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Energy Detector Based Sensing Throughput in Cognitive Radio Network

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Abstract
Cognitive radio networks allow secondary users to utilize the frequency bands of primary users during their idle state. Spectrum sensing is a process (which is implemented in Cognitive radios, CRs) for obtaining radio or spectrum information at a given time and location. This paper addressed the relationship between the throughput and sensing time in a cognitive radio network (CRN) using energy detector (ED). The sensing time is a period in the medium access control (MAC) protocol that the secondary user (SU) utilizes in sensing the spectrum and is critical to determine the performance of the SU and the interference to primary user (PU). The problem of designing the sensing duration to maximize the achievable throughput for the secondary network under the constraint that the primary users are sufficiently protected was studied. The sensing-throughput tradeoff problem was mathematically formulated, and used energy detection sensing scheme to prove that the formulated problem indeed has one optimal sensing time which yields the highest throughput for the secondary network. In cognitive radio (CR), increasing the sensing time is equivalent to increasing the SU performance. Accordingly, when the throughput of the SU decreases, the quality of service (QoS) of the SU is reduced. Numerical analysis examined the performance of the ED when the throughput is maximized as well as when distinct parameters values are assumed.

Keywords: *Cognitive Radio Network, Energy Detection, Primary User, Secondary User, Spectrum Reuse Spectrum Sensing, Throughput Maximization*

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1. Introduction

The growth of the wireless communication services has resulted in the scarcity of the available spectrum. Recent measurements done by the Federal Communications Commission (FCC) have demonstrated underutilization of a large percentage of the allocated spectrum. Spectrum occupancy has been observed to vary from milliseconds to hour thereby motivating the use of the cognitive radio (CR) which is the core of spectrum reuse, thereby increasing the spectrum efficiency (SE) considerably (Mitola and Maguire Jr., 1999; Haykin, 2005). The sensing duration strongly impacts the network throughput. An increase in the sensing duration results to a decrease in the throughput. However, a longer sensing time makes the SU more aware about the received signal while more protection is given to the PU.

In wireless regional area networks (WRANs), the main objective is to maximize the spectrum utilization of the TV channels. The CR is the main technology in the WRAN 802.22, where each medium access control (MAC) frame comprises of one sensing slot and one data transmission slot. The scheme to deal with this challenging issue requires that we formulate and efficiently solve the associated optimization problem that maximize the throughput subject to different constraints, such as probability of detection, probability of false alarm, maximum frame time, optimum threshold, and so forth. For instance, in (Liang et al., 2007; Peh et al., 2010), the sensing-throughput optimization problem in ED spectrum sensing was formulated as convex nonlinear optimization problems. Using energy detection scheme, it has been proven that there indeed exists an optimal sensing time which achieves the best tradeoff. Cooperative sensing using multiple secondary users and diversity reception using multiple mini slots are also studied based on the proposed tradeoff methodology. In recent times, a high level of importance has been given to the sensing time versus throughput tradeoff in the context of CRN (Cardenas-Juarez et al., 2015; Zhang et al., 2015).

In Liang et al. (2008), a convex nonlinear optimization problem was formulated to deal with the sensing-throughput optimization (STO) tradeoff in a single band cognitive radio network. In this sense, this contribution consists in a numerical analysis extension of the work in (Liang et al., 2008). The STO problem was solved expeditiously using the solver available in the MATLAB Optimization Toolbox. Simulation results demonstrate the quality of solution and the impact on the ED performance and some interesting results are discussed when the parameters of simulation are different to the initial problem considerations, revealing the ED performance dependence with such parameters. In Fan and Jiang (2010), the multichannel cooperative sensing optimization problem was formulated as a non-convex mixed-integer problem that is solved by dividing the original problem into convex mixed-integer sub problems.

2. Materials and methods

2.1 System model

Samples of the signals transmitted by the PU are tagged as s(i) while a circular symmetric complex Gaussian (CSCG) noise samples are represented by n(i). When the primary user is active, the discrete received signal at the secondary user can be written as:

$$y(i) = s(i) + n(i), \quad i = 1,2,\dots,\tau f_s \tag{1}$$

where τf_s = total number of samples, τ = sensing time and f_s = sampling frequency.

Two probabilities are of interest for spectrum sensing: probability of detection, which defines the probability of the algorithm correctly detecting the presence of primary signal; and probability of false alarm, which defines the probability of the algorithm falsely declaring the presence of primary signal. From the perspective of the PU, the higher the probability of detection, the better protection it receives. However, the lower the probability of false alarm, the higher the chances of the secondary user utilizing the frequency bands when they are available.

