TSRA: An Adaptive Mechanism for Switching between Communication Modes in Full-duplex Opportunistic Spectrum Access Systems

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Abstract—Full-duplex (FD) communications and self-interference suppression (SIS) techniques can be exploited in opportunistic spectrum access (OSA) systems for simultaneous transmission-sensing (TS) or simultaneous transmission-reception (TR). Motivated by the competing goals of primary user (PU) protection (in the TS mode) and secondary user (SU) performance (in the TR mode), we present an optimal adaptive switching strategy and an associated communication protocol for FD OSA systems. Specifically, we optimize the spectrum-awareness/efficiency tradeoff by allowing the SU link to adaptively switch between various modes, depending on the forecasted PU dynamics. The proposed three-stage adaptive mode-selection strategy maximizes an SU utility function subject to a constraint on the PU collision probability. We also propose a protocol that executes the switching mechanism in a distributed fashion. In practice, SIS is imperfect, resulting in residual self-interference that degrades the sensing performance in the TS mode. Accordingly, we study different spectrum sensing techniques in the TS mode, while illustrating their accuracy-complexity tradeoff. We evaluate the performance of the proposed switching scheme against the listen-before-talk (LBT) scheme using numerical results, simulations, and hardware USRP experiments.

Index Terms—Self-interference cancellation, full-duplex communications, cognitive radio, spectrum awareness/efficiency tradeoff.

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1 INTRODUCTION

In traditional half-duplex (HD) radios, bi-directional communications is achieved by separating the forward and reverse links in time (i.e., TDD) or frequency (i.e., FDD). Until recently, the idea that a wireless device can transmit and receive simultaneously on the same channel, i.e., operate in full-duplex (FD) mode, was deemed impossible. The problem of achieving FD communications is that the transmitted power from a given device is much larger than the received power of another signal that this device is trying to capture. While the device is receiving the second signal, its own transmission is considered a self-interference. The infeasibility of FD communications was challenged by several studies (see [1] for a survey), which have successfully demonstrated the possibility of FD communications using self-interference suppression (SIS) techniques.

In this paper, an opportunistic spectrum access (OSA) system is considered, where secondary users (SUs) have imperfect SIS capabilities, allowing them to suppress a fraction of their self-interference. Typical OSA systems use a listen-before-talk (LBT) scheme to protect primary users (PUs) from SU interference. According to this scheme, the SU device has to periodically interrupt its transmission (e.g., once every two seconds) and sense the channel for PU activity. If the channel is sensed to be busy, the SU has to

abort transmission over that channel and switch to another channel. Otherwise, the SU proceeds with its transmission until the next sensing attempt. Because of interference and noise, the outcome of the sensing process is not 100% accurate, so it may result in false alarms and mis-detection.

In contrast to the LBT-based approach, we consider an FD-capable OSA system whereby the SIS capabilities of an SU can be exploited to operate in either simultaneous transmission-sensing (TS) mode or simultaneous transmission-reception (TR) mode. The TS mode has two advantages over the LBT scheme. First, from the SU's perspective, sensing the spectrum while transmitting data enhances the SU throughput, because the SU no longer needs to interrupt its transmission to sense. Second, from the PU standpoint, the SU's ability to sense a channel while transmitting over it reduces the possibility of PU/SU collisions. On the other hand, if the likelihood of PU activity is low, SUs can achieve higher throughput by operating in the TR mode. The ability to operate in either TS or TR mode gives rise to a spectrum awareness/efficiency tradeoff, which motivates the need for the adaptive Transmission-Sensing-Reception Algorithm (TSRA) presented in this paper.

Besides the TS and TR modes, an SU may need to operate in a sensing-only (SO) mode to improve the sensing accuracy (which would otherwise be impacted by imperfect SIS). Considering the availability of multiple channels, the SU may decide to perform channel switching (CS) if an idle PU is likely to return soon to the current operating channel.

Two important design aspects of the underlying FD OSA system are: (1) the strategy to be followed by SUs

to adaptively switch between different modes (TR, TS, SO, and CS), and (2) the communication protocol that executes this strategy in a distributed and dynamic environment. We propose such an adaptive strategy, which consists of three stages. In the *belief stage*, we determine the optimal strategy that maximizes the SU's utility (e.g., goodput) under a constraint on the PU collision probability. This strategy is found to be threshold-based, with thresholds that depend on the SU's belief about the PU's state. Based on this belief, the SU can take an optimal action and then update its belief according to the action outcome. The other two stages (*traffic stage* and *periodic sensing stage*) are refinements to the belief stage. The traffic stage adjusts the SUs' action by taking the traffic load into consideration, while the periodic sensing stage ensures that the ultimate strategy is compliant with OSA standards.

The problem of finding the optimal access strategy at an SU device has been studied before [2]–[4], but for HD devices. In [2] the authors considered the quickest detection problem of the PU idle period when multiple PUs are present. In their scheme, the SU chooses an action from the following possible actions: spectrum sensing, channel switching, and data transmission. The authors in [3] studied the sensing-throughput tradeoff and proposed a scheme in which the SU can have multiple consecutive sensing or transmission periods, determined according to the SU's belief about the PU state.

In light of the recent developments in SIS techniques, several works investigated SIS/FD capabilities in the context of OSA networks [5]–[16]. To enable the TS mode, the authors in [14]–[16] focused on studying SIS techniques from an antenna perspective. The authors in [6], [8], [12] studied energy detection as a potential candidate for spectrum sensing in FD cognitive radio networks and analyzed the false-alarm and detection probabilities. Energy detection cannot accurately differentiate between an SU's residual self-interference (RSI) and the PU signal, especially with limited SIS capabilities. Accordingly, in [11] we explored the use of waveform-based sensing in FD OSA systems. In [11], we proposed a preliminary design of an adaptive strategy.

In this paper, we extend our work in [11] and provide a complete design of the adaptive scheme. This includes the aforementioned three stages as well as a communication protocol for executing them. In addition, we compare the performance and complexity of different sensing techniques for the TS mode. Finally, we conduct simulations and USRP hardware implementation of the proposed scheme.

The contributions of this paper are as follows. First, considering an OSA system where SUs have partial SIS capabilities, we study and analyze different spectrum sensing techniques for the TS mode. Second, we propose an optimal three-stage adaptive strategy for the SU to switch between the TR, TS, SO, and CS modes. The criteria for choosing the optimal action in the first stage is to maximize the SU's utility subject to a constraint on the PU collision probability. To achieve this goal, we formulate the problem as a partially observable decision process and analyze the four actions by formulating the myopic and long-term rewards. We also design the two other stages of the adaptive strategy to account for the SUs' traffic load and comply with OSA regulations. Third, we propose a protocol that executes the switching

mechanism between different operation modes. Finally, we evaluate the performance of the proposed scheme via numerical results, simulations, and hardware experiments.

The rest of the paper is organized as follows. We describe the system model in Section 2. In Section 3, we study the potential use of different sensing techniques in the TS mode. The two main components of TSRA (adaptive strategy and protocol design) are discussed in Sections 4 and 5. Finally, we evaluate the performance of the proposed scheme and conclude the paper in Sections 6 and 7, respectively.

2 SYSTEM MODEL

We consider an OSA network, where SUs operate opportunistically over licensed PU channels. The PU activity is modeled as an alternating ON/OFF random process. Let the OFF and ON durations be denoted by X and Y, with corresponding CDFs F_X and F_Y, and means $\bar{X}$ and $\bar{Y}$, respectively. Each SU is capable of partial or complete SIS, enabling it to operate in the TS or TR modes, along with the SO and CS modes. We use χ_i to represent the SIS capability of the ith SU, $\chi_i \in [0, 1]$. Specifically, χ_i is the ratio between the RSI signal and the original one. If $\chi_i = 0$, the node can completely suppress its self-interfering signal (i.e., perfect SIS); otherwise, it can only suppress a fraction $1 - \chi_i$ of its self-interference (i.e., imperfect SIS). χ_i may differ from one SU to another, depending on the employed SIS techniques.

At any given time and over any given channel, we assume at most one SU link can be active in a given neighborhood (i.e., collision domain). Hence, different SU links do not interfere with each other. Various spectrum access protocols have been proposed to handle SU-SU interference. These protocols can be classified into two categories: protocol models and physical models [17]. For protocol models, which is assumed in this paper, SU-SU interference is eliminated by enforcing an "exclusive channel occupancy" policy among SUs. Specifically, a channel is allocated to only a single SU link in a given geographical area. This is done using a modified version of contention-based channel access approaches (e.g., CSMA/CA). SUs can communicate over a non-dedicated common control channel (CCC) and perform a three-way handshake to exchange different control information. During this handshake, the channel assignment and transmission duration are announced. Neighboring SUs defer from using the channel until the ongoing transmission ends. Several papers in the literature have discussed how a CCC can be found in OSA systems [18]. Let P_i and σ_i^2 denote the transmission power and thermal noise variance at node i, and let h_{ij} be the channel gain between transmitter i and receiver j of the secondary link.

