Rapid Spectrum Sensing Algorithm in Cooperative Spectrum Sensing for a Large Network

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Abstract - *Cognitive radio is an emerging technology that enhances the utilization of available spectrum through dynamic access allocation. It autonomously identifies the unutilized portions, white spaces (spectrum holes) , in the licensed band and thus efficiently improving its usage. In co-operative spectrum sensing, decision of spectrum availability is taken based on collective decision by multiple cognitive users. For any detector applied to cooperative spectrum sensing, the ideal voting rule is obtained. The detection threshold was optimized when using energy detection .Finally, a rapid spectrum sensing algorithm is suggested for a big network that needs fewer cognitive radios in cooperative spectrum sensing is obtained*

Key Words: Cognitive radio, energy detection, optimization, spectrum sensing, throughput

1. INTRODUCTION

With advancement in wireless technology, spectrum as the major resource for wireless communication systems has now become much a scarcer resource.. Static spectrum allocation of licensed band by Government has resulted in spectrum scarcity in particular spectrum bands. Moreover, reports by Federal Communications Commission (FCC) show that 70% of the allocated spectrum bands in US are not fully utilized [1]. Hence, dynamic access to spectrum was proposed to solve these spectrum inefficiency problems. Dynamic spectrum allocation enables cognitive radio (CR) users to opportunistically utilize the vacant licensed spectrum bands in either temporal or spatial domain. CR networks, however, impose unique challenges due to the high fluctuations in the available spectrum, as well as the diverse quality of service (QoS) requirements of various applications. Here, we consider optimizing cooperative spectrum sensing with energy detection. The article includes cooperative spectrum sensing, cooperative spectrum sensing optimization, optimal voting rule, ideal threshold and rapid spectrum sensing techniques

1.1 System Modeling

A] Spectrum Sensing

We consider the cognitive network with K quantity of CRs, one primary user and one fusion centre (i.e. famous receiver).The spectrum sensing is separately performed by each CR.CR's choices are sent to the fusion centre and then the fusion centre decides whether the main user is present or absent. Two hypotheses are considered [1].

H_0: The primary user is absent.

H_1: The primary user is in operation.

When each i^{th} CR receives the signal, two hypotheses follow as above. Then the signal will be obtained as

$$x_i = \begin{cases} w_i(t), & H_0 \\ h_i(t)s(t) + w_i(t) & H_1 \end{cases} \tag{1.1}$$

where, $x_i(t)$ is the received signal at the i^{th} CR in time slot t , $s_i(t)$ is the PU signal. The $h_i(t)$ shows the complex channel gain between PU and i^{th} CR with the node. $w_i(t)$ is the AWGN (Additive White Gaussian Noise).

Assume that the sensing time is smaller than the coherence time of the channel. Then, the sensing channel can be viewed as time-invariant during the sensing process. Assume that the sensing time is smaller than the coherence time of the channel. Then, the sensing channel can be viewed as time-invariant during the sensing process.

Moreover, we consider that the status of the PU remains unchanged during the period of spectrum sensing .If prior knowledge of the PU signal is unknown, the energy detection

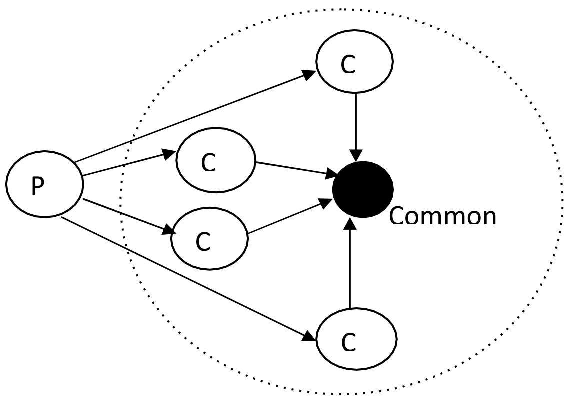

Fig-1: System Model

method is optimal for detecting zero-mean constellation signals [13]. We are going for the method of energy detection as the PU signal is unknown. We discover average detection probability, probability of missed detection and probability of false alarm over the AWGN channel with the following equations for each CR by energy detection [1];

$$p_{f,i} = \frac{r\left(u,\frac{\lambda_i}{2}\right)}{r(u)} \quad (1.2)$$

$$p_{d,i} = Q(\sqrt{2\gamma_i}, \sqrt{\lambda_i}) \quad (1.3)$$

$$p_{m,i} = 1 - p_{d,i} \quad (1.4)$$

Where, λ_i is the energy detection threshold and γ_i is the instantaneous signal to noise ratio (SNR) at the i^{th} CR. Also u is the energy detector's time bandwidth product, $\Gamma(a)$ is the gamma function and $\Gamma(a,x)$ is the incomplete gamma function isequal to

$$\tau(a,x) = \int_x^\infty t^{a-1} e^{-t} dt$$
(1.5)

