Distributed Opportunistic Spectrum Access Networks: From Theory to Practice

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***Abstract*—Opportunistic Spectrum Access (OSA) is foreseen as the future of wireless communications. OSA relies on the cognitive radio transceiver that tracks the spectral opportunities over a wide spectrum range (multiple GHz). The cognitive radio should be able to analyze the huge amount of acquired spectral information, decide the best course of action, and reconfigure its transceiver parameters accordingly in a very short time due to the highly dynamic nature of the radio environment. This poses stringent requirements on the hardware and processing power of the transceiver. Despite the recent advances in the radio transceiver technologies, existing radios do not allow for exploiting OSA to its full potential. Furthermore, the absence of a centralized entity that controls the spectrum access decisions in distributed ad-hoc networks makes implementing OSA more challenging. In this article, we experimentally demonstrate the ability of implementing distributed OSA schemes given the practical limitations of existing low-cost transceiver technologies. Furthermore, we evaluate the performance of different OSA approaches.**

I. INTRODUCTION

Opportunistic Spectrum Access (OSA) is a promising technique for tackling the spectrum scarcity problem by exploiting temporally unutilized spectrum bands [1]. Opportunistic access schemes are the focus of significant research interest, especially from a theoretical perspective. The resulting theoretical approaches are challenged by the practical limitations of cognitive radios: the key enabling technology of OSA. Our focus is on the less well-studied issue of implementing distributed opportunistic spectrum access techniques given practical radio transceiver technologies and to characterize the gains provided by different OSA approaches in real systems.

On the one hand, a cognitive radio transceiver is required to track the radio activities over a wide spectrum range (multiple GHz) in order to identify any available spectral opportunities that can be exploited. This places stringent requirements on the sensitivity, linearity, and dynamic range of the circuitry in the RF front-end, and more specifically, the antennas, power amplifiers and the analog-to-digital conversion units. Furthermore, a cognitive radio should be able to analyze the huge amount of acquired spectral information, decide the best coarse of action, and reconfigure its transceiver parameters accordingly in a very short time. Note that the OSA environment is highly dynamic due to both channel fading and the bursty nature of the traffic of the primary owners of the spectrum. This increases the processing power requirements of the signal processing units. Despite the recent advances in the radio transceiver technologies, existing radios do not allow for exploiting OSA to its full potential.

On the other hand, the absence of a centralized entity that controls the spectrum access decisions – as the case with the IEEE 802.22 standard – in distributed ad-hoc networks makes OSA more challenging. Node cooperation techniques and explicit inter-flow coordination can be used in distributed OSA networks. However, such techniques induce other implementation challenges due to the requirement of global network synchronization or information gathering and distribution mechanisms which further increase the complexity of implementing distributed cognitive radio networks.

In this article, we use the Wireless open-Access Research Platform (WARP) to demonstrate the ability of realizing distributed OSA given practical low-complexity radio transceivers [2]. WARP is well recognized by both the academic and industrial research communities for clean-slate prototyping. First, we instrument the basic functions common to different OSA approaches. Then we implement a suite of OSA schemes using this implementation framework. Our goals are to assess the gains of practical OSA techniques and to demonstrate how theoretical OSA approaches (originally developed for fully-capable radio transceivers) can benefit the individual practical components to cope up with the limitations of today's radio transceiver technologies.

The remainder of the article is organized as follows. In Section II, we overview the available implementation platforms. In Section III, we describe our hardware implementation framework. Then, we briefly present the OSA protocols we use for our performance evaluation in Section IV. In Section V, we present an extensive set of experiments to evaluate the performance of different OSA approaches. We conclude in Section VI.

II. HARDWARE PLATFORMS

A. Platform Requirements

Two main features are necessary for a candidate platform to be eligible to implement opportunistic spectrum access protocols:

- *Cognitive capability* that enables the platform to infer the current occupancy of the spectrum. The spectrum utilization information should be continuously available and updated at the spectrum allocation module of the platform so that the appropriate transmission parameters are set. Two spectrum sensing approaches can be used: wide-band sensing and narrow-band. Wide-band sensing requires a multi-GHz front-end transceiver to scan the entirety of the spectrum. However, wide-band sensing results in delayed spectrum utilization information that affects the accuracy of the spectrum access decision. On the other hand, narrow-band sensing only investigates the utilization of a small portion of the spectrum, and hence, can lead to missing spectrum access opportunities. However, the fast response in narrow-band sensing better tracks the dynamic nature of spectrum utilization. Our empirical performance evaluation study assumes cognitive radios with narrow-band sensing capability as the case with the wide-range of commercially available transceivers.
- *Re-configurability* of the RF module of the platform that allow the operating parameters of the transceiver to be configured on the fly (i.e., in real time) without making any changes to the hardware components that affect the radio emissions. The main transceiver parameters to be configured are the operating frequency band, modulation type and transmission power.

