Cognitive Radio Access Optimization Under Primary Queue Stability Constraint

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Abstract—We propose a network access optimization for cognitive radio nodes aimed at throughput maximization under the constraint of primary node queue stability. To maintain primary queue stability, our approach moves beyond the traditional listen-before-talk opportunistic access by allowing cognitive radios to over-hear and utilize ACK/NAK feedback signals on packet reception from the primary receiver. In addition to primary transmitter's activity sensing in listen-before-talk, the secondary cognitive radio can track the primary queue status through inference based on the primary feedback information. By defining a Lyapunov function that characterize the primary queue stability, we devise a distributed secondary power allocation strategy to control the access of cognitive radio nodes that approximates the optimal solution of a static global sum-utility maximization problem. This distributed cognitive access method can achieve high bandwidth utilization under the primary queue stability constraint.

I. Introduction

While opportunistic-spectrum-access (OSA) has firmly established as a new paradigm capable of overcoming the current debacle of spectral scarcity and under-utilization, most research efforts in this field focus on the traditional "Listen-Before-Talk" (LBT) framework and stress the mechanism of radio spectrum sensing. LBT is a sensing-based OSA that allows secondary users to access primary users' frequency bands, provided they are detected as "white space" [42], [43]. Indeed, the Federal-Communication-Commission (FCC) report on TV white-space prototype testing [41] only fuels the LBT-based research and development activities with respect to cognitive radio access.

We note, however, that the simple LBT framework has its special limitations. First, LBT focuses only on the primary transmitter activity, paying no attention to the quality of primary signal reception at the receiver side. A well known problem in LBT is its inability to protect a hidden (receiver) node. For this reason, LBT has to be conservative and highly sensitive in order to deal with the worst case fading environment and to anticipate the possibility of aggregated interference from multiple SU transmissions. For example, the sensing threshold is set 20dB below the noise level in the DTV detection scenario [41], which significantly under-estimates the amount of available spectrum opportunities. On the other hand, LBT assumes that the primary links are very fragile and does not allow SU systems to exploit extra capacity when a PU system, not fully loaded, can tolerate substantial interference. In particular, when an exposed (transmitter) node is discovered while the receiver node is far from the cognitive radio, LBT is a very conservative strategy since it does not take into account the ability of most well designed primary systems to apply mechanisms such as forward error correction, beamforming, or spectrum spreading to combat interference.

Recognizing the aforementioned weakness of LBT cognitive access, we would like to develop more advanced approaches to cognitive spectrum access that can better protect the primary user links and, at the same time, enable better utilization of the channel capacity when primary users are resilient. In fact, we advocate a more advanced form of "cognitive" radio: in addition to normal primary transmitter's activity sensing, *secondary users should exploit the inherent primary receiver's control signals that can provide useful information on primary communication link quality.* In most two-way digital communication systems, such information is available in a variety of forms, e.g.: "data-link-layer" ARQ information such as ACK/NAK packets feedback by primary receivers to their transmitters, LTE/WIMAX channel-quality-information feedback packets for power control, IS-95 1dB power level increase/decrease notification. Furthermore, many primary feedback information is typically transmitted at low data rate with high redundancy and error protection, thus is easier for SUs to detect, decode, and utilize.

More specifically, we consider the following problem which consists of a network with one PU pair whose bandwidth may also be accessed by multiple distributed SU pairs of lower priority. We hope to maximize the overall SU utility while maintaining PU transmitter's queue stability. Intuitively, we need to exploit multiple sources of information. The absence of PU transmission

and feedback information indicates an empty PU queue, which assures PU queue stability. The ACK/NAK feedback information from the primary receivers allows the SUs to learn the PU transmission process and to estimate aggregated SU interference. Through such observations and by inference, secondary users can extract information with respect to the interaction between the interference from their own secondary transmission and the primary transmission success. Secondary access based on this learning process can outperform pure LBT by making more intelligent channel access decisions.

In particular, we generalize the pure LBT algorithms such that, in addition to primary transmitter's activity sensing, secondary user access is controlled also by allowing secondary users to overhear primary receiver's ACK/NAK feedback packets. We show that, through primary's activity sensing, packet status (in terms of outage) eavesdropping and primary transmission rate knowledge, secondary users can better access primary users' frequency bands without de-stabilizing primary queues. Moreover, we show that information collection from the primary receiver helps cognitive radios shift from pure LBT style opportunistic channel access towards communication overlay strategies as mutual secondary-primary interference becomes less severe.

This paper is organized as follows. In Section II, we present works that relate to our paper; In Section III, we present the basic system model for investigation. In Section IV, we present the problem formulation and an effective distributed approximated solutions. We provide simulation results in Section VI, before concluding remarks in SectionVII.