The hypothesis taken to determine if the channel is idle or busy is represented as:

$$\begin{cases} H_0: y(i) = n(i), & i = 1,2,\dots,\tau f_s. \\ H_1: y(i) = s(i) + n(i), & i = 1,2,\dots,\tau f_s. \end{cases} \tag{2}$$

where H^0 and H^1 are the hypothesis of the absence and presence of the primary user respectively.

Figure 1 represents the basic MAC frame time structure considered in this paper. Spectrum sensing occurs in the first segment of the frame time while the second segment depicts the transmission time that impacts the throughput. Considering that the total frame time is fixed, the sensing time and throughput are conflicting parameters.

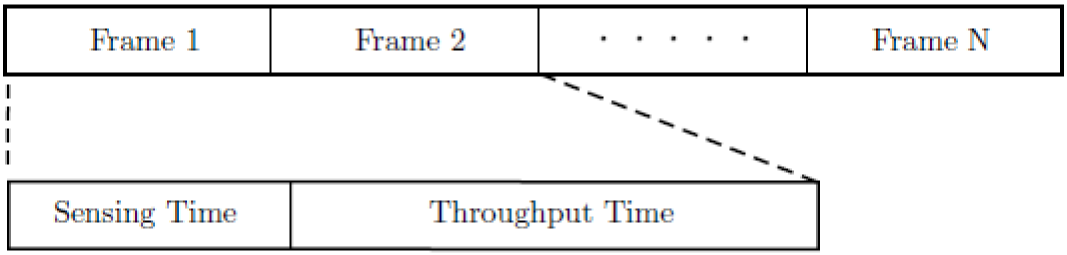

Fig.1: Frame structure for cognitive radio networks with periodic spectrum sensing

2.2 Energy detector

The energy detection technique simply detects spectrum holes or PU idle channels based on the sensed energy at the receiver (Atapattu et al., 2011; Thilina et al., 2012). To perform energy detection, CRs need to estimate the energy level for a time duration. The ED is the more simple form to spectrum sensing in CRN. The associated statistical test is formulated as:

$$T(y) = \frac{1}{\tau f_s} \sum_{i=1}^{\tau f_s} |y(i)|^2 \tag{3}$$

$$T(y) \underset{H^0}{\overset{H^1}{\gtrless}} \lambda, \tag{4}$$

The test is compared with a threshold level such that if the statistical test is smaller than threshold level λ, the SU acts as an idle channel, otherwise the channel is busy and the SU will not transmit. There are four scenarios that must be considered in the ED performance analysis:

1) A false alarm is detected when the channel is idle and the SU estimates that the channel is busy, therefore there is no transmission by the SU.

2) If the channel is busy and the SU estimates same, then the SU will not transmit and the PU is protected. A correct detection occurs.
3) If the channel is busy and the SU estimates that the channel is idle, then the SU will transmit and a wrong detection takes place.
4) A correct detection occurs when the channel is idle and the SU estimates that the channel is idle. The SU will transmit and maximum throughput occurs.

2.3 Sensing-time vs. throughput problem formulation

The probability of false alarm P_f (τ) and probability of detection $P_d(\tau)$ associated to the ED can be formulated using the central limit theorem (CLT) approach, as function of sensing time parameter, τ.

$$P_f(\tau) = Q(\sqrt{2SNR_p + 1}Q^{-1}(\overline{P_d}) + \sqrt{\tau f_s}SNR_P) \quad (5)$$

$$P_d(\tau) = Q(\frac{1}{\sqrt{2SNR_p+1}}Q^{-1}(\overline{P_f}) - \sqrt{\tau f_s}SNR_P) \quad (6)$$

where $\overline{P_d}$ and $\overline{P_f}$ are the probability of detection target and false alarm target, respectively, and the integral of Gaussian probability density function is defined as:

$$Q(x) \triangleq \frac{1}{\sqrt{2\pi}}\int_x^\infty exp\left(\frac{-z^2}{2}\right)dz. \quad (7)$$

The threshold value (λ) relates with the probability of detection $P_d(\tau)$ as (Liang et al., 2008)

$$P_d(\tau) = Q\left((\lambda - SNR_p - 1)\sqrt{\frac{\tau f_s}{2SNR_P+1}}\right) \quad (8)$$

When different values of probability of channel occupancy occur, then Equation (8) can be extended to:

$$P_d(\tau) = Q\left((\lambda - \beta - 1)\sqrt{\frac{\tau f_s}{2\beta+1}}\right) \quad (9)$$

The value of SNR_p is weighed to $P_r(H^1)$, which is the probability of the channel being busy.

