Experimental Study for Interference on Cognitive Radio Test-bed using Asyncronous Mode

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***Abstract*—Cognitive Radio is an emerging technology that enables for efficient utilization of the spectrum. As such, it has created great interests in industrial and research fields. Many people have proposed test-bed models to demonstrate the co-existence of primary and secondary users in a real-time noise environment. However, they assume the perfect time-slot synchronization and neglect the performance metrics that affects the interference of primary and secondary users. This paper provides an experimental test-bed in the presence of asynchronous mode for primary and secondary users, while providing an empirical solution for variations in throughput of primary and secondary users with the change of secondary user parameters (sensing frequency and transmission time).**

I. Introduction

From the beginning of the 20th century, there has been an increase in the usage of radio spectrum in areas such as Mobile communication, Wireless Local Area Network (WLAN), Bluetooth and Cordless phones. The Federal Communication Commission (FCC), which manages the radio frequency spectrum and its usage, has published a report on the precise usage of the spectrum and the rise of unlicensed users that could cause interference to the licensed users [1]. In addition, the report has stressed on frequency bands that are heavily occupied all the time or partially occupied or vacant most of the time [1]. The scarcity of spectrum and need for efficient usage has led to the development of a new field called as "Cognitive Radio".

Cognitive Radio (CR) is a type of radio, that is aware of its environment, in which the radio adapts its transmission for efficient usage of the underutilized spectrum. The central idea of CR is to allow the unlicensed bands of the Secondary Users(SU) to utilize the licensed bands of the Primary Users(PU), such as TV and mobile without interference. Moreover, the practical implementation of CR has been achieved by Software Defined Radio (SDR) that provides the flexibility of changing the operating parameters of the device. As SDR handsets can easily be re-configured to different wireless broadband technologies, they can be utilized to implement a CR Test-bed.

The remaining sections of the paper is organized as: Section 2 describes the state of art for the former test-beds and the issues that are resolved in the current paper. The testbed architecture is discussed in Section 3 followed by the spectrum sensing mechanism on the current testbed and decision statistics in Section 4. In Section 5, we describe the experimental setup and details of the experiments followed by the discussion on the results and remarks on OFDM implementation. Finally, the section 6 provides the conclusion of the work.

II. State of Art

Many CR test-bed models [2] [3] have demonstrated the coexistence of primary and secondary users on the same frequency band with various platforms (SDRs). The models validate the non interference of cognitive radio with licensed users in a real time environment and elaborate the need for standardized metrics to evaluate their performance. However, the experimental analysis for the test-bed assumes the perfect time slot synchronization and disregard the SU parameters that increases the interference of PUs and SUs. In our current test-bed, we analyze the co-existence issues between PU and SU in the presence of asynchronism by adapting the hidden semi-Markov traffic model for the PUs. Also, the metrics of PUs and SUs are analyzed with the variations of SUs parameters.

III. Test-bed Architecture

The test-bed is based on USRP (Universal Software Radio Peripheral) version 1 and GNU Radio. USRP is a low cost radio system that helps to utilize general purpose computers as high bandwidth software radios, while the USRP is interfaced to RF 2400 daughter-board that aids to utilize in the 2.4 GHz ISM band. On the other hand, the GNU Radio provides the software platform to USRP that involves hybrid python/C++ programming. The architecture of GNU Radio involves complex flow-graph model that consists of signal processing blocks and low-level algorithms.

The primary traffic is interpreted as hidden semi-markov model [4] with the hidden states as ON and OFF periods that indicate the presence and absence of primary traffic on the channel. The state observations are generated from the predefined state transition matrix P and current state. Also, the time of ON periods has an uniform distribution with the probability density function(p.d.f) $f_{T_{ON}}(x), x > 0$ and the number of packets for ON period depends on prior probabilities of available number of packets. For instance, the available packets for the ON periods are x, y, z, then the prior probabilities, $\Pr(\mathrm{x})$, $\Pr(\mathrm{y})$, $\Pr(\mathrm{z})$ determines the available number of packets for the current ON state. On the other hand, the OFF periods depends on the former ON periods. Also, the longer ON period requires longer OFF periods so as to provide the sufficient transition time for switching and to avoid ON period creep into OFF period.

The communication flow-graph for PUs and SUs is based on fixed size packet radio blocks that encapsulates fixed packet size with header, preamble and error detection(CRC) segments which are passed on modulation blocks and then through the USRP blocks. The flow-graph models for the PU and SU for different modulation techniques are provided in [5].

