Discrete Wavelet Packet Transform based Energy Detector for Cognitive Radios

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***Abstract*—As the wireless communication services grow quickly, the seriousness of spectrum scarcity has been on the rise gradually. In this context, an emerging technology, cognitive radio (CR) has been come out to solve today's spectrum scarcity problem. Among its fundamental functions, the most important function is spectrum sensing which requires precise accuracy and low complexity. Thus, in this paper, we propose the fast spectrum sensing algorithm using the discrete wavelet packet transform (DWPT) and infinite impulse response (IIR) polyphase filtering schemes. By simulations and complexity analysis, we verify our algorithm.**

I. INTRODUCTION

Current spectrum management model, command-and-control, is creating a fundamental cause to drop the spectral efficiency of the radio spectrums in times and spaces. The FCC announced a very interesting report [1] that relates to this fact. It pointed out that more than 70% of radio spectrums are underutilized in certain times or geographic locations. This means that spectrum scarcity is not due to fundamental lack of spectrum but wasteful static spectrum allocations. Hence, various spectrum sharing schemes which can raise spectrum utilization are investigated by many research institutes.

In this context, an emerging technology, cognitive radio (CR) has been come out in the wireless communication field. CR recognizes its environment and learns from the environment to make a decision. In addition, it also adapts operating parameters such as transmit power and modulation scheme according to the variation of real time environment [2]. Based on these fundamental tasks, it is anticipated that CR can alleviate today's spectrum scarcity problem. Recently, IEEE 802.22 is going on establishing the standard of CR technology. This standard is based on the scenario that unlicensed (or CR) users communicate using idle or unused licensed frequency bands without interfering with licensed users.

As aforementioned, CR has awareness, adaptation and reasoning functions. Spectrum sensing, adaptive processing, and optimization, therefore, are the most critical techniques for CR. Among other things, spectrum sensing, which makes users possible to recognize surrounding condition, needs signal processing techniques with precise accuracy and low complexity. Although many precise spectrum sensing techniques had been developed for signal identification in the field such as radar engineering, they are unsuitable for CR techniques because of their high complexity. On the other hand, spectrum sensing techniques based on the fast fourier transform (FFT) are easy to implement but have a drawback of low accuracy. As a solution for this problem, IEEE 802.22 suggested two-stage sensing architecture [4]. Two-stage sensing scheme provides performance of compromising between fast processing and precise accuracy.

In this paper, we propose the fast spectrum sensing algorithm as a coarse sensing for CR based on the proposed two-stage sensing architecture. It solves the problem of the conventional FFT scheme and makes spectrum sensing fast. These can be possible by using the discrete wavelet packet transform (DWPT) and the IIR polyphase filtering schemes. The DWPT can analyze an interested frequency band based on the multi-resolution, and the IIR polyphase filtering scheme reduces the complexity of the DWPT's implementation. Simulation results and complexity analysis show that the proposed algorithm is suitable for the spectrum sensing scheme for CR.

The remainder of this paper is organized as follows. Section II briefly describes the wavelet analysis and power measurement. The two channel IIR polyphase filters and complexity analysis are discussed in section III. In section IV, DWPT based energy detection algorithm is proposed. The simulation environments and results are provided in section V, and section VI concludes the paper.

II. WAVELET ANALYSIS AND POWER MEASUREMENTS

Construction of the wavelet transform and understanding of wavelet basis are provided by the multi-resolution analysis [5]. In addition, the efficient hierarchical algorithm for computing the wavelet transform is in the filter bank theory [6].

A. Discrete Wavelet Transform (DWT)

DWT is designed from the multi-resolution analysis that decomposes the given signal space into a approximate space, V, and detail spaces, W, as shown in equation (1).

$$V_{j+1} = W_j \oplus V_j = W_j \oplus W_{j-1} \oplus V_{j-1} \tag{1}$$

where W_j is the orthogonal complement of V_j in V_{j+1} and $\oplus$ represents the orthogonal sum of two subspaces. Two space, V_j and W_j are constructed by orthonormal scaling functions, $\phi_{j,k}$, and orthonormal wavelet functions, $\psi_{j,k}$, respectively. Scaling function, $\phi_{j,k}$, and wavelet function, $\psi_{j,k}$, are obtained as