2.1 SU Operation Modes

2.1.1 TS mode

Using SIS techniques, the SU can carry out spectrum sensing while simultaneously transmitting its data. This sensing process may be done over multiple (consecutive) short periods instead of one long sensing period. Specifically, the SU may perform m sensing actions, each of duration T_{Sk}, $k = 1, 2, \ldots, m$, while transmitting data for a period of T seconds (see Figure 1(a)). The motivation behind this

(a) Transmission-Sensing (TS) mode
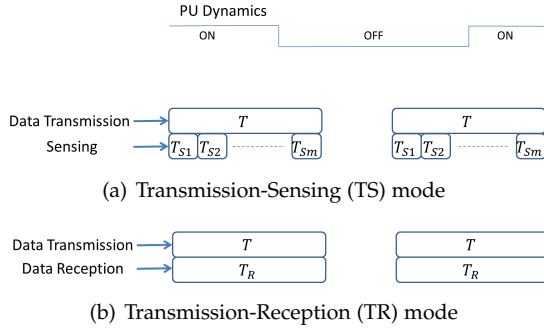
(b) Transmission-Reception (TR) mode

Fig. 1: FD-based operation modes at an SU.

approach is to account for the tradeoff between sensing efficiency and timeliness in detecting PU activity. Increasing T_{Si} improves the sensing accuracy (smaller false-alarm and misdetection probabilities). However, such an increase implies delaying the time to make a decision regarding the presence of a PU signal. If at the end of any given sensing period $k, k = 1, 2, \ldots, m$, PU activity is detected, the SU aborts transmission and updates its belief. We use the term *FD sensing* to refer to the sensing process in the TS mode.

2.1.2 TR mode

In the TR mode, the SU transmits and receives data simultaneously over the same channel, as shown in Figure 1(b). Denote the transmission and reception durations by T and T_R, respectively. For simplicity, we assume $T_R = T$, which can be justified as follows. To operate in the TR mode, both SUs must have data to send to each other. If their packets are not of the same size, then the duration T can be set to the smaller of the two packets. We account for traffic directionality in Sections 4 and 5. Although operating in the TR mode enhances the SU's throughput, it will not be able to monitor the PU activity. Hence, the probability of colliding with the PU will be higher than that of the TS mode.

2.1.3 SO mode

In this mode which we also refer to as *HD sensing*, the SU senses the spectrum for a duration T_S. Depending on the SIS capability, the TS mode may not always be efficient. Hence, the SU may switch to the SO mode to get more accurate sensing results.

2.1.4 CS mode

The SU may switch to another channel and carry out spectrum sensing on that channel if it believes that the PU is very likely to return to the currently used channel. Existing techniques can be used to select the channel sensing order (e.g., [19]).

Although we do not consider the transmission-only (TO) mode as an option (no advantage over the TS mode), we will use it for comparison purposes.

2.2 Concepts and Definitions

2.2.1 Sensing-Only-Algorithm (SOA)

To establish a link between two SUs, the initiating SU needs to find an idle channel from the available N channels. Since channels status (idle or busy) are unknown to the SU, it starts by executing an SOA. First, the SU senses various

channels sequentially. According to the sensing outcomes, the SU decides whether to use this channel or not. Specifically, if a chosen channel is believed to be idle, the SU will communicate over it. However, if the channel is deemed busy, the SU has to decide whether to spend more time sensing this channel, in case the PU becomes idle, or switch to another channel. Finding the optimal spectrum access strategy has been studied before [2], [20]. Once an idle channel has been found, an association process is executed to establish a connection between the two SUs. After that, the SU executes the three-stage strategy.

2.2.2 Master and Slave Devices

A *master device* (MD) is a designation we give to any SU that executes the three-stage decision algorithm discussed later. The MD makes the final decision about which mode to select (TR, TS, SO, or CS). In contrast, a *slave device* (SD) is the SU device that follows the MD's instructions with regard to starting, continuing, or stopping a transmission. This is done through control packets, defined as part of the proposed communication protocol. In the present design, the node that initiates the communication is the MD and the other one is the SD. However, these roles may change over time, depending on traffic directionality. We discuss MD and SD role switching in Section 5.

2.2.3 Data and Control Phases

After executing the SOA, if the MD discovers an idle channel, it divides time into two alternating phases: a data phase and control phase. The data phase involves either unidirectional (HD) or bidirectional (FD) transmission of one or more data packets. It may also include a segment of digitized and compressed media (voice/video). Spectrum sensing is also executed in the data phase. Each data phase is followed by a control phase, which has two purposes. First, the control phase is used to confirm the correct reception of packets transmitted in the preceding data phase. This is accomplished through the acquisition of certain parameters (ACKs/NACKs, belief probabilities, etc.). Second, the control phase is used to assign the roles of MD and SD to the two communicating SUs. Once these roles are assigned, the control phase is also used by the MD to trigger the SD to execute the actions recommended by the adaptive algorithm. If the two nodes switch to another channel, they will terminate the data and control phases and re-execute the SOA on the new channel. In SOA, the sensing durations can be optimized separately.

3 FD Sensing Techniques

Extensive literature has been published on spectrum sensing techniques (energy-based, waveform-based, cyclostationarity-based, and matched-filtering sensing) for traditional HD devices [21], [22]. In energy-based sensing, the average energy of the sampled received signal is computed and compared with a threshold (which depends on the noise floor) to determine whether the PU is idle or not. Waveform-based sensing utilizes known patterns in the PU signal, such as preambles and pilot symbols, which are typically used for channel estimation, synchronization, etc. To detect the presence of a PU signal, the known

pattern is cross-correlated with the received signal. The correlation coefficient is then compared against a threshold. Another method for detecting PU signals is to exploit the cyclostationarity features in the received signal, which are caused by the periodicity in the signal itself or in its statistics such as the mean and autocorrelation. Finally, in the matched-filtering approach, the SU demodulates the received signal to decide whether the PU is idle or busy.

Energy-based sensing is quite general, as it requires no prior knowledge of the structure/waveform of the PU signal. On the other extreme, matched-filtering requires perfect knowledge of the features of the PU signal (i.e., modulation scheme, frame format, etc) to demodulate this signal. Waveform-based sensing can be utilized by SUs for detecting PU signals with known signal patterns, which is quite common, while cyclostationary-based sensing can be used in cases where enough cyclostationarity features exist in the PU signal.

Consider an FD SU device with an arbitrary SIS factor χ. Under FD sensing, the hypothesis test of whether the channel is occupied by a PU or not can be formulated as:

$$r(n) = \begin{cases} \chi\, s(n) + w(n) & \text{under } H_0 \text{ (PU is idle)} \\ l(n) + \chi\, s(n) + w(n) & \text{under } H_1 \text{ (PU is busy)} \end{cases}$$

where $r(n), s(n), l(n)$, and $w(n)$ are, respectively, the nth samples of the received signal, the self-interfering SU signal, the received PU signal, and the additive white Gaussian noise with variance σ_w^2. We assume that $s(n)$ is a zero-mean complex random signal with variance σ_s^2. We also assume that all signal samples are independent, hence $r(n)$'s are also independent. In the case of HD sensing, the hypothesis test reduces to $w(n)$ (under H_0) and $l(n) + w(n)$ (under H_1).

Among the aforementioned sensing techniques, energy detection is widely used in HD sensing because of its low computational and implementation complexities. However, a key disadvantage of this technique is its inability to differentiate between a PU signal and noise (specially under low signal-to-noise ratios). Furthermore, for FD sensing, energy detection cannot differentiate between RSI, PU signal, and noise. Better accuracy can be achieved with waveform-based sensing which can robustly differentiate between different signal types. In terms of complexity, waveform-based sensing is a little bit more complex than energy detection, because it requires the SU to know the PU pattern. Hence, it can be considered as a good candidate, with reasonable complexity, for the TS mode. Note that although cyclostationary-based sensing can also differentiate between different types of signals, it sometimes has high overhead and bandwidth loss when the number of features inserted in the signal are increased to improve the detection reliability [23]. In the rest of this section, we will focus on energy- and waveform-based sensing.

The performance of any sensing technique is measured by the false-alarm probability (P_f) and the detection probability (P_d). P_f and P_d are defined as the probabilities that the SU declares the sensed channel to be busy given hypothesis H_0 and H_1, respectively. A good system should have high P_d to reduce collisions between SUs and PUs. At the same time, a lower P_f value improves the SU throughput by reducing the number of missed transmission opportunities.

Consider energy-based sensing. The main idea is to compute the average energy of N samples of the signal $r(n)$ and compare this average with a threshold γ_e to determine whether the PU is idle or not. The decision metrics for the energy detector and waveform-based sensing can be formulated respectively as $M_e \overset{\text{def}}{=} \frac{1}{N} \sum_{n=1}^{N} |r(n)|^2$ and $M_w \overset{\text{def}}{=} \text{Re}\left[\sum_{n=1}^{N} r(n)\, l^*(n)\right]$, where $l^*(n)$ is the conjugate of the known part of the PU signal. The metric M_w correlates the received samples with the samples of a static part of the PU signal. The value of M_w is then compared to a threshold γ_w to determine the presence/absence of a PU signal. Let M be a generic random variable that refers to either M_e or M_w, depending on the context. Also, let γ be an arbitrary threshold.

In the FD case, P_f and P_d can be formulated, respectively, as $P_f = \Pr[M > \gamma / H_0] = 1 - F_{M/H_0}(\gamma)$ and $P_d = \Pr[M > \gamma / H_1] = 1 - F_{M/H_1}(\gamma)$, where F_{M/H_0} and F_{M/H_1} are the conditional CDFs of the random variable M given hypothesis H_0 and H_1, respectively. Using the central limit theorem, we can determine these two CDFs. Specifically, for a large N, the pdfs of M/H_0 and M/H_1 can be approximated by Gaussian distributions with means μ_{M/H_0} and μ_{M/H_1} and variances σ_{M/H_0}^2 and σ_{M/H_1}^2, respectively. Hence, the false-alarm and detection probabilities can be written, respectively, as $P_f = Q\left(\frac{\gamma - \mu_{M/H_0}}{\sigma_{M/H_0}}\right)$ and $P_d = Q\left(\frac{\gamma - \mu_{M/H_1}}{\sigma_{M/H_1}}\right)$, where Q is the complementary CDF of a standard Gaussian random variable. Substituting for μ_{M/H_0}, μ_{M/H_1}, σ_{M/H_0}^2, and σ_{M/H_1}^2 in the aforementioned equations, we get the false-alarm and detection probabilities for FD sensing under both energy-based and waveform-based sensing (see [6], [11] for details). As reported in [6], [11], waveform-based sensing expectedly outperforms energy-based sensing in reliability and convergence time. Despite its susceptibility to synchronization errors, waveform-based sensing results in low false-alarm and mis-detection probabilities with very short sensing times. To compensate for the RSI, SUs need to increase their sensing times if energy-based sensing is used. In Section 6, we compare the performance of both techniques using numerical results and hardware experiments.

