Spectrum Sensing Measurement using GNU Radio and USRP Software Radio Platform

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Abstract— **Spectrum utilization can be significantly improved by adopting cognitive radio (CR) technology. Such radios are able to sense the spectral environment and use this information to opportunistically provide wireless links that meet the user communications requirements optimally. To achieve the goal of cognitive radio, it is a fundamental requirement that the cognitive user (CU) performs spectrum sensing to detect the presence of the primary user (PU) signal before a spectrum is accessed as to avoid harmful interference. Therefore, two probabilities are of interest; the probability of detection, P_d and the probability of false alarm, P_{fa}. In this paper, we investigate sensing performance implemented on real-time testbed of GNU Radio and USRP Software Defined Radio (SDR) communication platform operating at 2.48 GHz with a bandwidth of 4 MHz. Energy detector utilizing 1024 FFT bin is the sensing mechanism used in the experimental set-up. The acquired experimental results of P_d and P_{fa} are duly analyzed and verified to be comparable to the curve of the theoretical framework for line-of-sight indoor environment. It is observed that at a target P_{fa} of 5%, the optimal decision threshold for PU detection is -39 dB. The plot of measured number of samples needed for a desired P_d for various received signal levels, representing various signal-to-noise (SNR) conditions, is also included. At SNR of 0 dB and a target Quality of Service (QoS) set at P_d of 90%, it is found out that the required sensing time for our GNU Radio USRP based CR system is equal to 31.59ms.**

Keywords- Spectrum Sensing; Probability of Detection; Probability of False Alarm; GNU Radio; USRP.

I. INTRODUCTION

A recent spectrum occupancy measurement shows that a significant portion of the spectrum allocated to licensed services show little usage over time, with concentration on certain portions of the spectrum while a significant amount of the spectrum remains unutilized [1]. A new communication paradigm to exploit the existing wireless spectrum opportunistically is necessary to overcome limited available spectrum and inefficiency in spectrum utilization.

Originally introduced by Mitola, [2], Cognitive Radio (CR) technology allows unlicensed or cognitive users (CUs) to take advantage of the spectrum holes by intelligently identifying and using them, and possibly releasing them when required by the primary users (PUs). Hence, it is a fundamental requirement that the CU performs spectrum sensing to detect the presence of PU signal and also locate unoccupied spectrum segments, the spectrum holes, as accurately and quickly as possible.

Various approaches have been proposed for spectrum sensing such as matched filter, energy detection, feature detection and more recently, wavelet detection methods [3]. In local sensing, each CU senses the spectrum within its geographical location and makes a decision on the presence of PUs based on its own local sensing measurements. The matched filter (MF) is an optimum coherent detector. However it requires a prior knowledge on the behavior (modulation) of the received signal. Energy detection (ED) is a non-coherent detection method that uses the energy of the received signal to determine the presence of primary signals. This simple method is able to gather spectrum-occupancy information quickly. However, its sensing capability is vulnerable to noise. Cyclostationary detector exploits the inherent periodicity in the received signal to detect primary signals with a particular modulation type by implementing a two-dimensional spectral correlation function (SCF) rather than the one-dimensional power spectral density (PSD) of the energy detector. Its spectrum-sensing performance is robust to noise-like signal. However this method demands excessive Analog-Digital Converter (ADC) requirement and signal processing capabilities, thus accompanying a large amount of power consumption [4]. In this research, energy detector is chosen due to the assumption that CU has limited information on the primary signal (i.e. only the local noise power is known). Hence energy detector is optimal. In addition, IEEE802.22 standard on cognitive radio has spectrum sensing via energy detection in its provision.