IV. Spectrum Sensing

Spectrum sensing is considered as a primary component of the CR system. It is required for the proper allocation of secondary user traffic on primary channel based on sensing results. For the current test-bed, energy detector is implemented which is capable of sensing wide-band signals. The energy detection for the wide-band spectrum analyzer is based on average periodogram technique [6].

Average periodogram is used for the estimation of power spectrum, which is based on discrete Fourier transform (DFT) of finite length segments of discrete signals. It involves sectioning the data into finite segments to compute individual periodogram or modified periodogram and averaging the modified periodogram segments [6].

A. Wide-band spectrum analyzer in USRP

In USRP version 1, the USB bus limits the maximum spectral bandwidth to 8 MHz [7]. So, we perform the piece-wise average periodogram analysis for the wide band signals to examine the power spectrum and the RF front end of USRP is tuned to suitable steps, but not all at the same time. The Figure 1 depicts the block diagram for piece-wise average periodogram analysis.

The piece-wise spectrum analysis can also be represented on a time and frequency plot. Assume the primary carrier frequency f_c lies between f_L and f_H i.e., $f_L \leq f_c \leq f_H$, where $f_L$andf_H are the lowest and highest frequency components of the primary spectrum band and $f_H - f_L > W$ MHz. As USRP cannot scan more than 8 MHz, we scan in steps of W MHz ($W < 8$ MHz)[1] over the entire spectrum band. In addition, the frequency overlap between the spectrum bands are considered to prevent the frequency holes at the spectrum edges [8]. The Figure 2 explains the 2-D illustration of piece-wise spectrum analysis with 25% overlap.

In GNU Radio, the usrp_spectrum_sense.py program [8] helps to scan wide-band signals, but the program does't provide the average periodogram analysis on the collected statistics. There are two important parameters, t_n & t_d. The tune delay (t_n) is the time period over which FFT samples

[1]To prevent the loss of samples at low decimation rates i.e., high data rate. The loss of sample or USRP overrun is indicated as UOUOUO..... on the print screen [7].

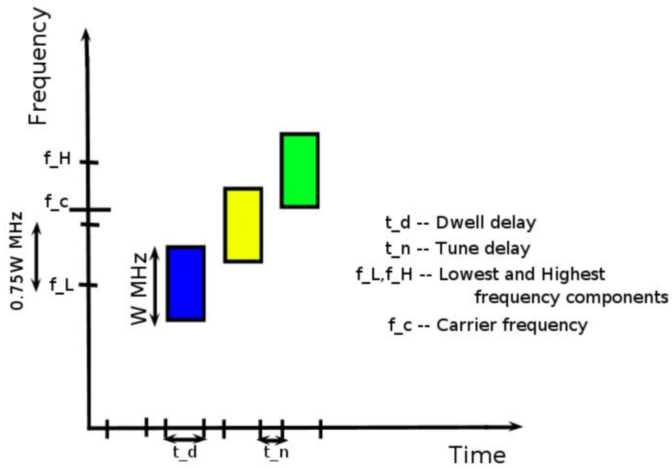

Fig. 2. 2-D Illustration of Piece-wise Periodogram Analysis

are discarded for the RF front end to settle for a new center frequency and dwell delay (t_d) is the time period over which the average (average power in each FFT bin) of vectors are determined for each center frequency. It is performed after discarding the tune delay samples. For each center frequency, the modified periodograms(FFT bins) collected for the dwell delay (t_d) are used to obtain the average periodogram in [6]. From the Figure 1, $I_0[k]$,$I_1[k]$ and $I_3[k]$ corresponds to three average periodogram for the three center frequencies (f_L, f_c and f_H). Finally, the average power statistics (P_{avg}) for the spectrum band is obtained by calculating the average of each average periodogram (obtained for each center frequency) over the entire spectrum band i.e.,

$$P_{avg} = \frac{I_0[k] + I_1[k] + I_2[k]}{3 * \text{size of FFT bin}} \tag{1}$$

B. Decision statistics based on MAP testing

The spectrum sensing (based on average periodogram analysis) provided by the CR is what allows it to learn about its overall spectral environment, and the performed calculations based on this sensing, specifically the average power statistics (P_{avg}), is crucial in determining how the radio will adapt its behavior according to what it has generated from sensing.

