Soft Sensing-Based Multiple Access for Cognitive Radio Networks

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Abstract—We consider the effects of spectrum sensing errors on the performance of cognitive radio networks from a queueing theory point of view. In order to alleviate the negative effects of those errors, a novel design of spectrum access mechanism is proposed. This design is based on the observation that, in a binary hypothesis testing problem, the value of the test statistic can be used as a confidence measure for the test outcome. This value is hence used to specify a channel access probability for the secondary network. The access probabilities as a function of the sensing metric are obtained via solving an optimization problem designed to maximize the secondary service rate given a constraint on primary queue stability. The problem is shown to be convex and, hence, the global optimum can be obtained efficiently. Numerical results reveal a significant performance improvement in the maximum stable throughput of both primary and secondary networks over the conventional technique of making a hard binary decision and then transmitting with a certain probability if the primary is sensed to be inactive.

I. INTRODUCTION

Cognitive radio technology prescribes the coexistence of licensed (or primary) and unlicensed (secondary or cognitive) radio nodes on the same bandwidth. While the first group is allowed to access the spectrum at any time, the second seeks opportunities for transmission by exploiting the idle periods of primary nodes. In [1] and [2] the cognitive radio problem is investigated from an information-theoretic standpoint, where the cognitive transmitter is assumed to transmit at the same time and on the same bandwidth of the primary link. Centralized and decentralized protocols at the media access control (MAC) layer aiming at minimizing secondary nodes interference with primary transmissions have been studied in [3] and [4] by modeling the radio channel as either busy or available according to a Markov chain. The question of how to efficiently and fairly share the spectrum among multiple dissimilar users has been addressed from a game theoretic viewpoint in [5], [6].

Spectrum sensing is an essential functionality of cognitive radios. In general, spectrum sensing techniques can be classified into three categories: energy detection [7], matched filter coherent detection [8], and cyclostationary feature detection [9]. While these classic signal detection techniques are well known, detecting primary transmitters in a dynamic wireless environment with noise uncertainty, shadowing, and fading is a challenging problem as articulated in [10].

In this paper we consider the effects of spectrum sensing errors on the performance of cognitive radio networks. While the issue of spectrum sensing errors has been investigated at the physical layer [10], [11], [12], [13], [14], cognitive multiple access design in the presence of sensing errors has received little attention. To mitigate the negative impact of sensing errors, we propose a novel spectrum access mechanism and make the following contribution.

Our design is based on the observation that, in a binary hypothesis testing problem, the value of the test statistic can be used as a measure of detection reliability. The further the value of the test statistic is from the decision threshold, the more confident we are that the decision is correct. Therefore, instead of using the hard decisions of the spectrum sensor to decide whether to access the channel or not, a secondary user can have different access probabilities for different values of the test statistic. For instance, the access probability can be higher for the values of the test statistic further away from the decision threshold, and vice versa. Using this technique, one can significantly reduce the probability of collision with primary users and also the probability of overlooking spectrum opportunities. This is reflected in a stable throughput for both the primary and secondary networks that considerably exceeds that obtained via the hard-sensing conventional scheme of determining whether the primary is active or not and transmitting with a certain probability in the case of inactivity. The access probabilities as a function of the sensing metric are obtained via maximizing the secondary service rate given a constraint on primary queue stability. The optimization problem is shown to be convex and, hence, can be solved efficiently [15]. Note that the idea of "soft" sensing was introduced in [16]. However, the focus was physical layer power adaptation to maximize the capacity of the secondary link.

The rest of the paper is organized as follows. We provide the system model and discuss spectrum sensing in Sections II and III, respectively. Our proposed spectrum access technique is presented in Section IV, whereas some numerical results are provided in Section V. Section VI concludes the paper.