B. Overview of Existing Platforms

Existing hardware/software platforms that can be used to implement opportunistic spectrum access protocols can be classified into two main classes: Software Defined Radio (SDR)-based and Field Programmable Gate Array (FPGA)-based platforms. SDR platforms are implemented via the integration of the GNU Radio that is a software development environment [3] and any of the Universal Software Radio Peripheral (USRP) product family that is used as the RF interface of the platform [4]. SDR platforms provide more flexibility in implementing spectrum sensing and spectrum management since they rely on software to implement such functionalities. Different open-source GNU radio software specifically written for cognitive radio networks are available such as the Cognitive Radio Open Source System (CROSS) [5], and the Papyrus software platform [6]. However, the throughput and latency of the prototypes implemented via SDR platforms are one to three orders of magnitude worse than realistic hardware designs and lag far behind the requirements of real-world communication schemes such as IEEE 802.11 [7] - despite their low cost.

On the other hand, FPGA-based platforms offer orders of magnitude improvement in the latency and throughput performance at the expense of increased hardware complexity and cost. An FPGA-based platform is often composed of a hardware component that consists of a compact FPGA board which implements the physical and link layers associated with a software environment that provide the basic physical and MAC layers functionalities and interfaces to the hardware component that allow the researchers to program the hardware as desired. Thus, FPGA-based systems combine the programmability of software and the high performance and predictability of hardware. Although other platforms exists (e.g., AirBlue [7]), we have chosen the Wireless open-Access Research Platform (WARP) [2] FPGA-based platform for our empirical performance evaluation study. A prototype of OSA implementation using WARP was presented in [8]. However, that prototype is a derivative of the IEEE 802.11 medium access approach. In contrast, we present the first implementation and performance evaluation of clean-slate opportunistic spectrum access approaches.

III. Opportunistic Spectrum Access Implementation Framework

The Wireless open-Access Research Platform (WARP) is an FPGA-based hardware platform with an open-source repository of wireless building blocks and reference designs [2]. The WARP implements an OFDM transceiver on the fabric of the FPGA. WARP is ideal for clean-slate medium access prototyping through a flexible interface between the physical and medium access layers. Using the WARP OFDM physical layer, we develop a framework for implementing OSA protocols. The OSA implementation framework is written in C-langauge, compiled and downloaded to one of the PowerPC cores of a WARP board where it directly interacts with the physical layer implementation.

Our implementation framework instruments the basic functionalities commonly used by different distributed opportunistic spectrum management schemes. We implement the following four mechanisms using the WARP OFDM reference design version 14: *(i)* spectrum sensing, *(ii)* common control channel, *(iii)* spectrum coordination packet handshake, and *(iv)* multi-rate multi-power packet transmission.

- **Spectrum Sensing.** The purpose of this function is to measure the cumulative interference of a given spectrum band and determine whether it is below the power mask of the corresponding primary network or not. This is realized by monitoring the received signal strength indicator (RSSI) averaged over a certain time window. By comparing the time-averaged RSSI with the spectrum power mask, an opportunistic spectrum access protocol can determine whether this band is clear (RSSI $<$ Power Mask) or not (RSSI $\geq$ Power Mask).
- **Common Control Channel.** Distributed opportunistic spectrum access protocols require a means by which a cognitive sender coordinates its spectrum decisions with its intended receiver. A common control channel is generally used for this purpose. Both the senders and the receivers are continuously listening to this channel if not involved in an active data exchange. We define channel 14 of the 2.4 GHz ISM band as the common control channel. Channel 14 of the 2.4 GHz band is not available for commercial purposes in the United States and can only be used for academic research. Using such a channel guarantees a robust common control channel.

- **Spectrum Coordination Packet Handshake.** We create the control packets to be exchanged over the common control channel for cognitive sender-receiver coordination. These control packets do not include any payload bytes and only include the sender and the intended receiver addresses in addition to other protocol-dependent control information such as the selected spectrum, the measured RSSI, the modulation rate, etc. For the tested OSA protocols, we only need a two-way control-message handshake in which the sender informs its receiver with its spectrum selections via a control packet and the receiver confirms or denies such selections with another control packet. The control packet handshake is transmitted using the base rate realized via the WARP QPSK modulation scheme.
- **Multi-rate Multi-power Packet Transmission.** Finally, we implement a data packet transmission scheme which parameters are configured on a packet-per-packet basis. For the considered opportunistic spectrum management schemes we allow the protocol to configure the transmission channel, the modulation rate and power. A data packet can use one out of three WARP modulation schemes: BPSK, QPSK, and 16 QAM with respective transmission powers of 12 dBm, 15 dBm, and 18 dBm.

