Coexisting with CSMA-based Reactive Primary Users

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***Abstract*— Cognitive radio has the potential to improve spectrum efficiency and to alleviate spectrum scarcity by opportunistically utilizing un-utilized or under-utilized spectrum. A cognitive radio device needs to monitor primary user (PU) activities to identify white spaces and utilize spectral opportunities for transmission, without significantly affecting the PU performance. Additional challenges exist when PUs are reactive. An example of a reactive system is a CSMA-based primary system where PUs react to secondary user (SU) activities. Besides collision and throughput, we also introduce a deterrence metric to capture the impact of SU activity on PU. We present and compare four different SU access schemes for a CSMA-based primary system that takes into account the reactive nature of the PU access mechanism. Both simulation and analysis results show that the SU can utilize the available spectrum opportunities at the cost of additional delay of PUs.**

I. INTRODUCTION

Spectrum is one of the most heavily regulated and expensive merchandise in US and around the world. One significant hurdle for new wireless services is the lack of unallocated spectrum. On the other hand, FCC Spectrum Policy Task Force report indicates a vast amount of un-utilized and under-utilized spectrum over time and across geographic areas [6]. Cognitive radio is a promising technology to alleviate such an imbalance. In this context, primary users (PUs) represent the legacy users in a spectrum band and secondary users (SUs) are the cognitive devices that opportunistically access the spectrum.

Because legacy users have access priority, a design goal of any opportunistic access strategy is to minimize the SU effect on PU transmissions. For example, in the DARPA XG project, one of the three major test criteria in the field test is “to cause no harm”. This goal has strong implications on both SU performance and incentive to implement such schemes, as the PUs will not agree to accommodate secondary cognitive networks to their own detriment. Therefore, to understand the impact of SU access on PU performance is critical to the deployment of cognitive radio networks.

A. Reactive Primary Users

Most existing work explicitly or implicitly assumes non-reactive PU access mechanisms such as TDMA and CDMA. In these networks, the PU’s access state is unaffected by the presence and transmission of SU. To elaborate, PU being non-reactive has the following two implications. First, in these networks the SU transmission in the absence of PU transmissions will not affect the PU. Second, when PU and SU transmit simultaneously, SU will only cause interference and potential data loss, but will not change the internal state of the PU. However, this is not the case in primary networks following a reactive medium access scheme such as Carrier Sense Multiple Access (CSMA). In such networks the PUs are more sensitive to the existence of the SU and their channel access behavior will be affected in two ways:

- Collisions between PUs and SUs will change the internal state of the PU such as the size of the backoff window and thus negatively affect the performance of the PU.
- Even when the PUs are not transmitting, the SU transmission can negatively affect the PUs’ backoff state during channel sensing. The SU transmission will lead the PUs to believe that the channel is busy and hence delay their transmission. In other words, the PU *channel* being idle is different from the PUs being idle (i.e., no packets in the queue).

Our objective is to understand the deployment of cognitive radio devices that can coexist with the CSMA-based reactive PUs. It is important to investigate and understand the compatibility of non-intrusive secondary networks with reactive primaries for the following reasons: 1) Such studies enhance our fundamental understanding of spectrum-agile systems; 2) Initial testings on spectrum-agile communications are likely to be deployed in unlicensed band where one major in-band application, namely WiFi, is CSMA-based. The compatibility study will facilitate such testings; and 3) The proposed schemes can be important for home networking applications, where multiple wireless networks coexist. Therefore, in this paper, we focus on understanding opportunistic access in the presence of reactive PU access schemes. We consider CSMA-based PUs.

The rest of the paper is organized as follows. In Section II, we discuss the system model and performance metrics. In Section III, we present four different SU access schemes and analyze the performance of PU system in the presence of p-persistent SU access. Simulation results are presented in Section IV, followed by discussion of future work in Section V. We discuss related work in Section VI and conclude the paper in Section VII.

II. SYSTEM MODEL AND IMPACT METRICS

A. PU model

We consider CSMA-based PUs. Assume that the system is time-slotted. We denote β as the length of an idle slot. In other words, β is the propagation and detection delay required for all nodes (PU and SU) to detect an idle channel after a transmission ends. We assume without loss of generality that each packet takes one unit of time to transmit. Usually, we have $\beta << 1$.