II. RELATED WORKS

In the past, LBT based cognitive access strategies have been extensively studied. Among others, the authors of [2] presented a survey on spectrum sensing for cognitive radios. Cyclostationary feature detection for OSA has been treated in [6]. In [5] [4], the authors analyzed the tradeoff between spectrum-sensing time and secondary throughput. Distributed cooperative spectrum sensing has been investigated, among others, in [10], [14] and [24]. The interesting SNR-wall limitations on spectrum sensing have been shown in [29] and [30]. A Markov decision process framework has been employed in [26], [27], [28], [38] and [37]. The authors of [27] and [28] devise secondary channel access policy for multiple primary user channels. On the other hand, cognitive access strategies utilizing primary receiver feedback signals have been studied in [36], [7], where the authors explored opportunistic spectrum access exploiting the hidden primary radio power loop. In [8] the authors investigated PU-SU cooperation for cognitive link throughput maximization. In [20] the authors proposed a secondary

user power allocation algorithm under an interference constraint based on primary's feedback observation. In [37] a Markov-decision-process framework was applied to maximize the secondary users' throughput, subject to limits on primary's performance loss. In [38], the authors explored overlay of secondary communications through exploiting primary H-ARQ feedback. The authors of [3] study primary transmission-rate guarantee through primary ACK/NAK eavesdropping by secondary users. In [1], the authors propose the framework we base the current paper on. They apply Lyapunov stability theory to devise a network-layer algorithm that maximizes the aggregated utility function of the nodes of a wireless network subject to network-layer queue stability. The authors of [12] and [13] proposed a secondary channel access control framework based on ACK/NAK packet eavesdropping from the primary receiver. The latter presents a strategy, where secondary transmitters access primary channel based on primary transmitter's activity sensing and primary receiver's ARQ observations.

III. SYSTEM MODEL
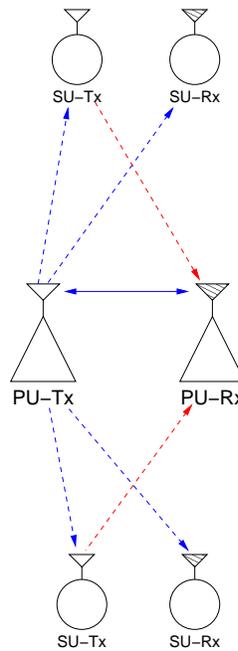
Fig. 1. An illustration of network topology.

We now present our basic system model of cognitive secondary user channel access under investigation. We consider a heterogeneous wireless network with one PU transmitter-receiver (Tx-Rx) pair and multiple SU transmitter-receiver pairs, as shown in Fig. 1. The PU pair has its own channel and accesses its channel for transmission whenever there are packets to send. The PU also has a low rate feedback channel from the receiver to

the transmitter. The SU pairs want to opportunistically access the same PU channel. Our objective is to maximize the aggregated utility of secondary users subject to primary transmitter's queue stability. For simplicity, we assume that both PU and SUs have fixed-length packets. Packet transmission time depends on channel conditions and mutual interference. Based on queue backlog and primary receiver's outage information sent on the feedback channel, the secondary users will control their transmission power to stabilize PU queue while maximizing SU performance.

We assume that the PU transmission system is time-slotted and that the SUs synchronize to the PU time-slot by tracking PU transmissions. We assume the PU-transmitter (PU-Tx) sends packets to the PU-receiver (PU-Rx) on a forward channel which SUs are willing to opportunistically access. The PU-Rx sends feedback packet through a reverse channel that the SUs are able to overhear. We further assume the primary forward and reverse channels are logically separated. Given a slot duration of t_s, we refer to the $t-$th time slot as the time interval $[(t-1) \cdot t_s, t \cdot t_s)$. If the PU-Tx has data to send, it will access the channel at the beginning of the next time slot. In this work, we do not consider any form of primary power control, though PU-Tx power control can certainly be incorporated into our framework. At the end of every primary transmission, the primary receiver (PU-Rx) feeds back a 1-bit information to the PU-Tx to notify the latest transmission success or failure. When PUs have no packets to transmit, we assume that both the PU-Txs and PU-Rxs are silent.

With respect to the cognitive users, we assume secondary transmitters (SU-Txs) can sense PU-Tx's activity via a signal detector and have the capability of detecting the feedback signal from PU-Rx on packet success and outage. We assume the sensing activity takes place at the beginning of each time slot and that it is short enough to allow SUs to sense and then to transmit their (shorter) packets for the remainder of the same time slot.

In addition, we will be using the following notations throughout the manuscript:

- $\mathbb{N}_s = \{1, \ldots, N_s\}$: the set of active secondary users.
- P_p: the transmission power of the PU-Tx.
- g_p: the large scale channel gain between PU-Rx and PU-Tx with full reciprocity between the primary and secondary nodes.
- g_i, g_{ip}, g_{pi}, $i \in \mathbb{N}_s$: the large scale channel gain between SU-Tx i and its receiver, the large scale channel gain between the $i-$th SU-Tx and the PU-Rx, the large scale channel gain between the PU-Tx and SU-Rx i, respectively.

