USE OF WAVELET TECHNIQUES IN SPECTRUM HOLES DETECTION IN OPPORTUNISTIC RADIO

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ABSTRACT:

Opportunistic Radio (OR) systems make use of the availability of spectrum holes in the primary systems. In OR spectrum hole availability needs to be identified through spectrum sensing procedures. Apart from the sensing of the spectrum, OR must be capable of detecting the primary system and move out of the spectrum once the primary system requires the spectrum usage. Therefore spectrum sensing and detection needs to be performed efficiently for the successful deployment of an OR system. One way of identifying the spectrum holes availability is identifying power spectral density (PSD) and their power levels within a selected portion of the spectrum. The selected spectrum can be divided into multiple numbers of spectrum sub bands and power level of each sub band can de determined from the shape of the PSD of the selected spectrum. According to the PSD levels spectrum sub bands can be categorized as into black, grey or white spaces corresponding to high, medium and low PSD levels. White spaces are usually considered as spectrum holes that can be picked by the OR system for opportunistic spectrum usage.

In the case of Opportunistic Radio spectrum sensing is in the interest of spectrum identification than the detailed spectrum shape over the entire wideband or the selected portion of the spectrum. The entire wideband can be considered as a train of consecutive frequency sub bands, where the power spectral characteristics is smooth within each sub band but exhibits a discontinuous change between adjacent sub bands. Such changes are irregularities in PSD, which carry key information on the locations and intensities of spectrum holes. Therefore the detection of the edges of the spectrum sub bands determines the number of available spectrum sub bands. The PSD level in each sub band clarifies the black, grey and white areas of the spectrum sub bands. This identifies the amount of spectrum holes within the spectrum wide band of interest.

In this work Continuous Wavelet Transform (CWT) techniques are used for the detection of the sub band edges. The Continuous Wavelet Transform (CWT) is a two-parameter expansion of a signal in terms of a particular wavelet basis function. Wavelets have scale aspects and time aspects. To clarify them somewhat arbitrarily, scale aspect can be presented as an idea around the notion of local regularity where as time aspects can be presented as a list of domains. In this work PSD signal discontinuity has been detected using different kind of wavelets. It is important to select the appropriate wavelet and its scale when identifying discontinuity of a signal. The results are based on a selection of Gaussian wavelets basis function at varying scales.

1. WAVELET TRANSFORM

The wavelet theory is based on analyzing signals to their components by using a set of basis functions [1]. The original wavelet function, known as mother wavelet function is used to generate all the basis functions. A very essential characteristic of the wavelet functions is that they are related to each other by simple scaling and translation.

It is important to create a mother function which provides an efficient and useful description of the signal of interest. It is not easy to do so, but based on several general characteristics of the wavelet functions it is possible to determine the most suitable wavelet for a specific application. A wavelet is a small wave with finite energy which is concentrated in time or space.

The important issue is how to divide the signal into many parts and then analyze the parts separately. To overcome the signal-cutting problem wavelet analysis uses fully scalable modulated window. This window is shifted along the signal of interest and the spectrum is calculated for every position. This process is repeated many times with a smaller or bigger window and the end result is a collection of time-frequency representation of the signal, all with different resolutions. Instead of usual time-frequency representation wavelet transforms generates time-scale representation.

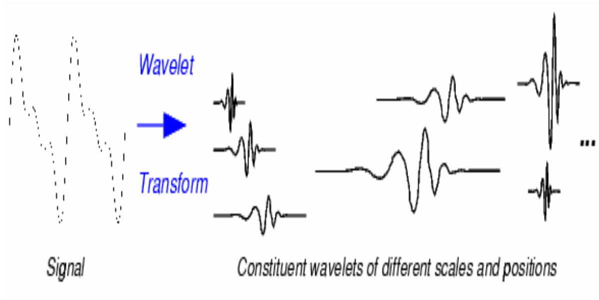

Figure 1. Wavelet transform [2]

In other words wavelet transform is the breaking of a signal into shifted and scaled versions of the original signal. This provides the ability to perform local analysis, to analyze a localized area of a larger signal.