A PU accesses the channel as follows. When a PU has a packet to transmit, it transmits with probability q_0 after sensing an idle slot. If a collision happens, the PU reduces its transmission probability to q_1 where $q_1 = q_0/2$, and so on. Therefore, after i consecutive collisions, q_i, the transmission probability of the packet after sensing an idle slot, is

$$q_i = \frac{q_{i-1}}{2} = \frac{q_0}{2^i}. \quad (1)$$

After a successful transmission, the PU's transmission probability resets to q_0.

The transmission probability reduction in (1), also known as exponential backoff, controls congestion in the PU network. Because collision reflects network congestion, a user experiencing collision reduces its transmission probability. A user assumes that a collision has occurred in its previous packet if no acknowledgment is received. For simplicity, we assume that a collision time slot has the same length as as a transmission time slot, which is one unit of time. A user not involved in the collision does not change its transmission probability because it is difficult to distinguish between a collision and a successful transmission.

We assume that there are M homogeneous PUs in the system. Let λ denote the packet arrival rate of a PU. Packet arrivals follow a Poisson distribution with rate λ. We assume infinite buffer at each PU.

B. Impact metrics

The following metrics determine the impact of the SU's presence on the PU:

- PU throughput
- PU-SU packet collision probability - probability that a PU packet collides with a SU packet
- PU packet delay

Throughput and packet collision probability have been widely used in the literature to quantify the impact of SU access, often with the implicit assumption of a non-reactive PU system. Delay and delay jitter have also been considered. In this paper we focus on the impact of SU access on the PU packet delay. PU delay in the presence and absence of SU reflects the *deterrence* effect of SU access. Deterrence is defined as the time that a PU's backoff counter or intended transmission is delayed by an SU transmission (even when collisions do not occur). This metric is needed especially for a CSMA-based PU whose backoff counter is affected in many ways by the presence of an SU. In practice, we use the difference of the PU delay in the presence and absence of the SU as the deterrence metric.

Main notations used in the paper are summarized in Table I for easy reference.

TABLE I

NOTATIONS.

q_i	PU trans. prob. after i collisions.
d_0	PU head of line (HoL) delay.
D	PU average delay.
τ	avg. trans. prob. of a PU in a time slot.
p	coll. prob. of a PU packet in a time slot.
$\bar{T}$	avg. slot length.

III. SU OPPORTUNISTIC ACCESS AND PERFORMANCE ANALYSIS

A. SU Access Protocol

We assume that there exists only one SU and the SU always has backlogged traffic. The objective is to maximize SU throughput (in terms of the amount of time it can successfully transmit) without causing significant performance degradation for PUs. In other words, the requirements from the PU system are 1) the PU system should remain stable; and 2) the average delay of the PU system should not increase significantly (i.e., deterrence caused by SU access is limited).

We propose several SU access protocols, and compare and evaluate the performance of these protocols through analysis and simulation.

a) p-persistent CSMA: In this scheme, the SU accesses the channel with probability q_s after sensing an idle slot. Here q_s is the tuning parameter of the SU aggressiveness. The larger the value of q_s, the more aggressive the SU is, and the higher delay that the PU will experience. The PU system may become unstable if q_s is too large. This p-persistent CSMA is the simplest protocol that allows analysis.

b) Collision-Aware CSMA: This is modified from the previous scheme. The SU accesses the channel with probability q_s after sensing an idle slot. If a collision happens, similar to the PU's backoff scheme, the SU halves its transmission probability to reduce congestion. Furthermore, if a successful SU transmission happens, the SU transmission probability is reset to q_s.

c) Delayed Access: In this scheme, the SU accesses the channel if it senses W consecutive idle slots. Here W is the parameter to tune SU aggressiveness. The intuition behind this scheme is that if the channel has been idle for W slots, then the PU is unlikely to be congested. The larger the value of W, the more conservative the SU is.

d) Genie-aided SU Access: In this scheme, we assume that there is a genie that knows perfectly the number of PUs with backlogged traffic. The SU transmits only if there is no PU packet. This idealized scheme serves as a performance benchmark for other schemes.

