Comparison of Nonquiet Spectrum Sensing in Filter Bank Multicarrier and OFDM Based Cognitive Radio Systems

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***Abstract*— Filter bank multicarrier (FBMC) and orthogonal frequency division multiplexing (OFDM) have been recognized as two physical layer (PHY) candidates for Cognitive Radio (CR) systems. Spectrum sensing plays an important role in a CR in order to detect spectrum opportunities. It is usually more desirable to perform spectrum sensing without additional hardware. In this paper, a comparison between performance of filter bank-based (FB-based) and fast Fourier transform-based (DFT-based) energy detectors (EDs) is presented. These methods are used in FBMC and OFDM PHYs with a slight modification to the hardware, respectively. For this comparison the area under the receiver operating characteristic (ROC) curve namely AUC is considered as a criterion. Moreover, the performance comparison is conducted under the condition that secondary users (SUs) continue their transmission even in the sensing period. As a result, the SU which is performing primary user (PU) detection receives the interference from SUs. This is called nonquiet sensing. The results indicate that although DFT-based ED is less complex, FB-based ED's performance is much better than DFT-based ED in heavy interference environment.**

I. INTRODUCTION

Considering the rapid growth of wireless communication technology and increasing number of wireless systems, manipulating the frequency resources and spectrum allocation have become more critical than ever before. Cognitive Radio (CR) has been introduced for efficient utilization of the spectrum by enabling the secondary users (SUs) to operate in the primary user (PU) frequency band when it is idle. As a result, one of the most important functions of CR is spectrum sensing which enables the radio to determine the presence of the PU. Afterwards, the CR user can utilize the PU channel for its transmission. As a result, it is crucial that SU uses an efficient signaling scheme and consequently an appropriate physical layer (PHY) which demonstrates acceptable performance both in spectrum sensing and signal transmission. Recently, multicarrier methods have been recognized as potential candidates for the PHY of CR systems [1]. Orthogonal frequency division multiplexing (OFDM), wavelet-based multi-carrier modulation, filter bank multi tone communication, and are among these multicarrier techniques [2]. Since 1990s, OFDM has been widely used in broadband wireless communication systems. Besides its extensive application, discrete Fourier transform (DFT), which is implemented through fast Fourier transform (FFT), as a part of OFDM-based receiver can be used as a means of spectral estimation to perform spectral analysis. Despite the advantageous properties of OFDM such as robustness against multipath fading and capability of dynamic spectrum use, one of the major problems of OFDM is the out of band components. To combat this problem the rectangular pulse shape in an OFDM transceiver is replaced by a pulse shape with smooth edges. Thus, it is defined as filtered OFDM [3]. Although there are other techniques proposed in [4]-[6], the simplest method is deactivating the neighboring subcarriers to the PU channel. With this method, a guard band is created for the protection of PU from interference. However, this will decrease the spectral efficiency.

Other candidates for multicarrier communications in CR networks are filter bank-based systems [7]. In [8], filter banks are proposed as a tool for spectrum sensing in CR networks. The detailed aspects of filter bank theory were developed largely during 1980s, subsequent to (and in many cases triggered by) the publication of Crochiere and Rabiner [9]. In [7], authors have proposed and discussed methods of using filter banks for multicarrier in a CR setup. Although the primary task of FB is to facilitate multicarrier communications, it actually makes the task of spectrum sensing easier by spectral estimation which comes at virtually no cost. Thus, one of the motivations behind applying FBMC is to integrate spectrum sensing ability with the existing PHY.

Coexistence problem is an issue of great importance in TV white space (TVWS) [10]. One aspect of the aforementioned problem is the mutual interference which is caused by

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different types of fixed and portable wireless devices operating in TVWS, specially the mutual interference from two neighboring channels. As a result, the power of out of band components will vary dramatically based on the PHY and signaling method of the SU. Due to the existence of the out of band components, performance of the detector will be affected. As it is indicated in [11], network-wide quiet periods for sensing are scheduled by CR network. The quiet periods are managed to decrease the interference while sensing is performed. On the other hand, the quiet periods will degrade the quality of service (QoS) in CR network. This is due to CR network traffic suspension. Thus, it is ideal that the CR network continues its transmission in the period of sensing. Consequently, there is a tradeoff between QoS of CR network and PU performance.