The flexibility of Software Defined Radio (SDR) makes it a well suited candidate for the implementation of cognitive features [5]. One of the first research works on implementation of spectrum sensing is reported in [3] using SDR platform called Berkeley Emulation Engine 2 (BEE2). The sensing mechanisms utilized are the energy and cyclostationary detectors. However, the measurements and analysis are based on the captured local data. While in [6], Dynamic Spectrum Access (DSA) mechanism is developed using an SDR platform consisting of USRP and GNU radio. GNU Radio is an open source software toolkit which consists of a huge numbers of signals processing blocks library (i.e modulators, filters, amplifiers and etc). This signal processing blocks can be linked together for building and deploying the baseband part of the dedicated radio [9], [10]. USRP is the hardware link between this baseband signal blocks and the real environment. Its function is to change the analog value of the spectrum to the digital domain and to change the digital domain signal to analog value [7], [8]. The overall block diagram is shown in Figure 1.

This research has two goals; (1) is to develop a DSA based CR system using GNU Radio and USRP, by combining the works of [3] and [6], in addition to having our own designed spectrum management and decision and (2) to do measurement and analysis based on the captured local data. However, this paper only highlights the use of GNU radio and USRP as the testbed for the implementation and measurement of ED sensing scheme and the determination of these parameters from the local data; sensing threshold, sensing time, probability of false alarm (P_{fa}) which is the probability of wrong detection of PU when it is absent, and the probability of detection (P_d) that is the probability of correct detection of a PU.

The paper is organized as follows: Section II presents a background on cognitive radio technology. While Section III defines channel sensing hypotheses and introduces the sensing performance metrics, the probabilities of detection and false alarm. Section IV discusses energy detector block diagram of of GNU Radio. The experimental set-up and preliminary results are presented in Section V. Finally, Section VI provides conclusion and future works.

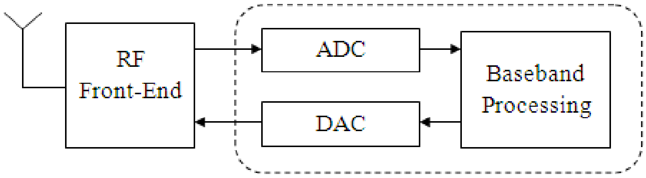

Figure 1. Software defined radio block diagram

II. COGNITIVE RADIO TECHNOLOGY

The vital objective of the CR is to achieve the best accessible spectrum through cognitive capability and reconfigurability. In other words, CR also embodies awareness, intelligence, learning, adaptivity, reliability and efficiency. Cognitive cycle consists of three major steps as follows [1],[2]:

a) Sensing of RF stimuli which involves the detection of spectrum holes to facilitate the estimation of channel state information and prediction of channel capacity for use by the transmitter.
b) Cognition/spectrum management which controls opportunistic spectrum access and capturing the best available spectrum to meet user communication requirements. Cognitive radios should decide on the best spectrum band to meet the Quality of Service (QoS) requirements over all available spectrum bands by managing functions such as optimal transmission rate control, traffic shaping and routing.
c) Actions to be taken can be in terms of re-configurable communication parameters such as transmission power, modulation and coding.

Those three tasks form a cognitive cycle as shown in Figure 2.

In this research work, DSA based CR system is developed using USRP and GNU radio as hardware and software platforms, respectively. The proposed design consists of four main functional blocks which are spectrum sensing, spectrum management, spectrum decision and data transmission [12]. However, the contribution of this paper is limited to spectrum sensing that concerns with the sensing parameters such as the sensing threshold, probability of false alarm, probability of detection and the sensing time, which are all decided based upon locally measured data. The analysis on the captured data is used to assess the platform characteristics in terms of sensitivity and best performance in local environment. The results are further utilized to set the desired Quality of Service (QoS) for the system.