We note that for these four schemes considered above, it is not possible for the SU to be deterrence-free to the PU system unless the SU does not transmit at all. There are multiple reasons. First, SU and PU may collide (in the first three schemes). Collisions set back future transmission probabilities of the PU. Second, even when the SU transmits successfully without colliding with a PU, it can deter PU transmission, i.e., PU senses the channel busy and waits. In other words, the PU channel being idle is not equivalent to PU idle. Last, even in the genie-aided scheme, an SU cannot guarantee zero deterrence on the PU system because PU packets can arrive during the SU transmission and thus be delayed by the SU transmission. Also, if multiple PU packets arrive during the SU transmission, PU-PU collision is possible which may have been avoided in the absence of SU.

B. Performance Analysis

We will study the system performance for the p-persistent SU access scheme. The simplicity of this protocol allows closed-form analysis. We consider a generic PU and use a two-level Markov Chain to model its performance, as shown in Figure 1. The upper level models the queue status of the generic PU, where the state i is the number of packets in the queue of the PU, including the head-of-line (HoL) packet. This is in the "macro" scale. The lower level queue models the collision state of the HoL packet, and the state i represents the number of collisions that it has experienced. This is in the "micro" scale. Note here that we decouple the queue state (macro) and collision state (micro). This utilizes the feature that after each successful transmission, the PU resets its transmission probability to q_0, i.e, its collision state returns to zero. We also make the approximation that the transmission time of each packet is independent. This allows the two-tier structure of the Markov chain and makes the analysis tractable based on M/G/1 approximation.

Next, we discuss the two chains in detail.

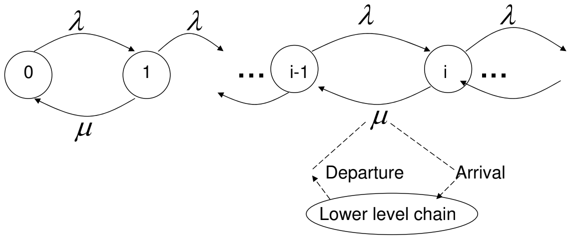

Fig. 1. Two level chain.

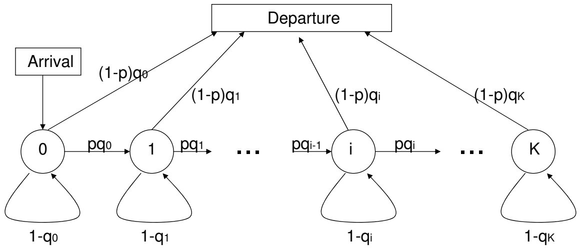

Fig. 2. Lower level chain.

In the upper level chain, i is the number of packets in the queue, λ is the packet arrival rate, and μ is the service rate (which is determined by the lower level chain). Let X_0 be a random variable representing the service time of a PU packet, and $d_0 = E(X_0) = 1/\mu$ and $\nu_0 = E(X_0^2)$. Assuming that the upper level chain follows the M/G/1 queueing model, we can apply the Pollaczek-Khinchin formula to approximate the average delay of a PU packet as

$$D \approx d_0 + \frac{\lambda \nu_0}{2(1 - d_0 \cdot \lambda)}, \tag{2}$$

where d_0 and ν_0 need to be determined through the lower level chain.

Next, we study the lower level chain, which is in discrete-time. The length of a time slot can take two values. If a time slot is idle, then its length is β. If a time slot is busy (either transmission or collision), it must be followed by an idle time slot, and thus we combine them to let $1 + \beta$ be the slot length.

We note that a packet always starts with collision state 0, as shown in Figure 2. For an HoL packet at state i during a given time slot, it has three possibilities in the next time slot. With probability $1-q_i$, it does not transmit and remains in state i. The length of this time slot can be either β or $1 + \beta$. If the PU transmits its packet, then the length of this time slot is $1+\beta$. If the transmission is successful, it departs with probability $(1-p)q_i$, where p is the collision probability. If a collision happens, it goes to state $i+1$ with probability pq_i.

An important approximation is made here to allow tractable analysis. We average the impact of other users using p, defined as the collision probability of a PU packet conditioned upon the packet being transmitted. This is motivated by the analysis of IEEE 802.11 protocol by Bianchi [3]. Both other PUs and the SU affect the value of p, as shown next.