The generalised Marcum Q-function i.e. $Q_u(a,b)$ is given by [1];

$$Q_u(a,x) = \frac{1}{a^{u-1}} \int_x^\infty t^u e^{\frac{t^2+a^2}{2}} I_{u-1}(at) dt \quad (1.6)$$

Where $I_{u-1}(.)$ is the first kind and order $u-1$ modified Bessel function.

Cooperative spectrum sensing, where number of CRs make binary decisions D_i based on local observation and forward a bit of decision to the common recipients. These choices are summarized at the common recipient and will determine whether the PU is present or in operation [1].

$$Y = \sum_{I=1}^{K} D_i \begin{cases} \geq n, H_1 \\ < n, H_0 \end{cases} \quad (1.7)$$

Y is the threshold representing the rule "n-out - of-K." If the amount of CR is one, i.e. n=1 it corresponds to the rule of OR and if n = K it relates to the rule of AND.

We find the distance between any two cognitive radios to be lower than the range between one CR and PU in the radio frequency setting around CR's. The signal obtained at each CR therefore follows the same path loss. For AWGN channel, $\gamma_1 = \gamma_2 = \ldots\ldots = \gamma = \gamma_k$ and for Rayleigh fading channel $\gamma_1, \gamma_2 \ldots\ldots \gamma_k$ because we suppose it is autonomous and distributed identically (i.i.d) with instant SNRs. These SNR's are also i.i.d. random variables with the same mean distributed exponentially. We take another hypothesis that each CR threshold is the same and that it is the same $\lambda_1 = \lambda_1 = \lambda_2 = \lambda_3 = \ldots\ldots = \lambda.$ As threshold is constant for all CR, $P_{f,i}$ will be independent of i , therefore $P_{f,i} = P_f$. For AWGN channel, $P_{d,i}$ is independent of i and we denoted as P_d . In Rayleigh fading channel, P_d is $P_{d,i}$ averaged over the different values of γ_1 [1-3].

Using the average probability of each CR, the prevalent receiver calculates false alarm probability and missed detection probability. The probability of false alarm is provided by[1],

$$Q_f = \sum_{l=n}^{k} \binom{k}{l} p_f (1-p_f)^{k-1} = Prob\{H_1\} \quad (1.8)$$

Also, the missed detection probability is given by;

$$Q_m = 1 - \sum_{l=n}^{k} \binom{k}{l} p_d{}^l (1-p_d)^{k-1} = prob\{H_0/H_1\} \quad (1.9)$$

2. OPTIMIZATION OF COOPERATIVE SPECTRUM SENSING

We evaluate ideal voting rule, optimization of CR number and detection threshold with cooperative spectrum sensing in this section.

2.1 Optimal Voting Rule

Let, K is then set the ideal value of n so we get the minimum error rate, this is the ideal voting rule and the ideal value of n is called as o p t n. We've plotted n=1 to n=10 chart. For each n, we calculated the error rate for distinct threshold values. We get more error rate and ideal rule AND rule for tiny threshold value (i.e. n=10). Optimal rule for big threshold value is OR rule. But if n = 5 for medium threshold values, we get more mistake rate [1].