IV. PROTOCOL IMPLEMENTATIONS

Our objective is not only to demonstrate the advantages of practical OSA approaches but also to study how much gain is attributed to their individual components. Moreover, we also show how traditional OSA approaches can benefit from the individual practical components. Consequently, we implement the following suite of OSA protocols needed for our empirical performance evaluation.

- **Random Sensing with Probabilistic Access.** The first OSA protocol we implement is the RAP-MAC protocol that we developed in [9] for low-complexity and practical cognitive radio networks. To counter the lack of a mechanism to assess the interference at the primary receivers and to avoid the overhead of explicit inter-flow coordination, RAP-MAC adopts random spectrum selection combined with a rate-adaptive probabilistic transmission policy. The random sensing component relaxes the requirements of the sensing module of a cognitive radio (since it does not require a wide-band front-end). Meanwhile, the rate-adaptive probabilistic component *(i)* counters the unavoidable inaccuracy in spectrum sensing due to hidden and exposed primary nodes (since spectrum sensing techniques only measure the transmission activities of the primary senders), and *(ii)* prevents a single cognitive sender-receiver pair from monopolizing a spectral opportunity, and hence, alleviates the need for explicit inter-flow coordination. We refer to such an OSA approach as random sensing with probabilistic access.
- **Sequential Sensing with Greedy Access.** This implementation reflects a wide range of existing opportunistic spectrum access protocols (e.g., [10], [11]). In such schemes, a cognitive radio node senses all of the available spectrum bands before deciding which band to use. Like other low-complexity single-radio transceivers, the WARP transceiver can be tuned to only one frequency channel at a time. Therefore, we implement a sequential spectrum sensing mechanism in which a cognitive node goes over the channels of interest and reports back the RSSI of individual channels. Unlike the RAP-MAC approach, such schemes adopt deterministic and greedy access mechanisms in which a sender only transmits if there exists a spectrum which its measured RSSI is below the power mask. Furthermore, they transmit using the highest possible power and rate for all the time. We use a modified version of the protocol presented in [11] for our implementation that is adapted to the limited capabilities of used hardware.
- **Sequential Sensing with Probabilistic Access.** The second protocol that we use for comparison is a derivative of the above implementation which still depends on sequentially scanning all of the available spectrum bands before deciding the best spectrum to use. However, this protocol adopts a probabilistic and non-greedy spectrum access approach similar to that developed for the RAP-MAC protocol instead of using deterministic and greedy spectrum access. Such a protocol helps identifying how much gain can be achieved by using a probabilistic access mechanism if adopted by the wide range of existing protocols that rely on greedy access strategies. Furthermore, this protocol implementation allows us to assess how much gain is due to random sensing since the sensing mechanism is the only difference between RAP-MAC and this protocol implementation.
- **Random Sensing with Greedy Access.** We also implement a variant of the RAP-MAC protocol which uses randomized sensing in conjunction with a greedy spectrum access mechanism. We refer to this protocol implementation as the random sensing with greedy access protocol. The greedy access mechanism of this protocol is the same one used by the sequential sensing with greedy access protocol. Hence, this protocol allows us to quantify the performance gain of randomized narrow-band sensing compared to sequential wide-band sensing. Furthermore, comparing the performance of this protocol implementation against the RAP-MAC illustrates the contribution of the probabilistic access component in the overall gain as will be demonstrated by our experiments.

V. PERFORMANCE EVALUATION

A. Experimental Setup

Implementing a cognitive radio network (CRN) environment poses significant design challenges. For example, any opportunistic spectrum access experiment requires the creation of multiple primary networks (PRNs) which spectral opportunities can be exploited by the cognitive radio network users when the primary users are inactive. Thus, the experiments must provide controllable primary network flows.

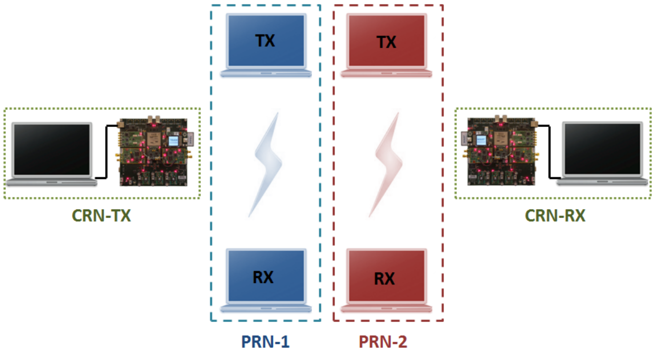


Fig. 1. Illustration of the experiment setup.

