

# Cognitive Multiple Access Using Soft Sensing and Secondary Channel State Information

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**Abstract**—We consider a random access primary network. At the beginning of each time slot, a number of secondary users sense the channel and make an access decision based on the spectrum sensing outcome and the channel state information (CSI). Specifically, the channel is accessed by a secondary transmitter with a probability that depends on both the sensing metric and the gain or signal-to-noise-ratio (SNR) of the channel between the transmitter and its respective receiver. Spectrum sensing operates in a “soft” mode where the sensing metric is used directly rather than making a binary decision concerning primary activity. We consider backlogged secondary users and primary users with infinite queues. The secondary access probabilities are obtained via solving an optimization problem designed to maximize the secondary throughput 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 secondary throughput with stable primary queues over the use of spectrum sensing with conventional detection or the implementation of sensing alone without making use of the CSI information.

## I. INTRODUCTION

Cognitive radio technology relies on the coexistence of licensed (or primary) and unlicensed (secondary or cognitive) radio nodes on the same radio resource, e.g., the same frequency channel. While the primary users are allowed to access the spectrum at any time, the secondary users seek opportunities for transmission by exploiting the inactive periods of primary terminals.

In [1] and [2] the cognitive radio problem is investigated from an information-theoretic standpoint, where the cognitive transmitter is assumed to transmit concurrently with the primary user. Centralized and decentralized protocols at the media access control (MAC) layer aiming at minimizing secondary interference on primary transmissions have been studied in [3] and [4] by modeling the radio channel as either busy or available according to a Markov chain. Probabilistic secondary access based on sensing and/or the feedback obtained from the primary or secondary receivers has been investigated in works such as [5], [6], [7], [8].

In this paper, we design a secondary access scheme that depends on channel knowledge availability and soft sensing at the secondary transmitters. The channel state information (CSI) between the secondary transmitters and their respective receivers are assumed to be known in the form of channel gains or signal-to-noise ratios (SNR). This CSI provides information

about the transmission reliability over a certain channel. The soft sensing approach has been introduced in [9] and employed in [10] and [11]. It 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 and CSI. Using this technique, one can significantly reduce the probability of collision with primary users and also the probability of overlooking spectrum opportunities.

The contributions of this paper are as follows. We devise a probabilistic secondary access scheme that relies on the concept of soft sensing and the availability of CSI. We provide a queueing analysis of the primary queues assuming backlogged secondary users. The secondary access probabilities as a function of the sensing metric and CSI are obtained via maximizing the secondary throughput given a constraint on primary queue stability. The optimization problem is proved to be convex and, hence, can be solved efficiently [12].

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

## II. SYSTEM MODEL

We consider a random access primary network. It consists of  $M_p$  source nodes. Each time slot is assigned to only one primary user with a probability  $\frac{1}{M_p}$ . The assignment is made at the very beginning of the time slot. A secondary network, consisting of  $M_s$  terminals, attempts to exploit the unutilized primary channel resources to communicate their own data packets using slotted ALOHA as their multiple access protocol.

### A. Channel Model

At the beginning of each time slot, the secondary transmitters sense the medium to detect its occupancy state. They also have knowledge of the channel gains between themselves and the secondary receivers. The channel gains are considered to

be fixed over a number of transmission slots. That is, we adopt a slow or quasi-static fading model. The method of obtaining the channel gains or CSI in practice depends on whether the system is time division duplexing (TDD) or frequency division duplexing (FDD). Under a TDD scheme, the transmission between two terminals occur over the same carrier frequency. Hence, it is reasonable to assume channel reciprocity, which means that the channel in either transmission direction is almost the same. Then the channel between the secondary transmitter and receiver can be obtained by using pilot symbols emitted by the secondary receiver. Under the FDD scheme, and since the transmission takes place over a different frequency band depending to the direction of communication, channel reciprocity cannot be invoked. Here, the receiver estimates the channel and feeds back its estimates to the transmitter. In this work, we do not delve into the technicalities of CSI estimation. We assume the presence of perfect estimates at the secondary transmitting nodes.

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

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

where  $G_i$  is the transmitting power, assumed to be the same for all nodes,  $\rho_{ij}$  denotes the distance between the two nodes,  $\gamma$  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 unit power. The i.i.d additive white Gaussian noise processes  $n_j^t$  have zero mean and variance  $N_0$ .

