Experimental Evaluation of Interference Avoidance Opportunistic Secondary Transmission for Coexistence with Primary Systems

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***Abstract*—In primary-secondary coexistence scenarios, protecting an incumbent primary user of the spectrum from secondary spectral emission is a key design requirement. We consider the GNU Radio based implementation and experimental evaluation of a co-existence system employing an opportunistic sense-and-carefully-transmit strategy. The interference mitigation is based on the interference avoidance partitioned frequency and time windowing (IA-PFT) strategy. The non-contiguous OFDM (NC-OFDM) based IA-PFT technique provides enhanced interference suppression using a unique combination of time domain and frequency domain processing. The energy-based sensing algorithm is enhanced with a noise level estimation technique operating in the presence of signal which is based on a rank order filtering algorithm. Such technique does not require "open" out-of-band frequencies or/and silent times for estimating varying noise floor. Experiments were carried out to evaluate the primary receiver's performance under the presence of secondary interference as well as the sensing module's performance in the presence of the primary transmission. The interference suppression has been verified by over-the-air experiments. In particular, experimental primary link performance results demonstrate around 10 dB BER gain relative to an NC-OFDM based suppression and confirm the interference suppression gain predicted by both the simulation power spectral density and measured spectrum.**

***Index Terms*—Interference avoidance, dynamic spectrum access, spectrum sensing, non-contiguous OFDM, cancellation carriers, IA-PFT, rank order filtering, in-band noise estimation**

I. Introduction

Traditional spectrum licensees have static and exclusive rights to a fixed amount of spectrum. With the proliferation of wireless broadband services the spectrum scarcity problem has today become one of national importance in countries facing this crisis. The concept of dynamic spectrum access (DSA) in which an unlicensed device opportunistically accesses the spectrum in the licensed frequency bands can help alleviate this problem. The licensed devices are primary users (PU) and the unlicensed devices are the secondary users (SU) of the band. However, this approach requires that the incumbent PU be protected from detrimental interference from the opportunistic SU. A parallel problem in this scenario is that the SU must also be assured some quality of service while having to overcome the interference from the PU(s). This is highlighted in Figure 1. Spectrum sensing to enable DSA is a widely researched topic. Various sensing techniques such as energy detection, matched filter detection and cyclostationary feature detection have been considered in this setting [1]. Matched filter and cyclostationary detection require some prior knowledge of the signal to be detected and also have greater complexity. Conventional energy detection approaches do not require prior knowledge of the signal but do rely on prior knowledge of noise power in the bandwidth of interest. Measuring the noise power requires taking the system offline for calibration purposes [2]. In addition to this being infeasible in realistic scenarios, calibrating a system this way is an extensive process. The thermal variations and aging of components cause the noise floor of the receiver to drift significantly. Further a single detection threshold over the entire band cannot be employed when the noise floor is frequency dependent. Therefore, for our system we developed an adaptive spectrum sensing scheme which can set a frequency dependent detection threshold to detect the PU. We use a rank-order filtering (ROF) [3] based algorithm that estimates the frequency dependent noise floor on-the-fly within the band and uses this to fix the threshold in a power spectral density based detector. Such technique does not require "open" out-of-band frequencies or/and silent times for estimating varying noise floor.

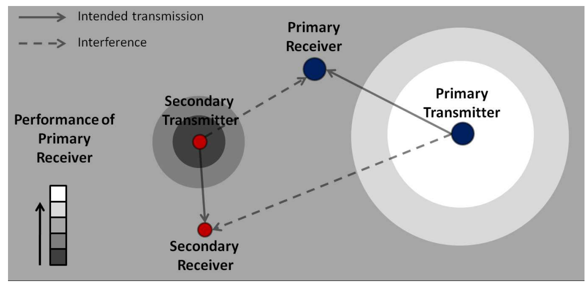

Fig. 1. Co-existing Primary and Secondary users

The most basic approach is to have no secondary transmission when a primary user is detected and transmit using OFDM when the primary user is not detected. This would cause minimal interference to the primary user. In some cases the primary user is narrow-band, and avoiding secondary transmission completely would lead to inefficient use of spectrum and poor secondary performance. These issues can be overcome by employing NC-OFDM transmission which has been used to achieve DSA [4], [5], [6]. When primary users are detected in the bandwidth of interest, the NC-OFDM sub-carriers corresponding to the frequencies of the primary users as well as few adjacent ones are deactivated i.e. turned OFF for transmission. This approach while increasing the efficiency of secondary spectrum access would cause interference to the primary users due to spectral leakage. For the third technique in addition to the non-contiguous secondary operation we have proposed an advanced interference avoidance technique referred to as IA-PFT[7]. The problem of spectral leakage is diminished by the use of time windowing and cancellation carrier schemes which result in maximum side-lobe suppression. Fundamental performance of IA-PFT in RF spectrum can be seen in [8]. In this paper, we carry out comprehensive experimental evaluations of IA-PFT for coexistence with primary systems: in particular, PU transmission performance in BER is measured under the presence of secondary transmission by IA-PFT.