Furthermore, the experimental setup must keep track of every cognitive radio network transmission as well as every primary networks' transmission and reception in order to assess the CRN decision mechanism and the outage performance of the primary networks, respectively.

Primary Networks Implementation. For our experiments, we create two primary networks each composed of a single sender and a single receiver. In order to have full control over the primary networks' performance and to not harm existing licensed networks, we configure the two primary networks to operate over non-overlapping channels in the unlicensed 2.4 GHz ISM band. More specifically, we configure the first PRN to use channel 1 of the 2.4 GHz and the second PRN to use channel 7 of the same band. We use laptops equipped with IEEE 802.11 wireless cards to create the primary networks. The transmission power of each network is set to 18 dBm and the physical layer transmission rate is set to 11 Mbps with the auto-rate feature turned off. We use *iperf* to generate a UDP flow from each primary sender and collect the UDP flow statistics at the corresponding receiver. We measure the backlog UDP capacity of the two primary network in the absence of any cognitive radio network activities to be 6.03 Mbps and 6.15 Mbps, respectively.

Cognitive Radio Network Implementation. We create a cognitive radio node by connecting a laptop (with its wireless interface disabled) to a WARP board via the WARP Ethernet port. By downloading the appropriate bit file of any of the implemented opportunistic spectrum access protocols to a WARP PowerPC, the WARP board will act as the wireless air interface of the laptop that runs that particular OSA protocol. We create a fully backlogged cognitive radio transmission between two such cognitive radio nodes using *iperf*. The cognitive radio sender and receiver nodes are at equal distance of approximately 2 meters from the senders and receivers of the two collocated primary networks. Figure 1 depicts a layout of the experiment setup.

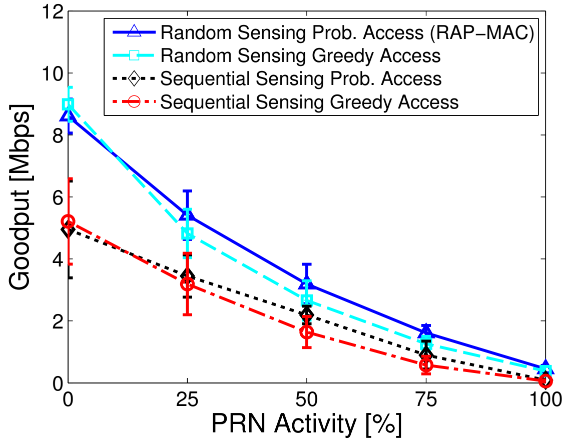
Our performance metrics are both the goodput of the cognitive radio flow as well as the outage probability of both primary networks. The reported results in the next subsection are the average of five runs each of one minute length. We run the experiments between midnight at the early hours of the morning to minimize the potential uncontrolled transmission activities over the used channels.

B. Experimental Results

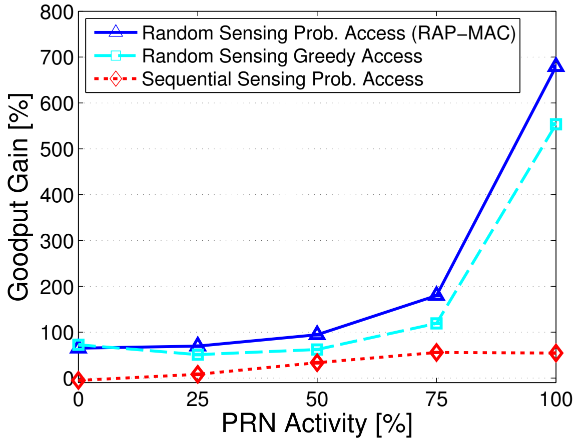
1) Baseline Experiment: We start by characterizing the performance of probabilistic access protocols in the worst-case scenario in which the primary networks are fully utilized. Our goal is to identify the values of the parameters of the rate-adaptive probabilistic component. Note that the optimal parameter values analytically derived in [9] do not directly apply to our testbed setup. We perform a two-dimensional sweep of the probability of transmission when the spectrum is clear and unclear. We found that the values that achieve the highest cognitive radio flow goodput while resulting in primary networks' outage below 5% to be 0.4 and 0.4, respectively. We use these values for the rest of our experiments.