For the secondary terminals and since we assume the availability of CSI at the secondary transmitters, the packet error probability is

$$1 - \left( 1 - k_1 Q \left( \sqrt{k_2 \frac{G_i |h_{ij}|^2}{\rho_{ij}^\gamma N_0}} \right) \right)^L, \quad (2)$$

where  $L$  is the packet size,  $k_1$  and  $k_2$  are constants that depend on the modulation scheme [13], [14]. Since the CSI is not known at primary transmitters, the primary packet error probability  $P_e$  is obtained by averaging the error probability of (2) with respect to the channel fading coefficient. Furthermore, we assume that whenever there is a collision due to the concurrent transmission of two or more terminals, 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  $i^{\text{th}}$  primary node's queue ( $i \in \mathcal{M}_p$ ), and the  $j^{\text{th}}$  secondary node's queue

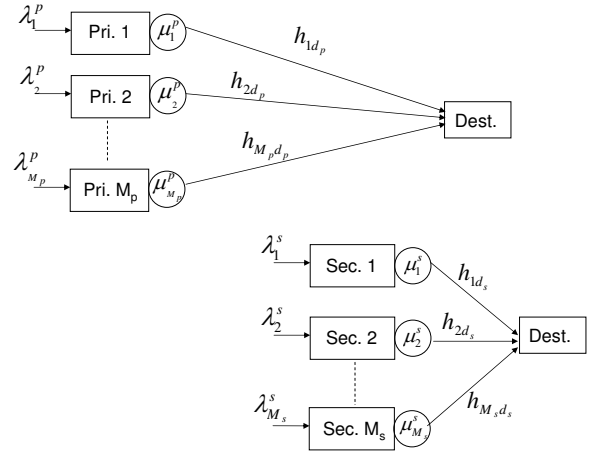


Fig. 1. Network queueing and channel model

( $i \in \mathcal{M}_s$ ) are Bernoulli random variables, i.i.d from slot to slot with mean  $\lambda_i^p$  and  $\lambda_j^s$ , respectively. Hence, the vector  $\Lambda = [\lambda_1^p, \dots, \lambda_{M_p}^p, \lambda_1^s, \dots, \lambda_{M_s}^s]$  denotes the average arrival rates. Arrival processes are assumed to be independent from one node to another.

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.,  $\lim_{t \rightarrow \infty} \Pr\{Q_i(t) = 0\} > 0$ . (For a rigorous definition of stability under more general scenarios see [15] and [16]). An arrival rate vector  $\Lambda = [\lambda_1^p, \dots, \lambda_{M_p}^p]$  is said to be stable if 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 [17]. 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; if the average arrival rate is greater than the average service rate then the queue is unstable.

The primary user successfully transmits a packet if there is no collision with the secondary users and there is no transmission error. Let  $P_p$  be the probability of primary unsuccessful transmission. Probability  $P_p = 1 - \frac{1-P_e}{M_p} \Pr\{\text{no secondary user transmits}\}$ . The probability  $\Pr\{\text{no secondary user transmits}\}$  is provided in the next section, whereas  $P_e$ , as previously mentioned, is obtained via averaging (2) over the channel gains.

The Markov chain modeling the evolution of the primary queue length is shown in Fig. 2. The transition probabilities are based on the assumption that packet arrivals occur near the end of the time slot, therefore, if the queue is empty an arriving packet cannot be transmitted during the same time

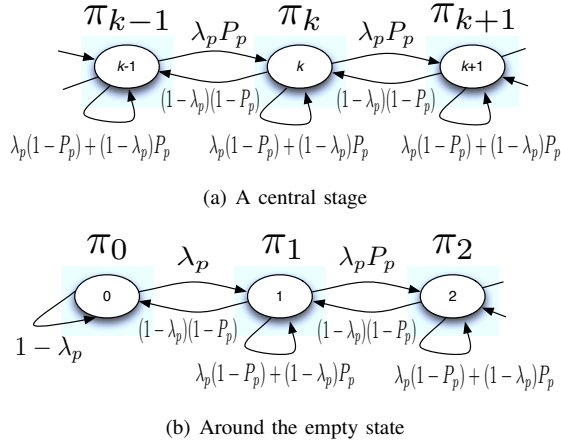


Fig. 2. The primary user's queue evolution Markov chain

slot. The probability of the queue length increasing by one is  $\lambda_p P_p$ . If the queue is nonempty, the probability of the queue length decreasing by one is  $(1 - \lambda_p)(1 - P_p)$ . For a queue length  $k > 0$ , if  $\pi_k$  is the probability of being in state  $k$ , we have the following balance equation

$$\begin{aligned} \pi_k \left( \lambda_p P_p + (1 - \lambda_p)(1 - P_p) \right) \\ = \pi_{k-1} \lambda_p P_p + \pi_{k+1} (1 - \lambda_p)(1 - P_p). \end{aligned} \quad (3)$$