The primary traffic is modeled as two hypothesis to represent the absence (H_0) and presence (H_1) of PUs on primary channel. The decision threshold for determining the presence or absence of primary traffic is based on MAP testing. The density functions of statistics and prior probabilities for each hypothesis are used in MAP testing. Consider, the collected statistics ($\underline{z}$) for the two hypothesis H_0 and H_1. The MAP testing is defined from [9].

$$\frac{P(\underline{z}/H_0)}{P(\underline{z}/H_1)} \underset{H_1}{\overset{H_0}{\gtrless}} \frac{\pi_1}{\pi_0}; \quad \text{where, } P(H_0) = \pi_0 \text{ and } P(H_1) = \pi_1 \tag{2}$$

For our experiments, the statistics(z) are average power (P_{avg}) that are used to distinguish between the two hypothesis H_0 (Primary traffic is OFF) and H_1 (Primary traffic is ON). The

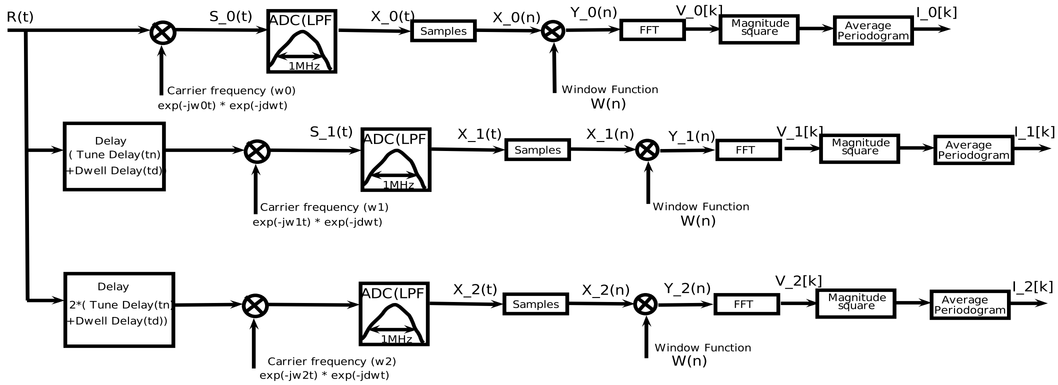

Fig. 1. Block Diagram for Piece-Wise Periodogram Analysis

experiments in [5] provide that histogram and density function of P_{avg} for H_0 and H_1 that are collected for 300 frames follows a Gaussian distribution i.e.,

$$P(\underline{P_{avg}}/H_0) = \frac{1}{\sqrt{2\pi\sigma_0^2}} \exp^{-\frac{(P_{avg}-\mu_0)^2}{2\sigma_0^2}}; \tag{3}$$

$$P(\underline{P_{avg}}/H_1) = \frac{1}{\sqrt{2\pi\sigma_1^2}} \exp^{-\frac{(P_{avg}-\mu_1)^2}{2\sigma_1^2}}; \tag{4}$$

The ratio of prior probabilities for the two hypothesis are evaluated from the transition matrix (P) of Hidden semi-markov model that is designed for the PUs. From equation 2 to 4, the resultant equation is provided as

$$\frac{P(P_{avg}/H_0)}{P(P_{avg}/H_1)} \underset{H_1}{\overset{H_0}{\gtreqless}} \frac{\pi_1}{\pi_0}; \tag{5}$$

The collected statistics for each time instant are substituted in equation 5 to determine the presence or absence of primary traffic.

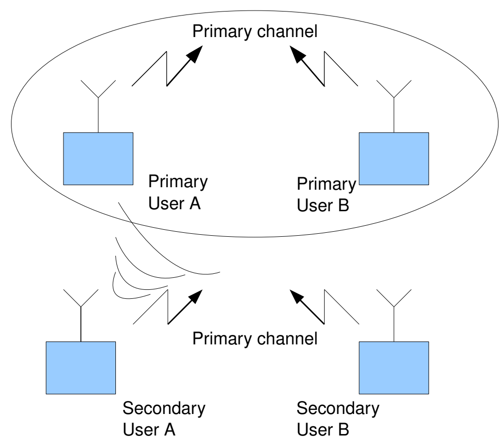

Fig. 3. Test-bed Model for PUs and SUs

V. Experimental Set-up and Details

The set-up consists of 4 USRPs, with two as PUs that communicate on primary channel and two as opportunistic cognitive radios(also called as SUs) that reconfigure their communication based on the primary traffic. The Figure 3 demonstrates the experimental set-up.

The PUs are capable of transmitting or receiving files sent over their communication channel. For the purposes of our experiment, one primary user will function as a transmitter, while the other user will receive the information from the transmitter; however, each primary user is equally capable of performing the transmitting or receiving capabilities. The hidden semi-markov traffic model is performed on the primary transmitter.