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$$\begin{aligned}\phi_{j,k}(t) &= 2^{j/2}\phi(2^j t - k) = \sum_l h_{l-2k}\phi_{j+1,k}(t)\\ \psi_{j,k}(t) &= 2^{j/2}\psi(2^j t - k) = \sum_l g_{l-2k}\phi_{j+1,k}(t)\end{aligned} \tag{2}$$

with high-pass filter, $g_{l-2k} = \langle \psi_{j,k}, \phi_{j+1,l}\rangle$, and low-pass filter, $h_{l-2k} = \langle \phi_{j,k}, \phi_{j+1,l}\rangle$. $\langle\rangle$ means inner product. Using these functions, DWT of a given signal, f, provides scaling coefficients and wavelet coefficients. The scaling coefficient at the jth level kth time is computed by

$$c_{j,k} = \langle f, \phi_{j,k}\rangle = \sum_l h^*_{l-2k}\langle f, \phi_{j+1,l}\rangle = \sum_l h^*_{l-2k} c_{j+1,l} \tag{3}$$

The wavelet coefficient at the jth level and kth time is

$$d_{j,k} = \langle f, \psi_{j,k}\rangle = \sum_l g^*_{l-2k}\langle f, \phi_{j+1,l}\rangle = \sum_l g^*_{l-2k} c_{j+1,l} \tag{4}$$

Fig. 1 and 2 show 2-level analysis part of the DWT and its frequency separation property.

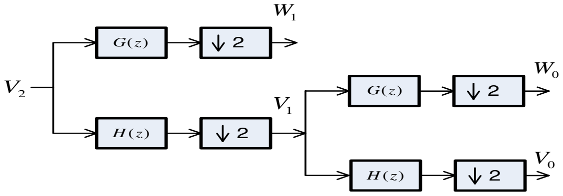

Fig. 1. 2-level analysis part of the DWT

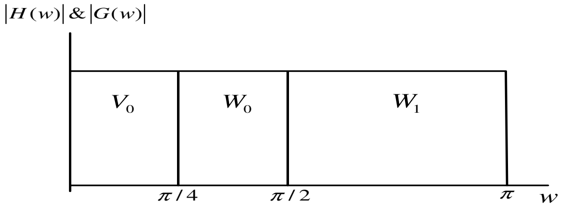

Fig. 2. Frequency separation of 2-level analysis part of the DWT in case of using ideal filter bank

B. Discrete Wavelet Packet Transform (DWPT)

The difference between DWT and DWPT just lies in the decomposition of detail space. DWPT decomposes not only the approximation space but also the detail space. This means that it can separate frequency band uniformly. Fig. 3 and 4 represent 2-level analysis part of the DWPT and its frequency separation property.

C. Power Measurements Using Wavelets

Power measurements using wavelets are explained in [7]. If a received signal, $r(t)$ is periodic signal with period T, then, the power of this signal is computed by

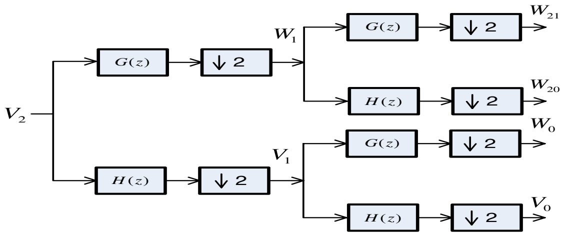

Fig. 3. 2-level analysis part of the DWPT

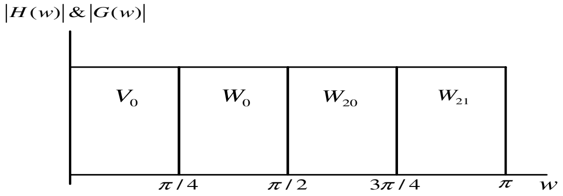

Fig. 4. Frequency separation of 2-level analysis part of the DWPT in case of using ideal filter bank

$$P = \frac{1}{T}\int_0^T r^2(t)dt \tag{5}$$

and $r(t)$ can be represented as

$$r(t) = \sum_k c_{j_0,k}\phi_{j_0,k}(t) + \sum_{j\geq j_0}\sum_k d_{j,k}\psi_{j,k}(t) \tag{6}$$

where $c_{j_0,k}$ and $d_{j,k}$ are scaling coefficients and wavelet coefficients respectively. Therefore, we can easily compute the power of the signal like following equation using orthonormal wavelet and scaling function properties.

