Performance Evaluation of Spectrum Sensing and Channel Access in Cognitive Radio Networks

Soudilya.P,
M.E Communication Systems,
Sri Venkateswara College Of Engineering,
Chennai, India.
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***Abstract*—Spectrum sensing is an essential functionality of cognitive radio networks. In the existing Cognitive Radio spectrum detection techniques secondary nodes base their channel access decisions solely on the outcome of the spectrum sensor without taking into consideration the possibility that those outcomes are incorrect. To alleviate these negative effects a combined design is proposed for the secondary nodes to have better channel access where the spectrum sensor outcome and reliability measure of spectrum sensor decisions are considered. Simulation for characterizing the detrimental effects of spectrum sensor errors and effectiveness of combined design is done using binary hypothesis condition. Results show considerable increase in secondary access probabilities which eventually increases the throughput and decreases the delay of both primary and secondary networks.**

Keywords: Cognitive Radio, soft sensing, multiple access.

1.INTRODUCTION

With the rapid development of wireless communications, spectrum resources become increasingly scarce. However, statistics shows that spectrum resources are not utilized to the full in terms of temporal and spatial. Cognitive radio (CR) is an emerging technology where the wireless transceivers with CR capabilities sense the surrounding environment for spectrum holes, can access and release spectrum with agility as to allow secondary users (unlicensed) to access the spectrum when primary users (licensed) are inactive. The current spectrum management policy adopted by the FCC, based on the property rights model, does allow secondary user operation in the licensed spectrum.

Spectrum Sensing is the process of detecting unused spectrum and sharing the spectrum without harmful interference with other users. In spectrum sensing, it is desired to minimize spectrum sensing error (i.e., sum of false alarm and miss detection probabilities) since minimizing spectrum sensing error both reduces collision probability with primary user and enhances usage level of vacant spectrum. This paper starts by studying the effects of channel sensing errors on the performance from the point of view of multiple access layer measures. This is achieved through a queuing theoretical analysis of the stability regions of both primary and secondary networks. The stability region is characterized for different operating points on the receiver operating characteristic (ROC) of the energy detector based spectrum sensor. The results reveal a significant reduction in the stability region of both networks due to sensing errors.

To mitigate the negative effects of sensing errors, a combined design of the spectrum sensing and access mechanisms is proposed. The design is based on the binary hypothesis testing problem observation, where the value of the test statistics is used as a confident measure of the test outcome. The farther the value of the test statistics from the decision threshold, the more confident the decision is. Therefore, a secondary user can have different access probabilities for different values of the test statistics instead of using the hard decisions of the spectrum sensor to decide the accessibility of the channel. For instance, the access probability could be higher for the values of the test statistics farther away from the decision threshold, and vice versa. Using this technique, one can set the target false alarm probability as low as possible for the secondary nodes not to overlook spectrum opportunities. Besides a low probability of collision with primary user could be maintained as the access probability can be set to an arbitrarily low value near the decision threshold, which is not the case with conventional designs, since lowering the false alarm probability results in an increased probability of missed detections, hence increased probability of collision.

2. MODELLING

Let's consider the uplink of a TDMA cellular network as the primary network. The primary network consists of A_p source nodes numbered 1, 2… Ap communicating with a base station (BS) b_p. A secondary network, consisting of A_s nodes numbered 1, 2... A_s tries to exploit the unutilized channel resources to communicate their own data packets using slotted ALOHA as their multiple access protocol.

A. Channel Model

The wireless channel between a node and its destination is modeled as a Rayleigh flat fading channel with additive white Gaussian noise. The signal received at a receiving node j from a transmitting node i at time t is then modeled as

$$x_{ij}^t = \sqrt{T_i d_{ij}^{-\gamma} f_{ij}^t} y_i^t + n_j^t \tag{1}$$

Where T_i is the transmitting power, assumed to be the same for all nodes, d_{ij} denotes the distance between the two nodes the path loss exponent ,f_{ij}^t is the channel fading coefficient between nodes i and j at time t and is modeled as an i.i.d zero mean, circularly symmetric complex gaussian random process with unit variance. The term y_i^t denotes the transmitted signal which has an average unit power and is assumed to be drawn from a constant modulus constellation with zero mean (M-ary PSK for instance). The i.i.d additive white Gaussian noise processes n_j^t have zero mean and variance N_0. Since the arrivals, the channel gains, and the additive noise processes are all assumed stationary, the index t is dropped without loss of generality.