Let τ denote the transmission probability of a PU during a time slot. Under the assumption that the transmissions of the PUs and the SU are approximately independent, we can compute $\bar{T}$, the average length of a time slot, by

$$\begin{aligned} \bar{T} &= (1-(1-\tau)^M(1-q_s))(1+\beta) \\ &+ (1-\tau)^M(1-q_s)\beta, \end{aligned} \tag{3}$$

where $1-(1-\tau)^M(1-q_s)$ is the probability that at least one PU or SU transmits during a given time slot. From a PU's perspective, we have

$$(1-\tau)^{M-1}\tau = \lambda\bar{T}, \tag{4}$$

where the left hand side is the average number of transmitted packet (of this PU) in a generic time slot, and the right hand side is the average number of new packet arrivals to this PU. If the PU queue is stable at the steady state, the equation has to be satisfied. Thus, we can solve (4) for τ. Subsequently, given τ, we can calculate the collision probability as

$$p = 1-(1-\tau)^{M-1}(1-q_s). \tag{5}$$

Let X_i be a random variable representing the delay of the HoL packet at state i, and let X_i' be an independent and identically distributed random variable with the same distribution. We have

$$X_i = \begin{cases} 1+\beta & \text{w.p. } (1-p)q_i \\ 1+\beta+X_{i+1} & \text{w.p. } p\cdot q_i \\ \bar{T}+X_i' & \text{w.p. } 1-q_i. \end{cases} \tag{6}$$

Next, we compute $d_0 = E(X_0)$ and $\nu_0 = E(X_0^2)$, which are needed to determine the average delay D in (2) for the upper level chain.

Denote d_i as the remaining transmission time of the HoL packet at state i. Because a packet always starts with collision state 0, based on (6), we can calculate the average delay d_0 as follows:

$$\begin{aligned} d_0 &= (1-q_0)(d_0+\bar{T}) + (1+\beta)(1-p)q_0 \\ &+(1+\beta+d_1)pq_1. \end{aligned} \tag{7}$$

In general, we have

$$d_i = (1-q_i)(d_i+\bar{T})+(1+\beta)(1-p)q_i+(1+\beta+d_{i+1})pq_i.$$

At collision state K, we have

$$d_K = (1-q_K+pq_K)(d_K+\bar{T}) + (1+\beta)(1-p)q_K,$$

and thus

$$d_K = \frac{1-q_K+pq_K}{(1-p)q_K}\bar{T} + (1+\beta).$$

Then we have

$$d_0 = (1+\beta-\bar{T})\frac{1-p^K}{1-p} + \frac{\bar{T}}{q_0}\cdot\frac{1-(2p)^K}{1-2p} + p^K d_K. \tag{8}$$

Letting $K\to\infty$, we have

$$d_0 = \frac{1+\beta-\bar{T}}{1-p} + \frac{1}{q_0}\frac{1}{1-2p}. \tag{9}$$

Similarly, we can calculate the second moment of HoL delay as

$$\begin{aligned} E(X_0^2) &= E[(\bar{T}+X_i)^2](1-q_0) + (1+\beta)^2(1-p)q_i \\ &+E[(1+\beta+X_{i+1})^2]pq_i. \end{aligned} \tag{10}$$

Using a recursive relationship, and letting $K\to\infty$, we have

$$\begin{aligned} \nu_0 &= d_0^2 + \bar{T}^2\left(\frac{1-q_0+2pq_0+8p^2q_0}{q_0^2(1-2p)^2(1-4p)} + \frac{p}{(1-p)^2}\right) \\ &+(1+\beta)^2\frac{p}{(1-p)^2} \\ &+\bar{T}(1+\beta)\left(\frac{4p}{(1-2p)^2q_0} - \frac{4+2p}{(1-p)^2}\right). \end{aligned} \tag{11}$$

We then substitute (9) and (11) into (2) to obtain the analytical expression for the PU delay for the p-persistent SU access scheme. Note that when we set $q_s = 0$, (2) gives the PU delay in the absence of SU.

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed SU access schemes through simulation. We also compare the analysis and simulation results of p-persistent SU access.