A. PU Stability

In this work, our goal is to develop a network-layer rate control algorithm for each SU-Tx to maximize the aggregate SU utility function, while maintaining PU queue stability.

To proceed, we first define the concept of PU queue stability. Additional notations are needed. For each time slot t, define:

- $A_p(t)$: the exogenous packet arrivals at the PU queue.
- $Q_p(t)$: the backlog of PU-Tx queue.
- $\mu_p(t)$: the instantaneous transmission rate of primary user.
- $\mu_i(t)$, $i \in \mathbb{N}_s$: the controlled transmission rate of secondary user i.

In order to control the SU transmission rates, we first need to characterize the effect of mutual interference between PU and SU transmissions on their data rates. Here, we assume SUs are distributed and sufficiently far apart that they do not interfere with each other. As a result, given the PU forward channel bandwidth of W Hz, we have

$$\mu_i(t) = W \log \left(1 + \frac{P_i(t) g_i}{N_0 + P_p g_{pi}} \right), \tag{1}$$

$$\mu_p(t) = W \log \left(1 + \frac{P_p g_p}{N_0 + \sum_{i=1}^{N_s} P_i(t) g_{ip}} \right). \tag{2}$$

The PU updates its queue as:

$$Q_p(t+1) = \max \left\{ (Q_p(t) - \mu_p(t), 0) \right\} + A_p(t). \tag{3}$$

Note that, without loss of generality (WLOG), we assume PU queue is at the network layer. We consider PU queue stable if:

$$\limsup_{t \to \infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\{Q_p(\tau)\} < \infty. \tag{4}$$

From the instantaneous rates, we define the following long-term average quantities

- λ_p $--$ the long-term average primary arrival rate:

$$\lambda_p = \lim_t \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\{A_p(\tau)\}. \tag{5}$$

- $\bar{\mu}_p$ $--$ the long term average primary transmission rate:

$$\bar{\mu}_p = \lim_t \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\{\mu_p(\tau)\}. \tag{6}$$

- r_i $--$ the long-term average throughput of secondary user i:

$$r_i = \liminf_{t \to \infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mu_i(\tau). \tag{7}$$

B. SU Model

We assume that SU-Tx nodes always have data to send. For each SU $i \in \mathbb{N}_s$, its utility function $f_i(\cdot)$ is defined as:

$$f_i(r_i) = \alpha_i \cdot r_i, \qquad (8)$$

where α_i is a constant merit factor, which reflects the importance of SU i throughput or the SU traffic priority.

In order to develop SU rate control optimization, we assume that the SU transmitters can accurately estimate the busy/idle state of the PU-Tx. This task can be accomplished by a combination of sensing PU transmissions and observing PU-Rx feedbacks. We assume that the SUs have been given the knowledge of the PU transmission power as well as the associated channel gains. We also assume SUs to have the knowledge on the arrival rate of the PU packet λ_p, possibly through estimation from PU's busy/idle activities.

We assume the SUs do not actively cooperate with one another. In other words, there is no message passing among them and there is no centralized SU controller. Each SU can only control its own transmission power based on the observation of the PU activities.

IV. PROBLEM FORMULATION

Without loss of generality, we assume that, in the absence of secondary transmissions, the PU network-layer queue is stable, i.e.,

$$\lambda_p < \lim \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}\{\mu_p(\tau)|\mu_i(t) = 0\}. \qquad (9)$$

With SU transmission, the interference at the PU-Rx becomes stronger, thereby reducing the effective PU transmission rate. For this reason, secondary opportunistic channel access can affect the PU queue stability.

In order to mitigate the impact of SU transmission on the PU link, our explicit objective for the secondary cognitive users is to maximize their sum-utility subject to the stable PU queue condition. More explicitly, our goal is to control the SU rates $\mu_i(t)$ to

$$\begin{array}{ll} \underset{\{\mu_i(t)\}}{\text{maximize}} & \sum_{i=1}^{N_s} f_i(r_i) \\ \text{subject to:} & \lambda_p < \bar{\mu}_p. \end{array} \qquad (10)$$

To optimally control the SU transmission rates $\{\mu_i(t)\}$, we should rely on a central controller with global network information such as channel state and queue backlogs available at every secondary user. Such a centralized optimal SU access scheme is less practical and potentially difficult to implement. In particular, global network information at all participating SUs would be difficult to obtain and update with sufficient accuracy. Therefore, our goal is to develop a distributed

solution to Problem (10) by allowing individual SU to control its rate/flow.

