Fast spectrum sensing algorithm for 802.22 WRAN Systems

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***Abstract*— As the wireless communication services grow quickly, the seriousness of spectrum scarcity has been on the rise gradually. Recently, the FCC (Federal Communications Commission) announced very interesting reports [1]. 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. In this context, IEEE 802.22 WG (Working Group) was organized in November 2004. Since it is originated by the secondary spectrum usage approach, its critical technology is spectrum sensing not to interfere with licensed users. Thus, in this paper, we propose the fast spectrum sensing algorithm based on the discrete wavelet packet transform focusing on the coarse detection. 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 spectrum in time and space like Fig. 1 by granting a right to Radio Access Technology (RAT) to access exclusively. In order to solve the spectrum scarcity, a number of bodies, headed by the FCC, have been taking actions to make new paradigm of spectrum management.

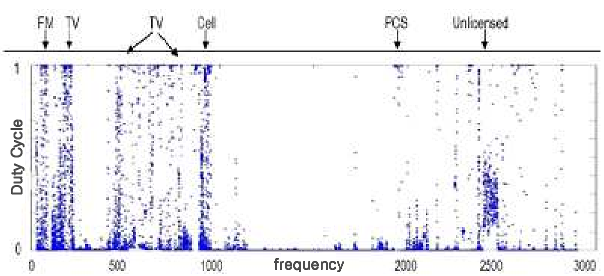

Fig. 1. Spectrum Utilization in New York

Recently, the FCC announced a very interesting report [1]. 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 research institutes.

In this context, IEEE 802.22 WG was organized in November 2004. IEEE 802.22 has a purpose to provide wireless internet service to WRAN (Wireless Regional Area Network) user (or secondary user) using idle or unused TV spectrums not to disturb VHF/UHF TV band users (primary user). Since there are two types of users in terms of spectrum access priority, this coexistence is regarded as vertical sharing [2] that the secondary user utilizes licensed spectrums by opportunistic manner. The outstanding advantage of this sharing is to be realizable by little modifications of current spectrum regulation. Therefore, IEEE 802.22 activities have received a plenty of attentions.

Since the QoS (Quality of Service) of privileged primary users must be guaranteed, in the secondary spectrum usage approach, one of the critical parts is spectrum sensing. Thus, low complexity with high sensitive detection technique is needed in the secondary user system. In IEEE 802.22, for example, if the DTV signal is a primary user, a secondary user has to detect up to -116dBm signal. To meet the time and sensitivity requirements, two stage spectrum sensing which consists of coarse and fine detection has been suggested [3]. The key functionality of each stage is to select multiple unoccupied candidate channels, and to identify the signal type and detect the weak signal respectively.

In this paper, we focus on the coarse detection part which selects multiple unoccupied candidate channels by the energy detection method. The swapping time is more important than the sensing sensitivity at this stage. Thus, we propose the fast spectrum sensing algorithm based on the discrete wavelet packet transform. Although the wavelet packet transform has almost the same complexity as the Fast Fourier Transform (FFT), the proposed wavelet based algorithm reduces the complexity and makes spectrum sensing faster. In the proposed scheme, furthermore, it is not necessary to confirm whether spectrums are unused or not because of the fundamental property of the proposed algorithm. We verify these advantages by simulations and complexity analysis.

The remainder of this paper is organized as follows. Section II briefly describes the related works that are proposed by IEEE 802.22 WG. Fundamental wavelet analysis and power measurements are explained in section III. In section IV, the wavelet based energy detector is proposed. The simulation environments and results are provided in section V, and section VI concludes the paper.

II. RELATED WORKS IN IEEE 802.22 STANDARD

In the proposal [3], they suggested the two stage sensing architecture as shown in Fig. 2. The procedure of the architecture is like followings. Using a wideband antenna and wideband RF front-end, the coarse detection based on energy detection schemes is first performed to select unoccupied candidate channels, and then one of the channels is examined by the fine/feature sensing to identify the incomming signal type and detect weak signals.