The SUs utilizes the channel only when it senses that there is no PUs communication. At any given time, the secondary transmitter operates in three modes; sensing, idle or transmission mode. In sensing mode, it senses the primary channel to evaluate the average power based on average periodogram analysis. In idle mode, it remains silent for the length of the duration specified by the user i.e., sleep period(t_s). In transmission mode, it transmits a fixed number of packets. Initially, it senses the primary channel and before returning to the sensing mode, it moves to idle or transmission mode based on the sensing decision. Usually, if the channel is busy, it remains on the idle mode and switch back to the sensing mode, but if the channel is deemed free, then it transmit data packets over the primary channel. On the other hand, the secondary receiver remain on the channel and receives the incoming packets. The Figure 4 represents the duty cycle of primary and seconary traffic with SU A as secondary transmitter and SU B as secondary receiver.

A. *Parameters and Asssumptions*

1) Primary Users: We assume, the number of packets available for transmission are 40, 60 and 80. The parameters for primary traffic are

- Modulation = Coded OFDM (QPSK) ; Code Rate = 1/2
- Interpolation = 128 ; Samples per symbol = 2

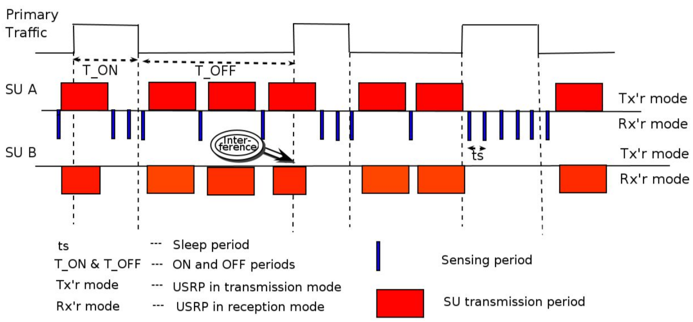

Fig. 4. Duty Cycle of Primary and Secondary Traffic

- Occupied tones = 200; FFT length = 512
- Packet size = 508 bytes ; Packet Overhead = 525 bytes
- Primary Carrier Frequency(f_{c1}) : 2.457 GHz
- Primary Transmission File Size = 1.3 MB
- Data Rate [2] = 780.25 Kb/sec
- Transition Matrix(P) = $\begin{bmatrix} 0.25 & 0.75 \\ 0.35 & 0.65 \end{bmatrix}$
- $\frac{\pi_1}{\pi_0} = \frac{0.75}{0.35}$
- $\Pr(40) = 0.25$; $\Pr(15) = 0.35$; $\Pr(20) = 0.40$
- $T_{ON40} = 0.846secs$; $T_{ON60} = 1.268secs$; $T_{ON80} = 1.692secs$
- $T_{OFF40} = 1.692secs$; $T_{OFF60} = 3.804secs$; $T_{OFF80} = 6.768secs$

2) Secondary Users: As the primary spectrum is a narrow bandwidth concentrated over the carrrier frequency (f_c). We perform the spectrum sensing for the three center frequencies surrounded around the carrier frequency. The sensing period depends on dwell delay and tune delay of center frequencies. As there are three center frequencies, the sensing period is $3 * (t_d + t_n)$. The parameters for secondary traffic are

- Scanning Frequency Range :2.5 MHz i.e., considering three center frequencies around primary carrier (2.4555 GHz-2.458 GHz)
- Packet size = 508 bytes
- Secondary Transmission File Size = 1.1 MB
- Data Rate = 390.625 Kb/sec
- $t_d = 10msec$ and $t_n = 1msec$; Sensing period for three center frequencies $T_s = 33msecs$

From [5], the values of μ_0 = 20.49, σ_0^2 = 0.063. Similarly, the values of μ_1 and σ_1^2 for the three different modulation techniques are obtained.

B. Performance Metric

The performance metrics provides to evaluate the interference free communication and coexistence of PUs and SUs. We define the throughput metric to evaluate the performance and comparison of various scenarios. It is defined as the average rate of successful messages over the communication channel. It is measured in terms of correctly received bits/packets per unit time. We define the metric as the number of correctly received packets per unit time i.e.,

$$\text{Throughput} = \frac{\text{Number of correctly received packets}}{\text{Transmission time for all packets}} packets/sec.$$

C. Experiments

All the experiments are averaged for 10 iterations. We observe the variations in PUs and SUs throughput by varying secondary transmitter parameters (size of communication window and sensing frequencies). In fact, the size of communication window is altered by changing the number of packets for transmission, while the sensing frequency is varied by changing the sleep time (i.e., the time taken for the secondary transmitter to remain idle, if the channel is deemed busy).