Statement 1: To find n_{opt} the minimum error rate value that we suggested as follows;

$$n_{opt} = min\left(k, \frac{K}{1+\alpha}\right) \tag{1.10}$$

Where,

$$\alpha = \frac{In\frac{p_f}{1-p_m}}{In\frac{p_m}{1-p_m}} \tag{1.11}$$

Proof:

From equation 7 and 8, we get, $(Q_f + Q_m) = 1 + G(n)$. For optimal value of *n*, error rate should be minimum, [1] i.e.

$$\frac{\partial G(n)}{\partial n} \approx G(n+1) - G(n) \tag{1.12}$$

Therefore, the difference is given by $G(n+1) - G(n)$

$$\frac{\partial G(n)}{\partial n} \approx G(n+1) - G(n) \tag{1.13}$$

$$= \sum_{i=n+1}^{k} \binom{k}{i} \left[p_f{}^1(1-p)^{k-1} - (1-p_m)^1 p_m{}^{k-1}\right] - \sum_{i=n}^{k} \binom{k}{l} \left[p_f{}^1(1-p_f)^{k-1} - (1 - p_m)^1 p_m{}^{k-1}\right] \tag{1.14}$$

$$= \binom{K}{n} \left[-p_f{}^n(1-p_f)^{k-n} + (1-p_m)^n p_m{}^{k-n}\right] \tag{1.15}$$

i.e. only l = n term remains

$$-p_f{}^n(1-p_f)^{k-n} + (1-p_m)^n p_m{}^{k-n} \tag{1.16}$$

$$-p_f{}^n(1-p_f)^{k-n} = (1-p_m)^n p_m{}^{k-n} \tag{1.17}$$

On simplifying, we get

$$n \approx \left[\frac{K}{1+\alpha}\right] \tag{1.18}$$

Where,

$$\alpha = \frac{In\frac{p_f}{1-p_m}}{In\frac{p_m}{1-p_f}} \tag{1.19}$$

We get certain values for n from equation 9;

a) If P_f and Pm are of same order then α ≈ 1 and n=K/2

b) If P_f ≤ Pm k-1 results in P_f<<Pm for large K then α ≥ K-1 and n=1 i.e. OR rule.

c) If P_m << Pf then α tends to zero and n=K i.e. AND rule.

2.2 Optimal Energy Detection Threshold

Here we find that K, n and SNR are then known what the optimum threshold π * will be to minimize the complete error rate. We have plotted distinct limit values for the complete error rate curve in Figure 1.Figure has the small error rate for specified n for only one threshold value. That is to say, there is one and only value λ for which $(Q_f + Q_m)$ is minimum [1]

$$\lambda^* = arg\{min(Q_f + Q_m)\} \tag{1.20}$$

For optimal energy threshold;

$$\frac{\partial Q_f}{\partial \lambda} + \frac{\partial Q_m}{\partial \lambda} = 0 \tag{1.21}$$

$$\frac{\partial Q_f}{\partial \lambda} = \sum_{l=m}^{k} \binom{k}{l} l.\, p_1{}^{l-1}.\frac{\partial p_f}{\partial \lambda}.(1-p_f)^{k-1} - \sum_{l=m}^{k} \binom{k}{l} p_1{}^{l}(K-I).\frac{\partial p_f}{\partial \lambda}.(1-p_f)^{k-l-1} \tag{1.22}$$

$$\frac{\partial Q_m}{\partial \lambda} = -\sum_{l=m}^{k} \binom{k}{l} l.\, p_1{}^{l-1}.\frac{\partial p_d}{\partial \lambda}.(1-p_d)^{k-1} + \sum_{l=n}^{k} \binom{k}{l} p_d{}^{l}(K-I) \tag{1.23}$$

2.3 Optimal Number of Cognitive Radios

In a single time slot, only one CR should send its local decision to the common receiver so as to easily separate decisions easily at the receiver end. Hence, for a cognitive radio network with a large number of CRs, cooperative spectrum sensing may become impractical.. As a result the sensing time can become intolerably long. This issue can be addressed by allowing the CRs to send the decisions concurrently. But it may complicate the receiver design when separating the decisions from different CRs. Another potential solution is to send the decisions on orthogonal frequency bands, but this requires a large portion of available bandwidth. To address these issues, So we suggested an effective sensing algorithm, defining some error bound and calculating the optimum amount of CR's. Each CR also sends a choice in one slot of time. By this technique we get the necessary error rate using only a few CRs. If SNR and threshold values are known, then we calculate the smallest number of CRs in cooperative spectrum sensing to attain target error limitations. i.e.