For the channel model in (1) the received SNR of a signal transmitted between any two nodes i and j can be specified as follows

$$SNR_{ij} = \frac{|f_{ij}|^2 d_{ij}^{-\gamma} T_i}{N_0} \quad (2)$$

B. Queuing Model

Each primary or secondary node has an infinite buffer for storing fixed length packets. The channel is slotted in time and slot duration equals the packet transmission time. The arrivals at the i^{th} primary node's queue ($i \epsilon Ap$) and the j^{th} secondary node's queue ($j \epsilon A_s$) are Bernoulli random variables, i.i.d from slot to slot with mean λ_{pi} and λ_{sj} respectively. Arrival processes are assumed to be independent from one node to another. The stability of queuing system is checked by Loyne's theorem. This theorem states that if the arrival process and the service process of queuing systems are strictly stationary, and the average arrival rate is less than the average service rate, then the queue is stable; if the average arrival rate is greater than the average service rate then the queue is unstable.

3. IMPACT OF SENSING ERRORS

A. Spectrum Sensing

In this section the effects of sensing errors is studied on the performance of both primary and secondary networks. Because of its simplicity and ability to locate spectrum occupancy information quickly, non-coherent energy detected will be adopted in our study of the effect of sensing errors on cognitive radio's performance. Detection of the presence of the i^{th} primary node by the j^{th} secondary node can be formulated as a binary hypothesis test as follows,

$$H_0 : x_{ij}^t = n_j^t$$

$$H_1 : x_{ij}^t = \sqrt{T_i d_{ij}^{-\gamma}} f_{ij}^t y_i^t + n_j^t \quad (3)$$

The null hypothesis H_0 represents the absence of the primary node, hence a secondary node can access the channel. And the alternative hypothesis H_1 represents a transmitting primary node. The performance of the spectrum sensor is characterized by the two types of errors and their probabilities, (i) false alarms having probability f_a, (ii) and missed detections having probability m_d, with

$$f_a \triangleq \Pr\{\text{decide } H_1 \mid H_0 \text{ is true}\}$$

$$m_d \triangleq \Pr\{\text{decide } H_0 \mid H_1 \text{ is true}\}$$

The false alarm type of errors where an idle channel is erroneously detected as busy does not affect performance of the primary system, but decreases the channel utilization of secondary nodes. On the other hand, the missed detection events, fails to detect a primary transmission that results in a collision between primary and secondary transmissions. Therefore, miss detection events will negatively impact the performance of the primary system. With the assumption that secondary nodes do not have prior Knowledge of primary activity patterns, the probability of miss detection m_d could be minimized subjected to the constraint that the probability of false alarm f_a is not larger than a given value f_a using the optimal Neyman-Pearson (NP) detector.

From the received signal model of (1), it follows that under hypothesis H_0 the received signal x_{ij} is a complex Gaussian random variable with zero mean and variance σ_0^2, and under hypothesis H_1, x_{ij} is a complex Gaussian random variable with zero mean and variance

$$\sigma_{ij}^2 = T_i d_{ij}^{-\gamma} + N_0 \quad (4)$$

Therefore, the likelihood ratio test for the optimal NP detector can be simplified as

$$\left\|x_{ij}\right\|^2 \underset{<H_0}{>H_1} \frac{\eta' - \log\frac{\sigma_0^2}{\sigma_{ij}^2}}{\frac{1}{\sigma_0^2} - \frac{1}{\sigma_{ij}^2}} = \eta \quad (5)$$