The balance equation between state 0 and state 1 is

$$\pi_0 \lambda_p = \pi_1 (1 - \lambda_p)(1 - P_p). \quad (4)$$

In this case, for  $k \geq 1$  we have

$$\pi_k = \pi_0 \frac{1}{P_p} \left( \frac{\lambda_p P_p}{(1 - \lambda_p)(1 - P_p)} \right)^k \quad (5)$$

The normalization condition  $\sum_{k=0}^{\infty} \pi_k = 1$  means that

$$\pi_0 = \frac{1 - \frac{\lambda_p P_p}{(1 - \lambda_p)(1 - P_p)}}{1 - \frac{\lambda_p P_p}{(1 - \lambda_p)(1 - P_p)} + \frac{\lambda_p}{(1 - \lambda_p)(1 - P_p)}} = \frac{1 - \lambda_p - P_p}{1 - P_p} \quad (6)$$

That is,

$$\pi_0 = 1 - \frac{\lambda_p}{1 - P_p} = 1 - \frac{\lambda_p}{\mu_p}. \quad (7)$$

where  $\mu_p = 1 - P_p$  is the probability of successful primary transmission. Note that for the sum  $\sum_{k=0}^{\infty} \pi_k$  to exist, the term  $\frac{\lambda_p P_p}{(1 - \lambda_p)(1 - P_p)}$  must be less than unity. This means that for a stationary distribution to exist for the Markov chain, the condition  $\lambda_p + P_p < 1$  must hold. This is the condition for the primary queue stability, and is equivalent to  $\lambda_p < \mu_p$ .

### C. Spectrum Sensing

Spectrum sensing is an essential functionality of cognitive radios, since the devices need to reliably detect weak primary signals of possibly unknown types [18]. 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  $i^{\text{th}}$  primary user by the  $j^{\text{th}}$  secondary user can be formulated as a binary hypothesis test as follows,

$$\begin{aligned} \mathcal{H}_0 : y_{ij}^t &= n_j \\ \mathcal{H}_1 : y_{ij}^t &= \sqrt{G_i \rho_{ij}^{-\gamma}} h_{ij}^t x_i + n_j. \end{aligned} \quad (8)$$

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.

Under the conventional hard sensing procedure, the performance of the spectrum sensor is characterized by the two types of errors and their probabilities, (i) false alarms having probability  $\alpha$ , (ii) and missed detections having probability  $\beta$ ,

$$\alpha \triangleq \Pr \{ \text{decide } \mathcal{H}_1 | \mathcal{H}_0 \text{ is true} \}, \quad (9)$$

$$\beta \triangleq \Pr \{ \text{decide } \mathcal{H}_0 | \mathcal{H}_1 \text{ is true} \}. \quad (10)$$

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  $\beta$  could be minimized subject to the constraint that the probability of false alarm is no larger than a given value  $\alpha$  using the optimal Neyman-Pearson (N-P) detector [19].

### III. 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 a much higher probability of being closer to zero and far away from the threshold, as can be seen in Fig. 3 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.

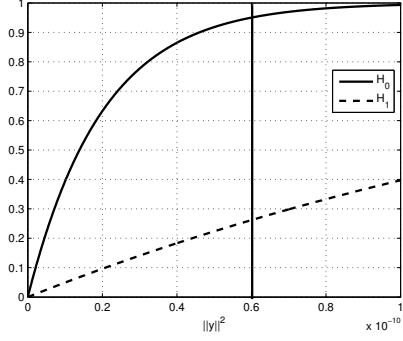


Fig. 3. CDF of the decision statistic under both hypotheses. The vertical line marks the position of the decision threshold.