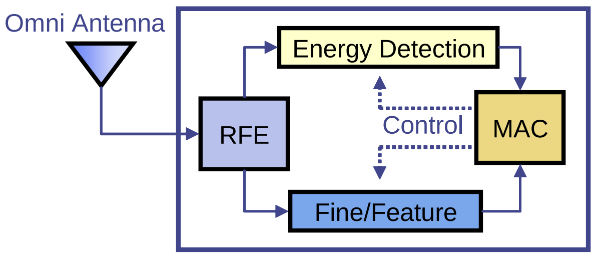

Fig. 2. Two stage sensing architecture

A. Energy Detection

The proposers suggested following schemes that can be used in 802.22 WRAN systems. However, they have not decided which scheme is appropriate for the two stage sensing, just have been examining the performance of each scheme.

- Received Signal Strength Measurement(RSSI): It is the scheme that selects unoccupied candidate channels using a received signal strength. One possible implementation is converting the energy in an interested band to the input signal strength.
- Multi Resolution Spectrum Sensing (MRSS): MRSS is the scheme which can sense an interested band in the analog domain using a wavelet transform that can be a basis of Fourier Transform. Since it is performed in the analog domain, spectrum sensing time can be reduced.

Since the energy detection schemes are performed in the wide band and have to compare their results with a specific threshold, fast sensing (or low complexity) and determination of the threshold are important parameters of the energy detection schemes.

B. Fine/Feature Sensing

Signal feature detection and cyclo-stationary feature detection are proposed in this sensing stage. Common disadvantage of these schemes is that we previously have to know the features of possible incomming signals. We doesn't specifically explain about these schemes because our concern is just in the energy detection.

III. WAVELET ANALYSIS AND POWER MEASUREMENTS

Construction of the wavelet transform and understanding of wavelet basis are provided by the multiresolution analysis [4]. In addition, the wavelet transform has the property of frequency separation is from the fact that it acts like filter bank [5].

A. Discrete Wavelet Transform (DWT)

Discrete wavelet transform of the signal space is to decompose the given signal space with approximate space, V, and detail space, 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. This means that $\phi_{j,k}$ and $\psi_{j,k}$ are the basis of V_j and W_j. Scaling functions, $\phi_{j,k}$, and wavelet functions, $\psi_{j,k}$, are obtained as

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

with $g_{l-2k} = \langle \psi_{j,k}, \phi_{j+1,l} \rangle$, $h_{l-2k} = \langle \phi_{j,k}, \phi_{j+1,l} \rangle$ and $\langle\rangle$ means inner product.

Discrete wavelet transform of a given function (or signal) f is to calculate the scaling coefficients, c, and the wavelet coefficients, d. 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. 3 shows 2 level analysis part of the discrete wavelet transform and its frequency separation property.

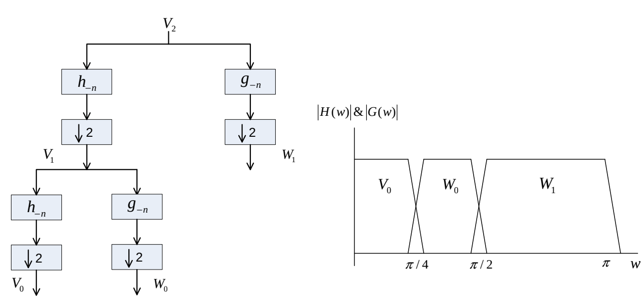

Fig. 3. 2 level analysis part of the DWT

B. Discrete Wavelet Packet Transform (DWPT)

The difference between the discrete wavelet transform and the discrete wavelet packet transform just lies in the decomposition of detail space. Discrete wavelet packet transform decomposes not only the approximation space but also the detail space. This means that it can separate frequency band equally. Fig. 4 represents 2 level analysis part of the discrete wavelet packet transform and its frequency separation property.

