Feedback-based access and power control for distributed multiuser cognitive networks

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***Abstract*—Cognitive radio networks enable secondary users to utilize spare bandwidth of primary users by limiting their interference. Moving beyond the traditional listen-before-talk paradigm, we propose a cognitive access methodology that exploits the feedback channel in two-way primary communication links for better spectrum utility and protection against interference. We let secondary users dynamically control access and power based on primary ACK/NACK messages. We develop an optimal access policy applicable to multiple secondary user pairs. We also devise a distributed power control policy for the multiple secondary users to maximize their individual throughput without significant cumulative interference to the primary link. Our distributed access and power control schemes can effectively provide good SU performance and primary protection without requiring central coordination.**

I. INTRODUCTION

Cognitive Radio networks (CRNs) have generated much research interest in recent years as a promising technology for improving the current static spectrum utilization and for enabling new wireless services [1], [2]. CRNs opportunistically access the spectrum resource of primary users (PUs) without negatively affecting the primary user activities. Cognitive radios (CRs) can access bandwidth assigned to PUs only if the level of interference generated by their communications is kept under a certain threshold.

Traditional works on cognitive radio have largely focused on the listen-before-talk (LBT) methodology based on spectrum activity sensing. As an important first step, LBT allows secondary users (SUs) to detect the presence or the absence of PU signals before channel access decisions. Although recent FCC reports showed that LBT does not degrade TV receiver quality, LBT based schemes still suffers several drawbacks: they need to handle the SNR-wall issue [11]; they do not solve the hidden receiver problem; they fail to effectively exploit the excess system capacity of interference-resistant PU networks.

In this paper, we propose CRNs that can exploit the inherent feedback information and, more generally, data link control (DLC) information that are available in most of “two-way” wireless communications. Such DLC information is present in many wireless systems such as HSDPA [3] and WiMAX [4], in the form of ACK/NACK packets and downlink/uplink profiles. Such information can be exploited by CRNs to learn about the primary communication characteristics and to quantify the impact of secondary access.

There exist several related works. In [17] the authors proposed a distributed algorithm that performs power control for wireless ad hoc networks. Every user announces a price that mirrors compensation for the interference caused by other users. Using game theory the authors proposed an asynchronous and distributed algorithm for updating power levels and prices in case of static channel conditions and one transmitter-receiver pair. In [18], a cognitive radio system varies transmission power according to information available to the spectrum sensor. The results show that the capacity optimal power adaptation requires a progressive reduction of the cognitive transmitter power as the probability of primary user presence increases. The authors of [19] formulated a joint power/rate allocation with max-min fairness criterion as an optimization problem. They also explored different systems and quality of service requirements. In [20], the authors designed a distributed algorithm for CRNs to maximize data rates over multiple user communication sessions. In [15], an SU transmits probing signals to observe the changing transmission power of the PU in response. In this way the SU can estimate the effective gain of the interference channel from the SU transmitter to the PU receiver. In [16], a wideband OFDM cognitive radio dynamically changes its subcarrier usage based on the reactive behaviors of the narrow-band PU devices.

In this work, we emphasize that better cognition requires knowledge and awareness of primary network characteristics and requires SU learning of user interactions. As a first step, we consider “two-way” primary communication systems equipped with inherent feedback mechanisms, particularly the ACK/NACK feedback from the primary receiver (PU-Rx) to primary transmitter (PU-Tx) upon receiving a data packet. Our approach differs from existing works by directly exploiting DLC information transmitted by the PUs. This approach also offers several advantages over the traditional LBT by providing (a) a more efficient spectrum utilization; (b) a way of implementing distributed multiple SU access while protecting the PU links and (c) a means of improving PU/SU existence and interaction.

To generalize, additional DLC information can be incorporated in the proposed schemes to improve the cognition of the CR devices and thus achieve highly efficient and harmless secondary spectrum access in CRNs. Such DLC information may include PU transmission power, channel quality indica-

Fig. 1. System model.

tors, or other information based on the QoS needs of both PUs and SUs. By exploiting these available control messages on the PU communication links, we can develop more flexible distributed schemes for multi-user cognitive channel access and power control.

II. SYSTEM MODEL

The following standard notations will be used throughout the paper: $\mathbb{E}$ denotes the expectation operation; $(x)^+$ is defined as $(x)^+ = \max\{0, x\}$.

Our basic system model is shown in Fig. 1. The “two-way” primary communication system consists of two channels: a forward channel from the PU-Tx to the PU-Rx, and a reverse channel in the opposite direction. On the forward channel, the PU-Tx sends data packets to the PU-Rx. On the reverse channel, the PU-Rx sends back the ACK/NACK packets to indicate whether the forward link data packet reception was successful or not.

The SU objective is to opportunistically access the forward channel bandwidth. We assume that the advanced SU-Tx may overhear the ACK/NACK packets on the reverse channel, and explore this feedback message to control its spectrum access. Since the PUs have higher priority in spectrum access, the interference effect from the SUs access to the PU-Rx should be kept insignificant. By listening to the ACK/NACK packets, the SU can learn about its interference effect to the PU-Rx, and adjust its transmission strategy (access policy or transmit power) accordingly. This approach can also resolve the notorious hidden receiver problem in the LBT approach since the SUs transmission adapt to the interference perceived by the PU-Rx directly, rather than only listening to the presence of the PU-Tx transmission.