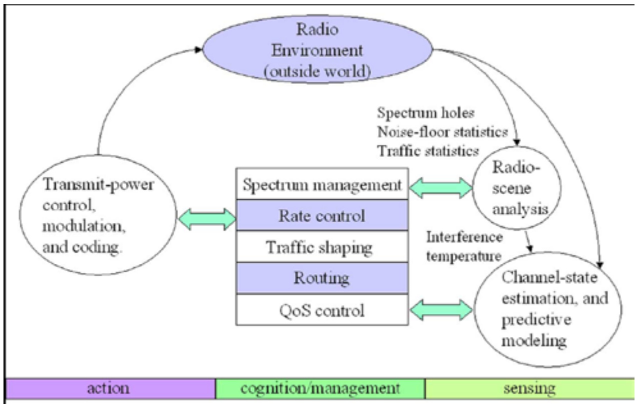

Figure 2. Basic cognitive cycle [2]

III. CHANNEL SENSING HYPOTHESES

The sampled received signal, $X[n]$ at the CU receiver will have two hypotheses as follows:

$$\begin{array}{lll} H_0: X[n] = W[n] & \text{if PU is absent} & . \\ H_1: X[n] = hW[n] + S[n] & \text{if PU is present} & (1) \end{array}$$

where $n = 1, \ldots, N$; N is the number of samples and h is the gain of channel that is assumed to be 0 under hypothesis H_0 and 1 under hypothesis H_1. The noise $W[n]$ is assumed to be additive white Gaussian (AWGN) with zero mean and variance σ_w^2. $S[n]$ is the PU's signal and is assumed to be a random Gaussian process with zero mean and variance σ_x^2.

Using energy detector, the decision based on Neyman-Pearson criterion will be

$$Y = \frac{1}{N}\sum_{n=1}^{N}(X[n])^2 \qquad (2)$$

where Y is the output of the energy detector which serves as the test statistic. Taking γ as the threshold to decide whether signal is present or not, the performance of energy detector can be characterized by a resulting pair of (P_{fa}, P_d) as the probabilities that the CU's sensing algorithm detects a PU under H_0 and H_1, respectively.

$$P_{fa} = P(Y > \gamma \mid H_0) \qquad (3)$$

$$P_d = P(Y > \gamma \mid H_1) \qquad (4)$$

If the noise term is assumed to be circularly symmetric complex Gaussian, using central limit theorem, Gaussian distribution approximation for the probability density function (PDF) of Y, it can be derived from (3) and (4) [13];

$$P_{fa} = Q\left(\left(\frac{\gamma}{\sigma_w^2} - 1\right)\sqrt{N}\right) \qquad (5)$$

$$P_d = Q\left(\left(\frac{\gamma}{\sigma_w^2} - SNR - 1\right)\sqrt{\frac{N}{2SNR+1}}\right) \qquad (6)$$

where signal-to-noise ratio (SNR) is taken as $\frac{|h|^2\sigma_x^2}{\sigma_w^2}$ and $Q(.)$ denotes the generalized Marcum Q-function. The challenge of the local spectrum sensing is to reliably decide on the two hypotheses to achieve high P_d for good protection of PU and low P_{fa} to provide satisfactory access for CUs.

IV. GNU RADIO ENERGY DETECTOR

The energy detector is known as a suboptimal detector, which can be applied to detect unknown signals as it does not require a prior knowledge on the transmitted waveform as the optimal detector (matched filter) does. Figure 3 depicts block-diagram of an energy detector. The ADC is used to convert the received signal to the digital domain. Then the square magnitude of the digitized signal is calculated by using the Fast Fourier Transform (FFT) and magnitude square function. To make the measurement more accurate, N numbers of samples is taken and the average value of the samples is used to make the decision whether signal is present or not by comparing it with the threshold.

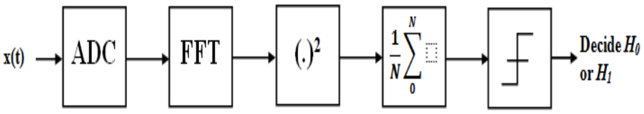

Figure 3. Block diagram of an energy detector

In this research, the GNU Radio energy detector flow graph design is a modification from the GNU Radio's spectrum analyzer which is available in the GNU Radio package. Figure 4 shows the flow graph of the energy detector used for this research. The Radio frequency (RF) signal is captured and down converted to the baseband frequency (DC) by the RFX2400 USRP front end [8] and then passed to the USRP Motherboard. The daughterboard is necessary since the ADC speed cannot cope with the high frequency RF signal in the air (i.e. 2.4GHz) as the ADC speed is only 64MS/s.