The tables provides the throughput interms of packets/sec for PUs and SUs. The experiments are performed for three different modulation schemes of SUs. Moreover, the PUs parameters are unaltered throughout the experiments.

TABLE I
SCENARIO 1: UNCODED OFDM WITH QPSK MODULATION

Communication window (secs) \ Sleep time (secs)		0.05	0.45	1.0	1.5
0.312	PUs	22.82	22.63	25.288	24.95
	SUs	18.62	17.49	16.64	16.42
0.624	PUs	20.51	22.50	18.84	23.31
	SUs	25.14	24.15	22.96	21.10
1.04	PUs	20.97	19.59	22.96	18.64
	SUs	35.53	33.43	31.58	29.03
1.56	PUs	20.30	20.04	19.92	18.35
	SUs	37.20	34.39	32.23	30.48

TABLE II
SCENARIO 2:CODED OFDM WITH QPSK MODULATION AND CODE RATE = 1/2

Communication window (secs) \ Sleep time (secs)		0.05	0.45	1.0	1.5
0.312	PUs	24.03	22.20	21.34	20.13
	SUs	14.62	14.58	14.48	13.39
0.624	PUs	18.60	18.76	23.72	21.60
	SUs	18.95	18.41	16.93	16.12
1.04	PUs	16.79	19.08	18.64	17.86
	SUs	20.74	19.78	19.60	19.16
1.56	PUs	16.73	18.06	16.56	14.45
	SUs	22.14	19.88	19.78	19.45

D. Results

The results of the experiments are demonstrated in the tables I to III. A few observations from the tables are given. For a particular sensing frequency or sleep time, the PU throughput decreases (not a monotonic decreasing function) as the time period of the communication window increases, whereas the SU throughput increases with the increase of time period of communication window. Also, the SU throughput decreases as the sensing frequency decreases (i.e., increase in sleep time) for a particular communication window.

[2] $DataRate(R_b) = \frac{(ADCSamplingRate*OccupiedTones)}{(FFTsize*Interpolationrate)} * (bitspertone)$; $ADCSamplingRate : 128MS/sec$;

TABLE III
SCENARIO 3: UNCODED GMSK MODULATION

Communication window (secs) \ Sleep time (secs)		0.05	0.45	1.0	1.5
0.312	PUs	23.12	22.34	23.89	26.68
	SUs	16.67	16.30	15.98	14.84
0.624	PUs	21.29	21.37	21.90	22.45
	SUs	27.13	25.52	24.60	22.35
1.04	PUs	22.20	24.70	22.60	22.54
	SUs	36.24	34.31	32.32	29.06
1.56	PUs	22.12	21.85	22.42	24.53
	SUs	39.56	37.84	34.31	32.16

We can also infer from the tables that for long time periods of communication window, GMSK performs better when compared to uncoded and coded OFDM. However, the uncoded OFDM performs better than coded OFDM and GMSK in terms of SU throughput for short time periods of communication window.

The tables validate the need for proper selection of SU parameters (communication window, sensing frequency and modulation schemes) so as to sustain throughput for PU and SU. For instance, the longer communication window aids to improve SU througput, but it affects the PU throughput.

E. Concerns in OFDM implementation

1) In the implementation of OFDM model on USRP, the receiver is prone to large frequency deviation as the carrier frequency increases. For the 2.4 GHz ISM band, the frequency offset(δ) doesn't fall in the search range of the carrier frequency(f_c), especially for the small bandwidth signals. For instance, if the OFDM symbols are constantly transmitted on the carrier frequency(f_c), then the receiver has to be tuned to various frequencies of $f_c \pm \delta$. Also, the value of δ varies by changing data rate.
2) There is trade-off between overhead and system efficiency for the uncoded and coded OFDM. The overhead of a packet is the additional amount of bits/bytes appended to the payload for synchronization, equalization and error detection, whereas the system efficiency is defined as the ratio of raw bits/bytes sent to the total number of bits/bytes utilized for transmission. For the uncoded and coded OFDM, the coded OFDM has the higher overhead bits/bytes, but the system efficiency is smaller.

VI. CONCLUSION

In this paper we provide a cognitive radio test-bed of primary and secondary (cognitive) users that operate in asynchronous mode by incorporating the hidden semi-markov traffic model for the PU, while an experimental study on testbed establish an empirical solution to the throughput of the PU and SU with the variation of modulation, sensing frequencies and time period for communication of the SU. The results in the tables validate the need for the proper selection of SU parameters so as to provide the necessary throughput. In addition, the concerns for OFDM implementation on the current testbed (USRP) brings out the frequency offset and trade off issues for the uncoded and coded OFDM.

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