The objectives of this paper are:

1) To evaluate the noise estimation and sensing algorithms using simulation.
2) To evaluate the amount of suppression gain achieved in the notch by employing IA-PFT.
3) To evaluate the PU system's performance in the presence of IA-PFT enabled NC-OFDM transmitter as compared to regular NC-OFDM transmitter.

We have implemented our system on GNU Radio; an open source software radio package [9] and USRP2; a commercially available software defined radio (SDR) [10]. The ORBIT wireless testbed at WINLAB, Rutgers University was used for our experiments [11]. The functionality of our DSA system was verified through over-the-air transmission spectrogram as shown in Figure 2. Both the enhanced interference suppression of IA-PFT and the ROF noise estimation + energy-based sensing performance were verified using over-the-air transmission spectrum.

The rest of the paper is organized as follows: Section II introduces the system model used during the experiments. Section III gives the implementation details of the proposed ROF based spectrum sensing scheme and the IA-PFT based secondary transmission system on the GNU Radio-USRP2 platform. Section IV discuss the setup of our over-the-air experiments. Section V discusses the evaluation results and Section VI concludes this paper.

II. System Model

We consider the following system setup:

1) Primary transmitter and receiver
2) Secondary transmitter
    a) Spectrum Sensing Module
    b) Regular NC-OFDM or IA-PFT based NC-OFDM transmitter

In this system, the primary transmitter is a wireless microphone user whose signal has been emulated using a Vector Signal Generator (VSG). The secondary transmitter is the crux of the system and consists of two main modules - the spectrum sensing module and a NC-OFDM based transmitter module.

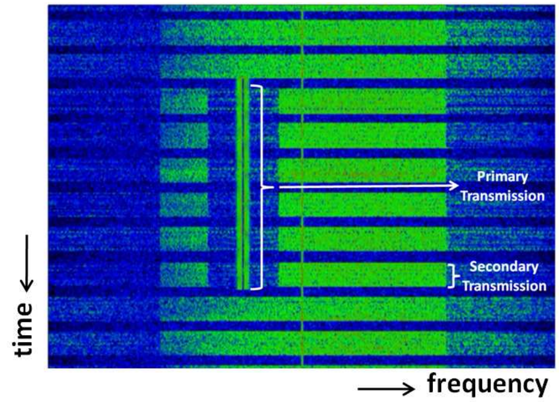

Fig. 2. Spectrogram illustrating the DSA operation

A. Primary Transmitter and Receiver

1) Wireless Microphone: In our system we have considered the primary transmitter to be a wireless microphone operating in a vacant TV channel. Wireless microphones typically use Frequency Modulation (FM) and have most of their power limited to a small portion of the bandwidth [12]. The center frequency is not fixed and could be located anywhere in the 6 MHz range of the TV channel. The maximum bandwidth of the wireless microphone is 200 kHz as specified by the FCC in Part 74 of the Code of Federal Regulations [13]. In [12] various modes for simulating the wireless microphone are provided. We generate the wireless microphone signal for the different modes in MATLAB and write these samples into the VSG. The signals from the VSG are amplified and transmitted over the air at the desired carrier frequency and transmit power.

2) Digital Transceiver: After verifying the DSA system, we consider a narrowband digital packet-based transceiver system as the primary transmitter instead of a wireless microphone. For this we use a readily available application in GNU Radio package which allows the users to control various parameters such as modulation scheme, bandwidth, transmit power etc. We consider the BER to evaluate the performance of this PU system in the presence of interference from the SU.

B. Spectrum Sensing Module

The spectrum sensing module is built around a PSD based energy detector[2]. Once the PSD is obtained the next step is to compare it to a detection threshold to determine if a signal is present. In this paper we have considered a novel approach to arrive at the detection threshold based on automatic noise floor estimation [3]. The authors have applied binary morphological processing and have suggested rank-order filtering approach as an alternative. The noise floor estimate returned by the ROF algorithm is averaged over the whole spectrum to obtain the noise power estimate. We use this noise power estimate to set the threshold for a neyman-pearson detector. The PSD is compared to the detection threshold to calculate the spectral mask. The spectral mask is a vector of size N_{FFT}, in which each element is a 1 or 0 depending on whether the corresponding frequency bin is occupied or vacant respectively.

C. Secondary Transmitter

We consider two types of secondary transmitters; a regular NC-OFDM transmitter and IA-PFT based NC-OFDM transmitter.