We consider the case that the PU transmission on the forward link is always active. Since the PU is always active, LBT strategies would disable all SU transmissions in this scenario. Thus, investigating this application scenario can allow us to better illustrate the advantage of our new approach. Depending on the locations of the SU-Tx and the PU-Rx, the SU transmission may or may not harm the PU-Rx. Generally, when the PU-Rx is far away from the SU-Tx and close to the PU-Tx, the interference from the SU-Tx is negligible at the PU-Rx. In this case, the SU-Tx can transmit over the primary channel if its power is controlled appropriately. For convenience, we assume that both PU and SU transmissions are slotted with the same slot duration and that the SU access is synchronized with the PU. This can be achieved by letting the SU listen to the broadcast control message common to many “two-way” communication links. We also assume that the feedback information from the PU-Rx to the PU-Tx has negligible delay when arriving at the SU. In addition, the SU access causes no interference on the reverse link.

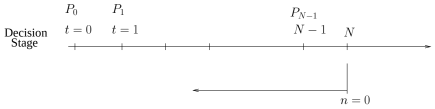

Fig. 2. Illustration of SU access decision.

As illustrated in Fig. 2, based on the observation history of the ACK/NACK messages on the primary reverse channel until time slot t, the SU decides its access and power control at the beginning of time slot t. The SU action space under consideration in the paper includes the transmission probability and transmit power. The SU can then learn its impact on the PU during time slot t from the ACK/NACK information transmitted on the reverse channel, which marks the successful/failed reception of the PU data packet. For each SU access action, we assign a reward function that reflects the successful transmission or data rate the SU obtains, as well as a cost function that penalizes the SU for its increased interference on the PU link. By optimizing the total expected net-reward (reward minus cost) through SU access control, we can achieve a balance between PU protection and spectrum efficiency.

Let Z_t denotes the observation outcome at the SU-Tx on ACK/NACK at the end of time slot t:

$$Z_t = \begin{cases} 0, & \text{if an ACK is received at time } t \\ 1, & \text{if a NACK is received at time } t. \end{cases} \tag{1}$$

Generally, Z_t is random owing to the many uncontrollable factors including channel fading and is affected by the previous SU access action. Hence, the SU access optimization under consideration here is generally a dynamic programming problem. Denote the probability of having a NACK on the PU links at time slot t as ζ_t. Obviously, the value of ζ_t depends on the interference effect of the SU action at time slot t.

The SU control policy, denoted as π, specifies a sequence of functions $\pi = [\mu(1), \cdots, \mu(t), \cdots]$, in which $\mu(t)$ defines a mapping from specified state space to the SU action space. In the following sections, we will explain the state and action space for access control and power control in more detail. Our objective is to find control policies that achieves the best trade-off between the two conflicting goals of protecting PU communications versus higher SU capacity.

In what follows, we focus on exploiting spectrum opportunities on the forward link using the feedback information on the reverse channel. Nevertheless, the results can be generalized to the opportunistic spectrum access on the reverse channel as well.

III. ADAPTIVE SU ACCESS CONTROL BASED ON PU ACK/NACK INFORMATION

In this section, we consider the design of an optimal SU access control policy in which the SU-Tx decides whether or not to transmit based on the observation of ACK/NACK message on the reverse channel. In this section, we assume that the SU-Tx transmits with a fixed transmit power. We address the issue of power control in the next section.

We define two states for the PU forward link as perceived by a given secondary user: an “error-resistant” (low interference) and an “error-prone” (high interference) state. This is because the channel between the PU-Tx and PU-Rx may experience impairment other than the SU transmission in question. Moreover, the two channel states can be used to approximate the effect of multiple uncoordinated SU transmissions. The “error-resistant” state accounts for the case in which no other SU-Tx interferes with the PU-Rx, whereas the “error-prone” state denotes the case in which there exist other interfering sources besides the given SU. If the chosen SU-Tx does not transmit during the “error-resistant” state, then the PU-Rx packet error rate is Q_0, whereas during the “error-prone” state the packet error rate is Q_1. On the other hand, if the SU-Tx transmits during the “error-resistant” state, the packet error rate is approximately Q_1, and during the “error-prone”state the packet error rate is Q_2. Clearly, it is sensible to have $Q_0 < Q_1 < Q_2$. Moreover, their values mirror the signal to interference and noise ratio (SINR) levels at the PU-Rx under the different situations. We assume that the SU-Tx does not know exactly which state the forward channel is in, but it has the knowledge of Q_0, Q_1, and Q_2 from experience and measurement.

Here, we consider the SU access control with infinite decision horizon. The SU decision state at time slot t is the probability that the PU forward link is in the error-resistant state, which is denoted by $q_t \in [0, 1]$.