It is worth mentioning that FBMC and OFDM have been studied and compared in literature as PHYs for transmission and reception in multicarrier communication systems [3]. Thus, regardless of the advantages and disadvantages of each method for the PHY of a multicarrier system, our goal is to compare them for the task of spectrum sensing. Comparison of the performance of the detectors have been studied in literature when SUs are quiet during the sensing period [12]. However, performance of the detectors has not been compared under nonquiet sensing condition. Our purpose is to compare the performance of spectrum sensing in both FB-based and OFDM-based PHY systems, where PHY is used for spectrum sensing rather than a dedicated sensor and SUs continue their transmission during the sensing period.

The reminder of this paper is organized as follows: Section II dedicated to modeling the system and network and detector design for each method. All results are presented and discussed in Section III. Finally, conclusions are drawn in Section IV.

II. System Model

A. Hypothesis Testing and Channel Modelling

We assume that the channel is AWGN and slowly fading such that the channel coefficients can be assumed to be constant for the sensing period [13]. This assumption is satisfied for a fixed wireless network and also is valid for OFDM multicarrier systems [14]. In our sensing framework, the only information that the SU needs to have is the noise power density and the channel coefficients between the PU and SU. The noise variance can be easily estimated by measuring the power level of a channel that is known to be idle. The channel coefficients can also be estimated by the use of pilots in OFDM signal. Let $r[n]$ be the time domain received baseband signal which is sampled and let N_{obs} be the number of observed samples of $r[n]$ which are considered in detector decision. Thus the hypothesis testing is defined as

$$\begin{cases} H_0 : r[n] = w[n] + I[n] \\ H_1 : r[n] = s[n] + w[n] + I[n] \end{cases} \quad n = 0,1,\ldots,N_{obs} - 1, \quad (1)$$

Where H_0 and H_1 denote the idle and the active state of PU, respectively, $w[n]$ is the zero mean complex-valued white Gaussian noise with variance σ_n^2, $s[n]$ is the PU signal and $I[n]$ is the interference signal. In case there is no interference, the term $I[n]$ is eliminated in (1).

B. Spectrum Sensing Methods

According to the existing PHY in the CR network, spectrum sensing methods are specified. Since we are trying to compare two specific PHY candidates which were introduced in Section I, we will explain the structure of two correspondent detectors in this section.

1) Filter Bank-based Energy Detector (FB-based ED): The main task of CR is to determine the absence and presence of PU's signal in a specific frequency band. Hence, we need a detector after the spectrum estimator based on OFDM or filter bank.

The filter bank can be implemented by means of polyphase structure which makes the filter bank computationally efficient as it is shown in Fig. 1. In filter bank spectral estimators (FBSEs) the random signal ($r[n]$) is passed through a bank of filters and the output power of each filter is measured as an estimate of the spectral power over the desired subcarrier [8]. This means that in each subcarrier the estimate of the power spectral density (PSD) is obtained as

$$\hat{S}\left(\frac{i}{N}\right) = \sum_{n=0}^{N_v - 1} \left| y_i[n] \right|^2 \quad i = 0,1,\ldots,N-1, \quad (2)$$

where i is subcarrier index, N is the number of subcarriers and N_v is the length of output of inverse discrete Fourier transform (IDFT) in each subcarrier. It is worth noting that for N_v valid outputs in each subcarrier we need $M + (N_v - 1)N$ samples of the received signal where M is the length of the prototype filter. Besides, as soon as $r[n]$ has complete overlap with the prototype filter the outputs of the IDFT are considered to be valid. It is worth noting that although the term IDFT is used in the structure of the filter bank, the implementation technique is generally known to be IFFT.

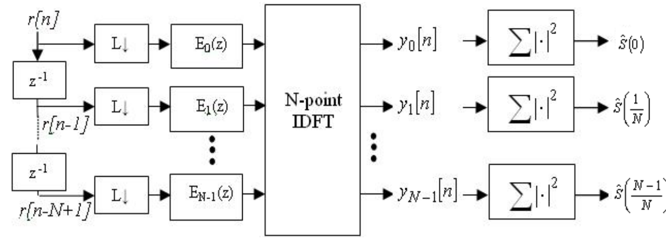

Figure 1. Polyphse structure of FBSE.

According to (2), an energy detector in frequency domain can be used in the total bandwidth of the received signal. Thus, the test statistic for the detector is defined as

$$\sum_{i=l_{\min}}^{l_{\max}} \hat{S}\left(\frac{i}{N}\right) \underset{H_0}{\overset{H_1}{\gtrless}} \eta_{FB}, \tag{3}$$

where η_{FB} is the decision threshold, $l_{\min}$ and $l_{\max}$ are the index of the first and the last active subcarriers in each subchannel, respectively.