1) NC-OFDM Transmitter: NC-OFDM is a modified OFDM transmitter which uses a carrier mask to turn ON or turn OFF specific sub-carriers in the transmitted spectrum. This enables us to create spectral notches around the PU's band of operation and avoid interference in it. The PU system occupies one resource block (RB). A RB as per the LTE standard [14], [15] occupies a bandwidth of 180 kHz. The SU transmitter creates a spectral notch in PU's RB as well as it's adjacent RBs. This further reduces the spectral emission from the SU transmitter into the PU's band.

2) IA-PFT based NC-OFDM Transmitter: The IA-PFT based NC-OFDM transmitter is a modified NC-OFDM transmitter that improves the amount of suppression in the spectral notches. It achieves this by simultaneously performing time domain and frequency domain processing on the information bits sent to the transmitter. Here we present the implementation details of this proposed scheme. The technical design details of this technique can be found in [7], [8].

The regular NC-OFDM transmission leaks power into the notches. This energy is above the average noise floor in the band and will degrade the performance of the primary receiver. Therefore it is imperative to suppress this leakage and the IA-PFT technique was particularly designed to achieve this. To achieve more suppression we process the information symbols in two streams namely, Time Windowing (TW) and Cancellation Carriers (CC). These two streams are generated by TW and CC blocks which use the over-all carrier-mask to determine the position of the notch. The TW block activates all subcarriers in the over-all mask except Q sub-carriers on either side of the notch. The CC block activates only those Q sub-carriers that were deactivated by the TW block. Therefore the CC mask and TW mask are complementary.

The TW block shapes the symbol stream using a raised cosine filter. This reduces the spectral leakage in the center of the notch. The CC block adds two specially modulated tones on either sides of the notch. This is efficient in suppressing the leakage at the edges of the notch. Together these two blocks provide a suppression that is uniform over the whole notch.

III. Experimental Setup

A. Hardware and Software Platform

The secondary transmitter applications are implemented in GNU Radio and USRP2 along with the XCVR2450 daughterboard were used for transmitting the waveforms. The baseband complex samples are sent from GNU Radio to the data converters in the USRP2 over a Gigabit ethernet interface and RF daughter board used with USRP2 then sends the RF signal over the air. XCVR2450 can operate in 2.4-2.5 GHz range with 20 dBm max transmit power and also in 4.9 to 5.85 GHz range with 17 dBm max transmit power.

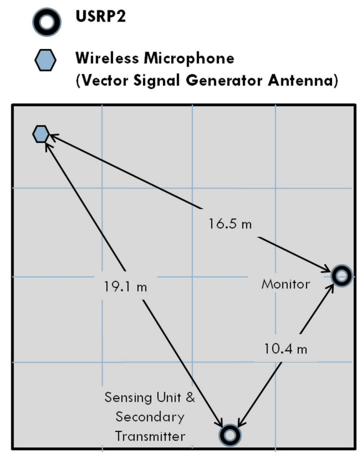

Fig. 3. Experimental Setup in the lab

The experimental setup for verifying the DSA operation with wireless microphone as the primary transmitter is shown in Figure 3.

B. Primary System Setup

1) Wireless Microphone: A vector signal generator (VSG) is used to emulate the wireless microphone signal. The wireless microphone signal is a frequency modulated signal whose tone frequency and frequency deviation depend on the mode of operation [12]. The bandwidth of the signal is 200kHz and the transmit power is set to -30dBm. The wireless microphone signal in this case is ON for 5 secs and OFF for 5 secs.

2) Digital Transceiver: The primary transmitter and receiver are set to operate with the following parameters: Bandwidth = 180 kHz, Modulation = GMSK, Transmit power = -55 dBm, Number of bits sent = 10^6

C. Spectrum Sensing Setup

- Bandwidth scanned = 3.84 MHz
- FFT size = 256
- Resource Block (RB) bandwidth = 180 kHz
- No. of RBs sensed = 12
- Total occupied bandwidth = 2.16 MHz

The noise floor is estimated over the scanned bandwidth using the ROF algorithm. The threshold for each bin i is calculated as follows:
$threshold_i = noise\_floor_i + x$
where x is a small increment that determines the probability of false alarm and missed detection. Using the thresholds, a bit vector of length 144 (12*12) bins is generated corresponding to the 12 RBs. A decision on each of the 12 RBs is now made using 12 frequency bins corresponding to each RB. A resource block is considered to be occupied if atleast 5 frequency bins out of the 12 are occupied.

D. Secondary Transmitter Setup

Secondary transmitter sends out packets for a fixed duration of time between the sensing durations.The number of packets sent depends on the number of resource blocks occupied. The secondary transmitter specifications are as follows:

- FFT size (N_{FFT}): 256
- Carrier mask with a specified notch
- Interpolation/Decimation:26
- Modulation: QPSK
- CP length: 18

The number of activated sub-carriers for CC is set as Q=10 for IA-PFT in our setup.

