gamma}, \sqrt{\lambda_2}) \tag{9}$$

$$P_{m,i} = P\{O_i \le \lambda_1 / H_1\} = 1 - \Delta_{1,i} - P_{d,i} \tag{10}$$

$$P_{f,i} = P\{O_i > \lambda_2 / H_0\} = \frac{\Gamma(u, \lambda_2/2)}{\Gamma(u)} \tag{11}$$

Using Q_d, Q_m, Q_f to denote the cooperative probability of detection, missing and false alarm respectively, then we have (The detailed deriving is described in Appendix A):

$$Q_m = \sum_{K=0}^{N-1} \binom{N}{K} \prod_{i=1}^{K} P_{m,i} \prod_{i=K+1}^{N} \Delta_{1,i} \left[1 - Q_{(N-K)u}(\sqrt{2\gamma_0}, \sqrt{\lambda})\right] + \prod_{i=1}^{N} P_{m,i} \tag{12}$$

$$\begin{aligned} Q_f &= 1 - \prod_{i=1}^{N} \left(1 - \Delta_{0,i} - P_{f,i}\right) \\ &= -\sum_{K=0}^{N-1} \binom{N}{K} \prod_{i=1}^{K} \left(1 - \Delta_{0,i} - P_{f,i}\right) \prod_{i=K+1}^{N} \Delta_{0,i} \left[1 - \frac{\Gamma\left[(N-K)u, \lambda/2\right]}{\Gamma\left[(N-K)u\right]}\right] \end{aligned} \tag{13}$$

$$Q_d = 1 - Q_m \tag{14}$$

Now we can see from the equations that the probabilities of $\lambda_1 < O_i \le \lambda_2$ for the i th secondary user under hypothesis H_0 and H_1, i.e., $\Delta_{0,i}$ and $\Delta_{1,i}$ respectively, play a significant role in the detection performance. It is evident that when $\Delta_{0,i} = \Delta_{1,i} = 0$, the performance in our proposed method will become the same as that of the conventional method discussed in Section Ⅱ.

IV. THEORETICAL SIMULATION RESULTS

In this section, we present simulation results to demonstrate the performance of the new detection method discussed above. Since we only concentrate on the AWGN channels, realistic fading and shadowing are ignored. The results of the conventional method, i.e., $\Delta_{0,i} = \Delta_{1,i} = 0$, are also shown for a comparison, while in our method $\Delta_{0,i} = \Delta_{1,i} = 0.01$ and $\Delta_{0,i} = \Delta_{1,i} = 0.1$. Other common simulation parameters are given as follows:

- $N = 10$
- $\gamma_1 = \gamma_2 = \cdots = \gamma_N = 10dB$
- $u = 5$

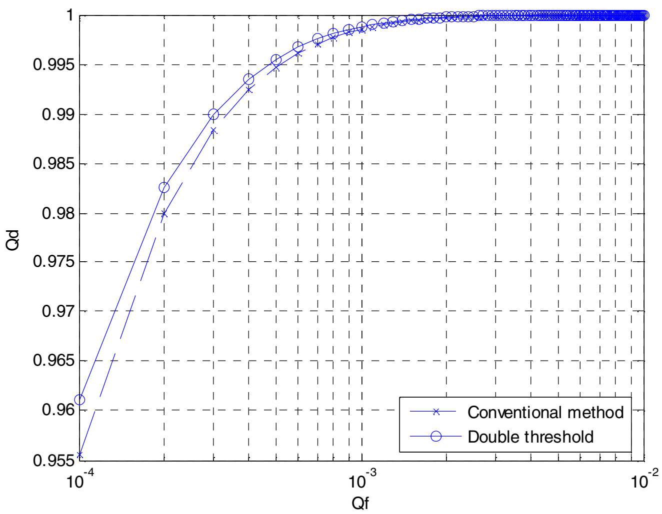

Figure 2 Q_d vs. Q_f in two kinds of cooperative spectrum sensing method, $\Delta_{0,i} = \Delta_{1,i} = 0.01$