II. SYSTEM MODEL

The uplink of a TDMA cellular network is considered as the primary network. It consists of M_p source nodes numbered $1, 2, ..., M_p$ communicating with a base station

(BS). A secondary network, consisting of M_s nodes numbered $1, 2, ..., M_s$, tries to exploit the unutilized channel resources to communicate their own data packets using slotted ALOHA as their multiple access protocol. Let $\mathcal{M}_p = \{1, 2, ..., M_p\}$ denote the set of primary nodes, and $\mathcal{M}_s = \{1, 2, ..., M_s\}$ denote the set of secondary nodes.

Secondary users independently exploit instantaneous spectrum opportunities in the channel (in the form of idle time slots). At the beginning of each time slot, secondary nodes sense the medium to detect its state. Based on the sensing outcomes, the secondary user decides whether to access the channel or not. At the end of the slot, the receiver acknowledges each successful transmission.

A. Channel Model

The wireless channel between a given 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 can be modeled as

$$y_{ij}^t = \sqrt{G_i \rho_{ij}^{-\gamma}} h_{ij}^t x_i^t + n_j^t, \tag{1}$$

where G_i is the transmit power, assumed to be the same for all nodes, ρ_{ij} denotes the distance between the two nodes, γ is the path loss exponent, and h_{ij}^t is the channel fading coefficient between nodes i and j at time t. The channel coefficients are modeled as independently and identically distributed (i.i.d) zero mean, circularly symmetric complex Gaussian random variables with unit variance. The term x_i^t denotes the transmitted signal which has an average power of unity, and is assumed to be drawn from a constant modulus constellation with zero mean (M-ary PSK for instance). The noise terms n_j^t are modeled as i.i.d additive white complex Gaussian processes with zero mean and variance N_0. Since the arrivals, the channel gains, and the additive noise processes are all assumed stationary, we can drop the index t without loss of generality.

Success and failure of packet reception is characterized by outage events and outage probabilities. The outage probability is defined as the probability that the Signal to Noise Ratio (SNR) at the receiver is less than a given SNR threshold ζ. For the channel model in (1) the probability of outage can be written as,

$$P_{ij}^{out} = Pr\left\{ \mid h_{ij} \mid^2 < \frac{\zeta N_0 r_{ij}^\gamma}{G} \right\} = 1 - \exp\left(-\frac{\zeta N_0 r_{ij}^\gamma}{G} \right). \tag{2}$$

Furthermore, we assume that whenever there is a collision between a primary transmission and a secondary transmission, or between two or more secondary transmissions, all the packets involved are lost.

B. Queueing Model

Each node in the primary or secondary networks has an infinite buffer for storing fixed length packets (see Fig. 1). The channel is slotted in time and a slot duration equals the packet transmission time. The arrivals at the ith primary
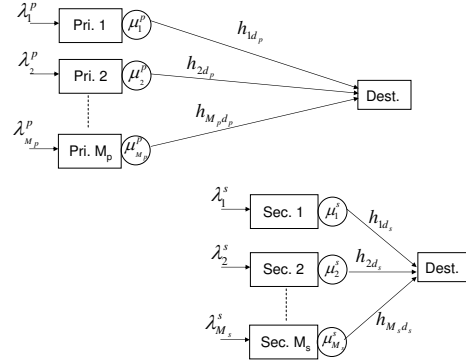

Fig. 1. Network queueing and channel model

node's queue ($i \in \mathcal{M}_p$), and the jth secondary node's queue ($i \in \mathcal{M}_s$) are Bernoulli random variables, i.i.d from slot to slot with mean λ_p^i and λ_s^j, respectively. Hence, the vector $\Lambda = [\lambda_p^1, ..., \lambda_p^{M_p}, \lambda_s^1, ..., \lambda_s^{M_s}]$ denotes the average arrival rates. Arrival processes are assumed to be independent from one node to another.