This paper investigates the use of Continuous Wavelet Transform (CWT) techniques for the detection of the sub band edges in a wide spectrum band of concern. The focus is on the identification of the frequency locations of the non-overlapping spectrum sub bands of a PSD signal. Each PSD signal is analyzed using large number of different wavelets to identify the best possible wavelets for sub band identification.

2. WIDEBAND SPECTRUM HOLE DETECTION IN OR

The objective in OR is to identify the spectrum hole in the wide band of spectrum concern. Depending on the spectrum usage within each sub band spectrum holes can be assigned for OR communication. Therefore the objective in OR is to identify the frequency locations of non overlapping spectrum sub bands and categorize them into white areas corresponding to the power spectral density (PSD) level being low. White spaces are usually considered as spectrum holes that can be picked by the OR user for opportunistic use. Evidently in OR spectrum sensing is in the interest of spectrum identification than the detailed spectrum shape over the entire wideband.

The entire wideband can be considered as a train of consecutive frequency sub bands, where the power spectral characteristics is smooth within each sub band but exhibits a discontinuous change between adjacent sub bands [Figure 2]. Such changes are irregularities in PSD, which carry key information on the locations and intensities of spectrum holes. In [4] suggested the use of wavelet transforms as powerful mathematical tool for analyzing singularities and irregular structures, which can characterize the local regularities of signals. The signal spectrum over a wide frequency band can be decomposed into elementary building blocks of sub bands that are well characterized by local irregularities in frequency. In literature [3] proposed a method of wavelet transforms to detect and estimate the local spectrum irregular structure. Local spectrum irregularities present important information on the frequency locations and power spectral densities (PSD) of the sub band. In [3] use of 1st and 2nd order derivatives of the wavelet transforms of the PSD are used to identify local maxima and thus locating the frequency boundaries of each sub band. Compared to [3] work our approach is based on use of wavelet transforms technique on detection of edges of the PSD and thus locating the frequency boundaries of each sub band. In our approach we directly use the CWT for edge detection of the bandwidth irregularities for the detection of spectrum holes. Apart from this the use of the most suitable wavelet families needs to be investigated against each signal of concern.

The Continuous Wavelet Transform (CWT) is a two-parameter expansion of a signal in terms of a particular wavelet basis function. Let the function $f_s(x)$ which is the wavelet basis function denotes the dilation of $f(x)$ by the scale factor s,

$$f_s(x) = \frac{1}{s} f\left(\frac{x}{s}\right) \quad (1)$$

For dyadic scales, s taking the values from powers of 2 (i.e., $s = 2^i$, where $i = 1, 2, \ldots, I$; *where I is the highest integer selected*) and letting * denotes the convolution, the continuous wavelet transform (CWT) of a function $\psi(x)$ is defined by

$$W\psi(s,x) = \psi * f_s(x) \quad (2)$$

The total available B Hz bandwidth for a wideband wireless network can be divided into N spectrum sub-bands denoting in the frequency range [f_1 to f_n]. Suppose the spectrum sub-bands lie within [f_1 to f_n] consecutively with their frequency boundaries located at $f_1 < f_2 < \cdots < f_n$. The PSD structure of such a wideband signal is illustrated in [Figure 2].

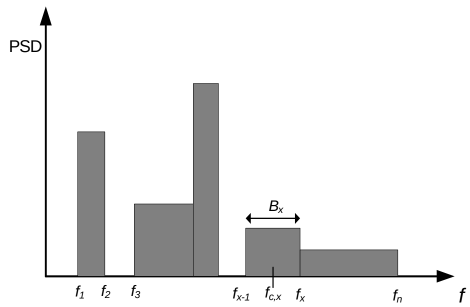

Figure 2. PSD of N spectrum sub-bands.