We propose several distributed solutions by extending the Lyapunov stability framework [1]. The basic idea is as follows. As in [1], we create an artificial control knob for each SU, as shown in Figure 2. In particular,
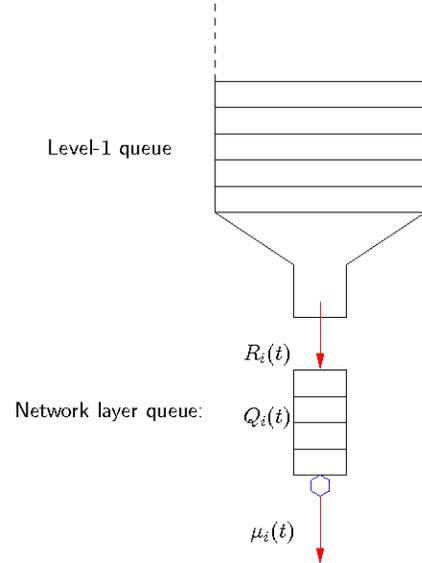
Fig. 2. Control-knob queues for user i

we define

- $R_i(t)$, $i \in \mathbb{N}_s$: the rate of data flowing from secondary user level-1 queue to its network-layer queue at time t, which is the artificial knob introduced here.
- $Q_i(t)$, $i \in \mathbb{N}_s$: the network-layer queue length of SU-Tx i at time t.

With these definitions, the network-layer queue at SU-Tx i is updated via

$$Q_i(t+1) = \max\left\{(Q_i(t) - \mu_i(t), 0)\right\} + R_i(t). \quad (11)$$

Each SU independently updates its queue and decides its transmission in two-steps [1]. **First**, for every SU-Tx, determine the amount of data to flow from the level-1 queue to the corresponding network-layer queue; and **second**, control the secondary transmission power (and hence rate) based also on primary queue backlog information.

More specifically, we investigate four different control algorithms that can be designed within this framework, each relying on different level of knowledge and assumptions.

- **AcQu** −− Based on the ideal case where all the SUs perfectly know the accurate PU queue length (AcQu), this idealized algorithm AcQu constitutes our benchmark optimum solution to be compared against.

- **EstQ** —— without knowledge on the PU queue length the SU power control modifies our baseline algorithm by letting every SU to estimate the PU's queue length assuming the knowledge of its average arrival rate λ_p.
- **Forced-queue-clearing (FQC)** —— FQC ensures PU queue stability by letting the SUs estimate the PU queue length and by forcing SUs to stop all transmissions if they observe a PU busy period longer than a pre-defined threshold $\tau > 0$. All secondary transmissions are then forbidden until a PU idle period is observed.
- **PU-assisted queue alert (PUaq)** —— as a generalization of the previous schemes, we let the PU-Tx broadcast an "alert" message whenever their queues reach a threshold Q_{th}. Similar to the FQC policy, when a SU receives this alert message, it quits transmitting until a primary idle period is observed.

The details of these SU access control algorithms will be described next.

V. SU CONTROL ALGORITHMS

This section is devoted to detailing the algorithms previously described. Note that, since in a realistic case SUs cannot directly observe the PU queue length, we associate the PU queue stability with the observation by the SUs of infinitely many PU idle periods.

A. AcQu SU Network Access Control

AcQu is the idealistic case where we assume each SU has perfect information on PU queue length. Under this assumption, the solution to Problem (10) AcQu is based on the following two steps:

(a) *Flow control*. Each secondary user $i \in \mathbb{N}_s$ solves the following optimization problem:

$$\underset{R_i(t)}{\text{maximize}} \quad V \cdot f_i(R_i(t)) - R_i(t) \cdot Q_i(t)$$
$$\text{subject to:} \quad R_i(t) \leq R_{\text{MAX}}, \tag{12}$$

where V is an adjustable parameter to characterize the aggressiveness of the secondary users whereas R_{MAX} is the maximum allowed per-slot data flow.

(b) *Resource control*. Each secondary user $i \in \mathbb{N}_s$ solves the following optimization problem:

$$\underset{P_i(t)}{\text{maximize}} \quad Q_i(t)\mu_i(t) + Q_p(t)\mu_p(t)$$
$$\text{subject to:} \quad P_i(t) \geq 0 \tag{13}$$
$$P_i(t) \leq P_{\text{MAX}},$$

where P_{MAX} is the maximum allowed secondary transmission power;

In what follows, we focus only on part (b) of the access control for SU-Tx , as it is the only part that affects primary user's queue backlog.

Note that AcQu algorithm is similar to the $CLC1$ algorithm proposed in [1]. To develop SU access control algorithms for more realistic scenarios, however, we need to address several challenges in our problem: 1) SUs are distributed and individually determines their own transmission power; 2) the PU transmission power cannot be controlled; 3) SU may have to estimate PU queue length based on its observations, which motivates the following algorithms designed for such more practical scenarios.

