Spectrum Sensing Testbed Design for Cognitive Radio Applications

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***Abstract*—In this paper, we proposed a cognitive radio (CR) implementation by using standard wireless communication laboratory equipments such as signal generator and spectrum analyzer. Equipments are controlled through MATLAB instrument control toolbox to carry out CR capabilities specified by IEEE 802.22 WRAN standard. Energy detection and maximum minimum eigenvalue detection algorithms are employed to sense spectrum for opportunistic access. The aim of this work is to provide a CR environment for spectrum sensing algorithms to perform a comparative study considering wireless microphone (WM) signals for research and educational purposes.**

***Index Terms*—802.22, cognitive radio, dynamic spectrum access, emulator, prototype, simulator, spectrum sensing, testbed, TV, wireless microphone, white space, WRAN.**

I. Introduction

Demands for more bandwidth requiring applications and increasing number of wireless devices caused inevitable evolution of wireless systems. In order to meet service requirements, WiMAX and LTE systems are being deployed currently and new standards are on the way. However, the spectrum is still limited and spectral crowd pushes more efficient spectrum usage. This brought the idea of cognitive radio (CR) [1] which senses the spectrum and aware of its surroundings, also learns and adapts itself to the current situation by maintaining communication in an opportunistic manner.

Federal Communications Commission (FCC), which is the regulatory agency in United States, initiated the development of TV band devices (TVBDs) with cognitive radio capabilities by the rule making in 2002 [2]. The requirements are modified several times after collaborating with industry and authorities [3]–[5]. Therefore, these regulations introduced an opportunity to increase spectral efficiency by opening unused TV bands, known as white spaces, for unlicensed/secondary users. In 2010, FCC eliminated the requirement for the detection of primary users (wireless microphone (WM) and TV signals) by TVBDs that are incorporating with geo-location and database access techniques, and required that WM devices must be registered to the network, before operating [6]. This is because TV stations are fixed and their coverage can be kept in a database. Also, there is not any technical standard defined for WM devices. Locations of WM systems may change and coverage is much less than TV stations. Hence, it may be difficult to track and update the database where WM systems are located. Detection of WM signals are still an existing problem for the devices which will not use any database or geo-location techniques. On the other hand, IEEE initiated the standardization of TV white space usage in 2004 [7] which is known as 802.22 for Wireless Regional Area Network (WRAN). IEEE 802.22 WRAN standard aimed at using CR techniques to allow sharing of geographically white spaces, on a non-interfering basis, to bring wireless broadband access. The standard determines the requirements in terms of sensing receiver sensitivity, channel detection time, probability of detection and false alarm. However, IEEE 802.22 WRAN does not specify the spectrum sensing algorithms as long as the sensing requirements and format is ensured.

In order to follow the standardizations and to meet the requirements, various algorithms and prototypes are proposed so far. CR sensing prototypes consisting of the processing in physical and MAC layers with spectrum sensing functionalities for TV bands are developed to demonstrate the feasibility of the unlicensed services for practical cases [8]–[11]. A multi-standard, fully software driven, cross-layer CR testbed has been developed in [12] to test CR systems. In [13], a feasibility study of spectrum sensing techniques are performed in realistic scenarios. Furthermore, FPGA-based software defined radio unit is provided as a testbed for frequency agile CRs using OFDM based communication schemes [14], [15]. Apart from these, the performance of the proposed sensing algorithm is evaluated by using equipments in [16]. However, there is a need in the literature for such an environment to test the performance of the proposed algorithms for practical cases.

Building a complete CR prototype to test the developed algorithms can be an expensive solution and time-consuming. Therefore, in this paper, a CR testbed is developed by using wireless communication laboratory equipments such as vector signal generator (VSG) and vector spectrum analyzer (VSA). WM signal detection algorithms are implemented to verify the performance of the testbed. Specifically, the effects of different detectors and WM signal types on the performance of the algorithms are studied. The rest of the paper is organized as follows. CR testbed setup and settings are explained in section II. A case study for WM signal detection is given in section III. The detection of WM signals are demonstrated in section IV. Lastly conclusions and further improvements are outlined in section V.

