On Reducing Multiband Spectrum Sensing Duration for Cognitive Radio Networks

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***Abstract*—In this work, the total spectrum sensing duration required for cognitive radios in multiband environments is studied to minimize the reactive handoff latency. Two spectrum sensing strategies, namely window-based and sample-based sensing, are evaluated to estimate channel workload and idle time probability. Channel workload is the percentage of time the band is used by other wireless networks. Idle time probability is defined as the probability of usable durations for the cognitive radio communications. The mean square error performance of the estimations is provided for both sensing strategies in the case of energy detection based sensing and realistic interarrival time distribution of packets. It is shown that, sample-based strategy requires half of the total multiband spectrum sensing duration compared to its window-based counterpart, if the hardware switching delay is under a specific threshold.**

I. Introduction

Cognitive Radio (CR) is a term for radios that are aware of their surroundings and adapt their transmission parameters (including, but not limited to, carrier frequency and bandwidth) to the environment and the interference situation. There are four spectrum related functionalities that enable a CR to achieve the aforementioned goal: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility [1]. In spectrum sensing, CR nodes determine the interference and occupancy level at all bands available for operation. Based on spectrum sensing results, CR nodes could decide on the best available communication band. Spectrum sharing coordinates spectrum usage among different CR nodes and finally, if the conditions are not suitable in a band to continue the communication, spectrum mobility (Spectrum Handoff) suspends the transmission, vacates the band, and resumes ongoing communication using another vacant band.

In this project, we focus on reactive spectrum sensing with regard to reactive spectrum handoff in multiband environments. One of the major drawbacks of reactive spectrum handoff is the handoff latency due to on demand spectrum sensing [2]. In [3], a spectrum handoff strategy is proposed to reduce the unnecessary handoff operations while considering a delay bound requirement. Authors in [4] optimized the required sensing duration to avoid multiple spectrum handoffs due to false alarms.

Most of the research performed on spectrum sensing with respect to spectrum handoff, assumes exponentially distributed interarrival time of packets for the wireless traffic in the available bands [5]. Unfortunately, this assumption is not valid for networks utilizing carrier sense multiple access with collision avoidance (CSMA/CA). Since CSMA/CA is used by many wireless technologies, such as 802.11, sensing should be studied with respect to the actual packet interarrival time distribution experienced in CSMA/CA oriented environments. In [6], it is shown that the interarrival time of packets in such networks follows Generalized Pareto (GP) distribution. The expansion of the 802.11 standard to cognitive radio bands, such as TVWS [7], expands the validity of such distribution. Thus, the GP-distribution is adopted in our work.

Another important aspect of reactive spectrum sensing is the sensing method. Methods may differ greatly in their complexity and required information to provide sensing results. Among them energy detection is the least complex method which is based on sampling the spectrum band. Since it can be used by any radio, we study energy detection in our work. The sensing results should be converted to sensing metrics to enable decision making by the cognitive radio. Here, we are focusing on two of those metrics, namely channel workload and idle time probability. Channel workload is a well-known metric used by many communication standards. It is defined as the percentage time that the band is utilized by other wireless networks [8]. Another metric of interest is idle time probability, which was first introduced in [9]. This metric provides the usable idle duration available in a band that can be used for CR communications.

The last aspect we study is the methodology of sensing to reduce total multiband reactive spectrum sensing duration. Among the methods studied, Window-Based sensing aims to finalize sensing in a band before switching to another one. Whereas the second strategy relies on sensing samples obtained from all bands for a short period and repeats the process until a desired confidence level is achieved. We compared those methods in terms of latency and show that the second method requires much less time to capture metrics with the same amount of estimation error for a low hardware switching delay.

The overall structure of the paper is as follows. In Section II we provide the system model and the mathematical definition of the sensing metrics. Section III details the sensing strategies. Simulation environments, results and how the sensed samples are generated, are presented in Section IV. Finally, Section V concludes the paper.