2) DFT-based Energy Detector (DFT-based ED): An OFDM-based receiver contains a DFT block. The size of DFT is chosen according to the OFDM-based standard. As it was mentioned earlier, DFT can be used to perform spectral analysis. Thus, the received signal is windowed by a rectangular window of the same size of DFT without overlap between consecutive windows and passed through the DFT block. As a result, spectrum of PU signal which is estimated by measuring the energy of the output of DFT block in each subcarrier is given by

$$\hat{S}\left(\frac{i}{N}\right) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N_v-1} \left| \sum_{n=0}^{N-1} r[kN+n] e^{-\frac{j2\pi ni}{N}} \right|^2 \quad i = 0,1,\ldots,N-1, \tag{4}$$

where N is the size of DFT or equally the number of subcarriers and N_v is number of samples per subcarrier in frequency domain. Thus, the test statistic for the DFT-based detector will be the same as (3), except the fact that η_{FB} is replaced with η_{DFT} .

C. Network Model

For performing the spectrum sensing in a CR network, network model and the communication scenario are of great importance. In this paper the simplest scenario is considered in our network model. As it is expected, there should be two networks, one for PU and one for SU. In the PU network, a PU base station (BTS) is considered with one user whereas in CR network depending on the communication scenario, network model will vary. Thus, we considered two different scenarios. In the first scenario, we assumed that the PU BTS is transmitting an OFDM-based signal and the SU1 is trying to perform the detection in the PU frequency band (Fig. 2). Pursuant to the PHY, SU1 will apply one of the detectors in Section II part B. It is worth mentioning that the assumption of OFDM-based signal for the PU is not trivial. Due to variety of existing OFDM-based standards, it is reasonable to consider such signaling method for PU.

In the second scenario, we assumed that the other SU (SU2) which is not performing the detection is not silent. This means that during the spectrum sensing period SU2 continues its transmission in a neighboring channel of PU. As a result, the signal which is transmitted by SU2 is considered as an

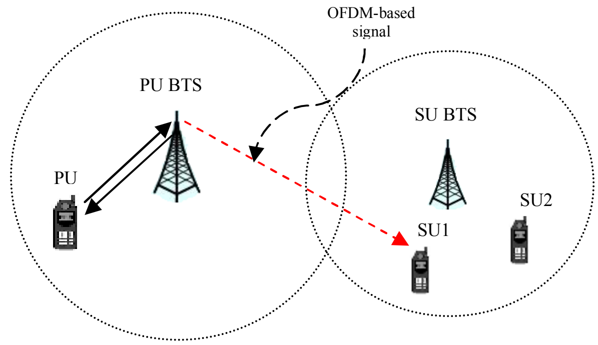

Figure 2. Quiet sensing (Scenario 1).

interference signal for SU1. In Fig. 3, it is seen that the signal and subsequently the interference which is transmitted by SU2 are proportional to the selected PHY in CR network. Consequently, we have chosen the staggered modulated multitone (SMT) signaling method in FBMC-based PHY [15].

As it was mentioned in Section I, our main purpose is comparing the performance of the detectors in nonquiet sensing condition. However, the comparison is also performed in quiet sensing condition in order to demonstrate the difference explicitly.

III. SIMULATION RESULTS

In this section, we present simulation results for both methods of the previous section. In our simulation an OFDM-based signal is considered for PU with a bandwidth of 8 MHz, 4-QAM modulation type, $N = 256$ and guard interval with the length of $N/8$. As it was mentioned in Section II part A, channel is considered to be AWGN. We assumed that SU searches a bandwidth of 8 MHz. According to (2), in filter bank design, a prototype filter with the length of KN with $K = 6$ and $N = 256$ is considered and downsampling factor (L) is set equal to N [8].

To compare FB-based and DFT-based EDs the number of samples in frequency domain based on which the spectrum is estimated is equal. As a result, if there are N_v valid outputs in FB-based ED, there are also N_v valid outputs for each subcarrier in DFT-based ED. Thus, $N_v = 1$ is considered for both detectors. The curves are obtained by Monte Carlo simulation with 5000 iterations.

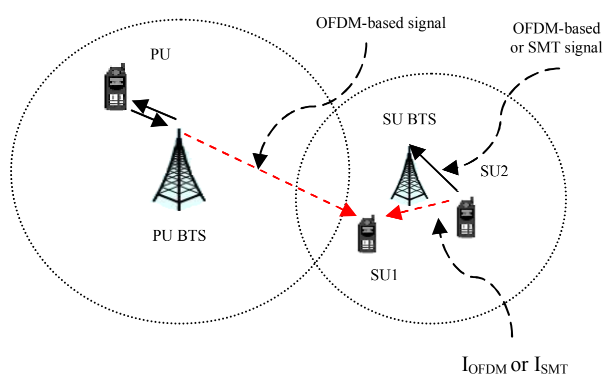

Figure 3. Nonquiet sensing (Scenario 2).