4 OPTIMAL ADAPTIVE SU STRATEGY

In this section, we present the stages of the adaptive strategy for operating an FD-capable SU link in an OSA network.

4.1 Belief Stage

The objective of this stage is to determine the optimal action that maximizes the SU link's utility, while taking the PU state into account. This is done by constructing a profile of the currently used channel at the MD and update this profile after each action.

4.1.1 Problem Formulation

To optimize mode selection for an SU link, we formulate the problem as a partially observable decision process. Let $\mathbb{S} = \{0, 1\}$ be the state space, which indicates the actual state (idle or busy) of the channel that is being observed by the MD. The action set at the SU is given by $\mathbb{A} = \{TR, TS, SO, CS\}$. While observing the PU channel,

the MD has to choose an action from the set $\mathbb{A}$. The outcome/observation space for the MD depends on the action taken. Because a TR action consists of two simultaneous processes (transmission and reception), there are two outcomes for each of these processes. Specifically, for the reception part, the MD may observe the outcome $\{D\}$, which means that the MD was able to decode the received message, or the outcome $\{U\}$, which stands for an undecoded message. For the transmission part of the TR mode, the MD may get an ACK or NACK from the SD, which are denoted by $\{A\}$ and $\{N\}$, respectively[1]. Similarly, a TS action consists of two simultaneous processes (transmission and sensing). The SU will also observe two possible outcomes for the sensing process: $\{F\}$ for free or $\{B\}$ for busy. The outcomes of the transmission part are similar to those of the TR mode. Finally, the observed outcomes for the SO/CS actions are $\{F\}$ or $\{B\}$. Altogether, these actions result in an observation space $\mathbb{O} = \{D, U, A, N, F, B\}$. Later on, we present a reward function, which maps the state and action space to a reward value.

The goal of the MD is to choose actions sequentially in time so as to maximize the expected reward over some random but finite horizon. This can be done via stochastic dynamic programming. First, note that a sufficient statistics for choosing the optimal action at any time t is the belief [24], which is defined as the a posteriori probability $p_t \in [0, 1]$ that the PU is idle at time t given the observation history. We consider a similar setup to [3] for the decision process part, where the time index t is defined here as the time elapsed since the PU switched from ON to OFF. Hence, $t = 0$ is the start of the PU idle period, which is assumed to be known to the SU[2], and therefore $p_0 = 1 - P_f$. Starting from $t = 0$, the SU keeps applying the optimal mode selection policy until switching to a new channel. At that point, the SU resets the algorithm and switches to the SOA until detecting the start of the PU idle period.

After any given action $a \in \mathbb{A}$ and depending on the observation $o \in \mathbb{O}$, the SU updates its belief p_t and computes the corresponding reward. Let π_t be the policy that maps the SU's belief p_t to the action space $a \in \mathbb{A}$ at time t. Define the value function $U(p_t, t)$ as the maximum expected total reward at time t when the current belief is p_t. This function specifies the performance of the optimal policy, denoted by π^*, starting from belief p_t. Based on Bellman equation [25], we have the following:

$$U(p_t, t) = \max \{U_{TR}(p_t, t), U_{TS}(p_t, t), U_{SO}(p_t, t), U_{CS}(p_t, t)\}$$

where $U_{TR}(p_t, t), U_{TS}(p_t, t), U_{SO}(p_t, t)$, and $U_{CS}(p_t, t)$ are the SU's expected total rewards if the SU decides to operate in the TR, TS, SO, and CS modes, respectively, at time t and then follows the optimal policy π^* after that.

4.1.2 Reward Function

In this section, we formulate the utility of the SU link for various actions. Define the immediate and expected future rewards that the link gains from taking action i,

1. NACK is used for simplicity. Practically, it should be ACK-timeout.
2. The SU may keep sensing a busy channel in the SOA until it gets a free outcome. In that case the initial belief $p_0 = 1 - P_f$.

$i \in \mathbb{A}$, as $R_i^{(M)}$ (M for myopic) and $R_i^{(L)}$ (L for long-term), respectively. The probability that the jth SU node observes outcome o is denoted by $w_o^{(j)}$. The updated belief probability for outcome o at node j is denoted by $\mathcal{E}_o^{(j)}$. Define $q_t^{(T)}$ ($q_t^{(S)}(k)$) as the probability that the PU will remain idle during the transmission period T (sensing period $T_{Sk}, k = 1, 2, \ldots, m$), given that the PU is idle at current time t. These last two quantities can be expressed as follows:

$$q_t^{(T)} = \frac{1 - F_X(t + T)}{1 - F_X(t)} \ , \ q_t^{(S)}(k) = \frac{1 - F_X\left(t + \sum_{j=1}^{k} T_{Sj}\right)}{1 - F_X\left(t + \sum_{j=1}^{k-1} T_{Sj}\right)}$$

where $F_X(t)$ is the CDF of a PU OFF period.

- *TR mode*: The myopic reward for an SU link, consisting of nodes 1 and 2, under the TR mode can be formulated as:

$$R_{TR}^{(M)} = \sum_{i \in \{1,2\}} w_D^{(i)} T \log\left(1 + SNR_{TR}^{(i)}\right) \quad (2)$$

where $w_D^{(i)}, i \in \{1, 2\}$ is the probability that the ith SU has successfully decoded the received packet. $SNR_{TR}^{(i)} = (P_j |h_{ji}|^2)/(\sigma_i^2 + \chi_i^2 P_i |h_{ii}|^2)$ is the SNR in the TR mode at node i, where h_{ii} is the self-interfering channel gain at node i and j is the other node of the link.

Since the two communicating SUs may experience different channel conditions, the two terms in the summation in (2) can be different. Furthermore, even though we assume that the PU signal affects both SUs equally, the interference level at both nodes may be different because of other interference sources. Hence, a successful decoding process at one node does not imply that the other node will successfully decode its packet. Also, the SU might get an ACK although the PU is ON, due to deep channel fading between the primary transmitter and the sensing SU. These aspects are captured in the probabilities $\delta_0^{(i)}$ and $\delta_1^{(i)}$, defined as the probability that the ith secondary transmitter receives a NACK given that the PU is OFF and ON, respectively [3]. When the ACK/NACK is triggered by PU collisions only, we have $\delta_0^{(i)} = 0$ and $\delta_1^{(i)} = 1$.

The probability that the ith SU, $i \in \{1, 2\}$, successfully decodes the received message is:

$$w_D^{(i)} = p_t q_t^{(T)} \left(1 - \delta_0^{\hat{i}}\right) + \left(1 - p_t q_t^{(T)}\right) \left(1 - \delta_1^{\hat{i}}\right) \quad (3)$$

where $\hat{i}$ denotes the peer node of SU node i (i.e., if $i = 1$, then $\hat{i} = 2$, and vice versa).

Using Bayes' rule, the probability that the PU is idle after T seconds given that the ith SU successfully decoded the received message is $\mathcal{E}_D^{(i)} = \left[p_t q_t^{(T)} \left(1 - \delta_0^{\hat{i}}\right)\right]/w_D^{(i)}$. Similarly, the probability that the ith SU fails to decode the received message and the corresponding belief update in that case can be written, respectively, as follows:

$$w_U^{(i)} = p_t q_t^{(T)} \delta_0^{\hat{i}} + \left(1 - p_t q_t^{(T)}\right) \delta_1^{\hat{i}} \quad (4)$$

$$\mathcal{E}_U^{(i)} = \left[p_t q_t^{(T)} \delta_0^{\hat{i}}\right]/w_U^{(i)}. \quad (5)$$

Assuming that transmission errors in ACK/NACK messages are negligible (e.g., protected with strong FEC codes), the probability of receiving an ACK/NACK at

node i is the same as the probability that its peer node succeeds/fails in decoding the message. This is also applied to the belief update for the corresponding cases. Hence, $w_A^{(i)}, \mathcal{E}_A^{(i)}, w_N^{(i)}$, and $\mathcal{E}_N^{(i)}$ for the ACK/NACK outcomes can be expressed similarly as $w_D^{(i)}, \mathcal{E}_D^{(i)}, w_U^{(i)}$, and $\mathcal{E}_U^{(i)}$.

There are four possible outcomes in the TR mode. An SU may receive an ACK for its data transmission and also be able to successfully decode the data packet sent by the peer SU, or the SU may get an ACK but not be able to decode the data packet. The other two outcomes are to either get a NACK and a decoded message, or a NACK and an undecoded message. Hence, the expected future reward for an SU link obtained at the ith SU can be formulated as follows:

$$R_{TR}^{(L)} = \sum_{k=\{A,N\}} \sum_{l=\{D,U\}} w_k^{(i)} w_l^{(i)} U\left(\mathcal{E}_k^{(i)} \mathcal{E}_l^{(i)}, t+T\right)$$

Note that the same above expression can be obtained from the $\hat{i}$th SU point of view because receiving an ACK at the ith SU is equivalent to successfully decoding a data packet at the $\hat{i}$th SU. The same remark applies to NACK and undecoded outcomes as we assume that the transmission errors in ACK/NACK messages are negligible.