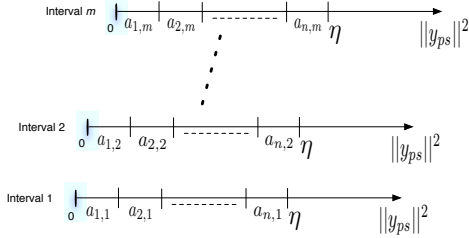


Fig. 4. Division of the sensing metric (e.g., measured energy) interval  $[0, \eta]$  into subintervals and the associated access probabilities as a function of discretized secondary CSI available at the cognitive transmitters. The CSI is assumed to be quantized into  $m$  levels.

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

- A value  $\eta$  for the sensing metric is chosen such that when  $\|y_{ps}\|^2 > \eta$ , the secondary user assumes that the primary user is highly likely to be actively transmitting. Therefore, the secondary user does not access the channel. The value of  $\eta$  can be obtained given some specification on the false alarm probability.
- The interval  $[0, \eta]$  is divided into  $n$  subintervals as shown in Fig. 4.
- Given the secondary channel statistics and noise power at the receiver, a maximum  $\epsilon$  can be chosen as the highest possible or practical channel gain, SNR, or any other transmission reliability CSI.
- The interval  $[0, \epsilon]$  is divided into  $m$  subintervals as shown in Fig. 4.
- For each subdomain  $i \in [1, n]$  and  $j \in [1, m]$ , assign an access probability  $a_{i,j}$ .
- Whenever the decision statistic or sensing metric falls in the  $i^{th}$  interval and the CSI lies in the  $j^{th}$  interval, the secondary user accesses the channel with the associated access probability  $a_{i,j}$ .

This scheme enables us to have higher access probabilities for the sensing metric 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. On the other hand, higher access probabilities are associated with subintervals with high index  $j$ , because a higher channel quality means a higher probability of transmission success.

In this work we consider the maximization of the secondary throughput given a constraint on the stability of the primary queues. That is, we seek to maximize the secondary throughput provided that all the queues of the primary users remain stable. For simplicity, we adopt a symmetry assumption under which the channel statistics are the same for all secondary users. Moreover, all the secondary users employ the same access probabilities. The throughput maximization with primary queue stability goal can be formulated as the following constrained optimization problem

$$\max_{a_{i,j}, i \in [1, n], j \in [1, m]} \mu_s, \text{ subject to } \lambda_p < \mu_p. \quad (11)$$

To solve the optimization problem of (11), we start by calculating the average primary and secondary throughputs,  $\mu_p$  and  $\mu_s$ , respectively, under the proposed secondary access scheme. The probability of secondary channel access while the primary is active is given by

$$\sum_{i \in [1, n]} \sum_{j \in [1, m]} p_i^1 q_j a_{i,j}, \quad (12)$$

where  $a_{i,j}$  is the access probability associated with subintervals  $i$  and  $j$  (see Fig. 4),  $p_i^1$  is the probability that the value of  $\|y_{ps}\|^2$  falls in the  $i^{th}$  subinterval when hypothesis  $\mathcal{H}_1$  is true (primary user exists in the channel),  $q_j$  is the probability that CSI falls in the  $j^{th}$  subinterval. Similarly, we define the probability that a secondary user accesses the channel when hypothesis  $\mathcal{H}_0$  is true as

$$\sum_{i \in [1, n]} \sum_{j \in [1, m]} p_i^0 q_j a_{i,j}, \quad (13)$$

where  $p_i^0$  is the probability that the value of  $\|y_{ps}\|^2$  falls in the  $i^{th}$  subinterval under  $\mathcal{H}_0$ . Therefore, the average primary throughput is given by

$$\mu_p = \frac{1 - P_e}{M_p} \left( 1 - \sum_{i \in [1, n]} \sum_{j \in [1, m]} p_i^1 q_j a_{i,j} \right)^{M_s}, \quad (14)$$

where  $P_e$  is the outage probability of the link between any primary node and its destination.

For a secondary terminal to have successful transmission, it should correctly identify the time slot as idle and access the channel. In addition, all other secondary users should abstain from transmission during the same time slot. Therefore, the

average secondary throughput is given by

$$\mu_s = \left( 1 - \frac{\lambda_p M_p}{(1 - P_e) \left( 1 - \sum_{i \in [1, n]} \sum_{j \in [1, m]} p_i^1 q_j a_{i, j} \right)^{M_s}} \right) \left( \sum_{i \in [1, n]} \sum_{j \in [1, m]} p_i^0 q_j c_j a_{i, j} \right) \left( 1 - \sum_{i \in [1, n]} \sum_{j \in [1, m]} p_i^0 q_j a_{i, j} \right)^{M_s - 1} \quad (15)$$

where  $c_j$  is the probability of transmission success when the CSI has the  $j^{\text{th}}$  value. The first term is  $1 - \frac{\lambda_p}{\mu_p}$ , which is the probability of the primary queue being empty as derived in the previous section. This term accounts for the assumption that successful secondary transmission dictates the silence of the primary terminal lest its transmission collide with that of the secondary user causing packet loss.