In Figures 3 and 4, we compare the performance of the proposed SU schemes, under relatively light and heavy PU traffic. In both simulations, we set $M = 20$, $q_0 = 0.04$, $\beta = 0.1$. We set $\lambda = 0.5/M$ and $\lambda = 0.1/M$, respectively, to reflect heavy and light PU traffic. In the figures, the x-axis is the average PU packet delay, the y-axis is the SU throughput. In the simulation, q_s and W are adjusted to achieve different tradeoffs of PU delay and SU throughput. We first consider the case of $\lambda = 0.1/M$, i.e., light PU traffic. In the absence of SU, the PU delay is around 3.85. For the genie-aided scheme, the PU delay is 3.96, and the SU throughput is 0.62, which is fairly large. The two random access schemes (the p-persistent and the collision aware) perform fairly closely, because the probability of SU-PU collision is relatively small. The delayed access scheme performs slightly better than the random access schemes. Clearly, as the SU becomes more aggressive, the SU throughput increases at the cost of increased PU delay. Under heavy PU traffic $\lambda = 0.5/M$, clearly the SU throughput is much smaller and PU delay is much larger. Without SU, the PU average delay is 11.32. For the genie-aided scheme, the PU delay is close to 11.32, and the SU throughput is 0.026, which is significantly smaller than that of the light PU traffic case. This is because under heavy PU traffic, the genie-aided scheme is too conservative that it only transmits in the absence of PU. Again, we observe that the delayed-access scheme performs better than the random access schemes. The collision aware scheme performs slightly better than the p-persistent scheme for large q_s.

Next, we examine the accuracy of the analytical expression (2) for the PU delay, assuming p-persistent SU access. In Figure 5, we plot the PU delay as a function of the SU transmission probability q_s, where $\lambda = 0.1/20, 0.3/20, 0.4/20, 0.5/20$, respectively. It is shown that (2) gives good approximation of the PU delay for the first three cases. For $\lambda = 0.5/20$, we observe a noticeable gap between (2) and the simulated value, due to a larger estimation error (about 5%) between the HoL delay approximation (9) and the average HoL delay obtained from simulation.

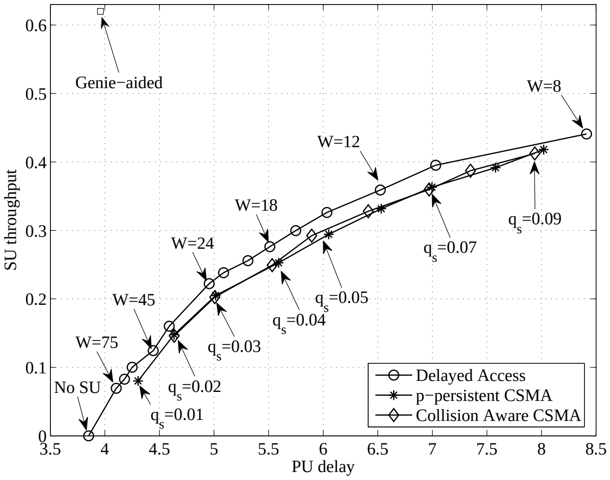

Fig. 3. Comparison of different SU access schemes under light PU load, $\lambda = 0.1/M$. Here we let $M = 20$, and $q_0 = 0.04$.

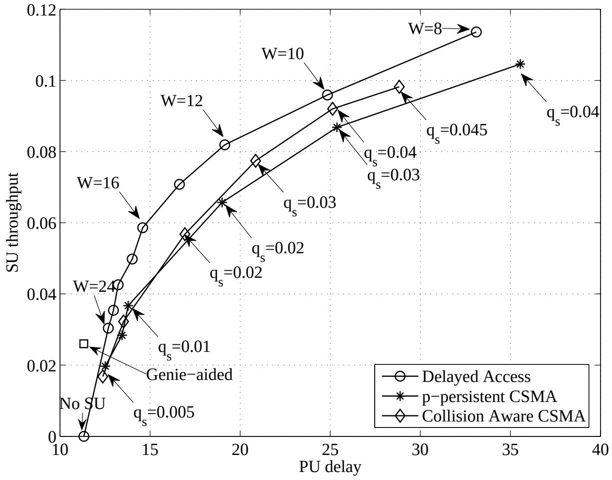

Fig. 4. Comparison of different SU access schemes under heavy PU load, $\lambda = 0.5/M$. Here we let $M = 20$, and $q_0 = 0.04$.