II. CR Testbed Setup and Settings

Although VSA and VSG equipments are powerful for signal analysis and generation, these equipments are developed for educational, experimental and research purposes, not for real time applications. Therefore, capabilities of our testbed is limited with the specifications of the equipments. A snapshot of the spectrum sensing testbed is given in Fig. 1. A cognitive radio unit is composed of VSG, VSA and a computer which represent CR transmitter, CR receiver and processor, respectively, as seen on the left side of Fig. 1. All these equipments are connected to a router and communication is established over TCP/IP protocol. The processor is responsible for performing baseband processing and CR functionalities such as spectrum sensing, channel allocation and transmission. For instance, processor suspends VSG, collects I/Q data from VSA and then after baseband processing, configures VSG with the new signal parameters. Furthermore, processor defines sensing step, FFT resolution and averaging count parameters which are important for detection and representation of a WM signal. The sensing step is the minimum bandwidth step where the algorithms search for the existence of a WM signal and FFT resolution is the frequency resolution of the sensing step. Averaging count which configures VSA to average the spectrum data at a defined time before presenting. Our testbed operates in 36 MHz range and covers six TV bands with 6 MHZ bandwidth of each. The term subchannel (SC) is used for the band of our signal which is assumed to be less than 6 MHz. Designed graphical user interface (GUI) can be seen on the display above the equipments, which facilitates to create the desired scenario and monitor the results of the algorithms as well as the current situation of the spectrum and the testbed. Moreover, measurement, sensing, decision and channel setting times are represented over GUI. Soft-realtime 3D spectrogram data is presented on the display and status of the SCs are updated whenever new data is collected. The other VSG on the right of Fig. 1 represents the interferer to generate primary user signals. OFDM based waveforms are generated to realize the operation of other TVBDs. Also frequency, dwell time and power interval of these signals can be predefined or random.

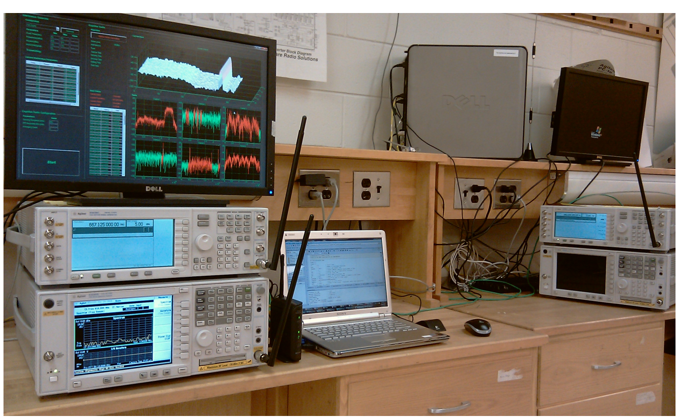

Fig. 1: A snapshot of the spectrum sensing testbed.

III. A Case Study: Wireless Microphone Signal Detection

A. Requirements

The detection of TV and WM signals are critical tasks for TVBDs. TV signals can be analog or digital and waveform of those signals are standardized and known apriori in terms of bandwidth, pilot locations and modulation type. However, frequency modulation (FM) or amplitude modulation (AM) schemes can be employed by WMs. Moreover, for FM modulated WMs, FM deviation and side-tone placement is not standardized. Despite this uncertainty, it can be said that the most common modulation type for WM is FM. According to [17], WMs may have three different states typically, based on input tones, frequency deviation and/or BWs as given in Table I, which may be exposed to two different channels depending on the indoor and the outdoor operation.

TABLE I: WM Signal Types

Type	Tone	FM Deviation
Silent	32 kHz	$\pm$ 5 kHz
Soft	3.9 kHz	$\pm$ 15 kHz
Loud	13.4 kHz	$\pm$ 32.6 kHz

TABLE II: FCC DFS Model Requirements

Parameter	WMs	TV Broadcasts
Ch. Availability Time	30 secs	30 secs
Non-Occupancy Period	10 mins	$\pm$ 10 mins
Ch. Detection Time	$\leq$ 2 secs	$\leq$ 2 secs
Ch. Setup Time	2 sec	2 sec
Ch. Opening Time	10 msec	10 msec
Ch. Move Time	2 sec	2 sec
Ch. Closing Time	100 msec	100 msec
Int. Det. Threshold	-107 dBm	-116 dBm