Finally, the expected total reward in the TR mode is $U_{TR}(p_t,t) = R_{TR}^{(M)} + \eta\, R_{TR}^{(L)}$, where $\eta \in [0,1]$ is a discount factor, that determines the relative weight of the future reward. By setting $\eta = 0$, the SU only cares about the immediate reward. The final belief p_{t+T} will be the multiplication of the two updates $\mathcal{E}_{O_1}^{(i)} \mathcal{E}_{O_2}^{(i)}$, where $O_1 \in \{A,N\}$, and $O_2 \in \{D,U\}$.

- *TS mode*: The myopic reward in the TS mode is different from that of the TR mode because the SU monitors the spectrum while transmitting. Hence, the SU could abort transmission if a busy outcome is observed after any $T_{Sj}, j = 1,2,\ldots,m$. Suppose that SU i is transmitting to SU j. The myopic reward in the TS mode can be formulated as follows:

$$R_{TS}^{(M)} = \prod_{l=1}^{m} w_{F,l}^{(i)} w_A^{(i)} T \log\left(1 + SNR_{TS}^{(j)}\right) \qquad (6)$$

where $SNR_{TS}^{(j)} = P_i |h_{ij}|^2 / \sigma_j^2$ is the SNR in the TS mode at node j. The probability of a successful transmission in the TS mode, $\prod_{l=1}^{m} w_{F,l}^{(i)} w_A^{(i)}$, depends on two events. First, SU i determines the sensed channel is idle after each sensing period $l, l = 1,2,\ldots,m$. This probability is denoted by $\prod_{l=1}^{m} w_{F,l}^{(i)}$, where $w_{F,l}^{(i)}$ is the probability that the ith SU decides a free-channel outcome after T_{Sl}, given that it got a 'free' channel outcome at $T_{S(l-1)}$. Second, SU i receives an ACK from SU j at the end of T, which occurs with probability $w_A^{(i)}$. Define $\mathbb{P}_f = [P_{f,1}\ P_{f,2}\ \ldots\ P_{f,m}]$ and $\mathbb{P}_d = [P_{d,1}\ P_{d,2}\ \ldots\ P_{d,m}]$ as m-dimensional vectors that represent the false-alarm and detection probabilities, respectively, at the end of the m FD sensing periods in the TS mode.

The probability of getting ACK/NACK from the transmission process and the corresponding belief update in these cases are the same as those of the TR mode. The sensing process has also two outcomes, either free or busy channel. We assume a homogeneous spectrum environment,

where if a specific PU activity is sensed free/busy at time t at one end of the SU link, then the other SU will detect the same activity. In Section 5.3, we discuss the general case of having heterogeneous spectrum environment. Also, we assume that if the PU is sensed busy at any sensing period, this yields a communication failure and the SU should abort the channel immediately.

Thus, the probability that the ith SU, $i \in \{a,b\}$, decides a free-channel outcome after T_{S1} can be expressed as follows:

$$w_{F,1}^{(i)} = p_t q_t^{(S)}(1)(1-P_{f,1}) + \left(1 - p_t q_t^{(S)}(1)\right)(1-P_{d,1}).$$

Similarly, the probability that the ith SU decides a free-channel outcome after $T_{Sj}, j = 2,3,\ldots,m$, given that it got a 'free' channel outcome at $T_{S(j-1)}$ is:

$$w_{F,j}^{(i)} = q_t^{(S)}(j)(1-P_{f,j}) + \left(1 - q_t^{(S)}(j)\right)(1-P_{d,j}).$$

The belief update after T_{S1} and $T_{Sj}, j = 2,3,\ldots,m$, in the case of a free outcome can be written, respectively, as follows:

$$\mathcal{E}_F^{(i)}(1) = \left[p_t q_t^{(S)}(1)(1-P_{f,1})\right] / w_{F,1}^{(i)} \qquad (7)$$

$$\mathcal{E}_F^{(i)}(j) = \left[q_t^{(S)}(j)(1-P_{f,j})\right] / w_{F,j}^{(i)}. \qquad (8)$$

Similarly, the probability that the ith SU, $i \in \{a,b\}$, decides the channel is busy after T_{S1} is:

$$w_{B,1}^{(i)} = p_t q_t^{(S)}(1)P_{f,1} + \left(1 - p_t q_t^{(S)}(1)\right)P_{d,1}. \qquad (9)$$

Generally, the probability that the sensing process leads to a busy outcome after $T_{Sj}, j = 2,3,\ldots,m$, given that it got a free-channel outcome at $T_{S(j-1)}$ is:

$$w_{B,j}^{(i)} = q_t^{(S)}(j)P_{f,j} + \left(1 - q_t^{(S)}(j)\right)P_{d,j}. \qquad (10)$$

The belief update after T_{S1} and $T_{Sj}, j = 2,3,\ldots,m$, in the case of a busy outcome can be written, respectively, as follows:

$$\mathcal{E}_B^{(i)}(1) = \left[p_t q_t^{(S)}(1)P_{f,1}\right] / w_{B,1}^{(i)} \qquad (11)$$

$$\mathcal{E}_B^{(i)}(j) = \left[q_t^{(S)}(j)P_{f,j}\right] / w_{B,j}^{(i)}, \qquad j = 2,3,\ldots,m. \quad (12)$$

The TS mode is different from other modes in that the SU may quit transmission before the end of T. This happens if the SU gets a busy outcome at the end of any sensing duration $T_{Si}, i = 1,2\ldots,m$. However, if the SU gets a free outcome after every sensing period $T_{Si}, i = 1,2\ldots,m$, then there are two possibilities. The SU may get a 'free' and ACK for correct reception, or 'free' and NACK for incorrect reception. Incorporating these possibilities, the expected future reward in the TS mode starting from the current time t (and viewed from node i's perspective) can be formulated as follows:

$$R_{TS}^{(L)} = \sum_{j=1}^{m} w_{B,j}^{(i)} \prod_{l=1}^{j-1} w_{F,l}^{(i)} U\left(\mathcal{E}_B^{(i)}(j) \prod_{l=1}^{j-1} \mathcal{E}_F^{(i)}(l), t+\sum_{l=1}^{j} T_{Sl}\right)$$
$$+ \sum_{k=\{A,N\}} w_k^{(i)} \prod_{l=1}^{m} w_{F,l}^{(i)} U\left(\mathcal{E}_k^{(i)} \prod_{l=1}^{m} \mathcal{E}_F^{(i)}(l), t+T\right)$$

Finally, $U_{TS}(p_t,t) = R_{TS}^{(M)} + \eta\, R_{TS}^{(L)}$.

- *SO mode*: The immediate reward $R_{SO}^{(M)}$ in the SO mode is zero, as no transmission takes place. The probability of getting a free/busy outcome and the belief update in each case can be formulated similarly as the sensing part of the TS mode, taking into consideration that the SO mode consists of a single sensing period T_S. Hence, the expected future reward in the SO mode at SU i can be expressed as $R_{SO}^{(L)} = \sum_{k=\{F,B\}} w_k^{(i)} U\left(\mathcal{E}_k^{(i)}, t + T_S\right)$, where $w_F^{(i)}$ and $w_B^{(i)}$ are the probabilities of getting a free and busy outcomes, respectively, after T_S seconds. $\mathcal{E}_F^{(i)}$ and $\mathcal{E}_B^{(i)}$ are the corresponding belief updates. Note that in formulating these quantities, we should include the false-alarm and detection probabilities in the HD case. Furthermore, the probability that the PU will remain idle during the sensing period T_S given that the PU is idle at time t can be expressed as $q_t^{(S)} = (1 - F_X(t+T_S))/(1 - F_X(t))$. Hence, we can write the maximum expected utility that the SU gains from the SO mode as $U_{SO}(p_t, t) = \eta R_{SO}^{(L)}$.

- *CS mode*: If the probability that the PU returns to the current operating channel is very high, then the SU may choose to switch to another channel (where no information about the PU state is available) and carry out spectrum sensing over the new channel. The analysis for this mode is the same as that of the SO mode, except for the value of the belief p_t. The belief for the new channel, denoted by $\hat{p}_t$, is the probability that the PU is idle at time t given that no previous information is available. It can be generally expressed as $\hat{p}_t = \bar{X}/(\bar{X} + \bar{Y})$.

The maximum expected utility for the CS mode is $U_{CS}(\hat{p}_t, t) = \eta R_{CS}^{(L)}$, where:

$$R_{CS}^{(L)} = \sum_{k=\{F,B\}} \hat{w}_k^{(i)} U\left(\hat{\mathcal{E}}_k^{(i)}, t + T_S\right) \tag{13}$$

$\hat{w}_F^{(i)}, \hat{w}_B^{(i)}, \hat{\mathcal{E}}_F^{(i)}$ and $\hat{\mathcal{E}}_B^{(i)}$ are formulated similarly as $w_F^{(i)}, w_B^{(i)}, \mathcal{E}_F^{(i)}$ and $\mathcal{E}_B^{(i)}$, respectively, after replacing p_t with $\hat{p}_t$.

In our online technical report [26], we discuss the convexity and other properties of the SU's utilities $U_{TR}(p_t, t)$, $U_{TS}(p_t, t)$, $U_{SO}(p_t, t)$, and $U_{CS}(\hat{p}_t, t)$ with respect to the belief. We also discuss the convexity of $U(p_t, t)$ with respect to p_t and prove, using backward induction, that $U(p_t, t)$ increases with p_t for a given t.