II. System Model

In this paper, a cognitive radio pair (CR transmitter and receiver) is assumed to be communicating over congested ISM bands. The pair operates on a frame-by-frame basis, where each CR node must perform spectrum sensing at the beginning of the frame to detect which band is suitable for communication. The CR node can transmit or receive data in the remaining duration of this frame if the current operating band is assessed idle. Otherwise, the CR node will initiate spectrum handoff procedures to find the idle bands and then resumes its unfinished communications at one of the idle bands. We consider that this CR pair can access a set of N non-overlapping frequency bands, where each band could be modeled as an ON-OFF source alternating between ON (busy) and OFF (idle) periods. Any signals which are above a given threshold will be part of the ON period. For band $i(i = 1, 2, \cdots, N)$, the sojourn time of an ON period can be modeled as a random variable T^i_{ON} with probability density function (PDF) f^i_{ON}. Similarly, the sojourn time of an OFF period is given as T^i_{OFF} with the PDF f^i_{OFF}. We assume that ON periods are independent and identically distributed (i.i.d) and so are OFF periods. For band i the channel workload ρ_i is defined as the ratio of ON periods to the total duration and can be written as [8]

$$\rho_i = \frac{E[T^i_{ON}]}{E[T^i_{ON}] + E[T^i_{OFF}]}. \tag{1}$$

To estimate the workload we assume that energy detection based sensing is utilized by the CR receiver. To estimate T_{ON} and T_{OFF} periods, the received signal at CR receiver is partitioned into blocks of L samples. The receiver then performs decision if a block is a part of T_{ON} or T_{OFF} period. As a hypothesis testing problem, the null-hypothesis is observing only noise $\mathbf{v}$ and deciding T_{OFF}. The alternative hypothesis will be observing a signal $\mathbf{x}$ with noise and deciding T_{ON}. This can be formulated as

$$\begin{aligned} \mathcal{H}_0 &: \mathbf{y} = \mathbf{v} \\ \mathcal{H}_1 &: \mathbf{y} = \mathbf{s} + \mathbf{v} \end{aligned} \tag{2}$$

where $\mathbf{y} = [Y[1], Y[2], \cdots, Y[L]]^T$ is the received signal vector at the CR receiver, $\mathbf{s} = [S[1], S[2], \cdots, S[L]]^T$ is the transmitted signal by other radios in the sensed band and $\mathbf{v}$ is a zero-mean additive white Gaussian noise (AWGN) vector with variance σ_0^2. Considering the assumption that the transmission standards of the other users are unknown, we further assume that the signal vector $\mathbf{s}$ is also drawn from a complex Gaussian distribution with zero-mean and variance σ_1^2

$$\begin{aligned} \mathbf{v} &\sim \mathcal{CN}(0, \sigma_0^2) \\ \mathbf{s} &\sim \mathcal{CN}(0, \sigma_1^2) \end{aligned} \tag{3}$$

For the above detection problem, the optimal Neyman-Pearson detector is given by

$$T(\mathbf{y}) = \frac{1}{L}\sum_{i=1}^{L} |Y_i|^2 \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} \zeta, \tag{4}$$

where L is the symbol period and ζ is a fixed threshold that is determined by the desired probability of false-alarm. The test statistic $T(\mathbf{y})$ is χ^2 distributed with $2L$ degrees of freedom and the probability of false-alarm is given by

$$\epsilon = 1 - \Gamma(\frac{L}{2}, \frac{L\zeta}{2\sigma_0^2}) \tag{5}$$

where $\Gamma(a, x) = \frac{1}{\Gamma(a)}\int_0^x t^{a-1}e^{-t}dt$ denotes the regularized incomplete lower gamma function. The values of L and ζ are set as $L = 10$ and $\zeta = \sigma_0^2 + 6[dB]$ in order to ensure that $\epsilon < 10^{-4}$. In each band, CR node performs spectrum sensing and samples the band for specific time duration T_{Sense}. Afterwards these channel samples are divided into groups of L samples in a way that $LN_S = T_{Sense}f_s$, where N_S is the number of L-sampled groups and f_s is the sampling frequency. Finally, decision (4) is performed over each group and a vector of 1s and 0s with a size of N_S is given. This vector is denoted by $\mathbf{c}^i = \{C^i_1, C^i_2, \cdots, C^i_{N_S}\}$, where i refers to the index of the sensed band. Hence, the band i workload can be estimated as