The speed of the digitized signal will be scaled down by the digital down converter (DDC) which is implemented inside the FPGA. The DDC value is programmable with even numbers in the range of 4 to 256. The baseband signal needs to be down converted again by the DDC because the speed of the signal have to be reduced to be transferred to the GNU Radio installed in Personal Computer (PC) through the USB 2.0 bus which has the bottleneck speed at 32MHz.

In GNU Radio, the transferred signal from the USRP which is in the format of a stream of data will first be converted to I & Q format (Vector) by a block called *gr.stream_to_vector*. Its task is to take a stream of items as its input and convert it into a stream of blocks containing *nitems_per_block* as its output [9]. In this research, *nitems_per_block* is equal to the size of our FFT which is 1024. Then, this signal will be pushed into the GNU radio FFT block, the *gr.fft_vcc*. The term *vcc* at the end of the block indicates that the input of the signal processing block is in complex vector type and the output is also a complex vector [10]. In the FFT block, windowing technique is used to optimize the FFT result. Windowing is a technique used to shape the time portion of the sampled signal. This is to minimize edge effects that will result in spectral leakage in the FFT spectrum and increases the spectral resolution the frequency domain result [11].

The complex output of the FFT block will then be connected to the complex magnitude block named *gr.complex_to_mag*. This block takes a complex number as its input and gives the magnitude (in float format) of this number as output. Then, the result of this block will be converted from the ADC value which represents the voltage to the dB value by using *gr.nlog10_ff* block. Lastly, the result in dB will be sent to a sink block called *gr.message_sink*. The sink block will then pass the value of the power spectral to the Python layer. Collecting and averaging N samples of FFT will be done in Python, and then the decision on the presence of PU will be made based on the result of the sensing and predetermined threshold.

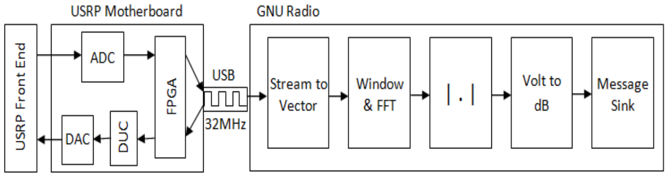

Figure 4. GNU Radio ED Block Diagram

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V. ENERGY DETECTOR EXPERIMENTAL RESULTS

The section provides the real-time testbed implementation to evaluate and verify the theoretical results on the performance and limitations of the GNU Radio energy detector. In particular, we measured the achievable probabilities of detection and false alarm as a function of sample size for various signal levels based on a predetermined threshold.

A. *Testbed Description*

The testbed used in the experiments is the Universal Software Radio Peripheral (USRP) as the Software Defined Radio (SDR) platform and GNU Radio as the SDR software implementation.

USRP consists of two main boards; the daughter board and the mother board. The mother board consists of four 12-bit Analog to Digital Converter (ADC) with sampling rate of 64MS/s, four 14-bit Digital to Analog Converter (DAC) with speed of 128MS/s, two Digital up Converter (DUC) to up-convert the baseband signal to 128MS/s before translating them to the selected output frequency, a programmable USB 2.0 controller for communication between USRP and GNU Radio and an FPGA for implementing four Digital Down Converter (DDC) and high rate signal processing. The daughterboard is acting as the RF front-end of the SDR.

GNU Radio consists of signal processing blocks library and the glue to tie these blocks together for building and deploying SDRs [5],[7],[9]. The signal processing blocks are written in C++ while Python is used as a scripting language to tie the blocks together to form the flow graph. Simplified Wrapper and Interface Generator (SWIG) is used as the interface compiler which allows the integration between C++ and Python language. Figure 5 shows the structure of GNU Radio and USRP SDR. The USRP will digitize the inflow data from the air and passing it to the GNU Radio through the USB interface. GNU Radio will then further process the signal by demodulating and filtering until the signal is translated to a packet or a stream of data.