In the first scenario, there is no interference from SU2. Thus, P_d is plotted versus SNR in $P_{fa} = 0.01$ which is a desired level in different spectrum sensing scenarios. In Fig. 4, it is clearly seen that performance of the detectors is nearly the same. Since the value of AUC demonstrates the area under ROC curve, it is possible to compare the overall performance of the detectors in different levels of SNR and different values of P_{fa}.

For our simulation, the AUC is calculated after obtaining the ROC curve in each SNR. As it is obvious in Fig. 5, the value of AUC varies between 0.5 and 1 which corresponds to the worst and the best detector, respectively. It is also clear that the overall performance of the FB-based ED is the same as DFT-based ED.

In the second scenario, SU2 is transmitting either a 4-QAM modulated SMT or an OFDM signal with the bandwidth same as that of PU. As we know, the power of transmitted signal by SU2 which is estimated by SU1 is proportional to their distance from each other. Therefore, to demonstrate the effect of interference power on the performance of the detectors, we have altered the power of the SU2 signal according to their distance. Fig. 6 indicates that by increasing the ratio of power of SU2 signal to power of PU signal (P_{SU2}/P_{PU}) or equivalently decreasing the distance between SU1 and SU2, FB-based ED outperforms the DFT-based ED. It can be inferred that because of the great amount of out of band components in OFDM-based signal the level of interference is much greater than SMT signal. Consequently, the signal to interference plus noise ratio (SINR) is decreased and this degrades the performance of the DFT-based ED.

In order to investigate the effect of SNR level on the performance of the detectors in the second scenario, AUC of the detectors is plotted with respect to SNR in a constant $P_{SU2}/P_{PU} = 200$. From Fig. 7 it is apparent that the difference between AUC of the detectors decreases by decreasing the SNR level. When power of the signal is constant, decreasing the SNR means increasing the noise power. As a result, when the level of the noise power reaches the level of interference

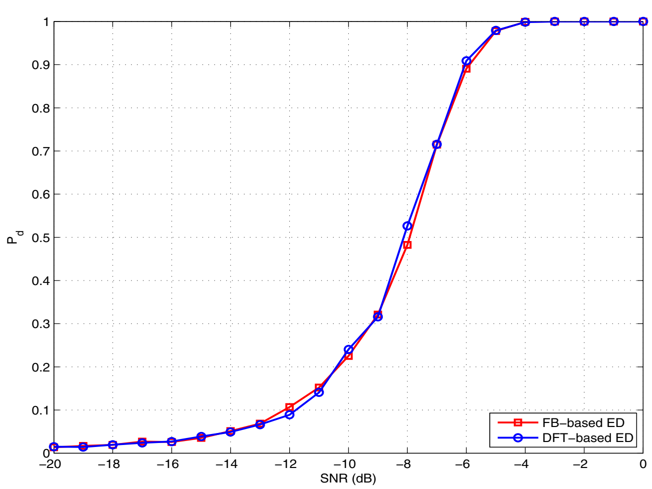

Figure 4. P_d with respect to SNR in $P_{fa} = 0.01$ in the first scenario.

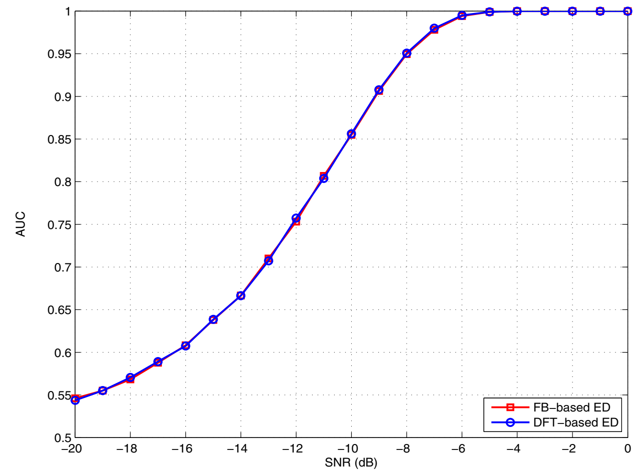

Figure 5. AUC curve with respect to SNR in the first scenario.