The actions that the SU-Tx can take at time slot t are:

$$a_t = \begin{cases} 1 & \text{“transmit”} \\ 0 & \text{“stay idle”} \end{cases} \tag{2}$$

Depending on the access decision the SU-Tx make, we have the probability of receiving an NACK at slot t as:

$$\lambda(a_t) = \begin{cases} q_t Q_1 + (1-q_t)Q_2, & \text{if } a_t = 1; \\ q_t Q_0 + (1-q_t)Q_1, & \text{if } a_t = 0. \end{cases} \tag{3}$$

At the end of each time slot, SU-Tx updates its state according to the Bayesian rule. If it transmitted a packet in the previous slot, i.e., $a_t = 1$, and successfully receives an ACK/NACK packet from PU-Rx, it will update its state according to

$$q_{t+1} = \begin{cases} \frac{q_t Q_1}{\lambda(1)} & \text{if } Z_t = 1; \\ \frac{q_t(1-Q_1)}{1-\lambda(1)} & \text{if } Z_t = 0. \end{cases} \tag{4}$$

In case it did not transmit in the previous slot, i.e., $a_t = 0$, while successfully receives an ACK/NACK packet, the SU-Tx will update its state according to

$$q_{t+1} = \begin{cases} \frac{q_t Q_0}{\lambda(0)} & \text{if } Z_t = 1; \\ \frac{q_t(1-Q_0)}{1-\lambda(0)} & \text{if } Z_t = 0. \end{cases} \tag{5}$$

When no ACK/NACK feedback is received, the state is unchanged as

$$q_{t+1} = q_t. \tag{6}$$

Since the event of correctly detecting (overhearing) an ACK/NACK feedback packet from the PU-Rx depends on many factors such as the channel conditions between PU-Rx and SU-Tx and PU-Rx’s transmission power. This event is regarded as random from the view point of SU-Tx and in this paper we defined the probability of correctly receiving a feedback packet from PU-Rx as $\eta \in [0, 1]$.

The immediate reward is a function of the state and the action at time t, which is defined as:

$$r(q_t, a_t) = \begin{cases} R_s - C\zeta_t & \text{if } a_t = 1; \\ 0 & \text{if } a_t = 0. \end{cases} \tag{7}$$

Here, R_s is a constant gain that accounts for the channel access and C is a constant penalty that accounts for the event of receiving a NACK. The reward function (7) means that every time SU-Tx transmits, it receives a reward of value R_s, whereas in case of NACK this reward is offset by a cost C. Whenever PU-Rx sends a NACK when SU-Tx transmits, i.e., $a_t = 1$, the SU-Tx pays a penalty of C. Thus, the expected cost is $C \cdot \zeta_t$.

The goal of the SU-Tx is to maximize its total expected discounted reward:

$$V(x) = \max_{\pi}\{\mathbb{E}_\pi[\sum_{t=t_0}^{+\infty} \alpha^{t-t_0} r(q_t, a_t) | q_{t_0} = x]\}, \tag{8}$$

where t_0 is the initial decision stage, and $q_{t_0} = x$ is the initial state. Note that $V(x)$ has the same form for any $t_0 < \infty$.

Based on (4) and (5), we define the following function $\theta(a, Z_{t_0})$ of two variables having four possible combinations

$$\theta(a, Z_{t_0}) = \begin{cases} \frac{xQ_1}{\lambda(1)}, & \text{if } a = 1,\ Z_{t_0} = 1; \\ \frac{x(1-Q_1)}{1-\lambda(1)}, & \text{if } a = 1,\ Z_{t_0} = 0; \\ \frac{xQ_0}{\lambda(0)}, & \text{if } a = 0,\ Z_{t_0} = 1; \\ \frac{x(1-Q_0)}{1-\lambda(0)}, & \text{if } a = 0,\ Z_{t_0} = 0. \end{cases} \tag{9}$$

This function allows us to replace the value of x at stage $t_0 + 1$. Consequently, (8) can be rewritten in a recursive Bellman form:

$$\begin{aligned} V(x) = \ & \max_{a \in \{0,1\}}\{r(x, a) + \alpha[(1-\eta)V(x)+ \\ & \eta\lambda(a)V(\theta(a, 1)) + \eta(1-\lambda(a))V(\theta(a, 0))]\}. \end{aligned} \tag{10}$$

$V(x)$ is a monotonically increasing and convex function of $x \in [0, 1]$. By virtue of these properties, the optimal access policy is a threshold policy. Specifically, the SU-Tx transmits a packet to the SU-Rx only if its estimated probability of PU channel being in the error-resistant channel state is above the threshold $\bar{q}$. In other words:

$$a_t = \begin{cases} 1 \text{ if } q_t \geq \bar{q} \\ 0 \text{ if } q_t < \bar{q}. \end{cases} \tag{11}$$

The threshold $\bar{q}$ can be calculated numerically.

The policy is optimal for one secondary user pair. We also apply this policy based on our definition of the two channel states to the case of multiple secondary users pairs. The results are shown in Sec. V.

IV. ADAPTIVE SU POWER CONTROL

In this section, we propose an adaptive power control scheme for a SU to maximize its transmit throughput while keeping its negative impact on the PU-Rx (in terms of additional NACKs) under control. The control variable for the SU is its transmit power on the forward link. We first develop an optimal power control policy for a single pair of secondary users assuming perfect reception of the ACK/NACK packets from the PU-Rx, and then extend the policy to multiple secondary user pairs with imperfect ACK/NACK receptions.