$(Q_f + Q_m) \leq \in$. where α is the target error bound. As previously indicated for optimum voting rule[1],

$$n^{opt}{}_{k=min}\left(K^*, \left[\frac{K^*}{1+\alpha}\right]\right) \quad (1.24)$$

Here, K* (1≤K*≤K) is the least number of CR's to satisfy target error bound $(Q_f + Q_m) \leq \in$. and α is calculated from, P_f, P_m, and known SNR and λ values. We define the function,

$$F(k, n^{opt}{}_k) = Q_f + Q_m - \varepsilon$$
(1.25)

Where k is the amount of collaborative spectrum sensors and n_k^{opt} Is calculated from above. The probability Q_f and Q_m are functions of k and n_k^{opt}. Therefore we get;

$$F[k^*, n^{opt}{}_k] \leq 0 F(k, n_k{}^{opt}) = Q_f + Q_m - \varepsilon$$

$$F(k^* - 1, n^{opt}{}_{k-1}) > 0 \quad (1.26)$$

We can use the above equations k* = [k0], Where k0 is the function's first zero crossing point F(k, n_k^{opt}) in terms of k. Hence, it is possible to implement quick sensing algorithms by considering only k* CR's instead of K. This decreases the time slot from K to k * to keep the target error bound for the prevalent receiver.

3. System Modelling With Energy Detection of Signal

Here, the signal energy is calculated and false alarm and detection probability is calculated. [92-94]. First, we define separate AWGN channel threshold values and calculate the energy obtained from the signal. If energy of received signal is $x_1(t) = s(t) + w(t)$, then the energy of $x_1(t)$ is calculated, also if received signal is $x_2(t) = w(t)$, then energy of $x_2(t)$ is calculated. If energy of $x_1(t)$ is higher than the limit value then the likelihood of detection and if the energy of the $x_2(t)$ is higher than the limit value then the likelihood of false alarm [2].

$$E_1 = \frac{1}{N_{02}} = \sum_n (s(n) + w(n))^2 \quad (1.27)$$

And

$$E_2 = \frac{1}{N_{02}} = \sum_n w(n))^2$$
(1.28)

where $N_{02}$is the two sided noise power spectral density [2] and is given by;

$$N_{02} = \frac{\sum_n s(n))^2}{(2 \times SNR)}$$
(1.29)

The SNR values are allocated exponentially for the Rayleigh Fading Channel. We consider SNR values with the same mean to be an exponential random number. We used Rayleigh to determine the fading channel gain [3]

$$h = \sqrt{\frac{(2 \times SNR)}{\sum_n (s(n))^2}}$$
(1.30)

Then we discover the authority of two sides of the noise [3]

$$N_{02} = \frac{\{h^2 \times \sum_n (s(n)^2)\}}{(2 \times SNR)} \quad (1.31)$$

Then using this value of 02 N and equation (31) we calculated the energy of the received signal and find probability of false alarm and detection using threshold values.

The energy becomes in Rayleigh Fading Channel;

$$E_1 = \frac{1}{N_{02}} \sum_n (h \times s(n) + w(n))^2$$
(1.32)

3 ROC of AND under AWGN

A. Energy Detector

The ED is the simpler method in CRN for spectrum sensing. In a determined spectrum bandwidth, it merely estimates the energy content. The statistical test connected with this is formulated as

$$T(y) = \frac{1}{\tau f_s} \sum_{i=1}^{\tau f_s} |y(i)|^2$$
(1.33)

Such statistical tests are likened to a threshold level

$$P_d(\tau) = Q\left(\frac{1}{\sqrt{2snr_p + 1}} Q^{-1}() - \sqrt{\tau f_s} SNR_p\right)$$
(1.34)

Where the statistical test is lower than the limit λ, the SU selects an idle channel, otherwise the channel will be busy and the SU will not broadcast.

Sensing-time vs. Throughput problem formulation

The likelihood of fake alarm $p_f(.)$ and detection likelihood $p_d(.)$ using the Central Limit Theorem (CLT) approach, associated with the ED can be formulated as a function of the sensing time parameter τ.

$$P_f(\tau) = Q(\sqrt{2SNR_P + 1}Q^{-1}(P_d) + \sqrt{\tau f_s}SNR_P)$$
(1.35)

$$P_d(\tau) = Q\left(\frac{1}{\sqrt{2SNR_P+1}}Q^{-1}() - \sqrt{\tau f_s}SNR_P\right)$$
(1.36)

where p_d and p_f The likelihood of detection target and false alarm target, respectively, and the essential function of the Gussian probability density is described as

$$Q(x)\Delta\frac{1}{\sqrt{2\pi}}\int_x^\infty exp\left(\frac{-z^2}{2}\right)dz$$
(1.37)