4.1.3 Optimal Policy

After expressing the SU utilities for the four possible actions and adding a constraint on the collision probability with the PU, the optimal mode-selection problem can be formulated as follows:

$$\begin{aligned} \underset{\pi}{\text{maximize}} \quad & U(p_t, t) \\ \text{subject to} \quad & P_i \leq P_i^*, \qquad i \in \{TR, TS\} \end{aligned} \tag{14}$$

where for $i \in \{TR, TS\}$, P_i is the PU collision probability in the TR/TS mode and P_i^* is a threshold on the allowed PU collision probability in that mode. P_{TR} and P_{TS} can be expressed as:

$$P_{TR} = (1 - p_t) + p_t\left(1 - q_t^{(T)}\right) = 1 - p_t q_t^{(T)} \tag{15}$$

$$P_{TS} = p_t \sum_{i=1}^{m} \left\{ \prod_{j=1}^{i-1} (1 - P_{f,j})\left(1 - q_t^{(S)}(i)\right) \right\} + (1 - p_t). \tag{16}$$

For certain probability distributions of the PU idle period (e.g., Gaussian, uniform, Rayleigh, etc.), $q_t^{(T)}$ approaches zero for large values of t. This means that the probability that the PU returns to the same channel increases with t, which is very intuitive for such distributions. To be able to derive the optimal policy, we define a technical condition similar to the approach in [3]. This condition states that for all $t > t^*$, the SU should not transmit any data (i.e. should not operate in either TR or TS modes) as the collision probability constraint will not be satisfied and hence, zero reward will be gained even if $p_t = 1$. This threshold time t^* is defined as the minimum time after which the PU collision constraint will not be satisfied (hence, $U(1, t) = 0, \forall t > t^*$).

$$t^* = \min\left\{t : q_t^{(T)} < 1 - P_{TR}^*\right\}. \tag{17}$$

Theorem 1. The optimal policy for the SU can be expressed as follows:

$$\pi^*(p_t) = \begin{cases} CS, & \text{if } p_t < \beta_c \\ SO, & \text{if } \beta_c \leq p_t < \beta_s \\ TS, & \text{if } \beta_s < p_t < \beta_r \\ TR, & \text{if } p_t \geq \beta_r \end{cases} \tag{18}$$

where β_r, β_s, and β_c are the transmission-reception threshold, transmission-sensing threshold, and channel switching threshold, respectively. The proof of the theorem is omitted due to space limit and can be found in [26]. The above theorem states that the SU should exploit its high belief that the PU is idle and operate in the TR mode if $p_t \geq \beta_r$. In that case, the SU will dramatically increase its throughput by transmitting and receiving data simultaneously over the same channel. If the belief decreases and falls in the range $\beta_s < p_t < \beta_r$, the SU should monitor the channel while transmitting (i.e., operate in the TS mode), as the probability that the PU returns is now relatively high. In that case, the SU achieves lower throughput than in the TR mode, but also a lower collision probability. The SU should stop transmitting and carry out HD sensing (i.e., SO mode) if p_t is relatively low (i.e., $\beta_c \leq p_t < \beta_s$) because in that case the probability that the PU returns to the channel is quite high and the PU collision constraint will not be satisfied. Hence, more accurate sensing and a temporary pause in the transmission are required. At very low belief values ($p_t < \beta_c$), where the PU is most likely to return to the channel, the SU should take the CS action. This happens when the probability that the PU is idle in a new channel (where no information is available) is higher than the current belief.

To obtain the thresholds for the optimal policy π^*, we need to determine t^* using (17), and then apply backward induction to find $\beta_c, \beta_s, \beta_r$ and the maximum utility for the SU $U(p_t, t)$ for different values of p_t and t. Backward induction starts at time t^*, where $U(1, t) = 0, \forall t > t^*$.

4.2 Traffic Stage

In the traffic stage, the MD will rectify the outcome of the belief stage by taking into account traffic directionality. Before

describing the details of this stage, we need to revisit some terminologies. The four possible modes (TR, TS, SO, and CS) represent a single SU's perspective. However, the operation of a link is actually determined by the operating modes of both communicating SUs, and hence should be expressed as: TR-TR, TS-R (or R-TS), SO, and CS. For instance, if SU_a is to transmit and receive data simultaneously, then SU_b must also transmit and receive data at the same time, which is indicated by the TR-TR mode. The belief stage discussed in the previous section provides the optimal operation mode at the MD (which is the same for the SD) from a utility's perspective, without considering traffic directionality. To account for traffic directionality, the MD should execute the following steps to determine the final decision:

- Rule 1: If the optimal decision in the belief stage at the MD is SO or CS, then the final decision in the traffic stage is the same as the belief stage.
- Rule 2: If the optimal decision in the belief stage is TR-TR, the MD will make the final decision based on which node has additional packets to transmit. This can be done in a variety of ways. For instance, in a packet-switched network, a "more packets" (MP) bit may be used in the header of each packet. This bit indicates whether the sending node node has more packets in its queue or not. Table 1 shows how the final decision is determined when the outcome of the belief stage is TR-TR. In this example, an MP bit of '1' indicates that a node has more packets in its queue and '0' indicates that the queue is empty.

TABLE 1: Outcome of the traffic stage when the outcome of the belief stage is TR-TR

MP for SU_a	MP for SU_b	Final Decision
0	0	Abort communication
1	0	TS-R
0	1	R-TS
1	1	TR-TR

- Rule 3: If the optimal decision in the belief stage is TS-R, the MD and SD may again utilize the MP bit in the packet header to determine the final decision, as shown in Table 2.

TABLE 2: Outcome of the traffic stage when the outcome of the belief stage is TS-R

MP for SU_a	MP for SU_b	Final Decision
0	0	Abort communication
1	0	TS-R
0	1	R-TS
1	1	TS-R (if SU_a is the MD)
1	1	R-TS (if SU_b is the MD)

4.3 Periodic Sensing Stage

OSA standards impose rules for operating opportunistic devices, one of which is to periodically sense the operating channel, say once every T_{req} seconds, to check for PU activity. Hence, the third stage of the adaptive strategy is to require communicating SUs to maintain a maximum duration of T_{req} seconds between any two successive sensing periods. Despite its triviality, the third stage is very crucial for adhering to the opportunistic access philosophy. Consider, for example, the scenario where SUs operate in the TR-TR mode. In the case of good channel conditions and high SU traffic load, both nodes will keep ACKing their

packets and updating their beliefs, and will not switch to any other mode unless they collide with PU transmission (in that case, they will get implicit/explicit NACKs), or when $t > t^*$. To avoid this blind communication during which the PU channel is not monitored, SUs should periodically switch to any of the sensing modes (SO, TS-R, or R-TS). Specifically, the final decision in the third stage will be the same as the second stage except for the following: If the decision of the second stage is TR-TR and the time elapsed since the current channel was last sensed is larger than T_{req} seconds, then final decision in the third stage will be either TS-R if SU_a is the MD or R-TS if SU_b is the MD.

5 COMMUNICATION PROTOCOL

In this section, we present a protocol for implementing the previously discussed mode-selection strategy. First, we should emphasize that the MD/SD roles initially assigned to the two SUs (say SU_a and SU_b) may change on a per-packet basis. At the start of the communication process, the initiating SU (say SU_a) assumes the role of an MD, treating the other user (SU_b) as an SD. Depending on various factors (including the feedback from SU_b), this MD/SD designation may stay the same or it may change. Initially (i.e., after the end of the SOA), the MD (SU_a) does not yet know if the SD has packets to send back, so the first mode of operation for the system is TS-R. The SD can then piggyback the MP bit in the ACK control packet. After that, any of the four possible previously discussed actions may be taken. Note that even if both SUs execute the SOA simultaneously, only one SU, the one who is faster in initiating the association process, will be the MD. This could be achieved using wide-band sensing, where the SD can sense different channels (i.e., executing the SOA) and simultaneously associate with the MD.

5.1 Switching between Modes

A few control packets are needed to allow two SUs to communicate with one another. One illustrative set of control packets that may be employed is shown in Table 3. As shown in the table, an ACK-CTX packet is transmitted if the MD was able to decode the received packet correctly and the optimal policy recommends continuing to operate in the TR-TR mode. When the SD receives this packet, it will transmit a new packet to the MD. If the MD decides to switch to another mode, it will inform the SD to stop transmission. This is done by sending an ACK-STX packet in case of correct reception at the MD. If the MD fails to decode a data packet, it will transmit either a NACK-RTX or a NACK-DTX packet to inform the SD to retransmit the corrupted packet in the next data phase or defer transmission, respectively[3]. For a NACK-DTX packet, the SD will save this incorrectly received packet in a buffer and keep silent for the following data phase(s) until it receives a ST-TX from the MD. Once it receives this control packet, the SD will fetch the stored data packet from the buffer and retransmit it to the MD.