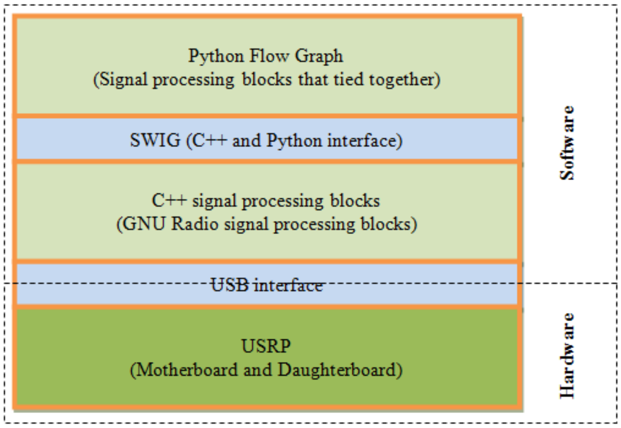
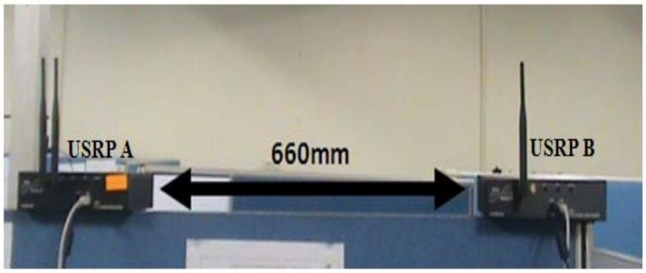


Figure 5. GNU Radio and USRP Structure

B. *Energy Detection Implementation*

Figure 6 shows the experimental setup consisting of two USRPs, one laptop and one PC. PC with USRP A acts as the receiver while the laptop and USRP B acts as the transmitter. Daughter boards used for these experiments are RFX2400 which can cover frequencies from 2.3GHz to 2.9GHz. There is a neighboring access point to consider which can interfere with the USRP frequencies. Therefore, the USRP center frequency is set at 2.48GHz to avoid the interference and jamming with the said access point operating at 2.4 GHz band.



(a) USRP hardware platform

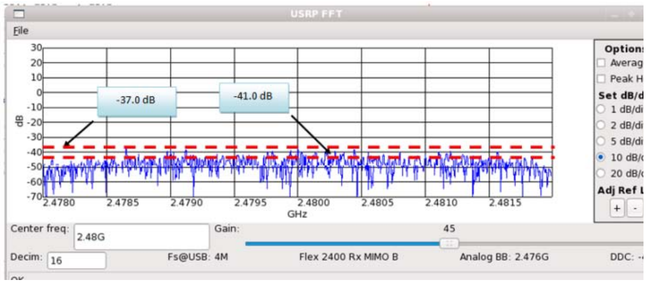
(b) Block diagram of overall setup

Figure 6. Experimental setup

The energy detector is implemented using 1024 point FFT with a fully parallel pipelined architecture for the fastest speed. Each block of FFT outputs is averaged and stored inside a buffer. *N*-numbers of the averaged FFT block will be collected and then averaged again to acquire the final result that will be used to make the decision on the presence of PU. *N* value is programmable and it will be set based on the selected P_d.