Based on [3] the PSD of the observed signal *y(t)* by an OR receiver can be written as,

$$S_y(f) = \sum_{i=1}^{N} \alpha_i^2 S_i(f) + S_w(f) \qquad (3\ )$$

Where α_i^2 denotes the signal power density of within the n^{th} spectrum sub-band and the additive noise component with PSD $S_w(f)$.

In this case the PSD in each spectrum sub-band B_x is assumed as smooth and almost flat, exhibiting discontinuities from its neighbouring sub-bands B_{x-1} and B_{x+1}. Therefore irregularities in PSD appear at the edges of the N sub-bands. This result in wideband spectrum sensing can be seen as an edge detection problem of a signal presented by the PSD $S_y(f)$ as in (3). Edges in the signal identify the location of frequency discontinuities which identifies each sub-band. Use of wavelet transform can effectively characterize these discontinuities presented in the singular structure of the PSD.

Once the OR user receives the PSD of the above format (3) within a known wide spectrum of bandwidth B, the objective is to find the number of spectrum sub-bands (N), their edge frequencies (f_1 to f_n) and the value of α_i^2 for $i = 1$ to N. Once the boundaries of the sub-bands are found the estimated value of PSD in each sub-band determines the availability of white, black or grey spectrum spaces depending on low, high and medium signal power density within each spectrum band.

3. EDGE DETECTION USING WAVELET TRANSFORMS

The first step in identifying spectrum holes is to determine the edge frequency of each sub band. CWT is considered as a very strong candidate for identifying edge detection in continuous signals. In our approach the boundaries or edge frequencies of each spectrum sub bands are identified by applying wavelet transforms to the original signal. In the resulting wavelet transforms the frequency edges are presented as sudden sharp increase or decrease of the amplitude representation in y axis. Therefore the location of these sharp changes in the wavelet transform identifies the discontinuities in the PSD. Selected wavelets with varying scaling factors can be used to detect the discontinuities of the PSD accurately.

3.1 Continuous Wavelet Transform (CWT)

The continuous wavelet transform (CWT) is an alternative approach to the short time Fourier transforms (STFT) and it was developed in order to overcome the resolution problem. The wavelet analysis is done in a similar way to the STFT. More specific the signal is multiplied with a function (the wavelet) and the transform is computed separately for different segments of the time-domain signal. The main difference between the CWT and the STFT is that the width of the window is changed as the transform is computed for every single spectral component, which is probably the most significant characteristic of the wavelet transform [6].

The CWT can be defined by the following formula:

$$CWT_x^{\psi}(\tau,s) = \Psi_x^{\psi}(\tau,s) = \frac{1}{\sqrt{|s|}} \int x(t)\psi^*\left(\frac{t-\tau}{s}\right)dt \qquad (4)$$

Where (τ, s) are translation and scale parameters respectively. *ψ(t)* is the transforming function and also called the mother wavelet. According to (4), the transformed signal is a function of the variables τ and s. Also we can observe that in CWT there is no frequency *(f)* parameter, instead there is a scale parameter *(s)*, which is defined as *(1/f)*.

3.2 Computation of CWT

This section explains (4), which defines the CWT. Let *x(t)* denote the signal that we want to analyze. First of all we need to choose the mother wavelet, which will act as a prototype for all the windows in the processes. All the windows that are used are dilated and shifted versions of the mother wavelet. There are many wavelet families such as Gaussian, Morlet, Daubechies, Mexican hat, which are dilated and shifted versions of the mother wavelet.

As soon as the mother wavelet is chosen the computation starts with $s=1$ and the CWT is computed for the values of s, smaller and larger than 1. Usually the starting value of *s* is 1 (for convenience), but this is not necessary. Then the procedure continues for increasing values of *s*, i.e. the analysis starts from high frequencies and then proceeds to low frequencies. The first value of *s* corresponds to the most compressed wavelet and as the values of *s* are increased, the wavelet will be dilated.