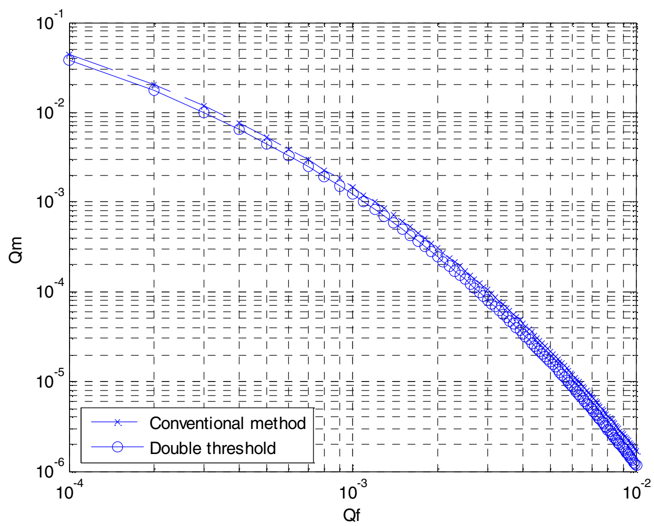

Figure 3 Q_m vs. Q_f. in two kinds of cooperative spectrum sensing method, $\Delta_{0,i} = \Delta_{1,i} = 0.01$

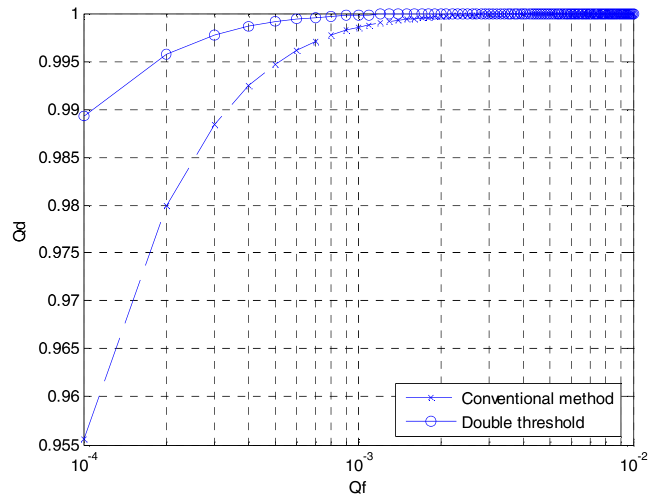

Figure 4 Q_d vs. Q_f in two kinds of cooperative spectrum sensing method, $\Delta_{0,i} = \Delta_{1,i} = 0.1$

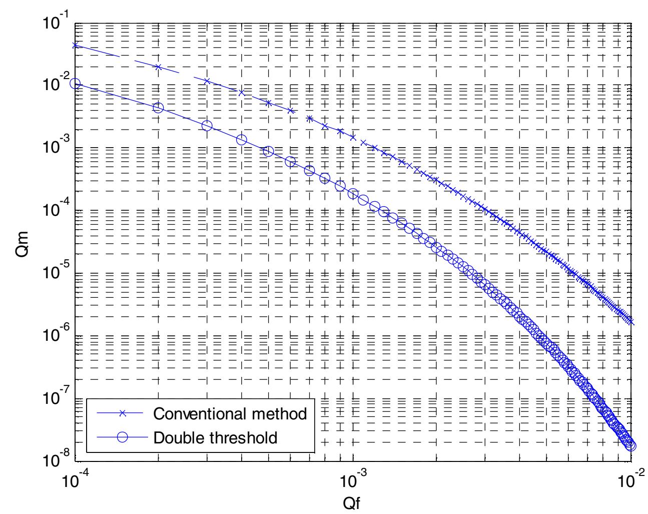

Figure 5 Q_m vs. Q_f. in two kinds of cooperative spectrum sensing method, $\Delta_{0,i} = \Delta_{1,i} = 0.1$

It can be seen from figure 2 and 3 that the double threshold energy detect method has a little performance improvement from the conventional cooperative method. When we increase $\Delta_{0,i}$ and $\Delta_{1,i}$, as shown in figure 4 and 5, the detection performance have improved significantly. While Q_f equals 0.0001, our method achieves 0.035 extra detection probability, and it has nearly 1dB improvement upon the conventional method. Furthermore, the improvement in Q_d increases as Q_f becomes greater. However, the detection performance gain was achieved by the increase of communication burdens introduced by the local energy values, so the practical implementation of our method should concern the tradeoffs between the spectrum sensing performance and the average communication burdens, which will be studied thoroughly in our future work.