$$\hat{\rho}_i = \frac{1}{N_S}\sum_{k=1}^{N_S} C^i_k. \tag{6}$$

The second metric of interest is called idle time probability and is related to packet based communication used by many CR systems. For a CR to transmit a data packet, a minimum duration would be necessary. We define such a duration as ψ. Any T_{OFF} duration which is longer than ψ can be utilized by the CR for transmission. The idle time probability can be calculated via finding the probability of the following event

$$P_{Idle} = P(T_{OFF} > \psi). \tag{7}$$

This probability indicates whether the sensed band is suitable for CR communications or not. Since we are sampling each band for a limited time duration, we define the following estimator to estimate the idle time probability

$$\hat{P}_{Idle} = \frac{\sum_{j=1}^{N_S} I\{T_{OFF_j} > \psi\}}{N_S} \tag{8}$$

($I\{.\}$ being the indicator function) and T_{OFF_j} is the idle duration derived from the sensing sequence $\mathbf{c}^i$. Regarding the mentioned metrics, i.e., channel workload and idle time probability, we consider if P_{Idle} is below a specific threshold (P_{Idle_t}) or workload $\hat{\rho}$ exceeds its threshold value ρ_t after sensing the current band used for CR transmission, spectrum handoff is triggered.

III. Sensing Strategies

Two spectrum sensing strategies are compared in order to estimate the metrics mentioned in Section II. These two strategies are called: Window-Based and Sample-Based sensing.

A. Window-Based Sensing

We illustrate the window-based sensing strategy in Fig. 1. In this strategy, the CR senses a band until it can estimate the workload as well as idle time probability, with an MSE below

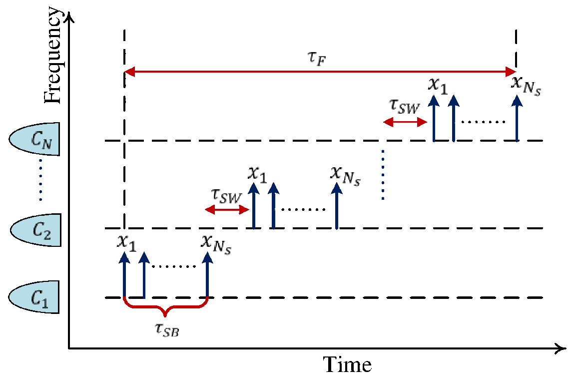

Fig. 1: Window-Based Sensing Strategy.

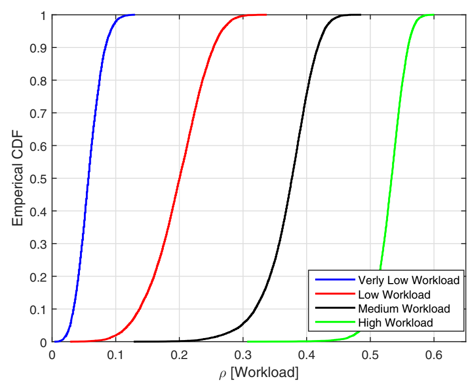

Fig. 2: CDF of channel workloads for different workload types.

a specific threshold η. The MSE for workload and idle time probability can be written as

$$MSE_{\rho} = E\{|\rho - \hat{\rho}_i|^2\} \leq \eta,$$
$$MSE_{P_{Idle}} = E\{|P_{Idle} - \widehat{P}_{Idle}|^2\} \leq \eta. \tag{9}$$

We define the required sensing duration as window size and denote it by τ_{SB}. The delay due to the hardware switching from one band to another is also considered and denoted by τ_{SW}. Therefore, total sensing overhead to sense all of the N bands can be calculated as

$$\tau_F = N\tau_{SB} + (N-1)\tau_{SW}$$
$$= N(\tau_{SB} + \tau_{SW}) - \tau_{SW}, \tag{10}$$

where τ_F denotes the total sensing overhead.