A. Problem Formulation

To illustrate the design principle of the adaptive power control policy based on the ACK/NACK reception from the primary feedback channel, we consider scenarios in which the primary system does not perform any power control. We assume that the statistics of the interference channel gain from the SU-Tx to the PU-Rx does not change during the time interval of interest $(0, T]$.

Define P_t as the transmit power of the SU-Tx at slot t, where $t = 1, \cdots, T$. We impose a maximum power constraint on the SU-Tx as $P_t \leq \bar{P}$. The immediate reward for the SU pair with action $P_t = P$ at time slot t is the supported data rate on the forward link given as

$$\gamma(P) = \log(1 + GP), \tag{12}$$

where the constant G is the effective channel gain for the SU-Rx.

For the PU-Rx, the transmission of the SU-Tx on the forward link degrades its channel quality and signal reception. The larger the SU transmit power, the higher the probability that the PU-Rx cannot decode its data packet correctly, and the higher its NACK rates ζ. We denote this interaction between the SU power P_t and PU NACK rate ζ_t by a function $\zeta_t = f_e(P_t)$, which is an monotonically increasing function. Note that since the channel statistics remain unchanged, we have the same function for all time slots. On the other hand, for a given transmit power at the PU-Rx, due to the channel fading, the SU-Tx may not observe the ACK/NACK packets on the reverse channel accurately, and the optimal power control can be obtained by solving a partially observable decision problem. Here, we first assume that the SU-Tx can decode the ACK/NACK packets accurately. We derive the optimal power control strategy for the SU-Tx before extending the general case. The performance of this approach is evaluated in Sec. V.

With the perfect ACK/NACK observation, the SU-Tx maintains a record on the total number of NACK received by the beginning of slot $t + 1$, X_t. We have:

$$X_t = \sum_{k=0}^{t} Z_k, \tag{13}$$

with the transition probabilities

$$\begin{aligned} \Pr[X_{t+1} = k | X_t = k] &= 1 - \zeta_{t+1}, \\ \Pr[X_{t+1} = k + 1 | X_t = k] &= \zeta_{t+1}, \end{aligned} \tag{14}$$

where $\zeta_{t+1} = f_e(P_{t+1})$. Based on the value of X_t, the SU can infer the interference impact of its past transmission to the PU-Rx, and make timely adjustment on its transmit power.

To limit the SU interference on the PU traffic, we introduce a terminal cost that penalize the SU based on the total number of NACKs caused during the entire access period. We denote this terminal cost by $f_c(x_T)$. The penalty function may have various forms, and should be chosen such that the NACK rate at the PU-Rx is under control. We require that $f_c(x_T)$ be an increasing function. The penalty function used here is $f_c(k) = T \cdot [(k - f_e(0)T)^+]^2$.

The SU power control policy specifies a sequence of functions $\pi = [\mu(1), \cdots, \mu(T)]$, where $\mu(t)$ defines a mapping from state space $\{X_t\}$ to the action space $[0, \bar{P}]$. Suppose that the number of NACK packets observed at the SU-Tx until time slot t is $X_{t-1} = x$. Let $V_t(\pi, x)$ be the total net-reward of the SU when there are $T - t + 1$ slots left until terminating slot T under a given power control policy π. We then have

$$V_t(\pi, x) = \mathbb{E}_\pi[\sum_{k=t}^{T} \gamma(P_k) - f_c(X_T) | X_{t-1} = x], \tag{15}$$

where the expectation is taken over the random variables $X_t, \cdots, X_T$ with respect to the policy π. The objective is to find a power control policy $\bar{\pi}$ that has the maximum expected total net-reward during the entire access period, i.e.,

$$\bar{\pi} = \arg\max_{\pi} \quad V_0(\pi, 0). \tag{16}$$

Here, we use the fact that at the beginning of the SU access, the number of NACKs is fixed as $X_0 = 0$. In what follows, for notation simplicity, we use $V_t(x)$ instead of $V_t(\bar{\pi}, x)$ to represent the reward-to-go at time slot t achieved by the optimal policy.

B. Optimal Power Control Policy

According to the Bellman optimality equation, we have the following iterative relation on $V_t(x)$:

$$\begin{aligned} V_t(x) = \max_{P_t \in [0, \bar{P}]} \big\{ & \log_2(1 + GP_t) + f_e(P_t) V_{t+1}(x + 1) \\ & + (1 - f_e(P_t)) V_{t+1}(x) \big\}; \end{aligned} \tag{17}$$

and $V_{T+1}(x) = -f_c(x)$. Backward induction can be used to obtain the optimal power control policy $\bar{\pi}$.

If $f_e(P_t)$ is a convex increasing function of P_t, with $f_e(0) = 0$, we can show analytically that the optimal power control policy can be iteratively derived by differentiating (17) with respect to P_t before setting the derivative equal to zero. Specifically, we have for $t \leq T$ and $\forall k \in [0, T]$, the optimal transmit power is the solution to the following equation:

$$f_e'(P_t) = \frac{1}{(1 + P_t G)[V_{t+1}(k + 1) - V_{t+1}(k)]}. \tag{18}$$

Note that we have used the fact that the maximum number of NACK packets during time interval $(0, T]$ is T.