The signal-to-noise ratio (SNR) of the primary user signal received in the primary user is given by

$$SNR_p = \frac{P_p}{N_0}$$

and SNR of the secondary user signal is given by:

$$SNR_s = \frac{P_s}{N_0}$$

where Pp and Ps are the transmission power of the PU and the SU respectively, while the same level of the noise power spectral density N_0 is assumed for both PU and SU user types. As a consequence, the throughput of the SU in the absence and in the presence of the PU are given respectively by:

$$C_0 = log_2(1 + SNR_s) \quad (10)$$

$$C_1 = log_2(1 + \frac{SNR_s}{SNR_p}) \quad (11)$$

where C_0 is the throughput of the SU when it functions in the absence of the PU and C_1 is the throughput of the SU when it operates 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 throughput when the channel is busy suffers interference from the PU signal. Therefore, the first and third scenarios lead to the sensing-throughput relations (Liang et al., 2008):

$$B_0(\tau) = \frac{T-\tau}{T}C_0 \quad (12)$$

$$B_1(\tau) = \frac{T-\tau}{T}C_1 \quad (13)$$

In the first case, the PU is not present then SU will 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 (Liang et al., 2008)

$$Pr(correct\ detection) = [1 - P_f(\tau)].P_r(H^0) \quad (14)$$

$$Pr(wrong\ detection) = [1 - P_d(\tau)].P_r(H^1) \quad (15)$$

where $P_r(H^0)$ and $P_r(H^1)$ is the probability that the channel is idle and busy respectively.

The probability $((1 - P_d(\tau))$ is called miss detection probability.

So, the throughput $R_0(\tau)$ and $R_1(\tau)$for the first and third scenarios are respectively expressed as:

$$R_0(\tau) = \frac{T-\tau}{T}C_0.[1 - P_f(\tau)].P_r(H^0) \quad (16)$$

$$R_1(\tau) = \frac{T-\tau}{T}C_1.[1 - P_d(\tau)].P_r(H^1) \quad (17)$$

Finally, the total throughput in the SU network is given by:

$$R(\tau) = R_0(\tau) + R_1(\tau) \quad (18)$$

For the case of the ED spectrum sensing, the throughput is given by Equation (9) (Liang et al., 2008). To simplify, it was considered that the probability of detection of the channel occupied is low (≤ 0.2) i.e. $P_r(H^1) \leq 0.2$ and the second term of the throughput function becomes insignificant and can be simplified as:

$$\hat{R}(\tau) = B_0(\tau)\left(1 - Q\left(2SNR_p + 1Q^{-1}(\overline{P_d}) + \sqrt{\tau f_s}SNR_p\right)\right)P_r(H^0) \quad (19)$$

Finally, the simplified sensing-throughput optimization (STO) problem can be expressed as max.

$$\begin{array}{lll} \underset{\tau}{max.} & \hat{R}(\tau) & \\ s.t. & (c.1.) & 0 \leq \tau \leq T \\ & (c.2.) & P_d(\tau) \geq \overline{P_d} \end{array} \quad (20)$$

where $\overline{P_d}$ = 0:9 is the probability of detection target according to the IEEE 802.22 WRAN.

The optimization problem in Equation (19) can be interpreted as a sensing-throughput tradeoff whose objective is to identify the optimal sensing duration (τ) for each frame time in the MAC layer, such that the achievable throughput of the SU is guaranteed, while ensuring the PU protection that is related with the value of the Pd.

3. Results and discussion

3.1 Reference simulation values

Table 1 depicts the main parameter values deployed in this work. The values of the throughput using such parameters are C_0 = 6.6582 and C_1 = 6.6137.

Table 1: Reference values used for simulations

Parameter	Value
$P_r(H^0)$	[0.8, 0.5, 0.2]
$P_r(H^1)$	[0.2, 0.5, 0.8]
SNR_s	20[dB]
SNR_p	-15[dB]
T	100[ms]
$\overline{P_d}$	0.9
f_s	6[MHz]
PU signal	QPSK

Using the simple but effective tool FMINCON of MATLAB Optimization Toolbox, the STO problem was solved easily and the solver returns the optimal sensing time value as τ^* = 2.6 [ms] for the three scenarios, i.e., for low, medium as well as high channel occupancy. The estimated optimal throughput ($\widehat{R^*}$), original optimal throughput and the difference are given in Table 2. Since the number of samples (Ns) is related to the sensing time and the sample frequency and considering that the optimum sensing time for the three scenarios results are the same, then