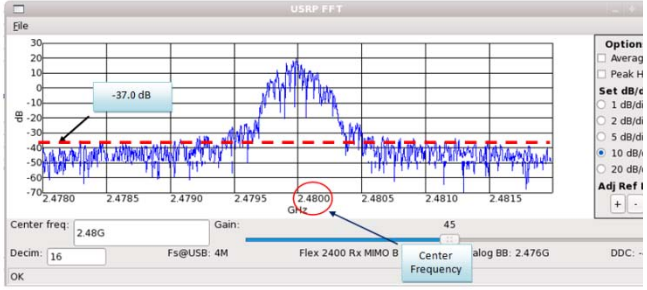
C. *Experimental Results*

We tested a GMSK signal centered at 2.48GHz carrier frequency. In the experiment to determine P_{fa}, the measurement is carried out when there is no signal transmission from PU and CU as shown in Figure 7. From this figure, it can be observed that the highest noise spike is around -37.0dB and more noise spike is recorded after -41.0dB. Therefore, in this work, the threshold is in the range of -37.0dB to -41.0dB. Thus, the curve for P_{fa} versus sample size is obtained and we estimated the detection threshold to meet the target P_{fa}. Then, we applied the threshold to the captured data when the PU signal is present, as shown in Figure 8, and computed the probability of detection, P_d. Each of the detection measurement is repeated 1000 times to obtain an accurate estimation of P_{fa} and P_d.



Center freq: 2.48G
Gain: 45
Decim: 16
Fs@USB: 4M
Flex 2400 Rx MIMO B
Analog BB: 2.476G

Figure 7. Absence of PU as observed using GNU Radio spectrum analyzer at 2.5GHz



Center freq: 2.48G
Gain: 45
Decim: 16
Fs@USB: 4M
Flex 2400 Rx MIMO B
alog BB: 2.476G

Figure 8. Presence of PU as observed using GNU Radio spectrum analyzer at 2.8GHz

Figure 9 shows the performance of P_{fa} against sample size, N. This graph will be used to determine the sensing threshold based on the desired P_{fa}. For instance, if a target P_{fa} of 5% is chosen, the threshold curves that intersect with the P_{fa} value of 0.05 will be considered. It should be noted that higher number of samples size will cause longer sensing time to the CR system. In this work -39.0 dB is chosen as the sensing threshold to decide on the presence of PU for P_d measurement since it crosses P_{fa} value of 0.05 and hence, satisfies the desired P_{fa} of 5%.

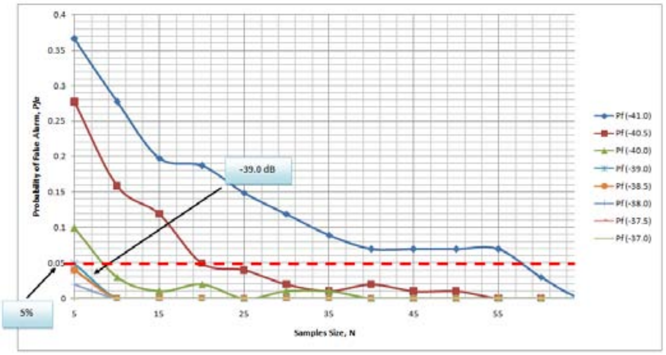


Figure 9. Probability of False Alarm versus Number of Sample

With the set P_{fa} of 5%, we do the measurement for P_d by sweeping the signal level from -37.0dB to -39.0dB and the obtained results are plotted in Figure 10. This graph is used to determine the required N for the desired P_d. At a predetermined noise threshold of -39.0dB, power received (P_r) of -39 dB, -38 dB and -37 dB can be translated to Signal-to-Noise ratio (SNR) values of 0, 1 and 2 dB, respectively. The higher the P_d, sample size needed will increase and hence, the longer the sensing time. For instance, for a target P_d of 90%, at least 35 samples are needed at SNR equals to 0 dB. Longer sensing time will reduce the data transmission time, and thus will result in a lower overall throughput.

Figure 11 shows the theoretical results performance of P_d against sample size under related SNR conditions. It can be observed that that the experimental results in Figure 10 follow the curve of the theoretical framework as in Fig. 11, especially for target Pd of 90% which gives sample size needed of 35 at SNR of 0 dB. The difference between the theoretical result and experimental result might be caused by the limitations of the SDR hardware used, the real room environment which differs from the considered theoretical AWGN channel and formula approximation.