Primary users access the channel by dividing the channel resources, time in this case, among them; hence, each node is allocated a fraction of the time. Let $\Omega_{\mathbf{p}} = [\omega_p^1, \omega_p^2, ..., \omega_p^{M_p}]$ denote a resource-sharing vector, where $\omega_p^i \geq 0$ is the fraction of time allocated to node $i \in \mathcal{M}_p$, or it can represent the probability that node i is allocated the whole time slot [17]. The set of all feasible resource-sharing vectors is specified as follows

$$F_p = \left\{ \Omega_{\mathbf{p}} = (\omega_p^1, \omega_p^2, ..., \omega_p^{M_p}) \in \Re^{+M_p} : \sum_{i \in \mathcal{M}_p} \omega_p^i \leq 1 \right\}, \tag{3}$$

where $\Re^{+M_p}$ is the set of M_p dimensional vectors with real, non-negative elements.

In a communication network, the stability of the network's queues is a fundamental performance measure. Stability can be loosely defined as having a certain quantity of interest kept bounded. In our case, we are interested in the queue size being bounded. For an irreducible and aperiodic Markov chain with countable number of states, the chain is stable if and only if there is a positive probability for every queue of being empty, i.e., $\lim_{t \to \infty} \Pr\{Q_i(t) = 0\} > 0$. (For a rigorous definition of stability under more general scenarios see [18] and [19]). An arrival rate vector $\Lambda = [\lambda_p^1, ..., \lambda_p^{M_p}]$ is said to be stable if there exists a resource sharing vector $\Omega_p \in F_p$ such that all the queues are stable.

If the arrival and service processes of a queueing system are strictly stationary, then one can apply Loynes's theorem to check for stability conditions [20]. This theorem states that if the arrival process and the service process of a queueing system are strictly stationary, and the average arrival rate is less than the average service rate, then the queue is stable, otherwise it is unstable.

It is important to note that, in the sequel, we assume that all M_p primary users have the same arrival rate λ_p, and all M_s secondary users have the same arrival rate λ_s. Moreover, all primary users share the same channel statistics, and all secondary users share the same channel statistics. That is, the channels of each network are symmetric.

III. SPECTRUM SENSING

In our study of the effect of sensing errors on cognitive radios performance, and in our proposed joint design technique, we adopt the non-coherent energy detection technique because of its simplicity and versatility. Detection of the presence of the ith primary user by the jth secondary user can be formulated as a binary hypothesis test as follows,

$$\mathcal{H}_0 : y_{ij}^t = n_j$$
$$\mathcal{H}_1 : y_{ij}^t = \sqrt{G_i \rho_{ij}^{-\gamma}} h_{ij}^t x_i + n_j. \tag{4}$$

The null hypothesis $\mathcal{H}_0$ represents the absence of the primary user, hence a transmission opportunity for the secondary user. And the alternative hypothesis $\mathcal{H}_1$ represents a transmitting primary user.

The performance of the spectrum sensor is characterized by the two types of errors and their probabilities, (i) false alarms having probability α, (ii) and missed detections having probability β,

$$\alpha \triangleq \Pr\{\text{decide } \mathcal{H}_1 | \mathcal{H}_0 \text{ is true}\}, \tag{5}$$
$$\beta \triangleq \Pr\{\text{decide } \mathcal{H}_0 | \mathcal{H}_1 \text{ is true}\}. \tag{6}$$

A false alarm occurs when an idle channel is erroneously detected as busy, thereby depriving the secondary users from a possible transmission opportunity. On the other hand, a miss event, where a secondary user fails to detect primary activity, results in a collision between primary and secondary transmissions and a degradation in the performance of the primary system. With the assumption that secondary users do not have prior knowledge of primary activity patterns, the probability of misdetection β could be minimized subject to the constraint that the probability of false alarm is no larger than a given value α using the optimal Neyman-Pearson (N-P) detector [8].