The π threshold value can be associated with the detection probability as [5].

$$P_d(\tau) = Q\left((\lambda - SNR_P - 1)\sqrt{\frac{\tau f_s}{2SNR_P+1}}\right) \quad (1.38)$$

When there are distinct channel occupancy probability values, then eq. (1.17) Available to:

$$P_d(\tau) = Q\left((\lambda - \beta - 1)\sqrt{\frac{\tau f_s}{2\beta+1}}\right)$$
(1.39)

where $\beta = P_r(H^1)SNR_p$. The value of SNR_p is weighted to $P_r(H^1)$, Which is the channel's likely to be busy.

As a consequence, in the lack and in the presence of the PU, the throughput of the SU is provided.

$$C_0 = \log_2(1 + SNR_8) \quad (1.40)$$

$$C_1 = \log_2\left(1 + \frac{SNR_8}{1+SNR_P}\right) \quad (1.41)$$

Where C_0 is the SU's output when operating in the absence of the PU and C_1 is the SU's output when operating in the presence of the PU. Obviously, the value of C_0 is always larger than the value of the C_1, i.e The PU signal interferes with the throughput when the channel is busy. The first and third scenarios therefore contribute to the relationship between sensing and performance [5]

$$B_0(\tau) = \frac{T-\tau}{T}C_0 \quad (1.41)$$

$$B_1(\tau) = \frac{T-\tau}{T}C_1 \quad (1.42)$$

In the first case, the PU is not present then SU not generate false alarm. For the second case PU signal is active. Hence, $B_0(\tau)$ and $B_1(\tau)$ represent the SU throughput dependent on the sensing-time duration (τ < T) when PU is absent and present, respectively. The probabilities for occurrence of the first and third scenarios are given by [5]

$$P_r(\text{correct detection}) = [1 - P_f(\tau)] \cdot P_r(H^0) \quad (1.43)$$

$$P_r(\text{miss detection}) = [1 - P_d(\tau)] \cdot Pr(H^1) \quad (1.44)$$

where $P_r(H^0)$ and $P_r(H^1)$ The channel is likely to be idle and busy (linked to first and third situations). The probability $(1-P_d(\tau))$ is called the likelihood of miss detection. So, the throughput $R_0(\tau)$ and $R_1(\tau)$ they are respectively for the first and third situations.

$$R_0(\tau) = \frac{T-\tau}{T}C_0.[1 - P_f(\tau)].P_\tau(H^0) \quad (1.45)$$

$$R_1(\tau) = \frac{T-\tau}{T}C_1.[1 - P_f(\tau)].P_\tau(H^1) \quad (1.46)$$

Finally, the complete SU network output is provided by

$$R(\tau) = R_0(\tau) + R_1(\tau) \quad (1.47)$$

The throughput is provided by eq for the ED spectrum sensing case. (1.26) [5], next page at the top. To simplify, we find the channel's probability to be small, i.e $P_r(H^1) \leq 0.2$ And the second word of the performance feature in (4.27) becomes meaningless and can be simplified as

$$\hat{R}(r) = B_0(\tau)(1 - Q(\sqrt{2SNR_P + 1}\,Q^{-1}() + \sqrt{\tau f_s}SNR_P))P_r(H^0)$$
(1.48)

Finally, the issue of streamlined optimization of sensing-throughput (STO) can be articulated as

$$max.\ \hat{R}(r) \quad (1.49)$$

$$s.t.\ (c.1)\ 0 \leq \tau \leq T \quad (1.50)$$

$$(C.2) \quad P_d(\tau) \geq P_d$$
(1.51)

Where $P_d = 0.9$ is the IEEE 802.22 WRAN detection target probability. The convexity of the issue of optimization (21) is shown in the appendix. The above issue of optimization can be viewed as a sensing-throughput tradeoff aimed at identifying the ideal sensing duration τ for each frame time in the MAC layer, such that the achievable throughput of the SU is guaranteed, while ensure the PU protection, that is related with the value of the P_d.