The spectrum sensing problem has been reduced to a simple comparison of the received signal energy $\|x_{ij}\|^2$ to a threshold η. The optimum threshold could then be calculated through the constraint on the false alarm probability. We first note that, from the received signal model of (1), $\|x_{ij}\|^2$ is exponentially distributed with parameter $1/2\sigma^2_{ij}$ and $1/2\sigma^2_0$, under H_1 and H_0, respectively. Therefore, the false alarm probability is

$$f_a = Pr\left\{\left\|x_{ij}\right\|^2 > \eta | H_0\right\} = e^{-\frac{\eta}{2\sigma_0^2}} \quad (6)$$

From which

$$\eta = -2\sigma_0^2 \log(f_a) \quad (7)$$

Finally, the probability of misdetection is

$$m_d = Pr\left\{\left\|x_{ij}\right\|^2 < \eta | H_1\right\} = 1 - e^{-\frac{\eta}{2\sigma_1^2}} = 1 - e^{-\frac{\sigma_0^2 \log(f_a)}{2\sigma_{ij}^2}} \quad (8)$$

It is noted that in the design above, the spectrum sensor has based its detection on a single sample of the received signal. Increasing the number of samples will increase the reliability of the sensing process. However, it is limited to this design for the purpose of mathematical tractability

B. Performance Analysis

To analyze the effect of sensing errors on the cognitive radio system, stability regions of the primary and secondary networks is adopted as the performance measure.

1) System with Perfect Sensing: Characterize the stability region for the primary system of queues. Since the primary network employs TDMA as a multiple access protocol, it follows directly from Loynes's theorem. For the secondary network, we recall that secondary nodes employ slotted ALOHA to share idle time slots among themselves. Therefore, when an idle time slot is detected, the i^{th} secondary node will try to transmit the packet at the head of its queue (if any) with access probability p_i^a

2) System with Non-Perfect Sensing: In the case of non perfect sensing, the events of misdetection will result in simultaneous primary and secondary transmissions leading to collisions and data loss. It is seen that the average primary service rate is a monotonically decreasing function of the misdetection probability m_d. Therefore, in order to minimize the severity primary performance degradation, spectrum sensors should be designed with the lowest possible m_d. Moreover, with lower primary service rate, the channel will busy with higher probability, which negatively affects secondary nodes, since there will be no enough idle time slots to used. But, decreasing m_d comes at the expense of a higher false alarm rate f_a, which will degrade the performance of secondary nodes.

C. Numerical Results

To see how non-perfect spectrum sensing affects the stability region of the system of primary and secondary nodes, we consider a network with Ap = 3 primary nodes and As = 3 secondary nodes. Nodes are uniformly distributed over a square region with 500m edges. Primary and secondary destinations are located at the center of the square region. SNR threshold is 5dB, transmit power is 100mW, path loss exponent $\gamma = 0.7$, and noise power $N_0 = 10^{-11}$ W. Results are obtained by averaging over 20 independent realizations. For ease of illustration we plot the aggregate primary arrival rate $\lambda_p = \Sigma_i \lambda_{pi}$ and aggregate secondary arrival rate $\lambda_s = \Sigma_i \lambda_{si}$

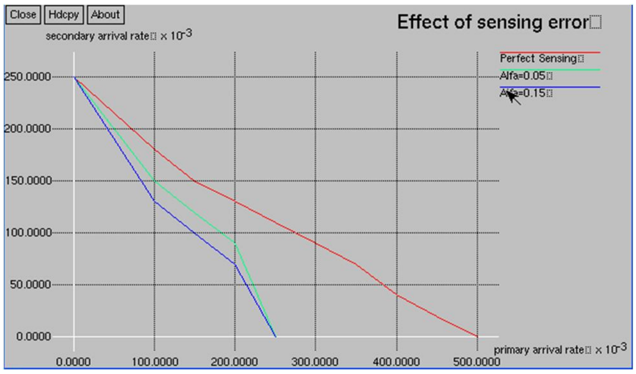

Figure 2:Impact of Sensing Errors on System Stability

It is observed that by allowing the false alarm rate to increase in the detector design, a very slight improvement in secondary throughput is noticed. This is mainly because of the reduction in missed detection probability associated with the increase in the false alarm probability. By reducing the missed detection probability, primary nodes will have better service rates, hence higher probability of having empty queues and idle time slots. The increase in false alarm rate and reduction in missed detection probability are affecting secondary throughput in opposite directions. However, the results of Figure 2 indicate that the gains of reducing the missed detection probability outweigh the degradation due to increased false alarm rate.