In practical systems, there are often only finite number of power levels for the SU-Tx to choose from. In such cases, by evaluating the right-hand-side of (17) at the known power levels, we can obtain the optimal transmit power for each slot as the one with smallest cost using backward induction.

The calculation of the optimal power control policy can be performed offline. The results can be stored in a $T \times (T+1)$ table [1], and the SU-Tx performs a table lookup operation at each slot according to the number of NACKs observed.

C. Imperfect ACK/NACK Detection

In practical systems, the reception of the ACK/NACK packets at the SU-Tx may not be perfect, especially when the SU-Tx is far away from the PU-Rx. Here, we propose a suboptimal approach is a modification of the optimal policy obtained for perfect ACK/NACK reception case. Due to the potential errors of the ACK/NACK detection, the SU-Tx does not know the exact number of PU packets lost. An iterative method is proposed for the SU-Tx to estimate the NACK rate perceived by the PU-Rx. Denote the estimated NACK rate at time slot t as $\hat{\zeta}_t$, we have:

$$\hat{\zeta}_{t+1} = \hat{\zeta}_t + \xi_{t+1}\left(\frac{X^{\mathrm{A}}_{t+1}}{X^{\mathrm{A}}_{t+1} + X^{\mathrm{N}}_{t+1}} - f_e(0)\right), \qquad (19)$$

where ξ_{t+1} is the step size at time $t+1$, X^{A}_{t+1} and X^{N}_{t+1} denote the number of successfully decoded ACK and NACK packets until time slot $t+1$, respectively. If the SU-Tx cannot decode the ACK/NACK packet successfully, it will update the value of X_{t+1} as:

$$X_{t+1} = X_t + \hat{\zeta}_t. \qquad (20)$$

The value of X_{t+1} is then rounded to the nearest integer and used to look up the transmit power in the pre-calculated table.

When there are multiple SU pairs transmitting on the PU channel independently, the interference to the PU-Rx will accumulate. In addition, there will be inter-SUs interference. The optimal design of a distributed optimal power control scheme is a challenging future research topic. Here, we adopt a suboptimal approach that each SU-Tx updates its transmit power based on its local observation of ACK/NACK packets delivered at the feedback channel. We use the estimated number of NACK packets to adjust its transmit power by looking up the corresponding power in the pre-calculated table. Since the SUs may not be able to predict the transmission of other SUs, the table that stores the optimal power control policy is calculated without considering the inter-SUs interference and errors in ACK/NACK detection.

V. SIMULATION RESULTS

In this section, we test the performance of the proposed feedback-based access and power control schemes. The simulation results show that exploiting the inherent feedback information of the primary systems makes it possible for SUs to control the interference level at the PU-Rx in a distributed fashion.

The locations of the PU pair and SU pairs used in the simulations are shown in Fig. 3. We use P_a and P_b to represent the fixed transmit power of the PU-Tx on the forward channel and the PU-Rx on the reverse channel, respectively. The distances between the PU-Tx (SU-Tx) and the PU-Rx are denoted by d_a and d, respectively; while the communication range of the SU pair is denoted by δ.

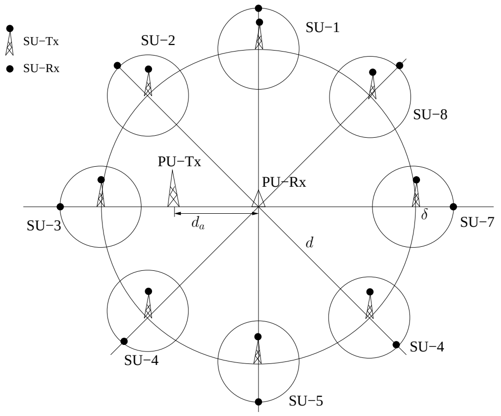

Fig. 3. Location of PUs and SUs.

A. Adaptive access control

We first present the simulation results for the proposed adaptive access control policy in Sec. III. The SU-Tx estimates the effect of its transmission on the PU-Rx through the feedback packets that are sent on the reverse link. We use the NACK rate, i.e., the number of the NACK packets sent by the PU-Rx in time, to illustrate the performance of our distributed algorithm in protecting the primary communication link. We assume all channels to be AWGN.

In an AWGN channel, the probability of packet error in the "error-resistant" state Q_0 is:

$$Q_0 = 1 - (1 - \mathrm{BER}_0)^{N_b}. \qquad (21)$$

Here BER_0 is the bit-error-rate of the "error-resistant" channel when the SU-Tx does not transmit and N_b is the number of bits in a PU packet. The BER is a function of the Gaussian distribution and is modulation-dependent. [2] Similar expression applies to probabilities Q_1 and Q_2, with bit-error-rate BER_1 and BER_2, respectively.

In our simulations, we define Q_0, Q_1 and Q_2 by considering the SINR at PU-Rx due to 0, 1, and 2 interferers, respectively. We use the resulting values to obtain the threshold $\bar{q}$ which characterizes the secondary transmission policy. Note that the actual packet error rate at the PU-Rx has been calculated at every time slot according to the effective number of secondary transmitters.