$$\begin{aligned}P &= \tfrac{1}{T}\int_0^T r^2(t)dt\\ &= \tfrac{1}{T}\left[\int_0^T \left\{\sum_k c_{j_0,k}\phi_{j_0,k}(t) + \sum_{j\geq j_0}\sum_k d_{j,k}\psi_{j,k}(t)\right\}^2 dt\right]\\ &= \tfrac{1}{T}\left[\sum_k c^2_{j_0,k} + \sum_{j\geq j_0}\sum_k d^2_{j,k}\right]\end{aligned} \tag{7}$$

It means that the power of each subband can be calculated using the scaling and wavelet coefficients.

III. TWO CHANNEL IIR POLYPHASE FILTERS AND COMPLEXITY ANALYSIS

The wavelet filter banks with IIR filters was explained in [8]. The main advantages of using IIR polyphase filter banks are their good frequency selectivity and low complexity.

A. Two Channel IIR Polyphase Filter Banks

The conventional two channel wavelet filters can be represented by two channel IIR polyphase filters like following equations.

$$\begin{aligned}H(z) &= E_{00}(z^2) + z^{-1}E_{01}(z^2)\\ G(z) &= E_{00}(z^2) - z^{-1}E_{01}(z^2)\end{aligned} \tag{8}$$

where $H(z)$ and $G(z)$ are conventional IIR low-pass filter and high-pass filter respectively and E_{00} and E_{01} are all-pass filters. Fig 5. shows the two channel IIR polyphase filter banks. It decimates a signal before the filtering and uses all-pass filters with small number of filter coefficients comparing to the original low-pass and high-pass filter. This makes the complexity low.

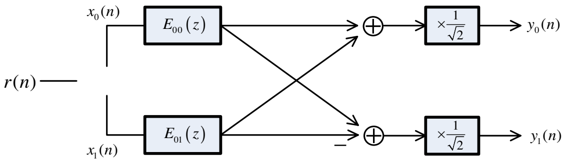

Fig. 5. Two channel polyphase structure

In the Fig. 5, $x_0(n)$ and $x_1(n)$ represent even and odd indices of $r(n)$ and $y_0(n)$ is the same as the output of the low-pass filter, $H(z)$, and $y_1(n)$ is the same as the output of the high-pass filter, $G(z)$.

A good frequency selectivity, one of main advantages of the IIR polyphase filters, is shown in Fig. 6. There are three kind of filters, Butterworth IIR wavelet filters ($L = 2$ and 4), and db5 FIR wavelet filters.

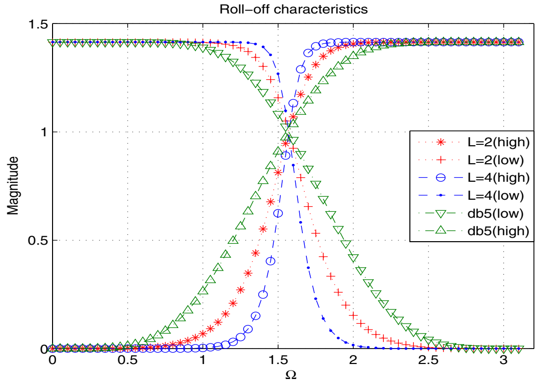

Fig. 6. Roll-off characteristics of filters

B. Complexity of Wavelet Analysis

An analysis of the number of mathematical operations (consider only real multiplications) shows the complexity of schemes. The total number of real multiplications for N sequences computation is compared as follows