It follows from the received signal model of (1) that under hypothesis $\mathcal{H}_0$ the received signal y_{ij} is a complex Gaussian random variable with zero mean and variance $\sigma_0^2 = N_0$, and under hypothesis $\mathcal{H}_1$, y_{ij} is a complex Gaussian random variable with zero mean and variance

$$\sigma_1^2 = G_i \rho_{ij}^{-\gamma} + N_0.$$

Therefore, the likelihood ratio test for the optimal N-P detector can be written as follows,

$$\Lambda(y_{ij}) = \frac{\Pr\{y_{ij}|\mathcal{H}_1\}}{\Pr\{y_{ij}|\mathcal{H}_0\}} = \frac{\frac{1}{\pi\sigma_1^2} e^{-\frac{||y_{ij}||^2}{\sigma_1^2}}}{\frac{1}{\pi\sigma_0^2} e^{-\frac{||y_{ij}||^2}{\sigma_0^2}}}$$
$$= \frac{\sigma_0^2}{\sigma_1^2} e^{-||y_{ij}||^2 \left[\frac{1}{\sigma_1^2} - \frac{1}{\sigma_0^2}\right]} \mathop{\gtrless}_{\mathcal{H}_0}^{\mathcal{H}_1} \eta', \tag{7}$$
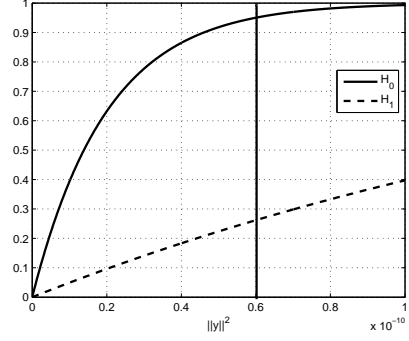

Fig. 2. CDF of the decision statistic under both hypotheses. The vertical line marks the position of the decision threshold.

which can be simplified to

$$||y_{ij}||^2 \mathop{\gtrless}_{\mathcal{H}_0}^{\mathcal{H}_1} \frac{\eta' - \log \frac{\sigma_0^2}{\sigma_1^2}}{\frac{1}{\sigma_0^2} - \frac{1}{\sigma_1^2}} = \eta. \tag{8}$$

From (8), the spectrum sensing problem has been reduced to a simple comparison of the received signal energy $||y_{ij}||^2$ 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), $||y_{ij}||^2$ is exponentially distributed with parameters $1/2\sigma_1^2$ and $1/2\sigma_0^2$, under $\mathcal{H}_1$ and $\mathcal{H}_0$, respectively. Therefore, the false alarm probability is

$$\alpha = \Pr\{||y_{ij}||^2 > \eta | \mathcal{H}_0\} = e^{-\frac{\eta}{2\sigma_0^2}}. \tag{9}$$

From which $\eta = -2\sigma_0^2 \log(\alpha)$. Finally, the probability of misdetection is

$$\beta = \Pr\{||y_{ij}||^2 < \eta | \mathcal{H}_1\} = 1 - e^{-\frac{\sigma_0^2 \log(\alpha)}{\sigma_1^2}} \tag{10}$$

It is noted that in the design above, the spectrum sensor operates on a single sample of the received signal. Increasing the number of samples certainly increases sensing reliability. However, we limit ourselves to this design for the purpose of mathematical simplicity and without loss of generality.

IV. PROPOSED SPECTRUM ACCESS MECHANISM

In a listen-before-talk cognitive radio network, secondary nodes' channel access decisions are solely based on the outcomes of the spectrum sensing phase. Occurrence of errors in spectrum sensing is inevitable, and results in either a lost transmission opportunity or a collision as explained above. To overcome the negative effects of spectrum sensing errors and for the secondary users to have better channel access decisions, it is necessary to find a method with which they can assess the reliability of the spectrum sensor outcomes. Here we propose the use of the decision statistic $||y_{ps}||^2$ used by the energy detector as a measure for the reliability of the spectrum sensor decisions.

The reasoning behind the use of the value of the decision statistic is that under hypothesis $\mathcal{H}_0$, the value of $||y_{ps}||^2$ has
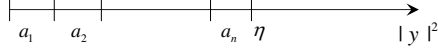
Fig. 3. Division of the interval $[0, \eta]$ into subintervals and the associated access probabilities.

a much higher probability of being closer to zero and far away from the threshold, as can be seen in Fig. 2 depicting the CDF of $||y_{ps}||^2$ under both hypotheses. Therefore, the lower the value of $||y_{ps}||^2$, the more likely hypothesis $\mathcal{H}_0$ is true, and the more reliable the decision is. On the other hand, as the value of the decision statistic 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 $||y_{ps}||^2$ is to the decision threshold, the less reliable the outcome of the spectrum sensor is.