We consider the application of our proposed threshold access strategy to the case of multiple secondary users. With

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[1] Note that since $X_t \leq t$, the actual size of the table can be made much smaller.

[2] For example, in case of M-PSK ($M \geq 8$) the corresponding BER is:

$$\mathrm{BER}_0 \cong \frac{2}{k} Q\left(\sqrt{2k\gamma_{(0,\text{PU-Rx})}}\sin\left(\frac{\pi}{M}\right)\right), \qquad (22)$$

with $k = \log_2(M)$ and $\gamma_{(0,\text{PU-Rx})}$ the SNR at the PU-Rx in case no SU-Tx is transmitting.

TABLE I
SU PERFORMANCE.

number of SUs	1	2	8
per SU throughput	0.7061	0.6122	0.2071
variance	0	$4.0 \cdot 10^{-7}$	$3.1 \cdot 10^{-4}$

respect to the SU distribution of Fig. 3, we consider the special cases of 8 secondary SU-Tx and 2 secondary SU-Tx randomly selected from among the 8. Fig. 4 shows the resulting NACK rate for the three cases of one SU, two SUs, and eight SUs, respectively. The x-axis is time (in slots). The initial state of the secondary transmitters (q_1) is randomly chosen over $[0, 1]$. Our results show that, regardless of the number of SUs, the NACK rate approaches 5%. This means that the primary user communication is protected in all three cases by the optimal access scheme. The convergence time is about 50 to 100 time slots, and it does not depend on the number of secondary transmitters. Since the state q is the estimation of the probability of being in the "error-resistant" state from the point of view of the SU transmitters, the results show that the distributed algorithm successfully enables multiple secondary transmissions without explicit cooperation and achieves the desired joint PU protection.

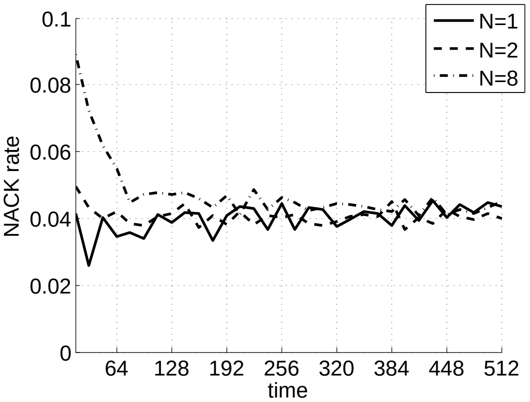

Fig. 4. NACK rate in case of 1,2, and 8 secondary pairs

Table I compares the per SU throughput. The per SU throughput is defined as the number of times a SU-Tx accesses the primary channel out of the total time of a simulation. Since the total channel capacity is limited, it is natural that as the number of SU-Tx increases, the throughput per SU declines. Nevertheless, because of spatial reuse, the aggregated SU throughput increases with increasing number of SUs. The protocol also results in good fairness because all the SU-Txs obtain very close values of throughput as shown by the low variance of the per SU throughput in table I.

In practical networks, a pre-determined NACK rate can be set by the PU according to its desired QoS. SUs will consequently adjust their cost/reward function to satisfy the specification.

In summary, the throughput result and the NACK rate in Fig. 4 show that the distributed primary channel access protocol for cognitive radios successfully protects the primary quality of transmission by keeping the NACK rate low. At the same time, it achieves fairness for multiple secondary transmitters whose individual throughput shows little difference from user to user.

TABLE II
PARAMETERS VALUES

T	$P_a/P_b/P$	Γ_a	Γ_b	d_a	δ	N_0
100	50dBm	10	2	1000m	100m	-100dBm

B. Adaptive power control

Next, we present simulation results for the proposed adaptive power control policy.

The PU and eight SU locations are illustrated in Fig. 3. To determine the function $f_e(P_t)$ and the probability of successful ACK/NACK reception at the SU-Tx, we consider both the path loss and Rayleigh fading effects in the channel model. First, we assume that the path loss factor is 4. We use notations h_a, h_i, and h_b to represent the random channel fading coefficients from the PU-Tx to the PU-Rx, from the SU-Tx to the PU-Rx on the forward link, and from the PU-Rx to the SU-Tx on the reverse link, respectively. We assume that h_a, h_b, and h_i follow independent Rayleigh distribution with unit variance.

Suppose that the required average SNR for decoding the packet correctly at the PU-Rx is Γ_a, and assume that all packets received with SNR lower than Γ_a will be in error. When there is no SU transmission, we have the NACK probability as:

$$\begin{aligned} f_e(0) &= \Pr[P_a \frac{d_a^{-4}|h_a|^2}{N_0} < \Gamma_a] \\ &= 1 - \exp\left(-\Gamma_a N_0 P_a^{-1} d_a^{-4}\right). \end{aligned} \tag{23}$$