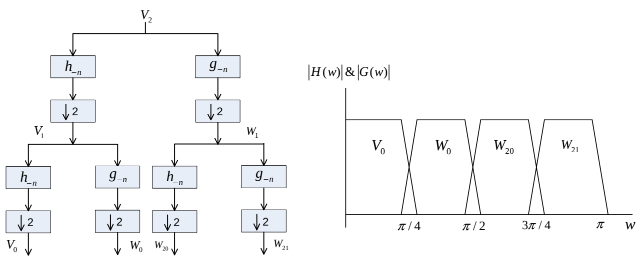

Fig. 4. 2 level analysis part of the DWPT

C. Power Measurements Using Wavelets

Power measurements using wavelets are explained in [6]. If the received signal, $r(t)$, is a periodic signal with the period T then, the power of this signal is computed by

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

Since $r(t)$ 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. We can easily compute the power of the received signal like following equation using orthonormal wavelet and scaling function properties.

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

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

D. Complexity Of Wavelet Analysis

Analysis of the number of mathematical operations (consider only multiplications) shows the complexity of the schemes. In the discrete wavelet transform, there are $\log_2 N$ level decompositions and only the output of low-pass filter goes through the next operation. Therefore, the complexity can be calculated as

$$\begin{aligned} \text{complexity} &= 2LN + 2LN/2 + \cdots + 2LN/2^{(\log_2 N-1)} \\ &= 2LN\left(2^0 + 2^1 + \cdots + 2^{(\log_2 N-1)}\right) \\ &= 4LN - 4L \end{aligned} \tag{8}$$

where L is the length of high-pass and low-pass filters. If $L \ll N$, the complexity approximately becomes $O(N)$.

In the discrete wavelet packet transform, the output of low-pass filter as well as the output of high-pass filter go through the next operation. This is the difference between discrete wavelet and discrete wavelet packet transform operation. Thus the complexity is easily obtained by

$$\begin{aligned} \text{complexity} &= 2LN + \cdots + 2\cdot 2^{(\log_2 N-1)} LN/2^{(\log_2 N-1)} \\ &= 2LN + 2LN + \cdots + 2LN \\ &= 2LN\log_2 N \end{aligned} \tag{9}$$

If $L \ll N$, the complexity approximately becomes $O(N\log_2 N)$. It is almost same as the complexity of the FFT, $O(N\log_2 N)$.

IV. WAVELET BASED ENERGY DETECTOR

The energy detection schemes that can be used in IEEE 802.22 WRAN systems have to sense radio spectrums faster and determine the threshold. Thus, we suggest a possible energy detector for IEEE 802.22 WRAN systems using the discrete wavelet packet transform to alleviate these problems.

A. The Algorithm Description

The discrete wavelet packet transform can separate the given frequency band into a low-frequency subband and a high-frequency subband. The proposed wavelet based energy detector is designed based on this fact and it maintains the two stage sensing architecture. Before commenting about the idea, we first assume that B_i and B_c are the interested frequency band (or scanning range) and the bandwidth of each channel respectively. Also, we assume that the ratio of between B_i and B_c is power of 2. The procedure of the idea, wavelet based energy detector, is shown in Fig. 5

1) Initialize the iteration parameter to zero.
2) Perform the 1-level discrete wavelet packet transform.
3) Compare the iteration parameter with RI. RI represents required iteration number of wavelet packet transform 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 discrete wavelet packet transform 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 the power of each channel.
6) Inform the order of sorted channel index to MAC to process the second sensing stage, fine/feature sensing.

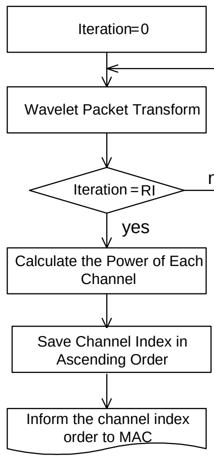

Fig. 5. The flow chart of the wavelet based energy detector

B. The Anticipated Performance Of The Algorithm

The proposed algorithm has two improvements of the energy detection schemes. One is that it can easily select the unoccupied candidate channels without confirming whether channels are unused or not. This is accomplished by sorting the channels in the ascending order based on the power of each channel and it 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, it performs the discrete wavelet packet transform not to the final level but to the RI level and its complexity becomes

$$\begin{aligned} \text{complexity} &= 2LN + 2\cdot 2LN/2 + \cdots + 2\cdot 2^{(RI-1)}/2^{(RI-1)} \\ &= 2LN + 2LN + \cdots + 2LN \\ &= 2LN \cdot RI \end{aligned} \tag{10}$$

where RI is the required iteration number of the discrete wavelet packet transform, L and N are the length of the wavelet filter and input signal respectively.