B. Sample-Based Sensing

As shown in Fig. 3, Sample-based strategy senses each band for a short amount of time before switching to the next one. It continues this process until estimation errors for both workload and idle time probability at all targeted bands are below the specific threshold η. Similar to Window-Based sensing, the sensing duration for all of the available channels can be calculated as

$$\tau_{Total} = \begin{cases} (N_S - 1)T_S + \tau_F - \tau_{SW} & \tau_F < T_S \\ N_S\tau_F - \tau_{SW} & \tau_F \geq T_S \end{cases} \tag{11}$$

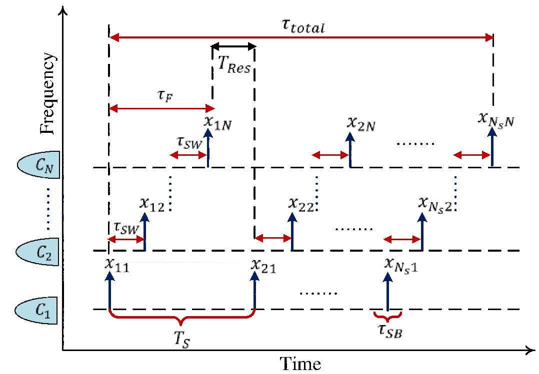

Fig. 3: Sample-Based Sensing Strategy.

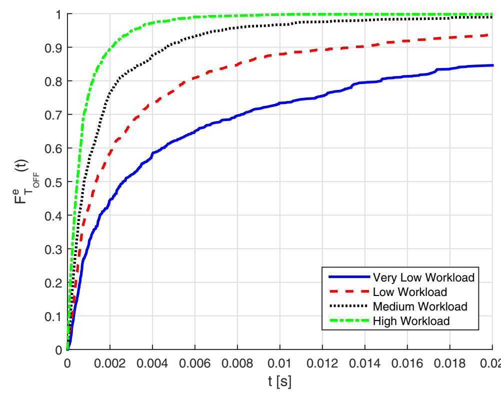

Fig. 4: CDF of the idle periods.

where τ_F can be calculated by (10), N_S is the number of sensing samples and T_{Res} as shown in Fig. 3 can be calculated as

$$T_{Res} = T_S - \tau_F - \tau_{SW}, \tag{12}$$

and τ_{SB} in (10) now refers to the duration of each sensing sample as shown in Fig. 3.

According to Fig. 3, the duration of T_{Res} gives a degree of freedom. Depending on the sampling duration T_S and T_{Res}, more channels can be sensed or the block size can be increased.

IV. Simulation Environment and Results

To estimate the introduced metrics in Section II, we need to generate a realistic channel behavior. Since nowadays most of the wireless communication systems use CSMA/CA, including 802.11 systems, we use Generalized Pareto distribution which fits best the distribution of the interarrival time of the CSMA/CA packets. The cumulative distribution function

	Very Low Workload	Low Workload	Medium Workload	High Workload
ξ	1.371	0.853	0.591	0.426
σ	$3.579 * 10^{-3}$	$1.11 * 10^{-3}$	$0.8 * 10^{-3}$	$0.55 * 10^{-3}$
Mean workload	0.0583	0.1978	0.3715	0.5312

Table I: Generalized pareto distribution parameters for different workload types.

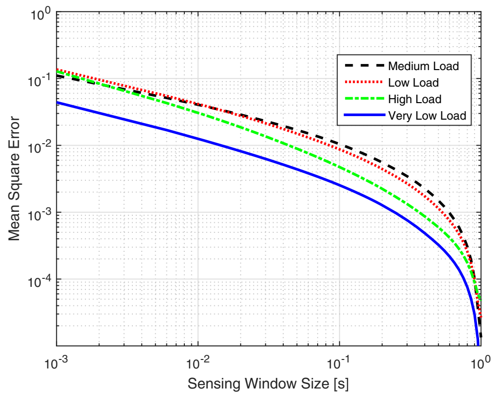

Fig. 5: Mean Square Error for workload estimation using Window-Based sensing strategy.