4. PROPOSED WORK

A. Joint Design of Sensing and Access Mechanisms

The main cause of these negative effects due to sensing errors is that secondary nodes base their channel access decisions solely on the outcomes of the spectrum sensor without taking into consideration the possibility that those outcomes are incorrect. For the secondary nodes to have better channel access decisions, it is necessary use a method with which they can assess the reliability of the spectrum sensor outcomes. Hence ,the decision statistics $||x_{ij}||^2$ is proposed which is used by the energy detector as a measure for the reliability of the spectrum sensor decisions.

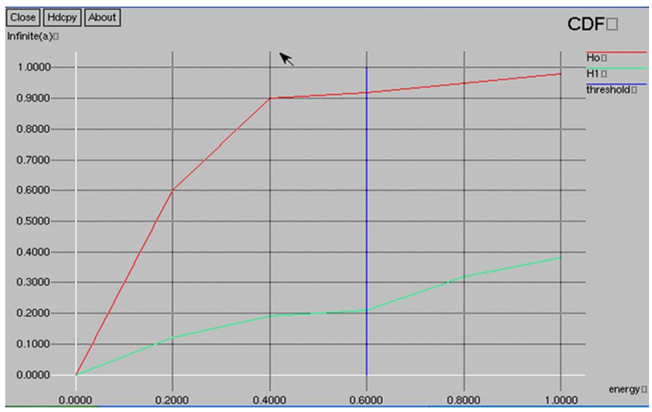

Figure 3: Decision statistics under both hypotheses.

The reasoning behind the use of the value of the decision statistics is that under hypothesis H_0, the value of $||x_{ij}||^2$ has a much higher probability of being closer to zero and far away from the threshold, as can be seen in Figure 3 depicting the CDF of $||x_{ij}||^2$ under both hypotheses. Therefore, the lower the value of $||x_{ij}||^2$, the more likely hypothesis H_0 is true, and the more reliable the decision is. On the other hand, as the value of the decision statistics approaches the decision threshold it is more or less equally likely that it is resulting from either one of the hypotheses. Therefore, the closer the value of$||x_{ij}||^2$ is to the decision threshold, the less reliable the outcome of the spectrum sensor is.

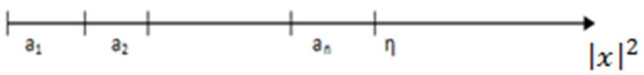

Figure 4: Division of interval [0,η] in sub intervals and associated probabilities

In order to exploit the reliability measure established above in taking channel access decisions, we propose the following scheme for channel access at the j^{th} secondary node:

1. The interval [0,η] is divided into n subintervals
2. For each subinterval kϵ[1,n], assign an access probability a_k^i
3. Whenever the decision statistics falls in the k^{th} interval, secondary node will access the channel with the associated access probability.
4. In the case when $||x_{ij}||^2$, secondary node does not access the channel.

This scheme will enable us to have higher access probabilities for the subintervals closer to zero, since in these subintervals there is a very low probability of colliding with primary transmissions. Moreover, assign lower probabilities to the subintervals close to the decision threshold, where there is a higher risk of collisions. It should be noted that under the proposed scheme, the decision threshold η is not necessarily chosen according to the Neyman-Pearson design criterion since it is the choice of the access probabilities a_j^k that will be governing the false alarm rate. However, for comparison purposes we will employ the Neyman-Pearson threshold as the threshold in our design.