Let  $b_{i+(j-1)n} = a_{i, j}$ ,  $u_{i+(j-1)n}^1 = p_i^1 q_j$ ,  $u_{i+(j-1)n}^0 = p_i^0 q_j$ , and  $v_{i+(j-1)n} = p_i^0 q_j c_j$ . Substituting in (15), we obtain

$$\mu_s = \left( 1 - \frac{\lambda_p M_p}{(1 - P_e) \left( 1 - \sum_{k \in [1, nm]} u_k^1 b_k \right)^{M_s}} \right) \left( \sum_{k \in [1, nm]} v_k b_k \right) \left( 1 - \sum_{k \in [1, nm]} u_k^0 b_k \right)^{M_s - 1} \quad (16)$$

Fortunately, the optimization problem of (11) using (14) and (16) can be converted to a convex program. The global optimum of convex optimization problems can efficiently be obtained via standard numerical techniques [12].

The convexity of problem (11) given (14) and (16) 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 [12]. Due to space limits, we consider here only the term  $1 - \epsilon (1 - u^T b)^{-M_s}$  with  $\epsilon = \lambda_p M_p / (1 - P_e)$ ,  $b$  is a column vector with elements  $b_k$ ,  $u$  is a column vector of  $u_k^1$ , and  $T$  denotes matrix transposition. We form the function

$$g(t) = \log \left( 1 - \epsilon (1 - u^T \bar{b} - tu^T w)^{-M_s} \right) \quad (17)$$

where  $t$  is a scalar parameter,  $\bar{b}$  belongs to the domain of the problem, and  $w$  is a vector such that  $\bar{b} + tw$  also belongs to the domain of the problem. The domain is specified by the inequality constraint of the optimization problem (11) and that  $0 \leq b_k \leq 1 \forall i$ .

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  $\log \left( 1 - \epsilon (1 - u^T b)^{-M_s} \right)$  is concave with respect to all  $b_k$ . The concavity of  $g(t)$  can be easily proven via differentiating twice and examining the sign of the second derivative, which

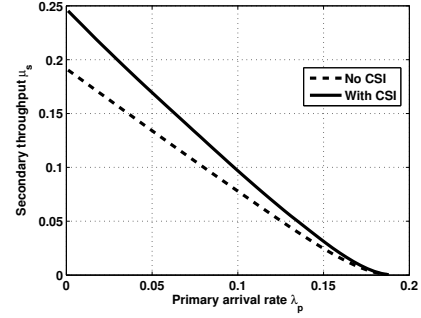


Fig. 5. Secondary throughput versus the primary arrival rate  $\lambda_p$  for the scheme leveraging secondary CSI compared to the scheme relying on sensing only without incorporating CSI information.

is given by

$$\ddot{g}(t) = \frac{\epsilon M_s (u^T w)^2 \left[ \epsilon - (M_s + 1) (1 - u^T \bar{b} - tu^T w)^{M_s} \right]}{\left[ (1 - u^T \bar{b} - tu^T w)^{M_s + 1} - \epsilon (1 - u^T \bar{b} - tu^T w) \right]^2}$$

Since the queueing stability condition requires that  $\epsilon < (1 - u^T \bar{b} - tu^T w)^{M_s}$ , then  $\epsilon < (M_s + 1) (1 - u^T \bar{b} - tu^T w)^{M_s}$ . Consequently,  $\ddot{g}(t)$  is negative and  $\log \left( 1 - \epsilon (1 - u^T b)^{-M_s} \right)$  is concave.

#### IV. RESULTS AND DISCUSSIONS

Here we compare the performance of the proposed joint design of spectrum sensing and channel access mechanisms with and without knowledge of the CSI at secondary transmitters. We consider a system with  $M_p = 4$  primary users and  $M_s = 2$  secondary users. The distance between the primary users and their destination is set to 100 m, the distance between the secondary users and their destination is also 100 m, and the distance between the primary and secondary users is 150 m. The transmit power is assumed to be the same for all users and is given by  $G = 10$  mW. The path loss exponent  $\gamma = 3.7$  and  $N_0 = 10^{-11}$  W.