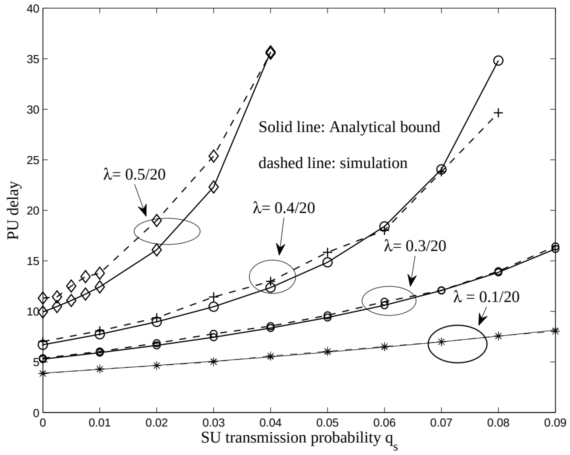

Fig. 5. Comparisons of analytical approximations with simulations assuming p-persistent SU access.

V. DISCUSSIONS

This paper presents a preliminary study of the sensing-based reactive PU systems. A lot more research is needed. First, the analysis can be improved for the case of more aggressive PU, (i.e., higher values of q_0). The proposed analysis assumes a fixed collision probability p, which matches well with simulation for relatively small q_0, in which case the PU traffic is less bursty. For larger values of q_0, we observe that the actual collision probability obtained through simulation can be much higher than the estimated p (results not shown here). We believe that more accurate models can be developed by letting p vary according to system dynamics.

Second, we would like to extend our study to analyze the co-existence with IEEE 802.11-based PU systems. One challenge is to better model the PU system. In [3], the author provides a good approximation model for IEEE 802.11 system assuming saturated traffic. Under the saturated traffic model, all users always have traffic to transmit, and thus it is effective to model the collision probability using a single parameter p. For our case of interests, however, the gain of the SU access is more pronounced for lightly loaded PU systems. Due to the dynamics of the system, it might be more realistic to model the collision probability differently.

We also conducted preliminary experiments on WiFi systems where the SU uses a two-state delayed-access scheme that takes into account the unique features of IEEE802.11 MAC [1]. We notice negligible impact on PU performance in a four-node testbed while the SU can achieve good throughput. Details can be found at [1]. A challenge in the experiment is that it is difficult to eliminate the impact of other WiFi transmissions, which is not a part of our testbed.

Last, it is interesting to understand the fundamental limit of SU access in reactive PU systems. For example, given a PU arrival rate and delay constraint, what is the optimal SU throughput and what access scheme(s) can achieve it? What PU system characteristics the SU can exploit to maximize the SU throughput while limiting its impact on the PU system?

VI. RELATED WORK

There has been a limited amount of work on reactive PU systems. In [13], an SU actively transmits probing signals to observe the changing transmission power of the PU in response. Based on the observation, the SU can estimate the effective interference channel gain from the SU transmitter (SU-Tx) to the PU receiver (PU-Rx). It can then implement power control to limit the interference to the PU receiver. In [4], the authors analyze the performance of SU access in a PU system with erasure code by observing the PU ARQ information. In [10], a wideband OFDM cognitive radio dynamically changes its subcarrier usage based on the reactive behaviors (e.g., average power and transmission probability) of the narrow-band PU devices. In [7], the authors develop distributed power control algorithms based on PU feedback information. A main theme to these ideas is to observe PU reaction to determine the impact of SU access and then to adjust SU access strategy accordingly. In comparison, our system model is different, we consider CSMA-based PU system. In our system, observing PU performance is difficult. Our focus is to analyze the impact of SU access on the PU system. Most of the proposed solutions in the literature measure the impact on the primary users in terms of the collision probability or interference. This metric, however, does not reflect changes in the internal state of the primary user like doubling of the backoff window when it detects some spectral activity.