According to [3] the PSD (α_i^2 for $i = 1$ to N) of each spectrum sub-band can be deduced from a simple estimator as below.

$$\alpha_i^2 = \beta_i - N_0/2 \text{ (for } i=1 \text{ to } n) \qquad (4)$$

$$where \;\; \beta_i = \frac{1}{f_n - f_{n-1}} \int_{f_{n-1}}^{f_n} S_y(f)\,df$$

The noise PSD $N_0/2$ is the minimum noise of all the sub-bands and can be measured offline or in an empty sub-band. Therefore the estimated noise is the smallest possible value of β_i.

Therefore for an OR receiver which receives a signal of the shape PSD within a known wide band of spectrum with the use of CWT it can be deduced the number of spectrum sub-bands (N), the boundaries of each sub-band (f_i , *for* $i=1$ *to* n) and the PSD of each spectrum sub-band (α_i^2, *for* $i=1$ *to* n). This can be used to detect the availability of spectrum holes in each spectrum sub-band depending on the PSD levels of in each categorizing into high, medium and low power or *black, grey or white* spectrum spaces.

4. CWT WAVELET ANALYSIS RESULTS AND DISCUSSION

The MATLAB Wavelet transform toolbox is used to evaluate wavelet transform functions of different PSD variations. In general it is possible to determine which wavelet is more suitable for a given application. CWT wavelets used initially are the Gaussian wavelets. Gaussian wavelets are obtained from derivatives of the Gaussian function.

The following section introduces different signals investigating the use of wavelet transforms for spectrum sub band edge detection. These signals have the same bandwidth (200MHz) but they differ in the shape of the PSD. More specific they differ in the number of sub bands, the number of the spectrum holes and the frequency range. Our goal is to investigate signals with different characteristics in order to have better and more accurate results. The characteristics of each signal are described in the following subsection.