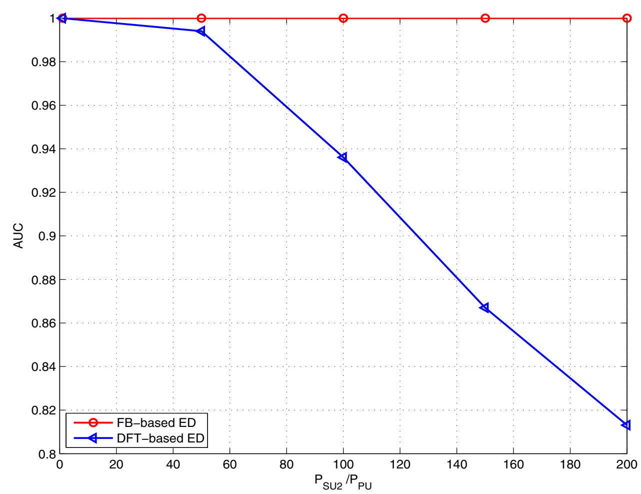

Figure 6. AUC curve in the second scenario for different values of P_{SU2}/P_{PU} in SNR = 0 dB in the second scenario.

power, both detectors are not able to distinguish between the noise and interference. Consequently, they will demonstrate the same performance.

As it is clearly seen, large side lobes of OFDM-based signal has negative effects on the performance of the detector. Although suggestions have been made to improve the side lobes of OFDM analysis and synthesis filters through the use of filtered OFDM, these solutions are generally very limited in performance [3]. One simple method for decreasing the power of out of band components in an OFDM-based signal is deactivating the neighboring subcarriers to the PU channel. However, as it was mentioned in Section I, deactivating the subcarriers will reduce spectral efficiency comparing to the SMT signaling method which is more spectral efficient than OFDM signaling [3].

Another important factor in our comparison is computational complexity of the detectors. As it is indicated in TABLE I, FB-based ED is $1 + K/\log_2 N$ times more complex than DFT-based ED. Considering $K = 6$ and $N = 256$, the computational complexity of FB-based ED is 1.75

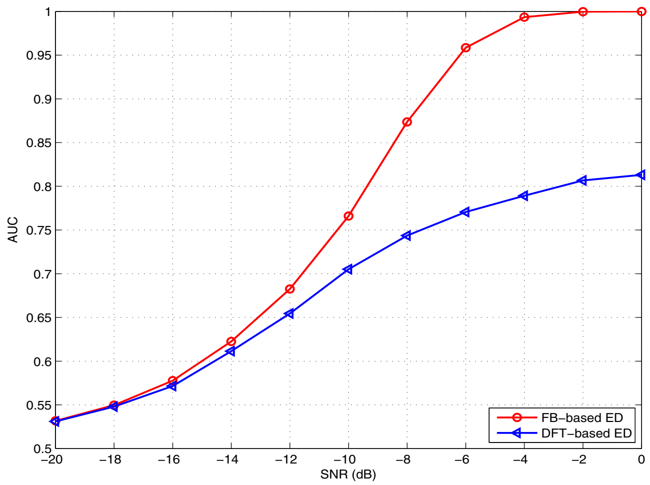

Figure 7. AUC with respect to SNR for $P_{SU2}/P_{PU} = 200$ in the second scenario.

times as that of DFT-based ED. In addition, when K is constant, the ratio of the complexity of the aforementioned detectors will decrease as the size of IDFT increases. As a result, there is a tradeoff between computational complexity of the detectors and their performance.

TABLE I. COMPARISON OF COMPUTATIONAL COMPLEXITY OF FB-BASED AND DFT-BASED ENERGY DETECTORS

Detector type	**Number of real additions**	**Number of real multiplications**
FB-based detector	$2NN_v\left(K+\log_2 N\right)$	$2NN_v\left(K+\log_2 N\right)$
DFT-based detector	$2NN_v\log_2 N$	$2NN_v\log_2 N$

IV. CONCLUSION

In this paper, we have compared the performance of spectrum sensing in FBMC and OFDM PHY with the assumption that no additional hardware is utilized for this purpose. We have shown that while FB-based ED and DFT-based ED demonstrate nearly the same performance in a quiet sensing scenario, there is a great difference between their performances in a nonquiet sensing scenario. Although performance of the DFT-based ED improves by deactivating the neighboring subcarriers to the PU channel, this will substantially decrease its spectral efficiency. From computational complexity point of view, it is apparent that if there is no filtering in the OFDM-based PHY, the corresponding detector will be less complex than FB-based detector.

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