- FFT:
  $= N/2\log_2 N$ complex multiplications
  $= 2N\log_2 N$ real multiplications
- db5 FIR wavelet filtering schemes for DWT:
  $= 2\times 10\,\text{coeff.}\times\left(\text{N}+\text{N}/2+\cdots+\text{N}/2^{(\log_2\text{N}-1)}\right)$
  $= 40\times(N-1)$
- Butterworth polyphase IIR filter for DWT (L=2):
  $= 2\times 2\,\text{coeff.}\times\left(\text{N}/2+\cdots+\text{N}/2^{(\log_2\text{N})}\right)$
  $= 4\times(N-1)$
- Butterworth polyphase IIR filter for DWT (L=4):
  $= 2\times 3\,\text{coeff.}\times\left(\text{N}/2+\cdots+\text{N}/2^{(\log_2\text{N})}\right)$
  $= 6\times(N-1)$
- db5 FIR wavelet filtering schemes for DWPT:
  $= 10\,\text{coeff.}\times\left(2\text{N}+\cdots+2^{(\log_2\text{N})}\text{N}/2^{(\log_2\text{N}-1)}\right)$
  $= 10\times(2N\log_2 N)$
- Butterworth polyphase IIR filter for DWPT (L=4):
  $= 3\,\text{coeff.}\times\left(2\text{N}/2+\cdots+2^{(\log_2\text{N})}\text{N}/2^{(\log_2\text{N})}\right)$
  $= 3\times(N\log_2 N)$

where coeff. represents coefficients.

From the above results, the total real multiplications of the IIR polyphase filtering schemes for DWT are smaller than conventional wavelet FIR filtering scheme and the FFT for large input sequences, N. Although the IIR polyphase filtering schemes for DWPT have almost the same complexity order, $N\log_2 N$, the proposed algorithm reduces the complexity and makes spectrum sensing faster using the multi-resolution property.

IV. DWPT BASED ENERGY DETECTION ALGORITHM

Since the spectrum sensing algorithm for CR has to sense surrounding condition with fast speed and precise accuracy, we suggest a possible energy detector based on the proposed two-stage sensing architecture like follwoings. As a coarse sensing, DWPT based energy detector, is first performed to select unoccupied candidate channels, and then one of the channels is examined by the fine sensing to detect weak signals. Finally, using outputs of above the sensing stages, unoccupied channel set is made for unlicensed (or CR) users.

A. The Idea Description

DWPT can separate a given frequency band into a low-frequency subband and a high-frequency subband. The proposed DWPT based energy detector is designed based on this property. Before commenting about the idea, we first assume that B_i and B_c are an interested frequency band (or scanning range) and a bandwidth of each channel respectively. We also assume that the ratio of between B_i and B_c is a power of 2. The procedure of the idea, DWPT based energy detector, is shown in Fig. 7.

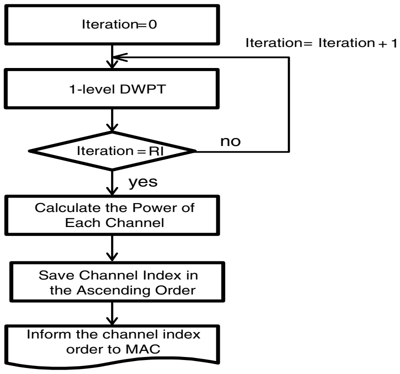

Fig. 7. The flow chart of the DWPT based energy detector

1) Initialize the iteration parameter to zero.

2) Perform the 1-level DWPT using the two channel IIR polyphase filter banks.
3) Compare the iteration parameter with RI. RI represents required iteration number of DWPT and is calculated by $\log_2\left(\frac{B_i}{B_c}\right)$. If the iteration parameter equals to RI, it goes to the next step. If not, the 1-level DWPT is performed again with increasing iteration parameter by 1.
4) Compute the power of each channel.
5) Sort the channels in the ascending order based on their powers.
6) Inform the order of sorted channel index to MAC to process the second sensing stage, fine sensing.

B. The Anticipated Performance of the Idea

The proposed algorithm has two improvements of the conventional energy detection schemes. One is that it can easily select the unoccupied candidate channels with simple structure. This is accomplished by using two channel IIR polyphase filter banks and sorting the channels in the ascending order based on the power of each channel. The latter is rational due to the fact that the channel with low power has high probability to be a unoccupied channel.