It follows from the received signal model of (1) that the received signal  $y$  is a complex Gaussian random variable with zero mean and variance  $\sigma_0^2 = N_0$  under hypothesis  $\mathcal{H}_0$  and  $\sigma_1^2 = G\rho^{-\gamma} + N_0$  under hypothesis  $\mathcal{H}_1$ . Note that we drop user-specific subscripts under the assumption of user symmetry mentioned in Section III. Given this, probability  $p_i^1$  in (12) is given by

$$p_i^1 = \exp \left( -\frac{(i-1)\eta}{2n\sigma_1^2} \right) - \exp \left( -\frac{i\eta}{2n\sigma_1^2} \right), \quad (18)$$

whereas probability  $p_i^0$  in (13) can be expressed as

$$p_i^0 = \exp \left( -\frac{(i-1)\eta}{2n\sigma_0^2} \right) - \exp \left( -\frac{i\eta}{2n\sigma_0^2} \right). \quad (19)$$

We use  $\eta/N_0 = 4.6$  and  $n = 4$  sensing subintervals. The secondary transmit CSI, taken as the secondary link SNR, is divided into  $m = 4$  regions, namely,  $[-\infty, 10]$ ,  $[10, 15]$ ,  $[15, 20]$ , and  $[20, \infty]$  dB. The probability  $q_j$  that the SNR lies in

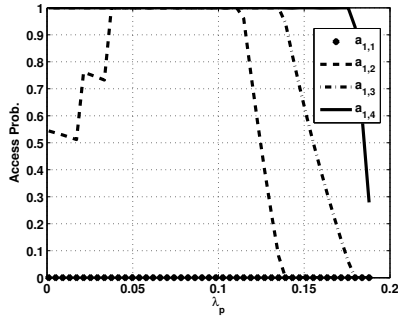


Fig. 6. Secondary access probabilities corresponding to the first sensing interval,  $i = 1$ .

the interval  $[l_B, u_B]$  with  $l_B$  and  $u_B$  expressed in linear scale is given by

$$\exp\left(-\frac{l_B N_0 \rho^\gamma}{G}\right) - \exp\left(-\frac{u_B N_0 \rho^\gamma}{G}\right) \quad (20)$$

The transmission success probabilities depend on the coding and modulation schemes employed by the secondary transmitters. Here, we assume binary phase shift keying (BPSK) modulation [14] for both primary and secondary transmissions and use (2) with  $L = 1024$  bits and  $k_1 = k_2 = 1$  to calculate the secondary success probabilities  $c_j$ 's, as well as the primary error probability  $P_e$ . Probabilities  $c_j$  are obtained by averaging (2) over the range of SNR values defining the  $j^{\text{th}}$  interval.

It can be clearly seen from Fig. 5 that the incorporation of two-bit quantized CSI into the channel access decisions improves the secondary throughput up to 25% at small  $\lambda_p$  under the primary queue stability constraint. This improvement is mainly because the proposed access scheme takes the reliability of the sensing measurements into consideration via the concept of soft sensing. Furthermore, the knowledge of the CSI, even quantized to four levels, allows the secondary nodes to transmit with a higher probability when there is a higher chance of transmission success, and to remain silent when the secondary channel is in deep fade. This reduces the probability of collision between the secondary nodes, and between the secondary and primary nodes.

To get more insight into how the channel access probabilities  $a_{i,j}$  are selected, Fig. 6 depicts the channel access probabilities for the first sensing interval (the interval nearest to zero) and different CSI (SNR) intervals as a function of primary arrival rate. It is noted the access probability is zero for the lowest SNR interval ( $j = 1$ ), and as the SNR increases the range over which each access probability is one increases. 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.

## V. CONCLUSIONS

In this paper, we employ both secondary CSI and soft sensing to implement a cognitive multiple access scheme. Our results for the system's performance under the proposed

scheme show a significant improvement over the sensing-only scheme in terms of the throughput of both primary and secondary networks. The future extension of this work involves the incorporation of automatic repeat request (ARQ) feedback into the secondary decision making. As an error control mechanism, ARQ is ubiquitous in networks and its leveraging is expected to provide more throughput gains.

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