B. EstQ SU network control based on PU queue estimation

Here, we describe a more realistic version of Problem (13) that does not require perfect primary user queue backlog knowledge. First, we use the following estimate of $Q_p(t)$:

$$\hat{Q}_p(t) = \begin{cases} ((\lambda_p + \epsilon) \cdot t - \mu_p(t))^+, & \text{if PU busy,} \\ 0, & \text{if PU idle.} \end{cases} \tag{14}$$

In (14), SUs assume a constant arrival rate of $(\lambda_p + \epsilon)$ at the primary transmitter. The primary queue length is shortened by the successfully transmitted packets $\mu_p(t)$ known to the SUs. Note that, in addition to tuning the parameter V, we also over-estimate the primary arrival rate by $\epsilon > 0$. The value of ϵ can also be dynamically adjusted to affect SU behaviors.

Given the queue estimate, the secondary access control can be modified into

(b) *EstQ resource control*. Each secondary user $i \in \mathbb{N}_s$ solves the following optimization problem:

$$\underset{P_i(t)}{\text{maximize}} \quad Q_i(t)\mu_i(t) + \hat{Q}_p(t)\mu_p(t)$$
$$\text{subject to:} \quad P_i(t) \geq 0 \tag{15}$$
$$P_i(t) \leq P_{\text{MAX}}.$$

C. Forced-Queue-Clearing (FQC) Algorithm

Simple queue estimation through Eq. (14) leads to primary queue instability if we set $\epsilon = 0$ or when the estimation of λ_p is poor. To remedy this issue, we also devise a heuristic solution that compels SUs to stop transmission if the current primary busy period exceeds a pre-determined threshold $\tau > 0$. We calculated τ as an integer multiple of the average busy period of an M/M/1 queue with average arrival rate λ_p and average departure rate equal to the primary departure rate without secondary interference. We then obtain a new SU control algorithm.

(b) *FQC resource control*. Let t_b denote the current primary busy duration (as estimated by the SU). Each secondary user $i \in \mathbb{N}_s$ solves the following optimization problem:

if $t_b < \tau$, then:

$$\begin{aligned} \underset{P_i(t)}{\text{maximize}} \quad & Q_i(t)\mu_i(t) + \hat{Q}_p(t)\mu_p(t) \\ \text{subject to:} \quad & P_i(t) \geq 0 \\ & P_i(t) \leq P_{\text{MAX}}. \end{aligned} \quad (16)$$

else

$$\mu_i(t) = 0, \text{ until primary channel is idle.} \quad (17)$$

Note that $\hat{Q}_p(t)$ is calculated through Eq. (14).

D. PUaq SU network control

In FQC, the SU-Txs stop transmission if primary busy period exceeds a certain pre-determined threshold. As a generalization, we consider a partially cooperative PU-Tx. Specifically, we require the PU-Tx to broadcast an alert message whenever its queue reaches a pre-defined threshold Q_{th}. In this PUaq scenario, SU-Tx stops transmission upon successful reception of alert messages. This PUaq scheme requires some explicit PU cooperation. Our goal is to examine whether PU cooperation can significantly improve PU performance. As a result, we can modify the resource control scheme into PUaq as follows

(b) *PUaq resource control.* Each secondary user $i \in \mathbb{N}_s$ solves the following optimization problem:

If no alert message received, then:

$$\begin{aligned} \underset{P_i(t)}{\text{maximize}} \quad & Q_i(t)\mu_i(t) + \hat{Q}_p(t)\mu_p(t) \\ \text{subject to:} \quad & P_i(t) \geq 0 \\ & P_i(t) \leq P_{\text{MAX}}. \end{aligned} \quad (18)$$

else

$$\mu_i(t) = 0, \text{ until primary channel is idle.} \quad (19)$$

In this case, $\hat{Q}_p(t)$ is calculated as in (14).

VI. SIMULATION RESULTS

In this section, we first consider the case with $N_s = 1$ to show that our algorithm successfully stabilizes PU queue in case of single SU transmitter. Next, we extend our results to the case with $N_s = 2$. In both cases, the SU system overlays atop of a single primary pair's forward link channel. The various parameters involved in the PU and SU pairs are summarized in the table VI:

P_p	PU power	1 [dBm]
λ_p	PU average arrival rate	2 [pkt/slot]
P_{MAX}	Max SU power	1 [dBm]
d_p	PU-Tx→PU-Rx distance	200 [m]
$d_i, i \in \mathbb{N}_s$	SU-Tx→SU-Rx distance	200 [m]
$\alpha_i, i \in \mathbb{N}_s$	Merit factor	$d_{\text{ip}}/40$
R_{MAX}	SU data-flow factor	20
t_s	Time-slot duration	1 [ms]
L_p	PU packet length	1024 [bits]
L_s	SU packet length	512 [bits]

Note that, in all the simulation results we assume: $d_{\text{ip}} = d_{\text{pi}}, \forall i \in \mathbb{N}_s$. This means that the distance between the ith SU-Tx and the PU-Rx is the same as the distance between the PU-Tx and the ith SU-Rx. It is worth mentioning that the results for $N_s = 2$ are obtained with $d_{1\text{p}} = d_{2\text{p}}$ to test SU-Txs behavior in case they experience the same interference from the PU-Tx.