V. CONCLUSIONS AND FUTURE WORK

A new method in energy detection of cooperative spectrum sensing for cognitive radio has been introduced in this paper. To improve the spectrum sensing performance, two threshold values are used in energy detection, and the fusion center receives two kinds of information: local decisions and observational values of the secondary users. Performance results of the proposed cooperative spectrum sensing method under theoretical analysis were studied. Simulation results showed that a significant improvement of detection performance had been achieved under the proposed spectrum method.

It is well known that energy detector's performance is susceptible to uncertainty in noise power [11], and our work have only studied the proposed method in AWGN channels. The impacts on performances of our method in fading environments needs to be studied in future works. Furthermore, the tradeoffs between the spectrum sensing performance and the average communication burdens should be studied thoroughly to implement practical designs.

APPENDIX A

In our new scheme, we assume that the fusion center receives K local decisions and $N-K$ energy detection values among N secondary users. Consequently, the number of local decisions K follows the binomial distribution, given as bellows:

$$P\{K \le k/H_0\} = \binom{N}{k}\left[1-P\{\lambda_1 \le O_i \le \lambda_2/H_0\}\right]^k P\{\lambda_1 \le O_i \le \lambda_2/H_0\}^{N-k} \tag{15}$$

$$P\{K \le k/H_1\} = \binom{N}{k}\left[1-P\{\lambda_1 \le O_i \le \lambda_2/H_1\}\right]^k P\{\lambda_1 \le O_i \le \lambda_2/H_1\}^{N-k} \tag{16}$$

From the above equations, now we can derive the probability of detection, missing and false alarm of the proposed method.

$$\begin{aligned}
Q_m &= P\{F = 0/H_1\} \\
&= P\{F=0, K \ne N/H_1\} + P\{F=0, K=N/H_1\} \\
&= P\left\{\sum_{i=1}^{K} L_i = 0, K \ne N \Big/ H_1\right\} P\{D=0, K \ne N/H_1\} \\
&\quad + P\left\{\sum_{i=1}^{K} L_i = 0, K = N \Big/ H_1\right\} P\{D=0, K = N/H_1\} \\
&= \sum_{K=0}^{N-1}\binom{N}{K}\prod_{i=1}^{K} P\{O_i \le \lambda_1/H_1\}\prod_{i=K+1}^{N-K} P\{\lambda_1 \le O_i \le \lambda_2/H_1\} P\left\{\sum_{j=1}^{N-K} O_j \le \lambda \Big/ H_1\right\} \\
&\quad + \prod_{i=1}^{N} P\{O_i \le \lambda_1/H_1\} \\
&= \sum_{K=0}^{N-1}\binom{N}{K}\prod_{i=1}^{K} P_{m,i} \bullet \prod_{i=K+1}^{N} \Delta_{1,i} \bullet \left[1 - P\left\{\sum_{j=1}^{N-K} O_j > \lambda \Big/ H_1\right\}\right] + \prod_{i=1}^{N} P_{m,i} \\
&= \sum_{K=0}^{N-1}\binom{N}{K}\prod_{i=1}^{K} P_{m,i} \bullet \prod_{i=K+1}^{N} \Delta_{1,i} \bullet \left[1 - Q_{(N-K)u}(\sqrt{2\gamma_0}, \sqrt{\lambda})\right] + \prod_{i=1}^{N} P_{m,i}
\end{aligned} \tag{17}$$