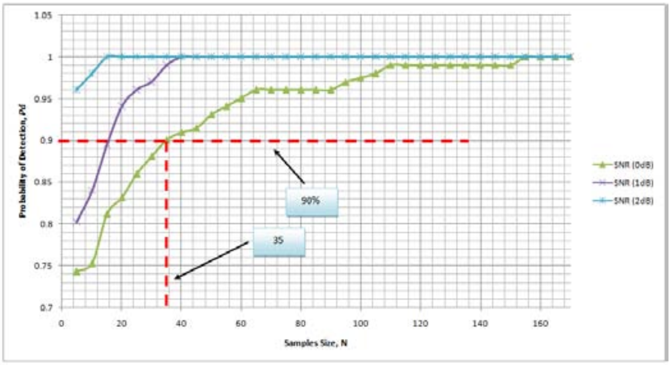


Figure 10. Probability of Detection vs. Number of Sample for Pfa=5%

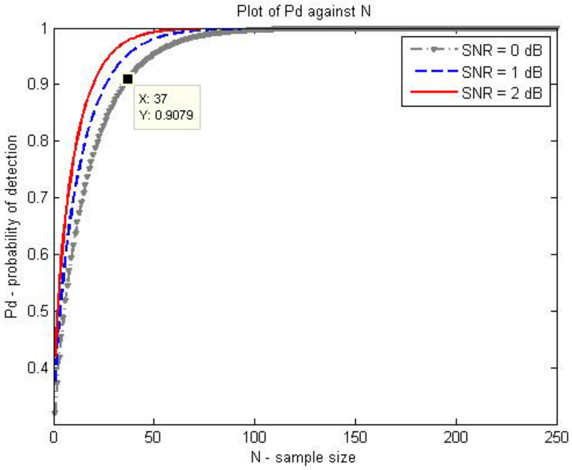


Figure 11. Theoretical Probability of Detection vs. sample size for Pfa=5% under various SNR conditions

In this experimental set-up, the sampling time, t used is 0.9025ms. This sampling time is obtained by using time stamping on the running designed CU sensing system of Figure 4. Since the experimental sensing performance closely matches that of the theoretical framework at P_d of 90%, the target Quality of Service (QoS) for P_d is set at the value. Hence, as observed in Figure 10, the required number of samples, N, will be 35. By using (7);

$$T_s = tN \tag{7}$$

the sensing time, T_s for our GNU Radio USRP based CU system is derived to be 31.59ms. The frame structure for our system is given in Figure 12 where T_f is the frame period and $T_f - T_s$ is for data transmission.

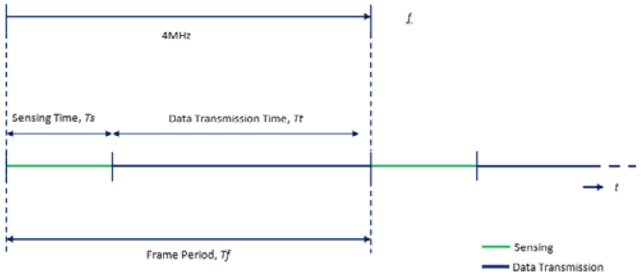


Figure 12. Frame Structure for CU System

According to [14], the frame period, T_f can be approximated using (8);

$$T_f \approx -\beta_0 \left(1 + W_{-1} \left(-exp \left(-\frac{\beta_0 + Ts}{\beta_0} \right) \right) \right) \tag{8}$$

where β_0 is the off time of the PU which in this work equals to 650 ms and W_{-1} is the negative branch of the Lambert's W function[14]. Substituting all the values in the formula will give the T_f equals to 224.25 ms and hence, transmission time is derived to be equal to 192.66 ms. It can be concluded from the frame structure that sensing time has a direct impact to the data throughput. Longer sensing time will reduce the transmission time, resulted in lower throughput and vice versa.

VI. CONCLUSION

Two main performance metrics for spectrum sensing were studied; probability of false alarm (P_{fa}) and probability of detection (P_d). P_{fa} is used to determine the threshold of the CR DSA system while P_d is used to determine on how much samples are needed by the CR DSA to meet the desired performance. The bigger the sample size, the longer the sensing time needed for the CU system, hence reducing the throughput. Future works will include attempts to minimize the sensing time using bio-inspired technique for decision making in achieving target QoS.

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