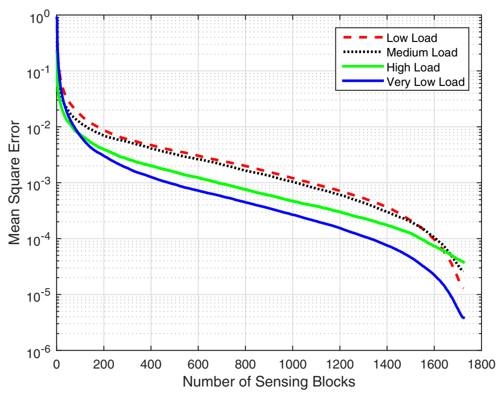

Fig. 6: Mean Square Error for workload estimation using Sample-Based sensing with a sampling period of $650\mu s$.

(CDF) of T_{OFF} can be estimated by [10]

$$T_{OFF} \sim F_{T_{OFF}}(t_{OFF}) = 1 - (1 + \frac{\xi(t_{OFF} - \mu)}{\sigma})^{\frac{-1}{\xi}}. \quad (13)$$

The parameters ξ and σ in the above formula are computed and presented in Tab. I (we assumed that $\mu = 0$). Four different workload types, namely, very low workload, low workload, medium workload and high workload based on 802.11 networks are considered in this work. Workload values for low workload type varies between 0 and 0.1. For low workload, they vary between 0.1 and 0.3. The medium workload bands have workload values between 0.3 and 0.5 and finally high workload ones vary between 0.5 to 1. These four types of workload provide a good insight for different workload conditions created by 802.11 networks. We checked these distributions via USRPs and 802.11n networks in experimental environments.

Since the main focus of this work is to determine spectrum opportunities, only the activity in the band rather than packets with special specifics are considered. Thus, ON periods are modeled by 1 and OFF periods by 0. The parameters shown in Tab. I are adopted to simulate the interarrival time behavior drawing from GP distribution for packets with duration of 1 second. Fig. 2 shows the CDF of the generated workload in

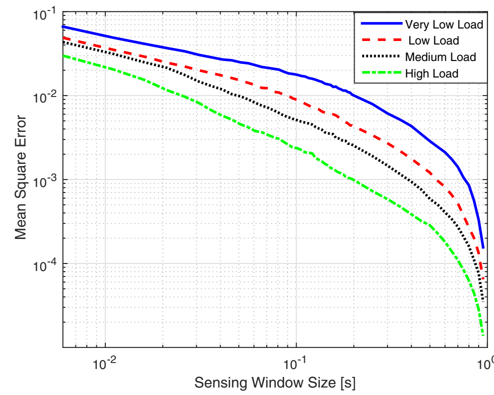

Fig. 7: Mean Square Error for idle time probability estimation using Window-Based sensing strategy.

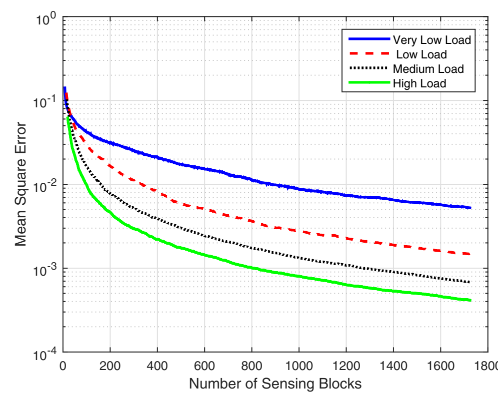

Fig. 8: Mean Square Error for idle time probability estimation using Sample-Based sensing with a sampling period of $650\mu s$.

each specific band type. As it is shown, generated workloads fall in the claimed intervals provided in the table. Fig. 4, depicts the CDF of the idle periods in each channel. it is shown that the bands with very low and low workload type offer longer idle periods.

The first set of simulations are done to determine the window size for Window-Based strategy. According to the results shown in Fig. 5, the very low workload band results in the lowest mean-square error for workload estimation. For the target mean-square error value of 10^{-2}, the very low workload channel requires a window size of 12 ms whereas the channel with the medium workload requires a window size of 100 ms.