In order to exploit the reliability measure established above in taking channel access decisions, we propose the following scheme for channel access:

- The interval $[0, \eta]$ is divided into n subintervals as shown in Fig. 3.
- For each subinterval $i \in [1, n]$, assign an access probability a_i.
- Whenever the decision statistic falls in the ith interval, secondary user will access the channel with the associated access probability.
- In the case when $||y_{ps}||^2 > \eta$, secondary user does not access the channel.

This scheme enables 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, lower access probabilities are assigned 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 detector design.

In this work we consider the stability of both primary and secondary networks' queues as our main measure of performance and design criteria. The cognitive principle is based on the idea that the presence of the secondary system should be "transparent" to the primary, and since we are interested in the stable throughput of primary and secondary networks, we define the secondary system "transparency" as not affecting primary stability. In other words, for a given stable primary system with arrival rate λ_p, the secondary activity is considered transparent if the primary system maintains its stability during the operation of the secondary system. Our main design criterion for secondary access is to maximize secondary throughput under the constraint that primary stability is not affected. This design criteria can be formulated as the following constrained optimization problem

$$\max_{a_i, i \in [1,n]} \mu_s, \text{ subject to } \lambda_p < \mu_p. \qquad (11)$$

To solve the optimization problem of (11), we start by calculating the average primary and secondary service rates, μ_p and μ_s, respectively, under the proposed secondary access scheme. First we note that because of collisions between primary and secondary transmission, the group of primary and secondary queues form an interacting system of queues. In other words, the service rate of a given queue is dependent on the state of all other queues, whether they are empty or not. Studying the stability conditions for interacting queues is a difficult problem that has been addressed for ALOHA systems [19], [21] [22]. The concept of dominant systems was introduced and employed in [19] to help find bounds on the stability region of ALOHA with collision channel. The dominant system in [19] was defined by allowing a set of terminals with no packets to transmit to continue transmitting dummy packets. In this manner, the queues in the dominant system stochastically dominate the queues in the original system. Or in other words, with the same initial conditions for queue sizes in both the original and dominant systems, the queue sizes in the dominant system are not smaller than those in the original system.

To study the stability of the interacting system of queues consisting of primary and secondary nodes' queues, we make use of the dominant system approach to decouple the interaction between queues. We define the dominant system as follows:

- Arrivals at each queue in the dominant system are the same as in the original system.
- Time slots assigned to primary node $i \in \mathcal{M}_p$ are identical in both systems.
- The outcomes of the "coin tossing" (that determines transmission attempts of relay and secondary nodes) in every slot are the same.
- Channel realizations for both systems are identical.
- The noise terms generated at the receiving ends of both systems are identical.
- In the dominant system, secondary nodes attempt to transmit dummy packets when their queues are empty.

Under this dominant system, the service process of the ith primary user can be defined as follows,

$$Y_i^t = \left[A_i^t \bigcap \overline{O_{id}^t} \bigcap_{l \in \mathcal{M}_s} \left\{ \mathcal{B} \bigcap P_s \right\} \right], \qquad (12)$$

where A_i^t denotes the event that slot t is assigned to primary user i, $\overline{O_{id}^t}$ denotes the event that the ith primary node link to its destination is not in outage. $\mathcal{B}$ is the event of a missed detection, and P_s is the event that a secondary node has permission to transmit. The joint event of misdetection and permission for channel access has a probability

$$\Pr \left\{ \mathcal{B} \bigcap P_s \right\} = p_s^1 = \sum_{i \in [1,n]} p_i^1 a_i, \qquad (13)$$

where a_i is the access probability associated with subinterval i (see Fig. 3), and p_i^1 is the probability that the value of $||y_{ps}||^2$ falls in the ith subinterval when hypothesis $\mathcal{H}_1$ is true (primary

user exists in the channel), which from the signal model of (1) is given by

$$p_i^1 = \exp\left(-\frac{(i-1)\eta}{2n\sigma_1^2}\right) - \exp\left(-\frac{i\eta}{2n\sigma_1^2}\right). \qquad (14)$$