V. SIMULATION ENVIRONMENT AND RESULTS

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

A. Simulation Environment

As shown in Fig. 6, the simulation environment is vertical sharing scenario. Specifically, there exist 3 primary users and 1 Customer Premise Equipment (CPE) that can sense the interested frequency band (or scanning range) for the secondary user. If we assume that each primary user's signal is sinusoid, the received signal at the CPE is numerically represented by

$$r(t) = a_1 \sin(2\pi f_1 t) + a_2 \sin(2\pi f_2 t) + a_3 \sin(2\pi f_3 t) + n(t) \tag{11}$$

where a_j and f_j represent attenuation factor and center frequency of each primary user's signal respectively, and $n(t)$ is AWGN with zero mean unit variance. Moreover we assume that each primary user uses different channel, the interested frequency band, B_i, is 1.6MHz and there are 16 channels in the frequency band, B_i.

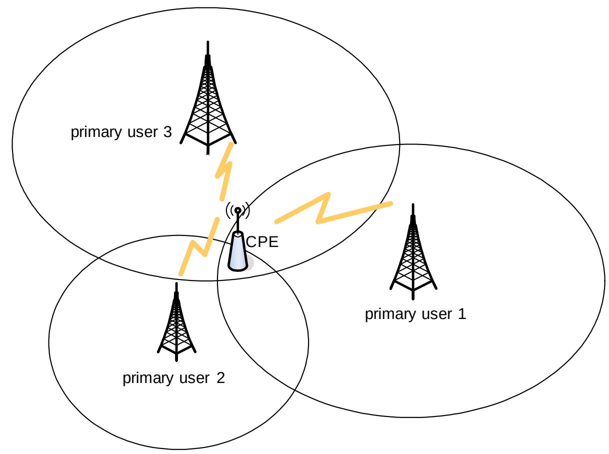

Fig. 6. Simulation environment scenario

Fig. 7 shows the procedure of separation of the interested frequency band based on the above simulation environments. Since there are 16 channels in B_i, B_c is 100KHz and 4-level discrete wavelet packet decompositions 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's center frequency exists in the frequency band $0 \sim 100$KHz, the power of the channel 1 has to be larger than other channels. "db20" wavelet is used in the simulation and Fig. 8 shows the magnitude characteristic of the wavelet filter.

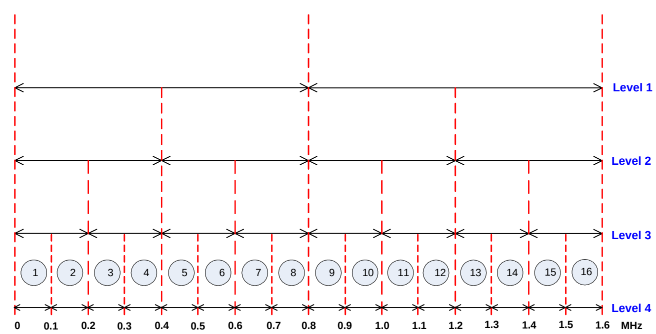

Fig. 7. Separation of the interested frequency band using the proposed shceme

B. Results

The simulations in this paper consider two cases which are different with center frequency and SNR.

1) case1: Center frequencies of 3 primary users' signal and their SNR are fixed as $f_1 = 250, f_2 = 650, f_3 = 1550$ KHz and SNR $= 0, -5, -10$dB in this simulation. Since the center frequencies are $250, 650, 1550$KHz, we can anticipate the powers of channel $3, 7$ and 16 are larger than other channels'. Fig. 9 shows this result and 16 channels are sorted like Fig. 10.