4. Result and Discussion

In figure.1, by maintaining SNR=10 db, we discovered error rate for various threshold values and amount of CR's. The error rate in the figure is small for n=5 and high for n=10 and n=1.i.e. We can achieve a small error rate with 5 CRs out of 10. This figure explains the optimal rule. The error rate is nothing but$(Q_f + Q_m)$. That is the likelihood of missed detection and if very few or high amount CR's are used, the false alarm probability is high.Thus the number of CRs used should be half of the total CR's, i.e. for n=5 the likelihood of missed detection and false alarm probability is low, so cooperative spectrum sensing allocation is done correctly. We also compare the outcomes of modeling and modeling by modeling the system. We compare outcomes obtained from n = 5 modeling and formulae. The two outcomes are the same. We use the equations described in section 3 for modeling.

As of MATLAB Optimization Toolbox. The numerical solutions discussed in this system confirm that the maximum is a global optimum and the objective function is a concave function.

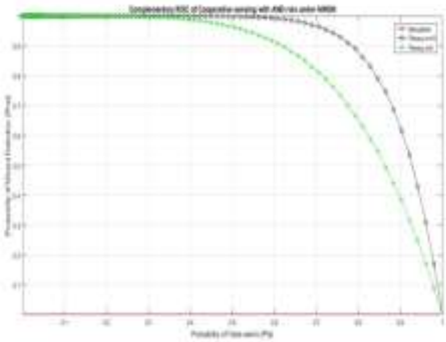

Figure 1: Complementary ROC curves for local spectrum sensing under AWGN and Rayleigh channel with m = 10

Comparing the values of P_d with values of threshold one can see that different values of threshold implies in values of $P_d \geq 0.9$, which respects the constraints. Comparing values of P_d with values of Ns and values of sensing time, it is possible to conclude that for values of $N_s \geq 15600$ samples, implies in values of Pd above 0.9, with no violation of the constraints limits. Hence, we concluded that the obtained solution respect the constraint of the optimization problem, in addition to maximize the throughput of the SU

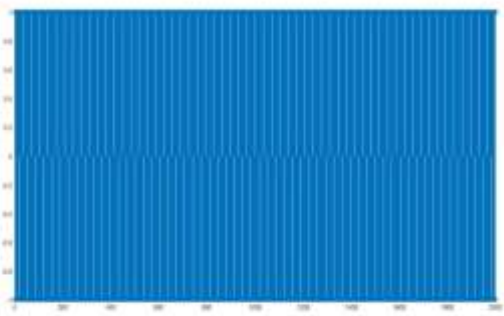

Figure 2: Energy Detection Graph

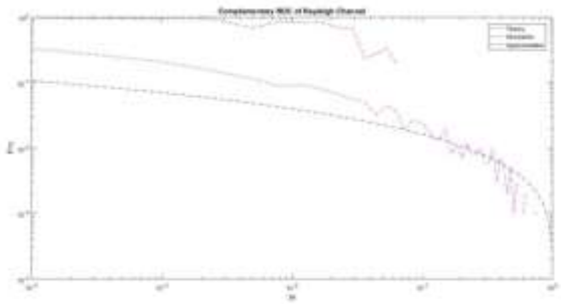

Figure 3: Complementary ROC curves for cooperative spectrum sensing using AND-rule under Rayleigh channel with m = 10 and SNR = -10 dB.

In the figure.1, we found error rate for different threshold values and number of CR's by keeping SNR=10 db. In figure, the error rate is low for *n =5* and it is high *n =10* and *n =1*.i.e. with use of 5 CR's out of 10 we can achieve low error rate. This figure explains the optimal rule. The error rate is nothing but $(Q_f + Q_m)$. That is probability of missed detection and false alarm probability is high if very few or high number CR's are used. So the number of CR's used should be half of total CR's, i.e. for n=5 the probability of missed detection and false alarm probability is low, so cooperative spectrum sensing allocation is done in correct way. Also, by modeling the system, we compare results get from modeling and formulae for *n =5*. The both results are same. For modeling, we use equations explained in section 4.We discovered optimum value of ' n ' i.e. ' n from K ' CR's in figure.2.We differ limit values from 10 to 40 and we discovered ideal value of ' n ' from equation 9 for distinct SNR values (0dB, 5dB, 10dB).From the graph we conclude that the necessary amount of CR's is more for low threshold value with low SNR.As we raise the limit value with low or equal SNR, we need very less CR. The ideal value of n also rises as SN rises. E.g. If SNR= 0dB and = 33, the ideal value of n is 1.We can attain a small error rate with 1 CR.