We assume that the SU-Tx does not have the channel state information of the interference link. The probability of a reception failure at the PU-Rx when $P_t \neq 0$ is:

$$\begin{aligned} f_e(P_t) &= \Pr[\gamma_a < \Gamma_a] \\ &= \Pr[\frac{P_a d_a^{-4}|h_a|^2}{P_t d^{-4}|g_i|^2 + N_0} < \Gamma_a] \\ &= \mathbb{E}_{|g_i|}[1 - \exp\left(\frac{-\Gamma_a(N_0 + P_t d^{-4}|g_i|^2)}{P_a d_a^{-4}}\right)] \\ &= 1 - \exp\left(-\Gamma_a N_0 P_a^{-1} d_a^{-4}\right)\left(1 + 2\Gamma_a P_t P_a^{-1} d^{-4} d_a^4\right). \end{aligned}$$

Since the channel statistics do not change over time $(0, T]$, the function $f_e(P_t)$ is the same for all time slots. Note that $f_e(P_t)$ is not convex. We assume the number of power levels supported by the SU-Tx to be finite. The value of η as a function of d can be calculated in a approach similar to (23) with the SNR threshold for correctly decoding ACK/NACK packets as Γ_b. In practical system, the SUs may be able to evaluate $f_e(\cdot)$ by probing and extensive measurement on the PU channel. The parameter values are listed in Table II.

For the single SU pair case, we consider the SU pair labeled as SU-8 in Fig. 3. The value of the effective channel gain G

TABLE III
SIMULATION RESULTS WITH MULTIPLE SUS

	d	NACK (%)	Individual SU Throughput
SU-1,5	500	1.41	0.068/0.068
SU-1,5	1500	2.09	4.95/4.95
SU-1,3,5,7	500	1.52	0.04/0.00/0.04/0.45
SU-1,3,5,7	1500	2.52	4.77/0.44/4.77/6.01
SU-1˜8	500	1.67	0.02/0.00/0.00/0.00/0.02/0.19/0.36/0.19
SU-1˜8	1500	3.32	4.48/2.51/0.26/2.51/4.48/5.41/5.69/5.41

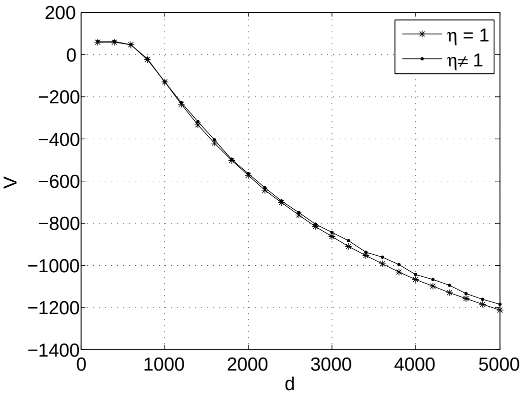

Fig. 5. Average SU value function(figure to be replaced).

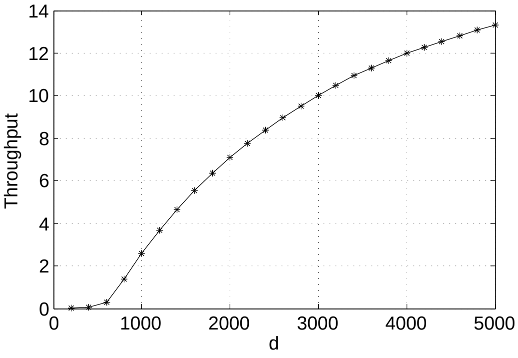

Fig. 6. Throughput performance with a single SU pair.

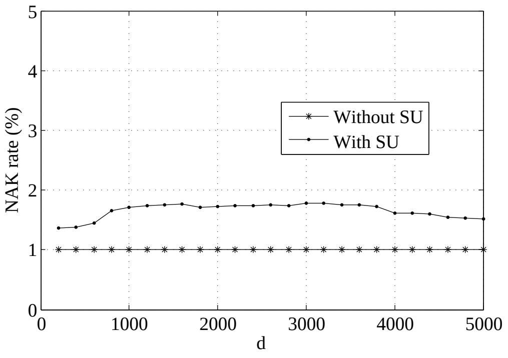

Fig. 7. NACK rate of the PU with a single SU pair.

in (12) is obtained as the inverse of the sum of noise floor and interference power from the PU-Tx. The step size in the estimation update (19) is set as a constant $\xi_t = 0.1$.

In Fig. 5 and Fig. 6, we show the achieved value function and throughput for SU-8, respectively, as the distance d varies. We can observe that the farther the SU-Tx is from the PU-Rx, the more net-reward the SU obtains. This is intuitive since the farther the SU-Tx is from the PU-Rx, the less its interference is, and consequently, the higher the power the cognitive radio can use. As a comparison, we also show the optimal value function obtained by assuming perfect observation on ACK/NACK packets (i.e., $\eta = 1$). We can observe that the SU performance with ACK/NACK reception uncertainty is slightly smaller than that with perfect ACK/NACK reception as shown in Fig. 5. The impact of the SU transmission on the PU communication is shown the PU-Rx in Fig. 7. We can observe a small increase in the NACK rate, but the NACK rate is under control for all the values of the distance considered. This clearly indicates that the power control policy enables the SU-Tx to adapt to achieve better PU protection.