Figures 2 shows a simplified example of two SUs (SU_a and SU_b) that execute the above protocol. In Figure 2(a), SU_a initiates the communication with SU_b by first executing the SOA until channel 3 is determined to be free. After the

3. Strong CRC code is assumed to enable error detection.

TABLE 3: Example of control packets needed to support the proposed adaptive switching strategy

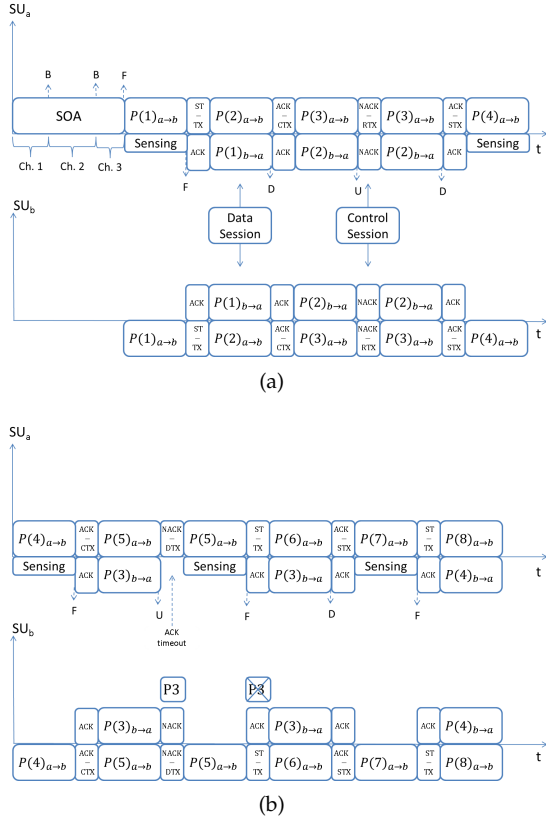| Control Packet	Definition
ST-TX	Request to start transmission
ACK-CTX	Acknowledge-request to continue transmission
ACK-STX	Acknowledge-request to stop transmission
NACK-RTX	Incorrect reception-retransmit corrupted packet
NACK-DTX	Incorrect reception-defer transmission

Fig. 2: Example of applying the proposed communication protocol.

Fig. 3: Example illustrating the process of switching roles between master and slave devices.

association process (not shown), SU_a starts in the TS-R mode and transmits its first packet in the first data phase. This transmission is indicated as $P(1)_{(a \to b)}$, where $P(i)_{(a \to b)}$ denotes the transmission of the ith packet from SU_a to SU_b. According to the example, SU_a receives an ACK, which includes the MP bit from SU_b, and senses the channel to be free. Hence, SU_a transmits a start-transmission (ST-TX) control packet to SU_b in the first control phase. Now, both users are operating in the TR-TR mode. After the second data phase, both users received ACKs, and the optimal policy in this example recommends continuing in the TR-TR mode. Hence, SU_a sends a continue-transmission (ACK-CTX) packet.

In Figure 2(b), the SUs continue the communication process, first operating in the TS-R mode and then switching to the TR-TR mode. After transmitting $P(5)_{(a \to b)}$, SU_a does not receive any confirmation from SU_b. Ideally, SU_b should retransmit packet 3 to SU_a in the next data phase. However, the optimal policy recommends using the TS-R mode. Hence, SU_a transmits a defer-transmission (NACK-DTX) control packet. SU_b saves packet 3 (P3) in the queue until it receives ST-TX control packet. In order to switch from the TR-TR mode to the TS-R mode, the MD will need to send either ACK-STX or NACK-DTX, depending

on whether or not the MD was able to decode the last received packet. Once the SD receives this control packet, it will stop transmission. The MD at this time can sense the spectrum during the subsequent data phases. If the MD decides to return to the TR-TR mode, it will send a ST-TX control packet to the SD, instructing it to start transmitting in the next data phase. The SD will check whether it still has negatively acknowledged packets or not. If so, the SD will retransmit this packet. If not, the SD will transmit a new packet.

5.2 Master and Slave Role Switching

In the discussion above, SU_a was assumed to be the MD because it was faster in initiating the communication with SU_b. However, SU_a does not operate as MD all the time. For instance, if at a later point SU_a no longer has data to transmit, but SU_b does, the SUs will switch their MD/SD roles and operate in the R-TS mode (assuming this mode is selected after the belief stage). Note that switching from the SO mode to the TR-TR mode requires the MD to first know whether the SD has more data or not by transmitting a ST-TX packet. The SD could respond by transmitting a packet (if it has any) or remain silent. Once the SD has more data to transmit, it will wait for the next control phase to notify the MD about its current status.

As discussed above, the MD is the node that is responsible for making various decisions. These decisions are made based on the belief update. Since the SD is not aware of this belief update, when MD/SD switch roles, the MD (which will become the SD) must transmit the belief update value to the SD that is becoming the MD. This information can be padded at the end of a packet, as needed. Figure 3 illustrates the process of switching roles between MD and SD. In the second data phase, both SUs have MP=1, which means that both users still have data to transmit. Since SU_a was the MD, it will continue in this role. In the third data phase, SU_a does not have more packets to send, while SU_b does. Hence, SU_b becomes the MD. This switching process can be accomplished in accordance with Tables 1 and 2 above. In the fourth data phase, nodes will operate in the R-TS mode, where SU_a is only receiving data and SU_b is transmitting and sensing the channel simultaneously. If SU_b decides to return back to TR-TR mode, it will need to transmit a ST-TX packet to SU_a.

5.3 Heterogeneous Spectrum Environment

In previous sections, we have assumed a homogeneous spectrum environment. The justification of this assumption is that signals transmitted by TV towers over TV whitespaces (54 - 698 MHz) have very good propagation characteristics and long range, while SU transmissions are usually short-range (e.g., an access point at home communicating with a hand-held device). As a result, the probability of having a heterogeneous spectrum environment is small.

However, to incorporate scenarios where actions' outcomes at different SUs could be different due to channel fading, we studied the case of a heterogeneous spectrum environment. The first issue that needs to be addressed is rendezvous (how SUs will meet on a specific channel). To solve this problem, all SUs should be doing spectrum sensing to maintain a backup-channel list (BCL) of idle channels. The two SUs exchange multiple packets (e.g., RTS, CTS), using the CCC, which include the BCLs of the two nodes. Once the two SUs agree on a specific channel, the initiator starts transmitting on that channel. Under the heterogeneous scenario, the TR-TR mode does not require any changes since the outcomes of the transmission/reception processes reflect the channel status at both the MD and SD.

There are two approaches for dealing with the TS-R mode in the heterogeneous scenario. Similar to the TR-TR mode, the TS-R mode takes into account the channel status at both ends of a link. As such, no modifications are needed to the TS-R mode. Further investigation of the TS-R mode reveals that the outcomes of the transmission process (ACK/NACK) reflect the channel status at the SD *only at the end of the transmission*, while the outcomes of the associated sensing processes (free/busy) at the MD reflect the channel status at the MD *for the whole transmission duration* due to the execution of multiple sensing processes during a single transmission. Hence, the second approach for dealing with the TS-R mode is to investigate simultaneous reception and sensing at the SD (i.e., TS-RS) [27]. We propose that once an SD detects a PU activity while operating in the RS mode, it emulates the PU signal by sending a similar PU signature to the MD. Since the MD is using waveform-based sensing to monitor the PU activity while transmitting, it will be able to detect the SD's signal (i.e., PU signature) and will stop transmission. Note that under the heterogeneous assumption the MD may not be able to detect the PU activity even if the SD detects it.

In the TR-TR or TS-R modes, the MD and SD are permitted to communicate on the PU channel, because the belief value about the PU activity is above the transmission threshold. Hence, the MD can inform the SD about the outcome of the optimal strategy via control packets. On the other hand, in the SO and CS modes, no transmission is permitted on the PU channel, hence, SUs need to communicate on the CCC. The question that we need to answer is, how the SD will know that it has to switch to the CCC. In contrast to the homogeneous scenario, in the heterogeneous case, both SUs should be sensing if the optimal operating mode is SO. When the MD decides to switch to the SO or CS mode, as recommended by the optimal strategy, it informs the SD about its operating mode via the CCC. After each operating mode, the SD sets a timer. If it does not hear any signal

from the MD, it knows that the MD is either in the SO or CS modes. The SD listens to the CCC to know the exact mode. If the operating mode is SO, the SD execute SO for the currently used channel to compensate for spectrum heterogeneity. It listens periodically to the CCC to check for any updates on the operating mode. On the other hand, if the operating mode is CS, the SD rebuilds its BCL and exchange it with the MD.

6 PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed design via numerical results, simulations, and hardware experiments.

6.1 Setup

Unless indicated otherwise, we set the sampling frequency $f_S = 6$ MHz, the SU transmission power to 20 dBm, the noise power to -90 dBm, $T_S = 1$ sec, $m = 30$, $T = 30$ secs, $\delta_0 = 0.01$, $\delta_1 = 0.99$ and the received PU SNR at the SU receiver to be 10 dB. For the simulations, we use LabVIEW 2014 software, developed by National Instruments. The simulation and hardware setups are as follows. We assume that the spectrum consists of two frequency channels, ch1 ($f_{c1} = 2.4$ GHz) and ch2 ($f_{c2} = 2.45$ GHz), which are utilized by two primary links. The PU activity over each channel is assumed to be an alternating ON-OFF random process, where the PU ON and OFF durations are uniformly distributed in the range $[0, 500]$ secs and $[0, 1000]$ secs, respectively. An ON period represents a continuous transmission of consecutive packets. We assume that the PU and SU signals are QPSK modulated, each with packet length of 500 bits.

Because the SOA is not the scope of this paper, we use a simple version of this algorithm. Specifically, the SU starts by sensing ch1. If ch1 is idle, the belief is set to $1 - P_f$ and then the SU determines the next optimal action according to this belief. If ch1 is busy, the SU switches to sensing ch2, and so on. We also compare the proposed scheme against the LBT scheme. In the LBT scheme, the two SUs' set of actions is {TO, SO, CS}. An SU starts the LBT scheme with the SOA. Once a channel is believed to be idle, the SU transmits on that channel (i.e., TO mode). If the SU gets an ACK, it switches to the SO mode; otherwise it switches to the CS mode. In the SO mode, the SU senses the channel in an HD fashion. If it gets an idle outcome, it switches to the TO mode; otherwise it switches to the CS mode.