$$Q_d = P\{F = 1/H_1\} = 1 - P\{F = 0/H_1\} = 1 - Q_m \tag{18}$$

$$\begin{aligned}
Q_f &= P\{F = 1/H_0\} = 1 - P\{F = 0/H_0\} \\
&= 1 - P\{F=0, K \ne N/H_0\} - P\{F=0, K=N/H_0\} \\
&= 1 - \prod_{i=1}^{N} P\{O_i \le \lambda_1/H_0\} \\
&\quad - \sum_{K=0}^{N-1}\binom{N}{K}\prod_{i=1}^{K} P\{O_i \le \lambda_1/H_0\}\prod_{i=K+1}^{N} P\{\lambda_1 \le O_i \le \lambda_2/H_0\} P\left\{\sum_{j=1}^{N-K} O_j \le \lambda \Big/ H_0\right\} \\
&= 1 - \prod_{i=1}^{N}\left(1-\Delta_{0,i} - P_{f,i}\right) \\
&\quad - \sum_{K=0}^{N-1}\binom{N}{K}\prod_{i=1}^{K}\left(1-\Delta_{0,i} - P_{f,i}\right) \bullet \prod_{i=K+1}^{N} \Delta_{0,i} \bullet \left[1 - P\left\{\sum_{j=1}^{N-K} O_j > \lambda \Big/ H_0\right\}\right] \\
&= 1 - \prod_{i=1}^{N}\left(1-\Delta_{0,i} - P_{f,i}\right) \\
&\quad - \sum_{K=0}^{N-1}\binom{N}{K}\prod_{i=1}^{K}\left(1-\Delta_{0,i} - P_{f,i}\right) \bullet \prod_{i=K+1}^{N} \Delta_{0,i} \bullet \left[1 - \frac{\Gamma\left[(N-K)u, \lambda/2\right]}{\Gamma\left[(N-K)u\right]}\right]
\end{aligned} \tag{19}$$

REFERENCES

[1] J.Mitola and G.Q.Maguire, "Cognitive radio: Making software radios more personal", *IEEE Pers. Commun.*, vol.6, pp. 13-18, Aug. 1999

[2] Ganesan.G and Li.Y, "Cooperative spectrum sensing in cognitive radio, Part I: Two User Networks", *IEEE Transactions on Wireless Communications*, vol.6, no.6 pp. 2204-2213, 2007.

[3] A.Sahai, N.Hoven, R.Tandra, "Some fundamental limits in cognitive radio", in *Allerton Conf. on Commun., Control and Computing*, Oct. 2004.

[4] Chunhua Sun, Wei Zhang, Letaief K.B, "Cooperative spectrum sensing for cognitive radios under bandwidth constraints", in *Proc. IEEE WCNC 2007*, pp. 1-5, 2007.

[5] A.Ghasemi, E.S.Sousa, "Collaborative spectrum sensing for opportunistic access in fading environgment", in *Proc. IEEE Dyspan 2005*, Nov. 2005, pp. 131-136.

[6] H.Urkowitz, "Energy detection of unknown deterministic signals", *Proceedings of IEEE*, vol.55, pp. 523-531, April 1967.

[7] A.H.Nuttall, "Some integrals involving the Q_M function", *IEEE Transactions on Information Theory*, vol.21, no.1, pp. 95-99. Jan. 1975.

[8] P.K.Varshney, "Distributed detection and data fusion", New York: Sringer-Verlag, 1997.

[9] Sun.C, Zhang.W, Letaief.K.B, "Cluster-based cooperative spectrum sensing in cognitive radio systems", in *Proc. IEEE ICC'07*, pp.2511-2515, 2007.

[10] Digham.F.F., Alouini.M.S., Simon.M.K., "On the energy detection of unknown signals over fading channels", *IEEE Transactions on Communications*, vol.55, no.1, pp. 21-24, 2007.

[11] A.Sonnenschein and P.M.Fishman, "Radiometric detection of spread-spectrum signals in noise", *IEEE Transactions on Aerospace Electronic Systems*, vol.28, no.3, pp. 654-660, July 1992.