Reducing the complexity is the other improvement. Specifically, the algorithm performs DWPT not to the final level but to the RI level. If the two channel IIR polyphase filtering scheme (L=4) is used for N sequences and RI is much smaller than N, the complexity is reduced to

$$\begin{aligned}\text{complexity} &= 3\,\text{coeff.} \times \left(2\mathrm{N}/2 + \cdots + 2^{\mathrm{RI}}\mathrm{N}/2^{\mathrm{RI}}\right)\\ &= 3{\cdot}N{\cdot}RI\end{aligned} \tag{9}$$

V. SIMULATION ENVIRONMENT AND RESULTS

In this section, we identify whether the proposed scheme senses licensed (or primary) users or not, and examine its whole procedure.

A. Simulation Environment

As shown in Fig. 8, the simulation environment is vertical sharing scenario [3]. Specifically, there exist 3 licensed (or primary) users and 1 customer premise equipment (CPE) that can sense the interested frequency band for CR users. We assume that each primary user's signal is band-pass signal with bandwidth of 200 KHz. In addition, the channel is additive white gaussian noise (AWGN) channel with zero mean and $\frac{N_0}{2}$ variance, the interested frequency band (or scanning range), B_i, is 3.2 MHz and there are 16 channels in the frequency band, B_i.

Fig. 9 shows the procedure of separation of the interested frequency band based on the above simulation environment. Since there are 16 channels in B_i, B_c is 200 KHz and 4-level DWPT (or $RI = 4$) has to be performed. For simplicity we put indexes to channels in the ascending order. From this figure, we can infer that if a primary user exists in the frequency band $0 \sim 200$KHz, the power of the channel 1 has to be larger than other channels'. Butterworth two channel IIR polyphase wavelet filter bank (L=4) is used in the simulation and the number of data that has to be computed is 8000 sequences.

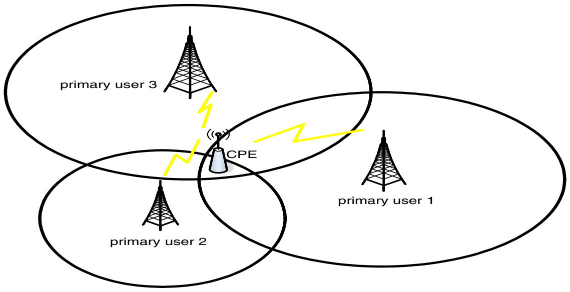

Fig. 8. Simulation environment scenario

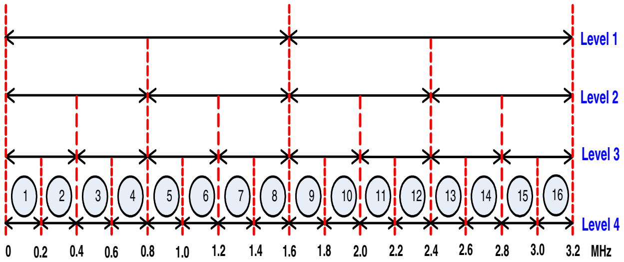

Fig. 9. Separation of input signal frequency band using the proposed shceme

B. Simulation Results

Two cases which are different with center frequency and SNR are considered in this paper.

1) case 1: Center frequencies of 3 primary users' signals and their SNR are fixed as $f = 0.5$, 1.5, 3.1 MHz and SNR = 20, 17, 14 dB. Fig. 10 shows the received signal at the CPE using the FFT scheme. Since center frequencies are 0.5, 1.5, and 3.1MHz, we anticipate the powers of channel 3, 8, and 16 are larger than other channels'. Fig. 11 shows this result and 16 channels are sorted like Fig. 12.