IV. Evaluation Results

The noise floor estimation algorithm was evaluated through MATLAB simulations. Figure 4 shows the probability of miss as a function of the SNR. It can be seen that the performance of the ROF algorithm is comparable to that of theoretical energy detection, where we assume that the exact noise power is known to the receiver.

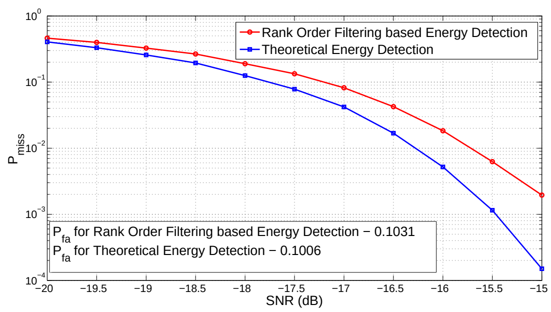

Fig. 4. Performance of the ROF based sensing algorithm

Figure 5 shows the transmitted spectrum of the IA-PFT based NC-OFDM transmitter. It is evident from Figure 5 that there is about 10 dB of additional suppression as compared to a simple NC-OFDM transmitter.

Figure 6 shows the co-existence of the primary and the secondary systems. The secondary transmitter does not transmit in the RBs occupied by the primary.

To analyze the bit error rate (BER) we fixed the transmit power of the PU and varied the secondary transmit power, thereby increasing the amount of interference to the primary receiver. The BER at the receiver degrades for increasing interference as shown in Figure 7. In Figure 7, the amount of performance gain achieved by employing IA-PFT technique is about 10 dB and it matches with the suppression gain shown in Figure 5.

V. Conclusions

In this paper we presented an experimental evaluation of our implementation of active interference avoidance opportunistic secondary transmission for primary-secondary co-existence scenarios. We first demonstrated our DSA technique with and adaptive sensing algorithm and verified our implementation by measuring the amount of suppression gain achieved by employing IA-PFT based NC-OFDM compared to regular NC-OFDM transmitter. We also showed the performance of the sensing algorithm using MATLAB simulations.

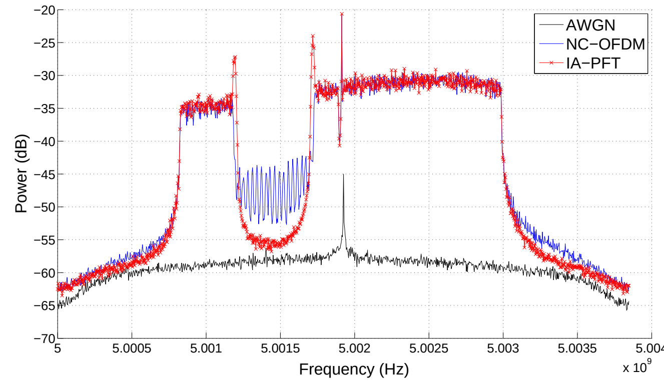

Fig. 5. RF transmitted signal spectrum of IA-PFT based NC-OFDM transmitter

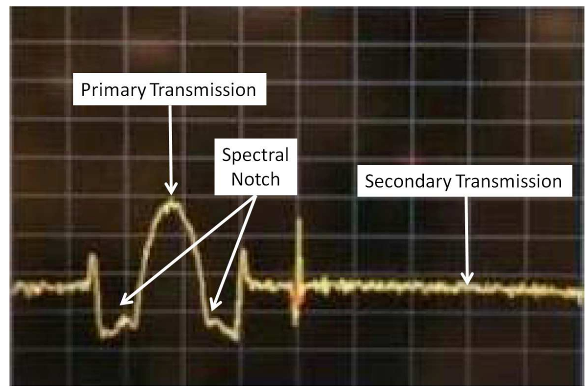

Fig. 6. Spectrum showing the co-existence of primary and secondary systems. [x-axis: 200 kHz/div, y-axis: 10 dBm/div]

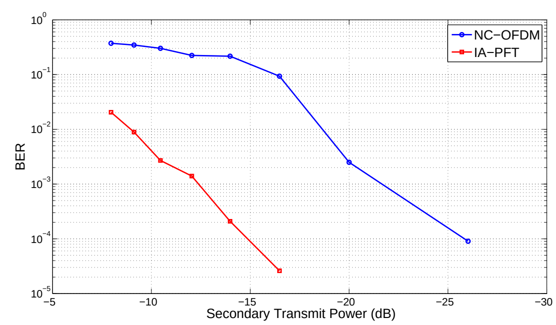

Fig. 7. BER at primary receiver vs. increasing secondary transmit power

The amount of performance gain in BER at the primary receiver by employing IA-PFT secondary transmitter matches with the suppression gain of about 10 dB in the RF transmitted signal.

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