For the hardware experiments, we use six NI USRPs 2922 and LabVIEW. Two USRPs (SU_a and SU_b), each equipped with two antennas, are used to represent the SU link. In the TS/TR mode, an SU transmits its signal on one antenna and receives the intended signal or senses the spectrum on the other antenna. Note that with more advanced SIS techniques, FD communications can be enabled using a single antenna, in addition to a circulator, and an analog cancellation circuit [28]. Because we are not interested in developing new SIS techniques, for simplicity we use two antennas per device to enable FD communication. These two SUs opportunistically access one of the two available channels (ch1 and ch2). ch1 is used by a pair of USRPs

(a) PU transmitted signal
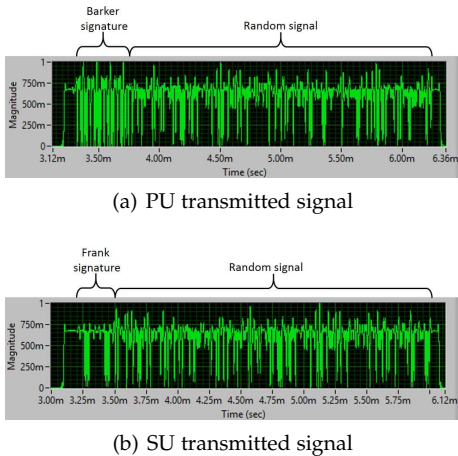

(b) SU transmitted signal

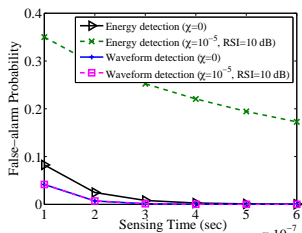Fig. 4: Transmitted PU and SU packets in the hardware experiments.

Fig. 5: False-alarm probability vs. sensing time for FD sensing.

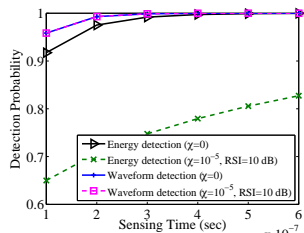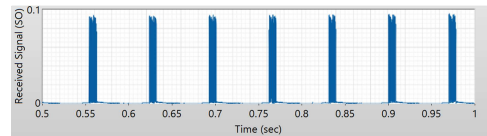Fig. 6: Detection probability vs. sensing time for FD sensing.

(a) Received signal by the SU while sensing the spectrum
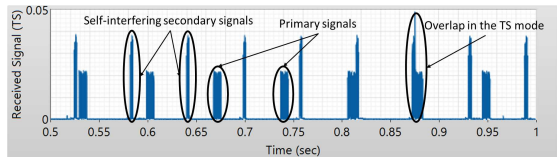

(b) Energy-based sensing outcome under the SO mode

(c) Waveform-based sensing outcome under the SO mode

Fig. 7: Testing energy- and waveform-based sensing for the SO mode.

$(PU_1$ and $PU_2)$, while ch2 is used by another pair $(PU_3$ and $PU_4)$. Since we are interested in testing the behavior of SUs while operating in FD fashion, we let the PUs operate in the traditional HD mode.

To enable the TR and TS modes at the SUs, we use analog and digital domain SIS techniques. In the analog domain, we use antenna separation [29] and exploit the antenna gain patterns to reduce the intensity of the undesired self-interference signal. In the digital domain, we first estimate the self-interference channel offline. Then, we use this channel estimation along with the known self-interference signal to subtract it from the received signal and partially cancel the RSI. The PU transmitted signal is shown in Figure 4(a). The PU uses a length-11 Barker sequence as its training sequence, while the SU uses length-16 Frank sequence, as shown in Figure 4(b).

6.2 Simultaneous Transmission-and-Sensing

We evaluate the performance of energy detection and waveform-based sensing when used in the TS mode. Figures 5 and 6 depict P_f and P_d versus the sensing duration for two values of χ. These results were obtained numerically based on the analysis in Section 3. Expectedly, the performance of any spectrum sensing technique improves (i.e., P_f decreases and P_d increases) with the sensing duration, as more samples are being used for PU detection. Also, as χ increases the performance of the energy detection scheme degrades significantly, due to the increase in the RSI. On the other hand, waveform-based sensing can sustain relatively high RSI levels. At perfect SIS, P_f and P_d converge to the HD case.

The hardware experiments can be divided into two parts. First, we test energy-based and waveform-based sensing under the SO mode to get a reference point. Second, we repeat the experiments for the TS mode. The PU's packet length is set to 1500 bits.
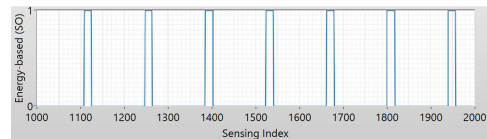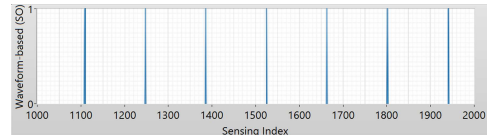
In the following set of experiments, we turn on one primary link (PU_1 and PU_2) to transmit packets continuously and test the SO mode. The received signal at SU_a is shown in Figure 7(a) for a capture time of 500 ms (the capture time is the interval during which we keep receiving the transmitted signal). We implement energy-based sensing in the experiments as follows. At a sampling rate of 2 M samples/sec, SU_a receives about 1 M samples during the given capture time. It carries out consecutive sensing actions, each with 1000 samples. SU_a calculates the average energy in these samples and compares it to a threshold ($= 2 \times 10^{-5}$) to determine the PU state. Figure 7(b) shows the outcome of the energy-based sensing technique, where "1" means that a PU signal is detected and "0" otherwise. The x-axis in Figure 7(b), labeled 'sensing index', represents the index of the sensing action. Figure 7(c) shows the outcome of waveform-based sensing. During a single sensing period, SU_a calculates the maximum correlation between the barker sequence and 1000 samples of the received signal. It then compares the correlation value to a threshold, selected empirically, to determine the state of the PU.

To test the TS mode, we simultaneously activate one PU link and let the SU link operate in the TS mode. We conduct two types of experiments and show only one of them because of space limitation. The first case (not shown) is the scenario where the received PU signal power is high. In this case, both energy- and waveform-based sensing can successfully detect the PU signal. In the second scenario, the received PU signal power is weak. As shown in Figure 8(a), in the TS mode, the SU may receive the RSI signal alone, the sensed PU signal alone, or both of them overlapped. The outcome of energy-based detection is shown in Figure 8(b), where SU_a falsely declares the residual-self-interfering signal as a PU signal. On the other hand, waveform-based sensing, shown in Figure 8(c), correctly differentiates between different signals.

(a) Received signal by the SU while sensing the spectrum
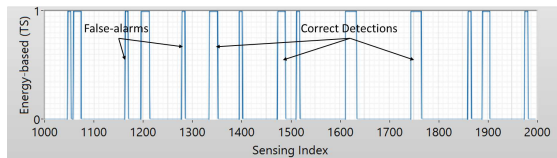
(b) Energy-based sensing under the TS mode
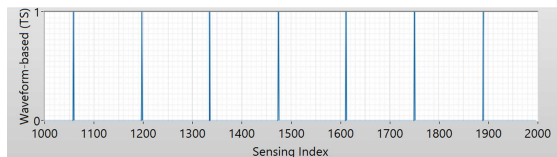
(c) Waveform-based sensing under the TS mode

Fig. 8: Testing energy- and waveform-based sensing for the TS mode under imperfect SIS.

6.3 Adaptive SU Strategy

Figure 9 shows the time variation in the PU collision probability for the TR, TS, and TO modes (obtained based on analytical results). As t increases, the collision probability increases, because the PU is more likely to return to the channel. The SU can achieve a lower collision probability in the TS mode than in the TR mode. In Figure 10 we show the achievable SU throughput in the TS and TR modes at different values of χ. The throughput in the TR mode decreases as χ increases due to RSI. Hence, working in a FD fashion is not always optimal, especially at high χ values.

For the numerical analysis of the adaptive strategy, we use backward induction to determine the optimal thresholds and the maximum SU utility. We set $\eta = 0.3, P_{TR}^* = 0.2, P_{TS}^* = 0.4, P_f = 0.01, P_d = 0.99, SNR^{(HD)} = 20$ dB, and $\bar{Y} = 2000$. The variations in β_r, β_s and β_c with t are shown in Figure 11. The SU operates in the TR mode as long as $p_t \geq \beta_r$. It switches to the TS mode when $\beta_s < p_t < \beta_r$, and to the SO mode when $\beta_c \leq p_t < \beta_s$. Finally, the SU switches to a new channel when $p_t < \beta_c$. The SU should also switch to a new channel if $t > t^*$, as the PU is more likely to return to the channel, which explains the convergence of β_r, β_s and β_c to 1 when $t > t^*$. Note that β_c is constant for $t < t^*$ because it depends on the channel availability statistics. Hence, $\beta_c = 500/2500 = 0.2$ according to this setup. Figure 12 depicts the maximum SU utilities in the TR, TS, SO, and CS modes as a function of p_t. The final SU utility is the maximum of these four utilities. Note that the utility in the CS mode is constant with p because it is independent of the SU belief in the currently used channel. The abrupt reduction in the SU utilities in the TR and TS modes is due to the violation of the PU collision probability constraints.