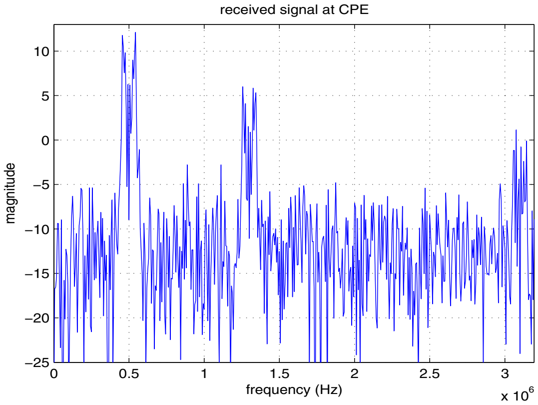

Fig. 10. Received signal at CPE for case 1

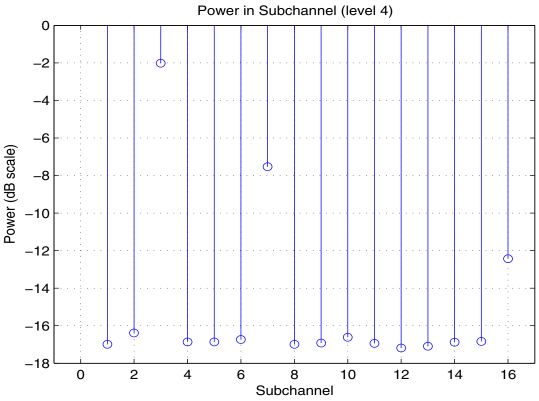

Fig. 11. Power of channels for case 1

12	13	1	8	11	9	14	4	5	15	6	10	2	16	7	3

Fig. 12. Sorted channels for case 1

2) case 2: Center frequencies of 3 primary users' signal and their SNR are fixed as $f = 0.1$, 1.9, 2.9 MHz and SNR = 10, 7, 4 dB. Fig. 13 shows the received signal at CPE using the FFT scheme. Since center frequencies are 0.1, 1.9, and 2.9 MHz, we anticipate the powers of channel 1, 10, and 15 are larger than other channels'. Fig. 14 shows this result and 16 channels are sorted like Fig. 15.

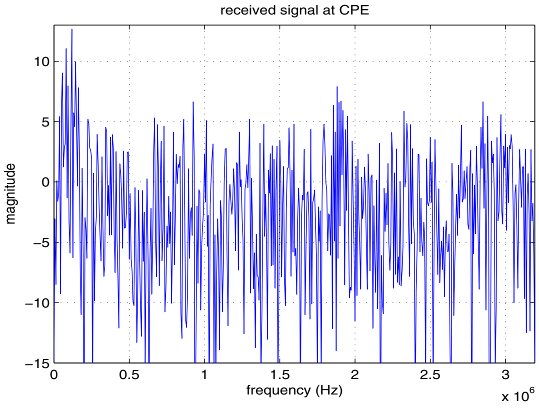

Fig. 13. Received signal at CPE for case 2

In both cases, the final outputs, sorted channel indexes, are sent to the MAC to process fine sensing. From above simulation results, the proposed algorithm is verified to identify the channels which primary users exist in. Since $RI = 4$ in these simulations, the computational complexity of the proposed scheme is 96000 using equation (9).

VI. CONCLUSION

The secondary spectrum has been issued due to its property that improves spectra efficiency. In this context, CR has received a plenty of attentions and one of the its critical technologies is spectrum sensing which requires fast processing and precise accuracy not to interfere with licensed users. Thus, in this paper, the fast spectrum sensing algorithm based on DWPT is introduced focusing on the coarse sensing. Using the multi-resolution property of DWPT and two channel IIR polyphase wavelet filter banks, the proposed algorithm has simple structure and reduces computational complexity comparing to the conventional schemes. Simulation results show that the proposed algorithm can sense surrounding environment. Therefore, we can conclude that the proposed scheme can be a possible energy detector for CR.

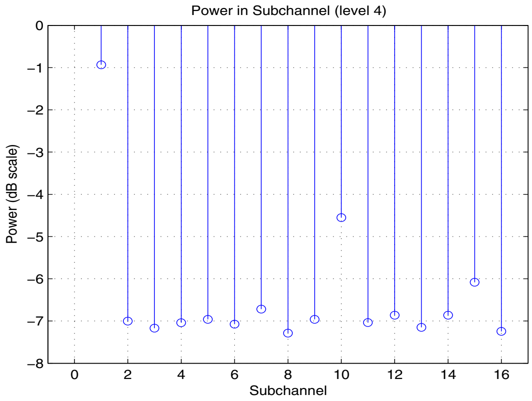

Fig. 14. Power of channels for case 2

8	16	3	13	6	4	11	2	5	9	12	14	7	15	10	1

Fig. 15. Sorted channels for case 2

ACKNOWLEDGMENT

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