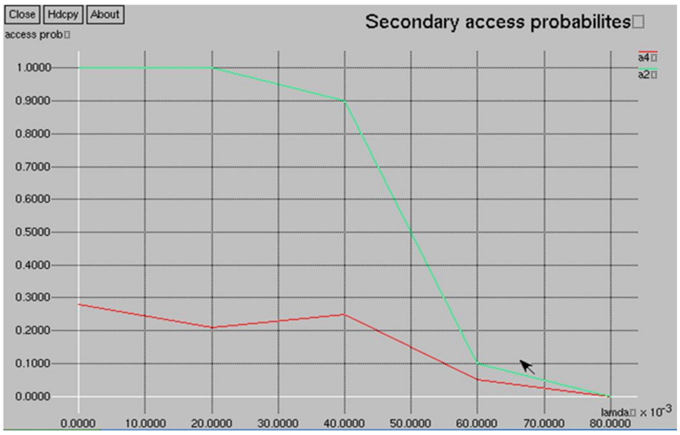

Figure 5: Secondary Access Probabilities

To get more insight into how the channel access probabilities are selected, Figure 5 depicts the channel access probabilities as a function of primary arrival rate. It is noted that a_1, the access probability for the interval nearest to zero, takes the highest values. This is expected since measurements that land in the corresponding interval have the highest probability of being generated when no primary users are in the channel; hence it is safe that secondary users transmit. As the primary arrival rate increases, all the access probabilities decrease to limit secondary interference to primary transmissions in order to guarantee the stability of primary queues. It is also noted that a_3 and a_4 are exactly zero for all values of λ_p, which means that to guarantee queues' stability transmissions in the corresponding intervals are not allowed.

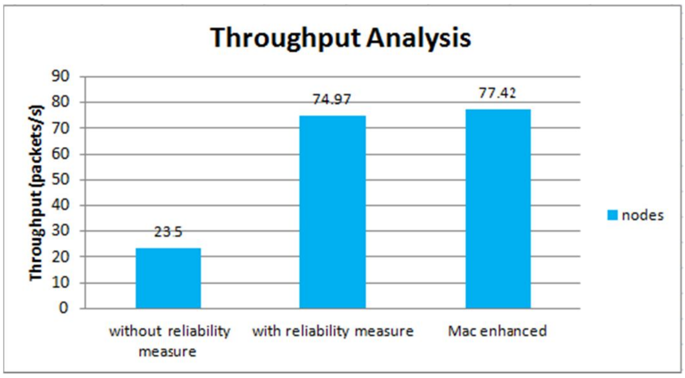

Figure 6: Throughput Analysis of Cognitive Networks

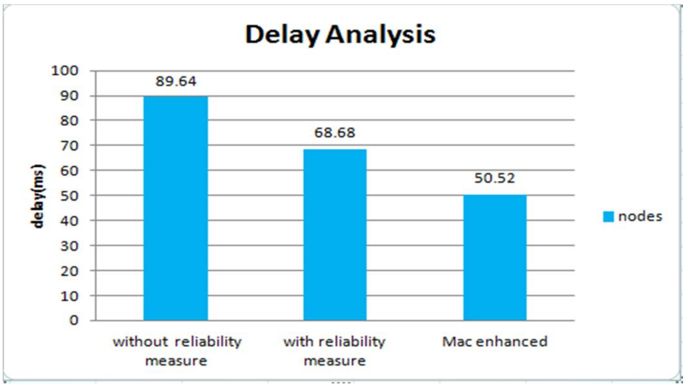

Figure 7: Delay Analysis of Cognitive Networks

5. CONCLUSION

The effect of spectrum sensing errors on the performance of a cognitive radio networks from a MAC layer perspective is investigated. Results reveal severe degradation in terms of throughput for both primary and secondary networks. The conclusion drawn is that separating the design of the spectrum sensing and the channel access mechanisms is suboptimal, and can have detrimental effects on the performance of both primary and secondary networks. Based on this observation, a combined design of spectrum sensing and channel access mechanisms is proposed and analyzed. The joint design made use of the fact that, in a binary hypothesis testing problem, the value of the test statistics could be used as a measure of reliability of test outcome. Results of the system's performance under the proposed scheme show significant improvements in secondary access probabilities besides throughput is maximized and delay is decreased considerably.

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