For high threshold value, the ideal value of n is small, so we get low likelihood of missed detection and false alarm likelihood for elevated threshold value with fewer CRs. This probability also decreases in AWGN channel by reducing SNR values for a tiny amount of ' n '

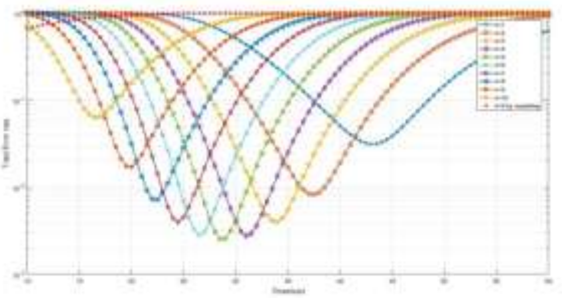

Chart 4: Total error rate of cooperative spectrum sensing in AWGN channel with 10dB SNR. Optimal voting rule for n=1,2,.........,10 and K=10.

5. CONCLUSION

The cooperative energy detection spectrum sensing using formula and system modeling was researched. Analysis of the scheme has been performed with optimum voting rule for minimum error rate and K/2 is the optimum value. In addition, threshold optimization was performed with minimum probability values for missed detection and false alarm probability. System analysis has been performed for the less likelihood of missed detection and false alarm probability, so the spectrum has been properly allocated to secondary consumer. The quick sensing algorithm was suggested and the smallest number of CR's calculated for a specified error bound. With quick sensing algorithm, the intolerably lengthy sensing time has been eliminated.

REFERENCES

[1] Wei Zhang, Member, IEEE, Ranjan K. Mallik, Senior Member, IEEE, and Khaled Ben Letaief, Fellow, IEEE "Optimization of Cooperative Spectrum Sensing with Energy Detection in Cognitive Radio Networks", IEEE transactions on wireless communications, vol. 8, no. 12, December 2009.

[2] Harry Hrkowitz, Member, IEEE, "Energy Detection of Unknown Deterministic Signals" Proceeding of the IEEE, Vol. 55,Issue no.4 , 1967, Pg.No. 523 –531.

[3] Fadel F. Digham, Member, IEEE, Mohamed-Slim Alouini, Senior Member, IEEE, and Marvin K. Simon, Fellow, IEEE," On the Energy Detection of Unknown Signals Over Fading Channels", IEEE transactions on communications, vol. 55, no. 1, January 2007.

[4] Fadel F. Digham, Mohamed-Slim Alouini, and Marvin K. Simon, "On the Energy Detection of Unknown Signal over Fading Channels", Communications, 2003, ICC '03. IEEE International Conference on, pg. no. 3575 – 3579, vol.5, 11-15 May 2003.

[5] Federal Communications Commission, "Spectrum Policy Task Force", Rep. ET docket no. 02-135, Nov. 2002.

[6] Danijela Cabric, Shridhar Mubaraq Mishra, Robert W. Brodersen, Berkeley Wireless Research Center, University of California, Berkeley, "Implementation Issues in Spectrum Sensing for Cognitive Radios",

[7] Marvin K. Simon Mohamed-Slim Alouini, "Digital Communication over Fading Channels", A Unified Approach to Performance Analysis A Wiley- Interscience Publication JOHN WILEY & SONS, INC.

[8] M. A. McHenry, "NSF Spectrum Occupancy Measurements ProjectSummary," Shared Spectrum Company, Aug. 2005.

[9] M. A. McHenry, P. A. Tenhula, D. McCloskey, D. A. Roberson, and C.S. Hood, "Chicago Spectrum Occupancy Measurements & Analysis anda Long-term Studies Proposal." the First ACM International Workshopon Technology and Policy for Accessing Spectrum, 2006.

[10] F. Khan and K. Nakagawa, "Comparative Study of Spectrum SensingTechniques in Cognitive Radio Networks," 2013 World Congress onComputer and Information Technology (WCCIT), Sousse, pp. 1-8, 2013.

[11] J. Mitola and G. Q. Maguire, "Cognitive Radio: Making SoftwareRadios More Personal," IEEE Personal Communications, vol. 6, no. 4,pp. 13-18, Aug 1999.

[12] L. Khalid and A. Anpalagan, "Emerging Cognitive Radio Technology:Principles, Challenges and Opportunities," Computers & ElectricalEngineering, vol.36, no.2, pp.358-366, Mar. 2010.