$N_s^* = \tau^* f_s = 15600$ (Number of samples)

$$R(\tau) = B_0(\tau)\left(1 - Q\left(\sqrt{2SNR_p + 1}Q^{-1}(\overline{P_d}) + \sqrt{\tau f_s}SNR_p\right)\right)P_r(H^0) \quad (21)$$

Table 2: Simplified original throughput and throughput difference

$P_r(H^1)$	0.2	0.5	0.8
$\widehat{R^*}$	5.1659	3.228	1.2815
R^*	5.295	3.550	1.807
ΔR^* %	12.8	32.2	52.6

3.2 Throughput vs. sensing time

The behaviour of the throughput as a function of the sensing time, i.e. the objective function in (20), is shown in Fig. 2. For the simulation results, 3.10^4 Monte Carlo simulation (MCS) trials were deployed and compared with the theoretical curve. It can be inferred that the throughput function has a unique maximum point, which is the global optimum. Hence, it can be concluded that the objective function is concave. Moreover, examining Fig. 2, it can be inferred by inspection that the maximum value of throughput is achieved in ≈ 2:55 [ms] for the three channel occupancy probability scenarios, in which is confirmed by the solution of the optimization problems.

3.3 Probability of detection vs. threshold

In order to obtain the probability of detection vs. threshold of the energy detector operating under the optimum sensing time, a number of MCS realizations equal to 3.10^4 trials were chosen. Fig. 3 depicts the probability of detection vs. threshold adopting $\tau^* f_s$ = 15600 samples. Values have been compared in which the channel occupancy probabilities are low, medium, high and when the channel is completely occupied. Examining Fig. 3, it can be concluded that the target probability of detection (P_d) = 0:9 are obtained for different values of threshold that can be obtained using Equation (9).

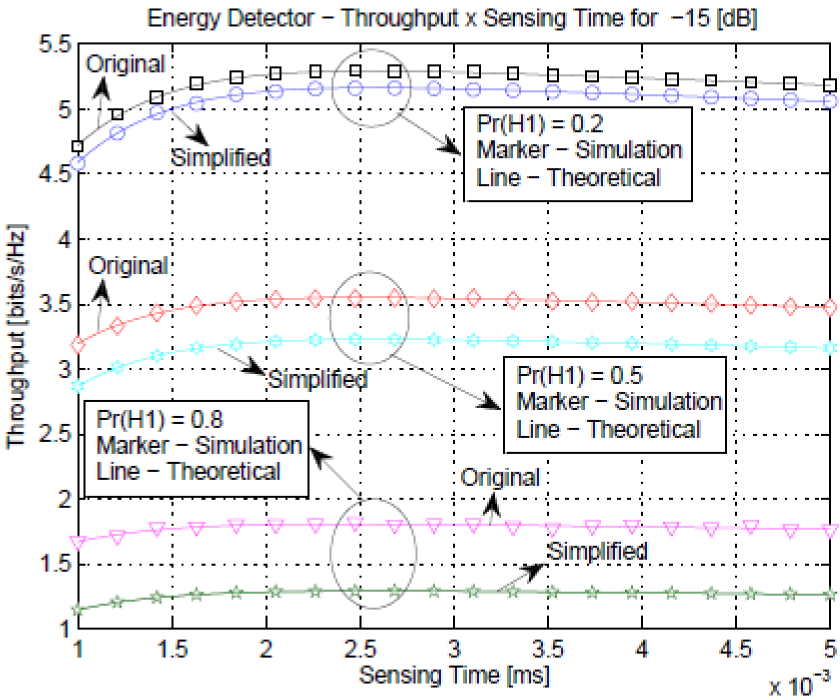

Fig. 2: Throughput vs. sensing time for SNRp = -15[dB]