As performance metrics, we generate the numerical results of different SU control algorithms in terms of the resulting average primary queue length and the average secondary user throughput (7). These numerical simulation results are obtained by averaging 100 different realizations of 1000 time-slots each. Note that we show the average secondary PU queue length in a logarithmic scale, whereas the average throughput results are plotted in a semi-logarithmic scale.

To demonstrate our ability to control the outcomes of the SU access, we adjust SU-Txs' aggressiveness tuning parameter V to assess its impact on the SU throughput and PU queue length. We understand from Problem (12) that larger V would lead to longer secondary queue length $Q_i, \forall i \in \mathbb{N}_s$, and that longer Q_i bolsters overlaid secondary transmission attempts because of the max-weight resource allocation of (13). Hence, more aggressive SU transmission has an obvious impact on primary queue length Q_p and long-term average throughput r_i, $\forall i \in \mathbb{N}_s$. This impact depends also on the mutual interference between the primary and secondary systems. In what follows, we show that, when the interference between the PU and SU pairs is high, LBT type of opportunistic channel access is favorable, whereas, as interference at the PU-Rx decreases, we expect our algorithms to migrate from LBT-style channel access, toward favoring overlaid secondary channel access. The behavior of the SU-Txs as a function of the parameter V shows that SUs aggressiveness is favorable only when distance between primary and secondary users is sufficient so as not to cause detrimental interference with each other.

We remark that the SU throughput results for $V \leq 0.1$ and $d_{\text{ip}} = 200$m correspond to a pure LBT-style channel access. Because of paper length constraint, we omit to show such a result that depicts the SU channel access policy as a function of time for a simulation realization.

A. AcQu Access

Figures 3 (a) and (b), show the statistical average primary queue length and the statistical average secondary throughput r_1, as functions of the distance $d_{1\text{p}}$ between the SU-Tx and the PU-Rx. From Figure 3 (a), it is clear that our algorithm successfully stabilizes the PU queue. As expected, for increasing values of V, the average PU queue length grows (while remaining stable).

(a)

(a)

(b)
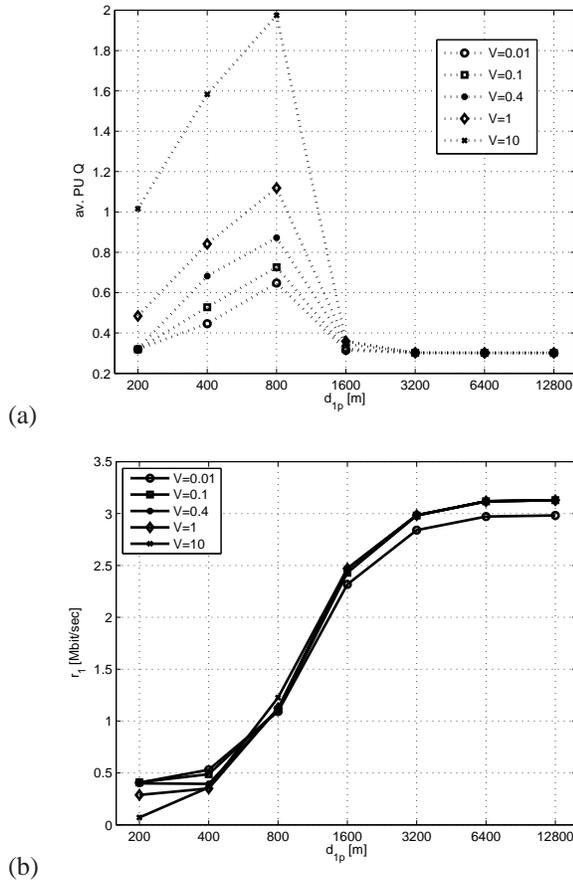
Fig. 3. AcQu Access. Average Pu queue length and r_1 for different values of V.

(b)

Fig. 4. EstQ algorithm. Average Pu queue length and r_1 for different values of V.

Figure 3 (b) shows that, for short distance between primary and secondary users, lower values of V result in higher SU throughput r_1.

As expected, higher values of V are not suitable when the mutual interference between primary and secondary systems is high. For example, the highest values of the SU throughput for $d_{1p} = 200$m correspond to a LBT-style channel access. When the SU-Tx and the PU-Rx are further apart so as not to cause severe mutual interference, more aggressive channel access policies at the SU-Tx can improve the throughput r_1.