2) CRN Goodput Performance: Figure 2 illustrates the goodput achieved by the cognitive radio flow according to different protocol implementations versus the primary network activity. As shown in Figure 2(a), the practical random sensing with probabilistic access approach achieves the highest goodput while the sequential sensing with greedy access approach – widely used for OSA – results in the lowest goodput. The goodput gain ranges from 66% to 673% depending on the PRN activity. Using the goodput of the other two implementations we found that 70% to 80% of this gain is attributed to random sensing while the remaining percentage is due to the non-greedy probabilistic access. Furthermore, either techniques can be used to improve the performance of the family of spectrum management approaches that use sequential sensing with greedy access as depicted in Figure 2(b).

3) PRN Outage Performance: Next, we evaluate the outage performance of the primary networks for the different opportunistic spectrum access protocol implementations. Two observations can be made regarding the outage probability curves depicted in Figure 3. First, probabilistic access schemes result in slightly higher PRN outages compared to their greedy access counterparts. However, probabilistic access has a weaker impact on the PRN outage when sequential sensing is used. With the inaccuracies of random sensing, the impact of probabilistic access increases. Second, random sensing results in approximately 2.6 times the outages due to sequential sensing protocol irrespective of the access protocol. This is because sequential sensing protocols assess the interference levels on both channels before deciding the transmission action. On the other hand, random sensing protocols simply pick a channel at random for transmission. Note that despite resulting in higher primary network outages, random sensing protocols including RAP-MAC adhere to the targeted 5% maximum outage constraint. However, the significant multi-fold goodput gain of such protocol illustrated in Figure 2 outweighes the excess primary outages resulting from such protocols. Furthermore, as the number of the primary networks increases, the sensing time required to assess the interference on all channels will increase. Hence, the RAP-MAC goodput gain is expected to further increase.

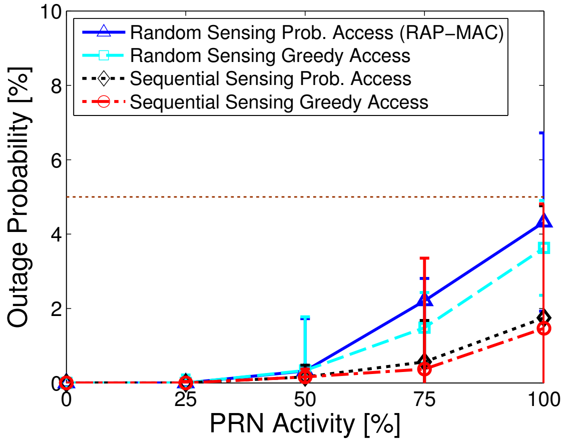


(a) CRN flow goodput.

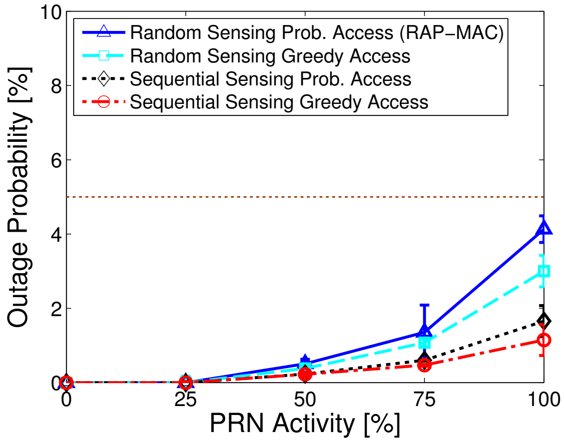


(b) Gain w.r.t. sequential sensing with greedy access.

Fig. 2. RAP-MAC achieves significant goodput gain over traditional opportunistic spectrum access scheme. While both components contribute to the overall gain, the goodput gain due to randomized sensing is higher than the gain due the probabilistic access mechanism.



(a) Primary network operating using channel 1.



(b) Primary network operating using channel 7.

Fig. 3. The outage probability of the primary networks versus the activity factor for different protocol implementations. While both satisfy the 5% PRN outage constraints, random sensing results in more primary outages compared to sequential sensing.

VI. CONCLUSIONS

In this article, we have presented an experimental study of the less-well studied topic of distributed opportunistic spectrum access implementation. Our goal is to demonstrate that while existing hardware technologies do not provide the cognitive transceiver requirements needed to exploit OSA to its full potential, suboptimal OSA approaches developed to target low-complexity transceivers can achieve significant performance improvement compared to theoretically-optimal approaches. We have also shown that other theoretical OSA approaches can exploit the gains of individual practical components.

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