Similarly, we define the probability that a secondary user accesses the channel when hypothesis $\mathcal{H}_0$ is true as

$$p_s^0 = \sum_{i\in[1,n]} p_i^0 a_i, \qquad (15)$$

where

$$p_i^0 = \exp\left(-\frac{(i-1)\eta}{2n\sigma_0^2}\right) - \exp\left(-\frac{i\eta}{2n\sigma_0^2}\right). \qquad (16)$$

Therefore, the average primary service rate is given by

$$\mu_p = \frac{1 - P_{pd}^o}{M_p}\left(1 - \sum_{i\in[1,n]} p_i^1 a_i\right)^{M_s}, \qquad (17)$$

where P_{pd}^o is the outage probability of the link between any primary node and its destination.

For a secondary user to gain uncontested access to an idle time slot, it should correctly identify the slot as idle and have access permission. At the same time for all other secondary users not to access that slot, they either do not have access permission or they detect the time slot as busy. Therefore, the service process of the kth secondary user can be modeled as

$$Y_k^t = \sum_{i\in\mathcal{M}_p}\left[A_i^t\bigcap\{Q_i^t=0\}\bigcap\overline{O_{kd}^t}\bigcap\overline{\mathcal{A}}\bigcap P_s\right.$$
$$\left.\bigcap_{l\in\mathcal{M}_s\setminus k}\left\{\mathcal{A}\bigcup\overline{P_s}\right\}\right], \qquad (18)$$

where $\mathcal{A}$ is the event of false alarm, and $\{Q_i^t = 0\}$ denotes the event that the ith primary node's queue is empty, i.e., the node has no packet to transmit. According to Little's theorem [23], the probability of the queue being empty is $(1 - \lambda_p/\mu_p)$. The average secondary service rate is then given by

$$\mu_s = \left(1 - \frac{\lambda_p M_p}{\left(1 - P_{pd}^o\right)\left(1 - \sum_{i\in[1,n]} p_i^1 a_i\right)^{M_s}}\right).$$
$$(1 - P_{sd}^o)\left(\sum_{i\in[1,n]} p_i^0 a_i\right)\left(1 - \sum_{i\in[1,n]} p_i^0 a_i\right)^{M_s-1} \qquad (19)$$

Fortunately, the optimization problem of (11) using (17) and (19) can be converted to a convex program. The global optimum of convex optimization problems can efficiently be obtained via standard numerical techniques [15].

The convexity of problem (11) given (17) and (19) can be shown by taking the logarithm, which is a monotonic function, of both the objective function and the constraint, and applying the rule that a function is convex if and only if it is convex when restricted to any line that intersects its domain [15]. Due to space limits, we consider here only the
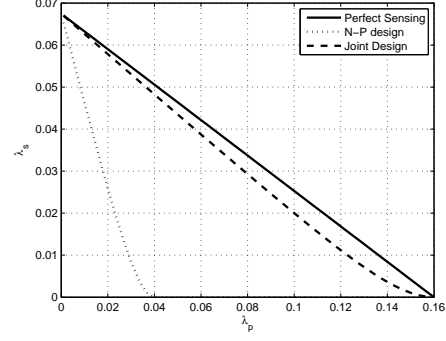

Fig. 4. Comparison between the joint design and the N-P design.

term $1 - \epsilon\left(1 - p^T a\right)^{-M_s}$ with $\epsilon = \lambda_p M_p/\left(1 - P_{pd}^o\right)$, a is a column vector with elements a_i, p is a column vector of p_i^1, and T denotes matrix transposition. We form the function

$$g(t) = \log\left(1 - \epsilon\left(1 - p^T\bar{a} - tp^Tv\right)^{-M_s}\right) \qquad (20)$$

where t is a scalar parameter, $\bar{a}$ belongs to the domain of the problem, and v is a vector such that $\bar{a} + tv$ also belongs to the domain of the problem. The domain is specified by the inequality constraint of the optimization problem (11) and that $0 \le a_i \le 1 \; \forall i$.