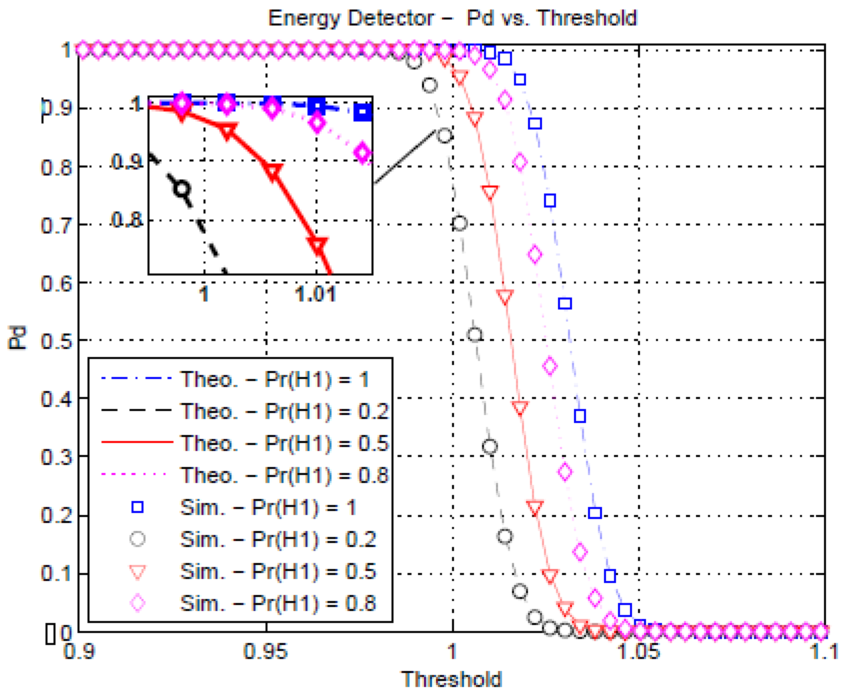

Fig. 3: Probability of detection vs. threshold for Ns = 15600 samples

3.4 Probability of detection vs. number of samples

To obtain the figure of merit described by the probability of detection vs. Ns in the context of CRN equipped with ED, the same number of MCS trials (3.10^4) was chosen. As a consequence, Fig. 4 shows the probability of detection vs. N_s adopting value of the $\overline{P_d}$ = 0.9 and the PU SNR value is SNRp = -15 [dB]. Notice that in Fig 4, values were compared in that the probability of the channel being occupied are low, medium, high and when the channel is completely occupied; notice that a guaranteed 0:9 probability of detection is attained under the four scenarios when N ≥ 15600 samples.

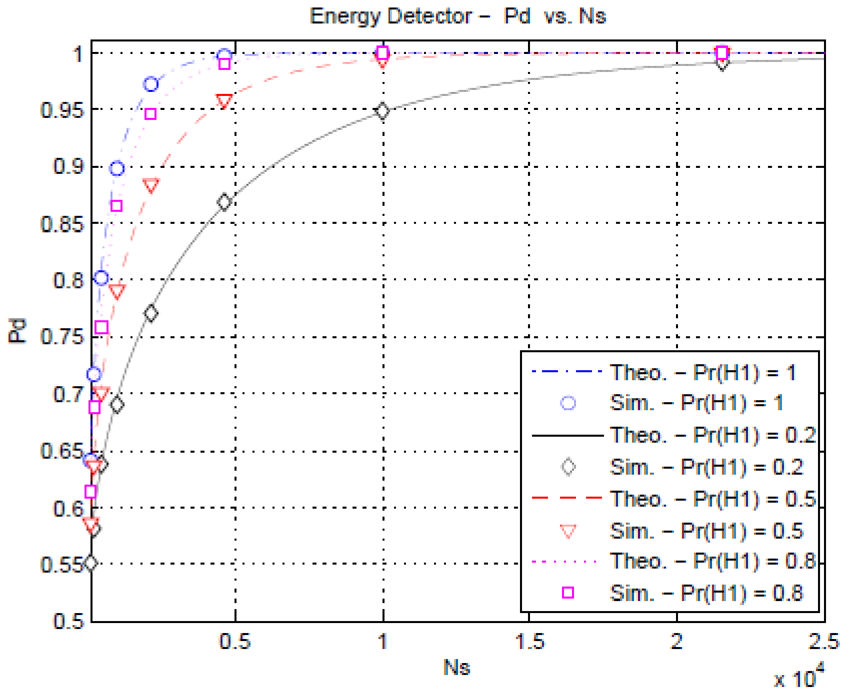

Fig.4: Probability of energy detectors vs. Ns = 25000 samples

4. Conclusions

In order to address the sensing versus throughput tradeoff in a CRN having one PU and one SU in a single-band spectrum sensing scheme, an optimization problem was formulated. The equivalent and simplified optimization problem is convex but nonlinear in τ, and can be solved optimally using efficient solvers, such as FMINCON tool of MATLAB Optimization Toolbox. Comparing the values of P_d with values of threshold, it is can be seen that different values of threshold imply 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 can be concluded that values of Ns ≥15600 samples imply in values of P_d above 0.9, with no violation of the constraints limits. The numerical solutions discussed in this paper confirm that the maximum is a global optimum and the objective function is a concave unction. Hence, it was concluded that the obtained solution respect the constraint of the optimization problem as well as maximize the throughput of the SU.

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