We also test the cases with multiple SU pairs with their locations shown in Fig. 3. SU pairs are uniformly distributed around the PU-Rx. Hence, the ACK/NACK reception probability is the same at each SU-Tx, though the ACK/NACK observation is assumed to be independent among different SU-Tx's. Each SU independently performs the power control algorithm based on the estimated number of the NACK packets (with errors). The individual throughput of each SU pair and the accumulated NACK at the PU are summarized in Table III.

From the results of Table III, we have the following observations:

- The NACK rate increases slightly with the number of SUs. This is due to the accumulated interference from multiple SU-Tx's to the PU-Rx. However, with the proposed power control policy, the increase in the number of the PU packet failures is very slow as the number of SUs increases.
- Unlike the fairness results in access control simulations, the individual SU throughput differs significantly with power control. The main reason for the lack of fairness in this power control scheme is that the interference power from the PU-Tx is much larger to some SU-Rx's. The reward is relatively small for these SU-Tx's to transmit

when considering the potential penalty.
- When the distance from the PU-Rx to the SU-Tx increases, SUs can obtain better throughput performance, while the NACK rate is kept low.

These results show the efficacy of the proposed algorithm to adapt to its surrounding radio environment.

VI. CONCLUSION

In this work, we present a new framework for distributed cognitive radio access and power control by utilizing the primary feedback information. We explore a novel idea of cognition with the secondary users adapting their access based on the ACK/NACK message they overhear from the primary reverse channel. We derive an optimal channel access policy and an optimal power control policy for cognitive radios. We show that the proposed schemes leads to little additional packet loss for the PU link while enabling SUs to achieve good spectral utilization in a distributed manner. Both access and power control schemes offer stable PU packet protection regardless of the number of secondary users. In this work, we limited the discussion to exploiting the ACK/NACK message of the "two-way" primary communication systems. The more general use of other DLC information for cognitive access is currently under investigation.

REFERENCES

[1] FCC, "Spectrum Policy Task Force Report,", Nov. 2002.

[2] FCC, "Office of engineering and technology releases TV white space phase II test report," http://www.fcc.gov/oet/projects/tvbanddevice/Welcome.html, Nov. 2008.

[3] *3GPP Technical Specification Group Radio Access Network Physical layer procedures (FDD) (Release 5)*, 3rd Generation Partnership Project Std. S25.214 V5.11.0, 2005.

[4] *Air Interface for Fixed Broadband Wireless Access Systems*, IEEE Std. 802.16-2004, 2004.

[5] J. Mitola III, "Cognitive radio for flexible mobile multimedia communications," in *Sixth International Workshop on Mobile Multimedia Communications*, 1999.

[6] J. Mitola and J. Maguire, G. Q., "Cognitive radio: making software radios more personal," *IEEE Personal Communications [see also IEEE Wireless Communications]*, vol. 6, no. 4, pp. 13–18, 1999, 1070-9916.

[7] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, 2005.

[8] Q. Zhao and B. Sadler, "A survey of dynamic spectrum access: signal processing, networking, and regulatory policy," *IEEE Signal Processing Magazine*, vol. 55, no. 5, pp. 2294–2309, 2007.

[9] A. Sahai, N. Hoven, and R. Tandra, "Some fundamental limits on cognitive radio," in *42th Allerton*, 2004.

[10] R. Tandra and A. Sahai, "Fundamental limits on detection in low SNR under noise uncertainty," in *WirelessCom 05 Symposium on Emerging Networks, Technologies and Standards*. Maui, Hawaii: IEEE, June 2005.

[11] ——, "SNR walls for signal detection," *IEEE Journal on Selected Topics in Signal Processing*, pp. 4 – 17, 2008.

[12] S. Huang, Z. Ding, and X. Liu, "Non-intrusive cognitive radio networks based on smart antenna technology," in *IEEE Global Telecommunications Conference (GLOBECOM)*. IEEE, 2008.

[13] K. Liu and Q. Zhao, "Link throughput of multi-channel opportunistic access with limited sensing," *in IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, 2008.

[14] Q.C. Zhao, S. Geirhofer, L. Tong, and B. M. Sadler, "Optimal dynamic spectrum access via periodic channel sensing," in *Proc. Wireless Communications and Networking Conference (WCNC)*, 2007.

[15] R. Zhang and Y. C. Liang, "Exploiting hidden power feedbacks in cognitive radio networks," *Poster Session, the 3rd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, 2008.

[16] H. Rahul, N. Kushman, D. Katabi, C. Sodini, and F. Edalat, "Learning to share: narrowband-friendly wideband networks," *SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 4, pp. 147–158, 2008.

[17] J. Huang, R. Berry, and M. Honig, "Distributed interference compensation for wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 5, pp. 1074–1084, May 2006.

[18] S. Srinivasa and S. Jafar, "Soft sensing and optimal power control for cognitive radio," *IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 1380–1384, Nov. 2007.

[19] L. Le and E. Hossain, "Qos-aware spectrum sharing in cognitive wireless networks," *IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 3563–3567, Nov. 2007.

[20] Y. Shi and Y. Hou, "A distributed optimization algorithm for multihop cognitive radio networks," *The 27th Conference on Computer Communications. IEEE INFOCOM 2008*, pp. 1292–1300, April 2008.