B. EstQ algorithm

Figures 4 provides comparative results of r_1 and average PU queue length in the more realistic scenario where PU queue length is estimated via Eq. (14). Since we noticed that a value of $\epsilon = 0$ is not enough to stabilize PU queue, the SUs over-estimate PU average arrival rate by an excess margin $\epsilon > 0$. In our tests, the EstQ algorithm uses $\epsilon = 0.01$. As it can be seen from Figure 4 (a), the PU queue is stabilized. As

in the AcQu case, more aggressive SU-Tx's channel access policies correspond to longer average PU queue length. Moreover, Figure 4 (b) shows that, for shorter distance d_{1p}, the SU-TX throughput r_1 is a decreasing function of the parameter V. For larger distance d_{1p}, the lower mutual interference between the primary and the secondary systems lead to system overlay and therefore favors higher values of V in terms of throughput r_1.

C. FQC algorithm

Figures 5 shows the average PU queue length and the secondary average throughput r_1 for the FQC cognitive access control as the distance d_{1p} between the PU-Rx and the SU-Tx vary. We tested FQC with $\epsilon = 0$ to show that this version of the algorithm can successfully stabilize PU queue in this case. From Fig. 5 (a), we can see that, as expected, larger V leads to longer PU queue length. Additionally, the SU throughput increases as d_{1p} increases because, when the SU-Tx is far from

(a)

(a)

(b)

(b)
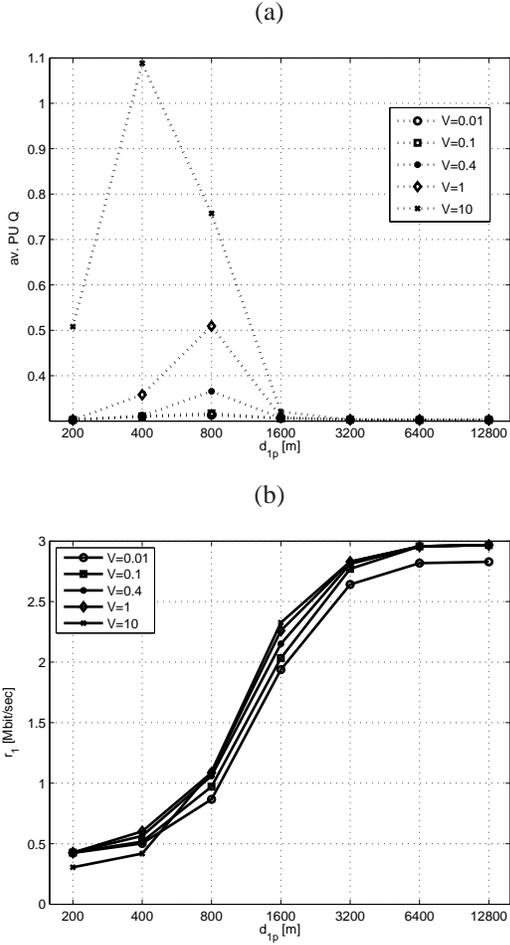
Fig. 5. FQC. Average Pu queue length and r_1 for different values of V.

Fig. 6. PUaq. Average PU queue length and r_1 for different values of V.

the PU-Rx, LBT-style channel access is less favorable than overlaid cognitive access.

D. PUaq algorithm

For the last algorithm, Figures 6 (a) and (b) show the average secondary rate r_1 and the average PU queue length as a function of d_{1p}, and for different values of V. As expected, this control algorithm also successfully stabilizes PU queue. As pointed out in the previous subsections, for low values of d_{1p}, LBT channel access is preferable. When d_{1p} increases, higher values of V lead to more overlaid transmissions and can lead to higher SU throughput than LBT.

E. Algorithm comparison, $N_s = 2$

In this test, we activate two SU transmitters that implement the same access strategy for power control. Figures 7 (a) (b) and (c) show the resulting average queue length, and the resulting SU rates r_1 and r_2 for

the two users, respectively. Figure 7 (a) shows that the proposed algorithms successfully stabilize the PU queue when both SU-Txs are active and control their own access without cooperation. As discussed earlier, larger parameter V corresponds to longer PU queue backlog. Perfect queue knowledge also leads to higher average PU lengths as the SU-Tx can afford to be more active. This is due to the fact that "EstQ", "FQC" and "PUaq" algorithms control the SUs' aggressiveness by either over-estimating PU length or stopping SU transmissions before the PU queue becomes too long.