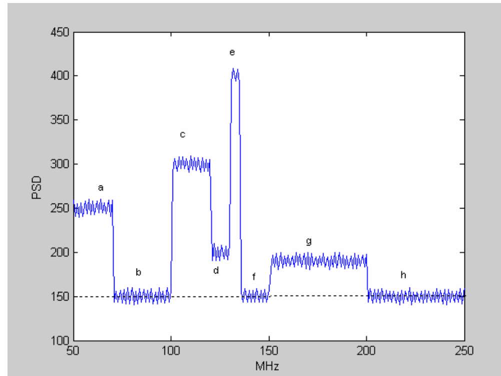

Figure (3a) Observed Signal PSD

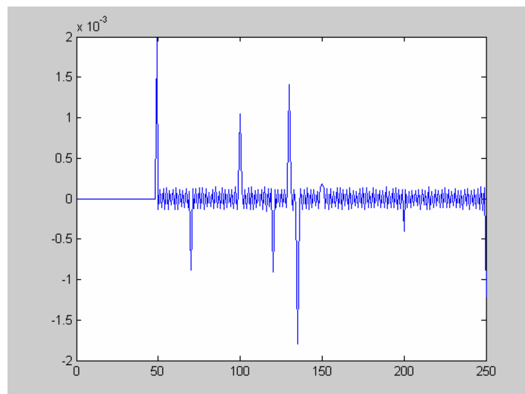

Figure (3b) Wavelet transform of the signal Gaussian Wavelet at scale = 1

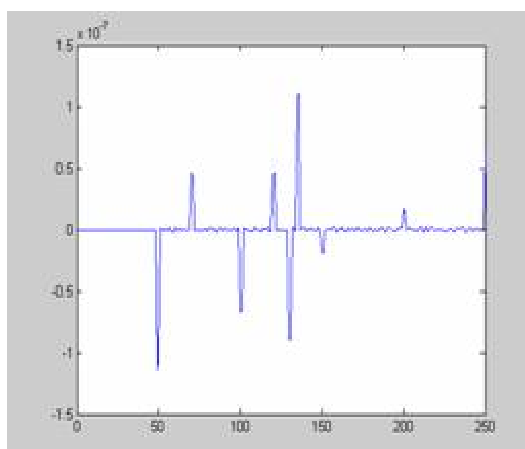

Figure (3c) Wavelet transform of the signal Gaussian Wavelet at scale = 100

[Figure 3a], [Figure 3b] and [Figure 3c] present the results based on spectrum holes detection based on wavelet transform technique. The considered wide band for spectrum hole identification is in the range of [50, 250] MHz. the following presents the PSD $S_y(f)$ observed by the opportunistic radio (OR).user. The noise floor of the PSD is considered as $S_w(f)$ = 150. During the observed burst of transmissions there are a total of $N = 8$ sub bands $\{B_x\}$ with frequency boundaries at $\{f_n\}_{n=0}^{8}$ = [50, 70, 100, 120, 130, 135, 150, 200, 250]. Among these bands *a*, *c* and *e* have relatively high signal PSD at levels 100, 150 and 250 respectively, while *d* and *g* has low signal PSD at a level of 50 and 40, all with reference $S_w(f)$ = 150. The rest three bands *b*, *f* and *h* are not occupied and thus spectrum holes.

Gaussian wavelets with two different scales are used to for edge detection of PSD. As the scale factor increases (from 1 to 100) the wavelet transforms becomes smoother within each frequency band thus clearly identifying the edges in the PSD.

The spectral density estimation scheme proposed in equation (4) is used to estimate noise and the signal PSD levels. The estimated values are $\{\alpha_i^2\}_{i=0}^{8}$ = [98.86, 1.423, 145.06, 54.46, 218, 6.74, 39.07, 0] corresponding to a true signal PSD values of [100, 0, 150, 50, 200, 0, 40, 0] respectively and the estimated noise floor is 150.69 corresponding to the true noise floor of 150.

In the second example a wideband of interest in the range of [0,200] MHz is considered. The PSD $S_r(f)$ that is observed by a CR is illustrated in [Figure 4] with the noise floor at $S_w(f)$=200. During the transmissions there are 6 bands (N=6) with frequency boundaries at $\{f_n\}_{n=0}^{6}$ = [0 70 120 150 170 174 200] MHz. The bands B_1, B_3 and B_5 have relatively high signal PSD at levels 24 30 and 36, while B_6 has low signal PSD at a level of 3, all with reference to $S_w(f)$=200. The sub bands B_2 and B_4 can be considered as spectrum holes.

As can be seen in the [Figure 5], [Figure 6] and [Figure 7] the wavelet transform of the signal with respect to different wavelet families are investigated. It is evident in all Haar, Daubechies and Biorthogonal wavelet families the wavelet coefficients lines, clearly identifies the edges in the PSD detecting the sub band edges. Therefore these wavelet families can be effectively used for capturing the edges thus resulting in identification of spectrum holes in OR. For comparison purposes the same values (-60, 60) were used for the y axis, in order to able to compare the effects of the different wavelets to the signal.

After investigating under varying wavelet families in the MATLAB wavelet toolbox the best wavelets correspond to those that can give us a very accurate illustration of the edges at the beginning and at the end of the bands, and the worst to those that we can hardly understand where the different sub bands are.