Secondary services must vacate the TV channel, if WM signal level is above -114 dBm within that channel [5]. For a noise floor around -96 dBm in the receiver circuitry (with respect to 6 MHz bandwidth and a 10 dB noise figure), spectrum sensing algorithms need to reliably detect WM signals at a very low SNR of at least -18 dB which may be below the dynamic range of the TVBD. Table II lists the requirements for the Dynamic Frequency Selection (DFS) model ordered by FCC [18]. According to IEEE 802.22 standard, TVBDs must be able to sense the spectrum in those quiet periods (QPs) where operating TVBDs terminate transmission simultaneously for a short time interval and collect data for measurement. Moreover, two types of sensing approaches are proposed for the detection of primary services in IEEE 802.22 standard, fast sensing and fine sensing. During fast sensing , a simple energy detector can be performed in a short time such as 1 ms per channel. High performance spectrum sensing algorithms can be employed in fine sensing periods because of the longer sensing time such as 25 ms per channel. Furthermore, antenna should have an omnidirectional pattern and also a directed antenna can be cooperated to ensure communication between base station and TVBD in order to cause less interference to the primary users.

B. Scenario and Algorithms

Our scenario is composed of a VSA & VSG pair, which represents a transceiver and a computer for control purposes to implement CR algorithms as given in Fig. 2. Another VSG is used as an interferer (or primary/secondary user generator) which is also shown in Fig. 1. Furthermore, some of the TV bands are occupied by TV channels and there can be other WM devices operating in the environment which is represented as a cloud. GUI is designed to easily create the desired scenario by defining number of primary users, TV channels and transmission durations of those signals as well as their output powers and carrier frequencies. The user can configure the system to create a desired scenario in three main steps as; i) configuration of interferers, ii) configuration of CR parameters and iii) running the testbed. Then after interference pattern is created and algorithms are initialized. Our testbed

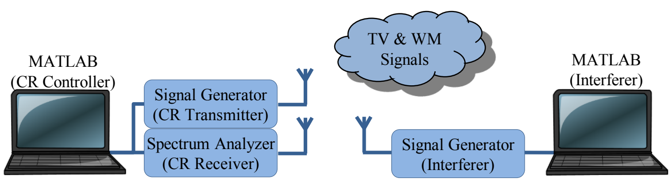

Fig. 2: Scenario

follows the flow chart shown in Fig. 3. Sensor clock time is recorded to terminate transmission in QPs by comparing the current time with the recorded time. I/Q data is collected from VSA within QPs and unless primary users are detected, VSG is configured to continue to transmit and sensor clock is updated with the current time for the next QP. If primary user is detected at the current subchannel, spectrum sensing is performed for the next subchannel. Spectrum map is also updated to show occupied subchannels. If all subchannels of the channel are occupied by primary users, the next channel is selected and subchannels are scanned. This process continues until an available subchannel is found. Then the sensor clock is recorded for the next QP and VSA is reconfigured to present status of the channel at spectrogram. Testbed continues to run as explained as long as data exists to be transmitted.

Energy detection (ED) is implemented during fast sensing periods and creation of the initial map of the spectrum for spectrum sensing. Maximum minimum eigenvalue (MME) [19] algorithm is implemented during fine sensing periods for the detection of low power primary users. MME method compares the ratio of maximum to minimum eigenvalue of sample covariance matrix to a threshold. We denote a practical issue here caused by the input filter of VSA. Filter correlates the captured samples and noise becomes colored. This causes an increase to the maximum eigenvalue of the sample covariance matrix and increases false alarm rate. Then, the filter coefficients are estimated with an auto-regressive (AR) model which performs least squares solution. After solving a set of Yule-Walker equations, filter coefficients are found and pre-whitening filter is applied to the received samples as explained in [19].

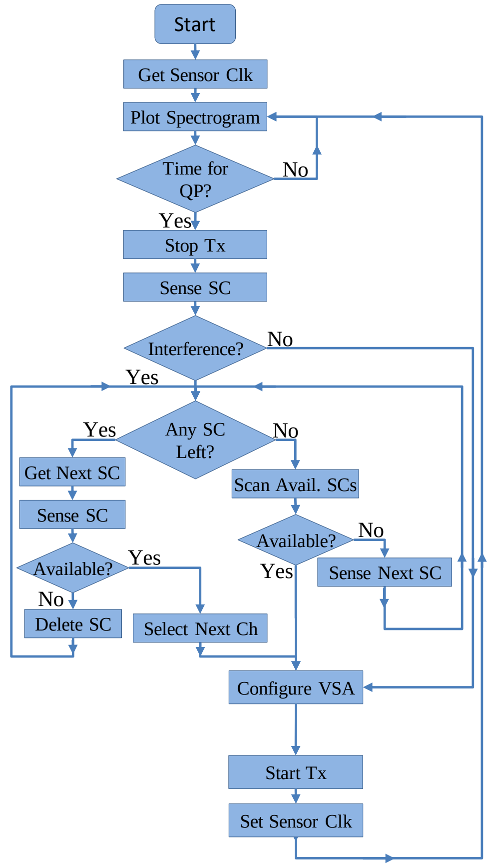

Fig. 3: Detailed Flow Chart of the algorithm.