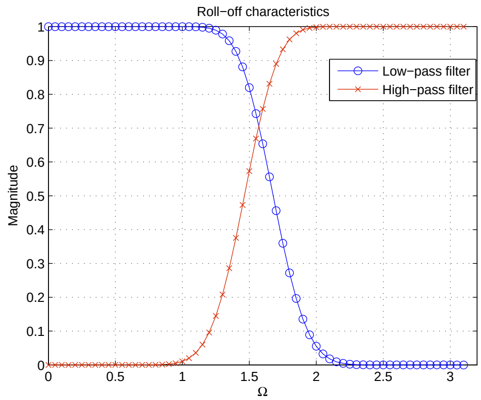

Fig. 8. Frequency response of the "db20" wavelet filter

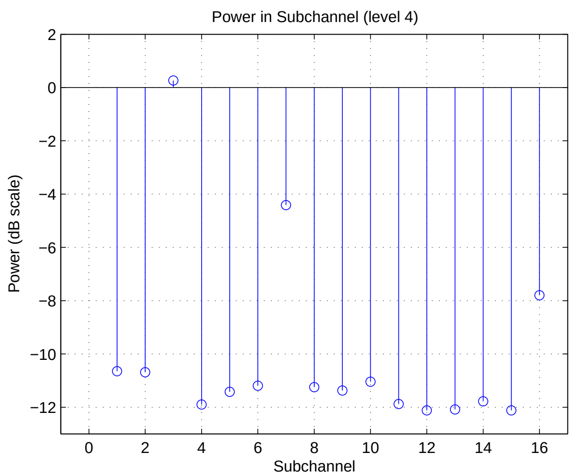

Fig. 9. Power of channels in case1

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

Fig. 10. Sorted channels in case1

2) case2: Center frequencies of 3 primary users' signal and their SNR are fixed as $f_1 = 50, f_2 = 950, f_3 = 1450$ KHz and SNR $= 0, -15, -20$dB in this case. Since the center frequencies are $50, 950, 1450$KHz, we can anticipate the powers of channel $1, 10$ and 15 are larger than other channels'. Fig. shows this result and 16 channels are sorted like Fig. 11.

In both cases, the final outputs, sorted channel indexes, are sent to the MAC. This makes possible for the proposed scheme select the unoccupied channel candidates without confirming whether spectrums are unused or not. From above simulation results, furthermore, the proposed scheme is verified to identify the channels which primary users exist in. Since $RI = 4$ in these simulations, the complexity of the proposed scheme is $8LN$ using equation 10.

VI. Conclusion

The secondary spectrum has been issued because of improving spectra efficiency. In this context, IEEE 802.22 WG

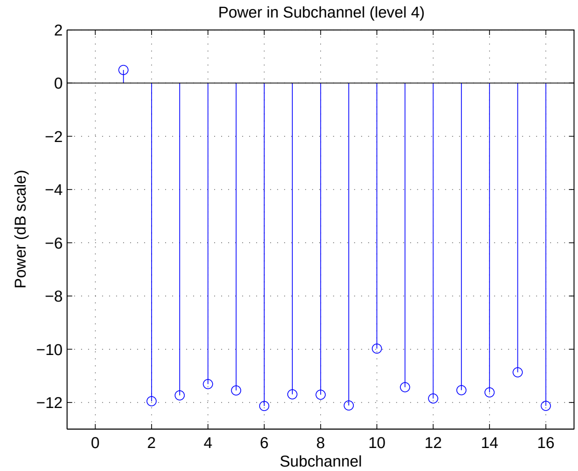

Fig. 11. Power of channels in case2

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

Fig. 12. Sorted channels in case2

was organized in November 2004. Its critical technology is spectrum sensing not to interfere with licensed users. Thus, in this paper, we propose the fast spectrum sensing algorithm based on the discrete wavelet packet transform focusing on the coarse detection. Basically, since the proposed algorithm reduces complexity, it makes spectrum sensing faster. Furthermore, it is not necessary to confirm whether spectrums are unused or not because of the fundamental property of the proposed algorithm. Therefore, the proposed scheme can be an alternative energy detector of two stage spectrum sensing in IEEE 802.22 WRAN systems.

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