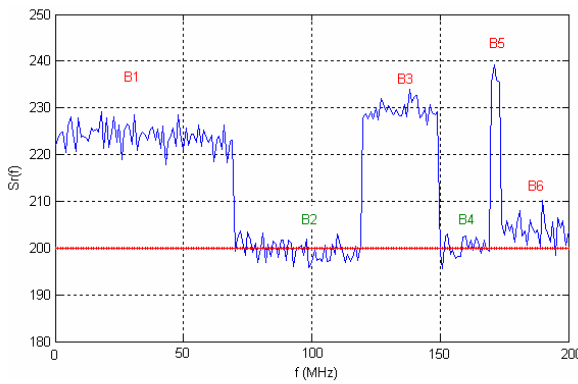

Figure 4 Observed PSD signal – 2nd Example

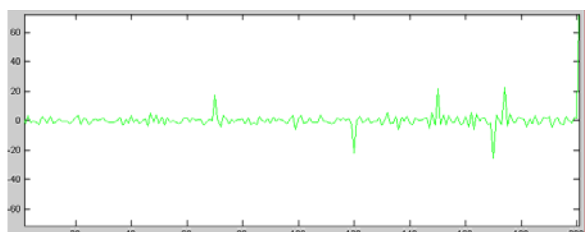

Figure 5 Haar Wavelet at scale 2^1

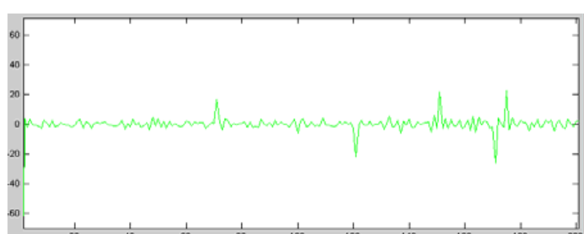

Figure 6 Daubechies wavelet at scale 2^1

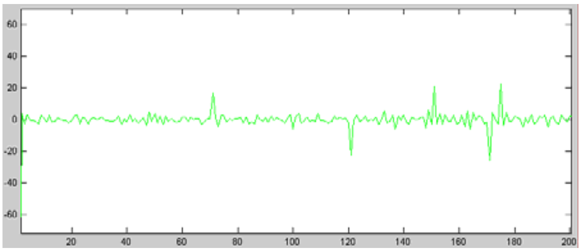

Figure 7 Biorthogonal at scale 2^1 (Reconstrauction factor = 1, Decomposition factor = 3)

According to (4) the estimated noise and the signal PSD values are as follows;
$\{\hat{a}_n^2\}$ = [24.17, 0, 29.7,0, 35.23, 3.24], which corresponds to the true PSD values [24, 0, 30, 0, 36, 3] respectively, of the original signal and $\hat{S}_w(f)$ = 199.7945 corresponding to the true noise PSD value 200 of the original signal.

[Figure 5] to [Figure 7] captures the edges of the non-overlapping spectrum bands of considered PSD signal. The edges of the spectrum sub bands have been clearly identified and have been estimated the PSD levels of each one of them. The next step is to categorize these sub bands according to their PSD levels. As it was mentioned above PSD signal PSD has 6 sub bands, whose estimated PSD levels are [24.17, 0, 29.7, 0, 35.23, 3.24] respectively. Therefore bands 2 and 4 are characterized as gray or white spaces due to their low PSD levels, while bands 1, 3, and 5 are characterized as black spaces due to their high PSD levels. Band 6 has medium PSD level, so is characterized as gray space.

5. CONCLUSIONS AND FURTHERWORK

OR networks are developed in order to solve current wireless network problems which result from the limited available spectrum and the inefficiency in the spectrum usage by exploiting the existing wireless spectrum in an opportunistic manner. OR networks, using the capabilities of the cognitive radio, will provide an ultimate communication paradigm in wireless communications, which is spectrum-aware.

The cognitive spectrum identification task is formulated as an edge detection problem. In this work the wavelet edge detection approach is considered for sub band identification of wideband channels. A solution based on the coefficients lines of the continuous wavelet transform is derived and tested for different signals. The proposed scheme is able to scan over a wide bandwidth in order to identify simultaneously all the piecewise smooth sub bands, without any prior knowledge of the number of the sub bands, within the frequency range of our interest.

This study identifies wavelet transforms as a strong candidate for the detection of the non overlapping sub band edges. Mainly Haar, Daubechies and Biorthogonal wavelet families are capable of detecting these frequency transitions and thus detecting edges. These wavelet families have been designed by researchers, in the past, for many different applications. Therefore in order to have better results it would be a challenging task to design more specific wavelet families suitable for spectrum holes detection in OR environment. These wavelets need to be based on the characteristics of the signal PSDs that needs to be investigated and analyzed.

ACKNOWLEDGEMENT

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