IV. Simulation and Results

The specifications of our testbed is based on the IEEE 802.22 WRAN standard and the requirements that are listed in section III. We meet the requirements as long as the capabilities of the equipments allow. We employed omnidirectional antennas for reception and initial map of the 36 MHz is created at the startup of the testbed. This process is longer than channel detection time because 6 channels are scanned. On the other hand, spectrum sensing is performed in less than 2 seconds with the measurements taken within the QPs. Although communication with the equipments and on/off switching of the transmitter extends QPs, it does not prevent our implementation. However, it is difficult to measure channel opening and closing times with the current setup. Detection performances of these algorithms in terms of received SNR of the WM signal is shown in Fig. 4 through our testbed. MME algorithm performs much better than energy detector for practical scenarios. Because MME algorithm does not need an estimated noise level and looks to the correlations between oversampled received signal. Due to the imperfect pre-whitening of noise, there is still some correlation exist between noise samples. Consequently an offset is applied to the detection threshold in order to decrease false alarm rate. Performance of the ED algorithm is worse because of noise estimation errors, especially in low SNR region. Detection

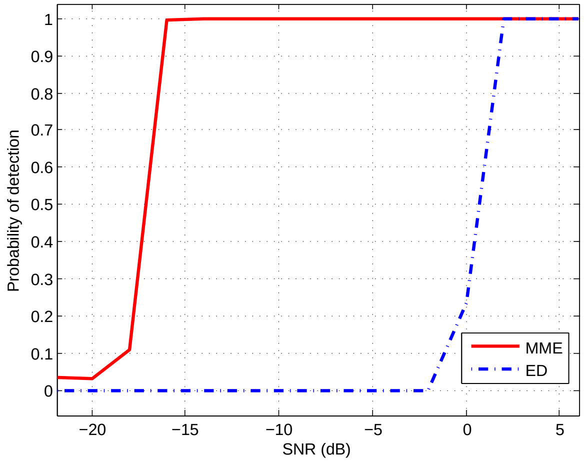

Fig. 4: Probability of detection comparison (MME and ED) for WM signal.

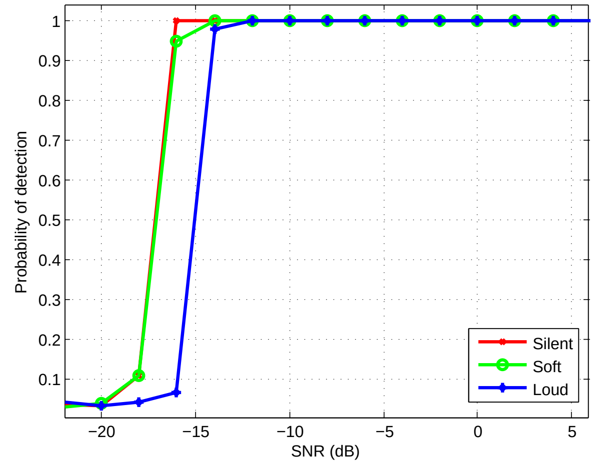

Fig. 5: Probability of detection for different WM signals.

performance of MME algorithm for different WM signals is also shown in Fig. 5. According to the results, the performance of MME algorithm for the silent and soft speaker mode is better than loud speaker. The reason is that received silent and soft speaker WM signals are more correlated than loud speaker.

V. Conclusion

In this work, we presented a spectrum sensing testbed for CR applications based on IEEE 802.22 WRAN standard. The requirements for our testbed are listed in section III.A which are satisfied as long as the capabilities of the equipments allow. We provided a realistic test environment for spectrum sensing algorithms. Theoretical performances of algorithms may differ in practice, especially in low SNR region. Therefore, we showed the performance of WM signal detection methods using the testbed. Periodic spectral usage map of a region can be extracted to decrease sensing time and improve the sensing capabilities. Moreover, proposed testbed can be used as an example to show fundamental functionalities of a CR for educational purposes.

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