We use LabVIEW to simulate the proposed adaptive scheme, referred to as TSRA, and compare its performance with the LBT scheme. Some Figures are drawn with a 95% confidence interval. Figures 13 and 14 show the histogram of the selected mode for the LBT scheme and TSRA, respectively, vs. the noise power (PU traffic load is 0.1). In contrast to the LBT scheme, and because of the belief update process in TSRA, SUs can keep track of the PU activity in a probabilistic fashion. Hence, as the SNR decreases (i.e., noise power increases), the SU starts getting more negative results (busy sensing outcomes, NACK, etc), which forces the SU to be more conservative. As shown in Figure 14, this conservative approach forces the SU to decrease its blind communication (i.e., the TR mode) as noise power increases, while increasing the TS occurrence frequency to be able to monitor the PU activity while transmitting. Note also the increment of the SO occurrence frequency with noise power to protect the PU from collisions.

Figures 15 and 16 depict the average throughput and collision rate, respectively, as functions of the noise power for TSRA and the LBT scheme. In some cases, TSRA achieves up to 2x throughput gain over the standard LBT scheme, and reduces the average collision rate by more than 30%. To study the impact of the PU traffic load (the average PU ON period divided by the sum of the average ON and OFF periods), we let the OFF period be uniformly distributed in the range $[0, 1000]$ and change to the parameters of the uniformly distributed ON period to achieve different traffic loads. Noise power is -6 dBm. Figures 17 and 18 show the histogram of the mode occurrence frequency for the LBT and TSRA, respectively, as a function of the PU traffic load. As shown in Figure 17, the CS occurrence frequency increases with the PU traffic load because of the reduction in the white spaces of the spectrum. In Figure 18, the TR occurrence frequency is dominating at low PU traffic load because of the available white spaces and the belief update process (In contrast to Figure 17, where the SU should sense the spectrum before any transmission). Similar to the LBT case, the CS occurrence frequency increases with the PU traffic load because of the shortage of the white spaces.

Figures 19 and 20 show the variation of the average throughput and the average collision rate, respectively, with the PU traffic load for TSRA and the LBT scheme. As shown in Figure 19, the average SU throughput decreases with the PU traffic load because of the reduction in the available white spaces. Also, the SU can achieve much higher throughput while operating in TSRA compared to the LBT scheme. At the same time, the SU can achieve much lower collision rate on average while operating under TSRA compared to the LBT scheme.

For hardware experiments, the histograms of the modes occurrence frequency of the SU link versus the PU traffic load are shown in Figures 21 and 22 for the LBT and TSRA schemes, respectively. Similar to the simulations, we found from the experiments that the SU can achieve much higher throughput while operating in TSRA compared to the LBT scheme (see Figure 23). As shown in Figure 24, the SU can achieve much lower average collision rate under TSRA compared to the LBT scheme. During the hardware experiments, we faced some challenges such as complexity and delay. Since the designed LabVIEW code was a bit heavy for the desktops, there was a delay in the switching process between different modes, which sometimes makes a problem in coping with the fast varying PU dynamics. Furthermore, there was high communications overhead be-
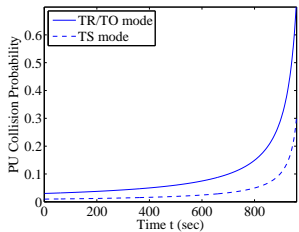
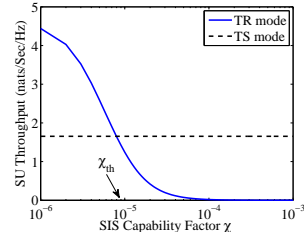Fig. 9: PU collision probability vs. t when $p_t = 1$ and $P_f = 0.1$.

Fig. 10: SU throughput vs. χ ($p_t = 1$, $P_f = 0.01$, $P_d = 0.99$).
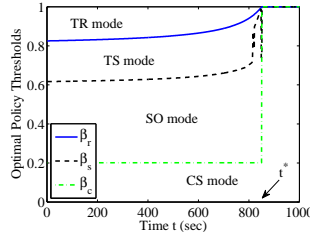

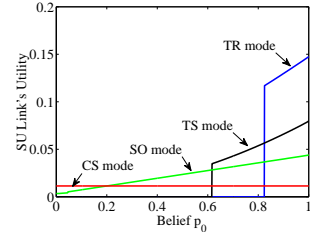Fig. 11: Optimal policy thresholds vs. t.
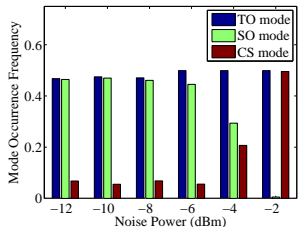

Fig. 12: SU utilities vs. the belief at $t = 0$.

Fig. 13: Histogram for the SU modes under the LBT scheme as a function of the noise power.
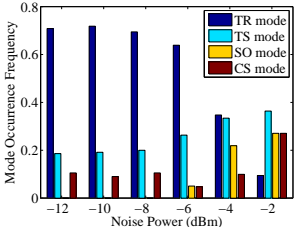

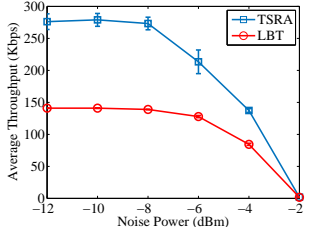Fig. 14: Histogram for the SU modes under TSRA scheme as a function of the noise power.

Fig. 15: Average SU throughput vs. noise power in dBm for TSRA and LBT schemes (Simulations).
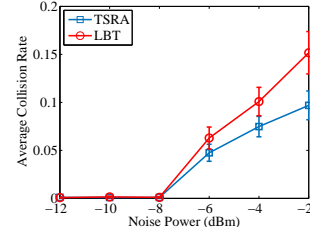
Fig. 16: Average SU collision rate vs. noise power in dBm for TSRA and LBT schemes (Simulations).
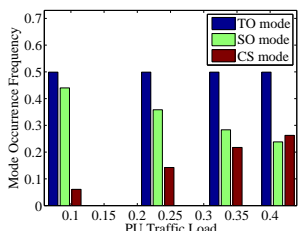
Fig. 17: Histogram for the SU mode under the LBT scheme vs. the PU traffic load.
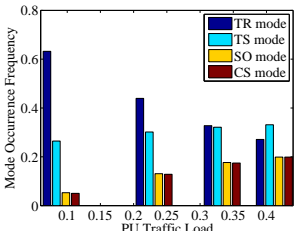

Fig. 18: Histogram for the SU mode under TSRA scheme vs. the PU traffic load.
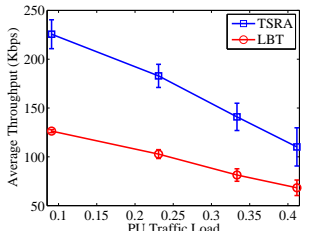

Fig. 19: Average SU throughput vs. PU traffic load for TSRA and LBT schemes (Simulations).
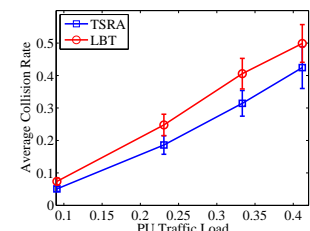

Fig. 20: Average SU collision rate vs. PU traffic load for TSRA and LBT schemes (Simulations).
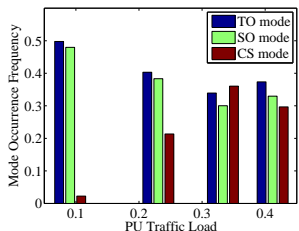

Fig. 21: Histogram for the SU mode under the LBT scheme vs. the PU traffic load (Hardware).
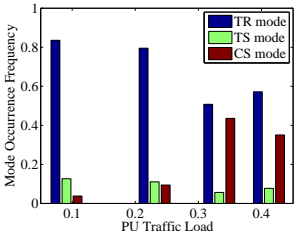

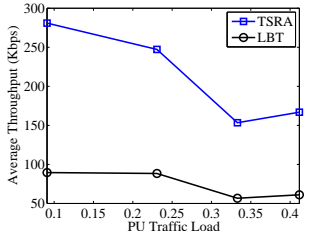Fig. 22: Histogram for the SU mode under TSRA scheme vs. the PU traffic load (Hardware).

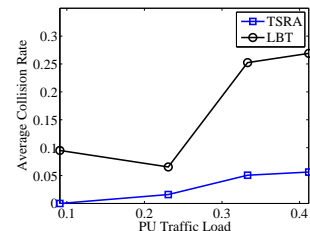Fig. 23: Average SU throughput vs. PU traffic load for TSRA and LBT schemes (Hardware).

Fig. 24: Average SU collision rate vs. PU traffic load for TSRA and LBT schemes (Hardware).

tween the USRPs and the desktops via the Ethernet cables, which causes delay. One solution for these problems is to implement our code on FPGAs.

7 CONCLUSIONS

Motivated by recent advances in FD communications and the tradeoff between spectrum awareness (simultaneous transmission-sensing (TS) mode) and spectrum efficiency (simultaneous transmission-reception (TR) mode) in OSA systems, we propose TSRA, which consists of two main components. First, we propose a three-stage switching strategy that determines "when" SUs switch between different FD/HD modes. A threshold-based strategy is obtained, which depends on the SU's belief regarding the idleness of the PU. Our results indicate that the SU should operate in the TR mode if it has a high belief that the PU is idle. As this belief decreases, the SU should adaptively switch to the TS mode to monitor any change in the PU activity while

transmitting. At very low belief values, where the PU is more likely to be active, the SU should stop communication over this channel and either solely sense the spectrum or switch to another channel. Second, we propose a wireless protocol design to determine the switching mechanism (i.e., "how" SUs will switch between modes). To enable the TS mode, we explore different candidates for spectrum sensing techniques in the presence of RSI.

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