A simple way of co-existing with primaries is Dynamic Frequency Selection (DFS), a method first specified by the ITU and later by the FCC, and being developed by the IEEE 802.11h subcommittee. Capar et al. [5] proposed a spectral pooling system that uses OFDM modulation and a TDMA access scheme. In [9], the authors present a CSMA-based MAC protocol for data communication in a CR network based on the channel segregation technique proposed in cellular networks. The nodes use a common control channel to negotiate among themselves and pick a data channel for communication. Lien et al. [8] proposed a class of CSMA MAC protocols based on power and rate adjusting mechanisms for the cognitive radio to operate along with the primary users. Jones et al. [11] proposed a cognitive MAC protocol based on opportunistic spectrum access and setup a testbed to characterize the relationship between secondary users loading and interference on primary users. However, all these schemes focus on increasing the throughput of the cognitive radio and they do not address the impact of the secondary users spectrum utilization on the primary users carrier sensing.

Hsu et al. and Hung et al. addressed this issue in [2] and [12] respectively. Hsu et al. [2] proposed a cognitive MAC protocol called SCA-MAC that uses the principle of Statistical Channel Allocation (SCA). Statistics of spectrum usage are collected by the CR device by sensing the environment and the probability of successful transmission and interference is estimated. On the other hand, Hung et al. [12] proposed a decentralized, asynchronized, and connection-prone MAC protocol for the CR network that can coexist with existing WLAN devices. It uses a primary traffic predication model and transmission etiquette to avoid causing fatal damage to licensed users. Both these papers show the performance of their proposed protocols in terms of throughput enhancement and the collisions.

VII. CONCLUSION AND FUTURE WORK

In this paper, we study opportunistic SU access in sensing-based reactive PU systems. We present four different SU access schemes and compare their performance under different PU traffic scenarios. We develop closed-form analysis on p-persistent SU access. Reactive PUs present additional challenges because their internal states change in the presence of SU activities, even without collision or data loss. Directions for future research include the study of the fundamental limit of the reactive system and the IEEE802.11-based PU systems.

REFERENCES

[1] Shri Vidhya Alagesan, I-Jeng Wang, and Xin Liu. A cognitive mac protocol to coexist with reactive primary users. http://www.cs.ucdavis.edu/l̃iu/vidhyaTR.pdf.

[2] Alex Chia-Chun Hsu, David S. L. Wei and C.-C. Jay Kuo. A Cognitive MAC Protocol Using Statistical Channel Allocation for Wireless Ad-hoc Networks. In *Wireless Communications and Networking Conference*, pages 105–110, 2007.

[3] Giuseppe Bianchi. Performance analysis of the ieee 802.11 distributed coordination function. *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS*, 2000.

[4] K. Eswaran, M. Gastpar, and K. Ramchandran. Bits through arqs. arXiv:0806.1549v1.

[5] F. Capar and F. K. Jondral. Resource Allocation in a Spectrum Pooling System for Packet Radio Networks Using OFDM/TDMA. In *IST Mobile and Wireless Telecommunications Summit*, June 2002.

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

[7] S. Huang, X. Liu, and Z. Ding. Distributed power control for cognitive user access based on primary link control feedback. In *IEEE Infocom*. IEEE, 2010.

[8] Shao-Yu Lien, Chih-Cheng Tseng, and Kwang-Cheng Chen. Carrier sensing based multiple access protocols for cognitive radio networks. In *ICC '08. IEEE International Conference on Communications, 2008*, pages 3208–3214, May 2008.

[9] Mansi Thoppian, S. Venkatesan and Ravi Prakash. CSMA-Based MAC Protocol For Cognitive Radio Networks. In *2007 IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks*, pages 2–8, 2007.

[10] Hariharan Rahul, Nate Kushman, Dina Katabi, Charles Sodini, and Farinaz Edalat. Learning to share: narrowband-friendly wideband networks. *SIGCOMM Comput. Commun. Rev.*, 38(4):147–158, 2008.

[11] S. Jones, N. Merheb and I.-J. Wang. An experiment for sensing-based opportunistic spectrum access in CSMA/CA networks. In *IEEE Symposium on New Frontier in Dynamic Spectrum Access Networks*, Nov 2005.

[12] Shao-Yi Hung, Yu-Chun Cheng, Eric Hsiao-Kuang Wu and Gen-Huey Chen. An Opportunistic Cognitive MAC Protocol for Coexistence with WLAN. In *ICC '08. IEEE International Conference on Communications, 2008*, pages 4059–4063, May 2008.

[13] Rui Zhang and Ying Chang 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.