According to the aforementioned property of convex functions, if $g(t)$ is proved to be concave with respect to t (and, hence, its negative would be convex), then the function $\log\left(1 - \epsilon\left(1 - p^T a\right)^{-M_s}\right)$ is concave with respect to all a_i. The concavity of $g(t)$ can be easily proven via differentiating twice and examining the sign of the second derivative, which is given by

$$\ddot{g}(t) = \frac{\epsilon M_s\left(p^Tv\right)^2\left[\epsilon - (M_s+1)\left(1 - p^T\bar{a} - tp^Tv\right)^{M_s}\right]}{\left[\left(1 - p^T\bar{a} - tp^Tv\right)^{M_s+1} - \epsilon\left(1 - p^T\bar{a} - tp^Tv\right)\right]^2}$$

Since the queueing stability condition, $\lambda_p < \mu_p$, requires that $\epsilon < \left(1 - p^T\bar{a} - tp^Tv\right)^{M_s}$, then $\epsilon < (M_s+1)\left(1 - p^T\bar{a} - tp^Tv\right)^{M_s}$. Consequently, $\ddot{g}(t)$ is negative and $\log\left(1 - \epsilon\left(1 - p^T a\right)^{-M_s}\right)$ is concave.

V. RESULTS AND DISCUSSIONS

Here we compare the performance of the proposed joint design of spectrum sensing and channel access mechanisms with the conventional approach based on the Neyman-Pearson detector design. We consider a system with $M_p = 4$ primary users and $M_s = 2$ secondary users. Distance between primary users and their destination is set to 100m, distance between secondary users and their destination is also 100m, and distance between primary and secondary users is 150m. SNR threshold is 25dB, transmit power is 100mW, path loss exponent $\gamma = 3.7$, and $N_0 = 10^{-11}$.

Fig. 4 illustrates the stability regions for the ideal case with no sensing errors, the N-P based detector, and our joint design
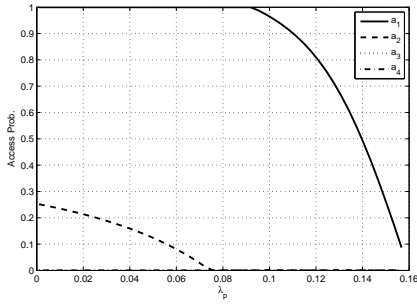
Fig. 5. Secondary access probabilities.

scheme with $n = 4$ subintervals, using the same threshold as the one used by the N-P design for a false alarm rate $\alpha = 0.1$. It is clearly seen that due to sensing errors the conventional design based on the N-P criterion suffers from a huge performance degradation from the point of view of the stability of both primary and secondary networks. The proposed channel access scheme, on the other hand, is able to achieve a stability region which is at least 80% of the stability region of the perfect sensing case. This significant improvement is mainly because the proposed access scheme does not blindly rely on the outcome of the spectrum sensing operation, but also takes the reliability of the measurements into consideration.

To get more insight into how the channel access probabilities are selected, Fig. 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. Furthermore, it indicates that our access scheme is not affected by the choice of the threshold η since access probabilities are adapted accordingly.

VI. CONCLUSIONS

In this paper we considered the negative effects of spectrum sensing errors on the performance of a cognitive radio networks from a MAC layer perspective. To mitigate these negative effects a novel design of the spectrum access access scheme was 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 how reliable the test outcome is. Analytical results of the system's performance under the proposed scheme show significant improvements in terms of the throughput of both primary and secondary networks.

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