As mentioned earlier, since we assume $d_{1p} = d_{2p}$, the two SU-Txs experience the same interference from PU-Tx. We assume also that all SUs perfectly decode PU-Rx feedback messages. For these reasons, all SUs make the same decisions at the same time and experience the same throughput values. As expected, when the mutual interference between the secondary and primary users decreases, LBT-style channel access is abandoned, favoring overlaid communications. When the mutual

(a)

(b)

(b)
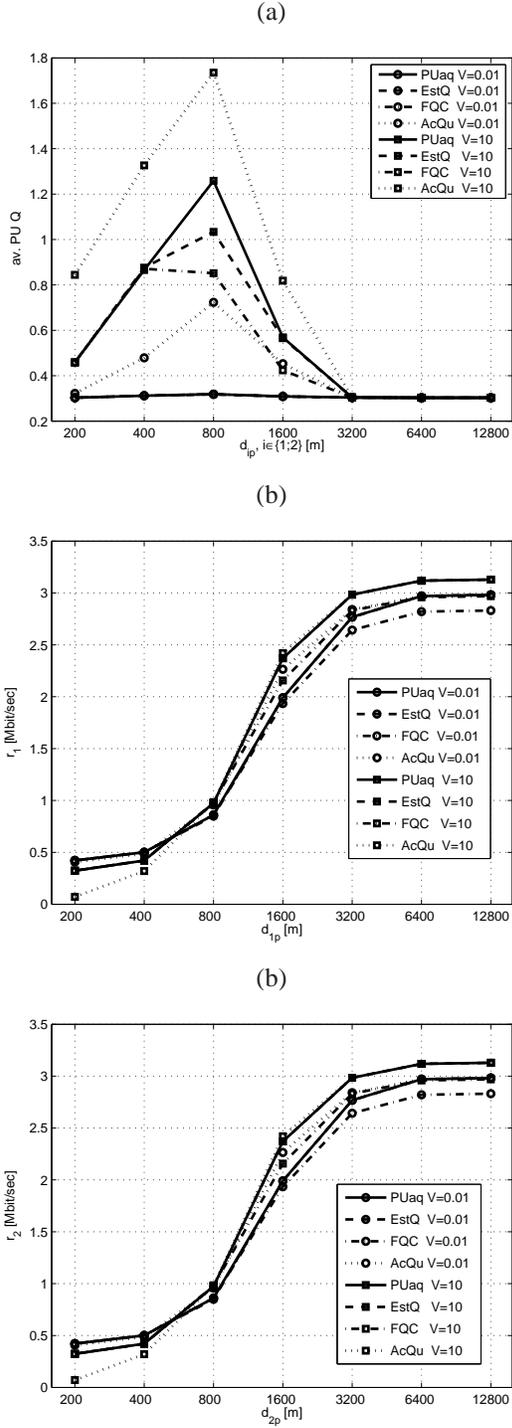
Fig. 7. Algorithm comparison. Average PU queue length and r_1 for different values of V.x

interference is high, LBT channel access is optimal, for this reason, high values of V lead to lower throughput.

We close this section with a SU throughput comparison in case $N_s = 1$ and $N_s = 2$ for perfect

queue knowledge. Figure 8 shows that, as expected,
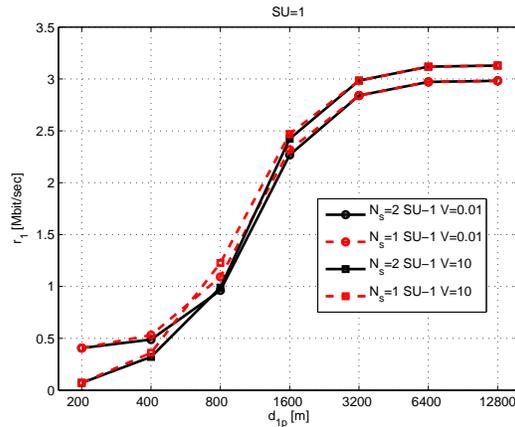
Fig. 8. AcQu. Average throughput for SU-1 for $N_s = 1$ and $N_s = 2$.

when N_s=1, r_1 is always higher than the case with multiple SUs. In case $d_{1p} = 800$m and $V = 10$, the SU throughput with one SU outperforms the case of two SUs by almost 30%. This phenomenon is mirrored by a higher average PU queue length with respect to the case of two SUs.

VII. CONCLUSIONS

In this work, we introduced a power control algorithm for SU-Tx channel access. By learning from both PU-Tx's activity and PU-Rx's feedback information, we developed a distributed SU power control framework that approximates the optimal solution to Problem 10. We showed that, when the mutual interference between SU-Tx and PU-Rx is high, LBT-style channel access performs better than overlaid communications, whereas the opposite is true when the mutual interference between the primary and secondary systems is weak. We compared several of our approximation algorithms both in case of perfect PU queue length knowledge and in case of queue length estimation. We showed that the proposed access control algorithm EstQ, based on primary queue estimation, can successfully stabilize the PU queue. We furtherly explored PU cooperation through PU-alert messages broadcasted whenever PU queue reaches a pre-determined threshold. We established primary queue stability by applying our proposed approximation algorithms.

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