The second set of simulations provides MSE performance for idle time probability. In contrast to the previous results, in this case the lowest MSE is observed at the high workload

Required No. of Samples for MSE ≤ 0.01	
$T_S[\mu s]$	N_s
50	12300
150	3787
250	2621
350	1481
650	847

Table II: Different sampling period with their corresponding number of sensing samples.

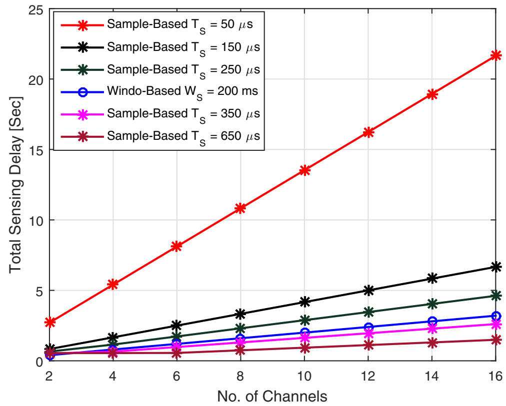

Fig. 9: Total multiband spectrum sensing delay comparison between Sample-Based and Window-Based strategy.

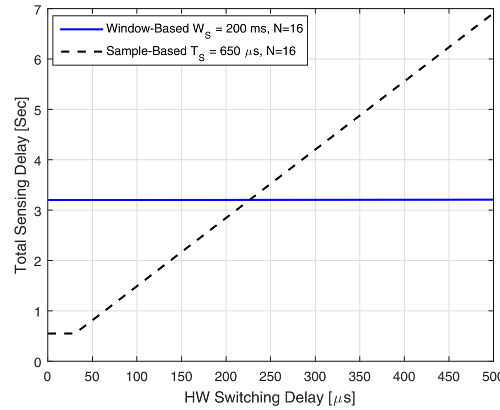

Fig. 10: Total multiband spectrum sensing delay for sensing 16 bands with different hardware switching delays.

band. Given a target MSE value of 10^{-2}, the required window size is equal to 200 ms. For a reliable sensing performance in terms of both workload and idle time probability estimation, the maximum value of window size should be selected. Between the results shown in Figures 5 and 7, 200 ms is the minimum required window size to have an MSE less 10^{-2} for both sensing metrics.

Next set of simulations provide performance results for Sample-Based Strategy. As explained in the previous section, selection of the sampling period is important for this strategy. Tab. II provides necessary number of samples with different sampling period which achieves a target MSE of 10^{-2}. The highest T_S value that achieves target MSE is $650\mu s$. Fig. 6 illustrates the MSE performance for workload estimation with $T_S = 650\mu s$. Similar to previous results, the band with very low workload has the best MSE performance. On the other hand, the results for the idle time probability estimation in Fig. 8 indicates that the highest MSE is observed if the workload type is very low.

Based on the previous results, we now compare the resulting sensing delay between Sample-Based and Window-Based strategies. For the hardware switching delay of $100\mu s$ this comparison is shown in Fig. 9. Our results show that the Sample-Based strategy with T_S values of 350 and $650\mu s$ offers a better sensing delay performance than its Window-Based counterpart with a window size of $200ms$. For a better comparison, the effect of hardware switching delay should be taken into account. Fig. 10 plots the total sensing delay of the Sample-Based strategy with T_S of $650\mu s$ in an environment with 16 bands. It is shown that if the hardware switching delay is less than $220\mu s$, Sample-Based strategy requires half of the total multiband spectrum sensing duration that is necessary for the window-based strategy to achieve the same estimation performance.

V. Conclusion

In this paper, we compared two different spectrum sensing strategies, Window-Based and Sample-Based sensing, in order to reduce the multiband spectrum sensing overhead for CSMA/CA based Cognitive Radios. For modeling packet interarrival time, Generalized Pareto distribution is used to obtain realistic results. We observe that the hardware switching delay plays an important role for Sample-Based sensing. For hardware switching delay durations up to $220\mu s$, Sample-Based strategy requires less durations to sense the multiband environment compared to Window-Based strategy.

Acknowledgments

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