Distributed Spectrum Sensing Based on the Gabor Time-Frequency Analysis for Cognitive Networks

Yinhui Luo[1,2], Zhiyong Bu[3]

1. Department of Electronic Engineering, Shanghai Jiaotong University, Shanghai, 200240, China
2. Computer Engineering Lab Department of Computer,Civil Aviation Flight University of China, Guanghan Sichuan, 618307, China
E-mail: loyinhv@sjtu.edu.cn
3. Shanghai Institute of Microsystem and Information Technology (SIMIT), Chinese Academy of Sciences(CAS),865 Chang Ning Road Shanghai, 200050 ,China
E-mail:zhiyong.bu@jushri.com

Keywords: Gabor transform, Interference detection, Spectrum sensing, Cognitive networks

Abstract

Due to the independent design and development and the unexpected dynamics during deployment of co-existing networks and devices, the limited frequency spectrum will be extremely crowded for wireless sensor networks. Cognitive radio is an efficient approach for the opportunistic use of under-utilized spectrum since they are able to sense the spectrum and use frequency bands if no other user is detected. Once deployed, the automatic detection of transient interference is also a difficult problem for network setup. In this paper, we propose a Gabor analysis based algorithm for the spectrum sensing and transient interference detection problems. Simulation results and performance analysis are also presented.

1 Introduction

The rapid development in small, low-power and low-cost Micro-Electro–Mechanical (MEMs) sensor technology has led to the emergence of wireless sensor networks (WSNs) as a new class of system with wide variety of purposes. However, the co-existence and overlap of WSNs is an important problem in the near future. As a result, how to solve the crowded spectrum reuse for sensor networks is our assignment in this paper, known as cognitive WSNs[1]. Once deployed, the network self could detect the transient interferences automatically and robust detection scheme is required. Aiming at more efficient spectrum utilization, the traditional spectrum management approaches are revisited and moving toward the adoption of spectrum sensing strategies in cognitive radio[2]. Cognitive radio have been proposed to implement opportunistic sharing since they are able to sense the spectrum and adapt their usage.

Distributed spectrum sensing is a fundamental and significant capability for several cognitive radio sensor networks to co-exist[3][4]. This task is rendered difficult due to challenges in sensing the spectrum in a reliable manner. In fading channels, single radio sensing is unreliable due to the multipath, shadowing and local interference, which could result in SNR regimes below the below threshold and lead to the signal detection infeasible[5]. However, due to the variability of signal strength at various locations, this worst case could be avoided by the distributed sensing schemes via network cooperation. Meanwhile, once the network is deployed, automatic interference detection is also required. As a result, distributed interference and fault detection is another application of spectrum sensing. In this paper, we propose a distributed spectrum sensing algorithm based on Gabor Time-Frequency analysis to solve the above two problems.

Spectrum sensing is considered as a detection problem, which has been extensively investigated on time and frequency domain since early days of radar. In addition, spectrum sensing is also a cross-layer design problem in the context of wireless networks. Currently, existing spectrum sensing techniques are largely categorized into energy detection and feature detection. If the signal arrival time is known, energy radiometric in time domain is an optimal detector for narrow-band continuous interference[6][7]. However, in the future sensor networks where the spectrum utilization is high, the significant spectrum scarcity would call for different spectrum sharing mechanisms such as ultra-wideband cognitive radios, which in turn entail different wideband sensing tasks for spectrum overlay. A wavelet approach is proposed to implement the wideband spectrum sensing and spectrum holes detection for cognitive radio network[9]. However, our goal in cognitive sensor networks is to implement a distributed Generalized Maximum Likelihood Ratio test algorithm in Gabor domain due to presence of noise uncertainty and background interference without any prior information, especially for unknown and transient interferences.

The rest of the paper is organized as follows: the Gabor transform based Time-Frequency (TF) analysis is introduced in Section 2. The Gabor analysis based spectrum sensing method is presented in Section 3. The simulation results and performance analysis are given in Section 4. At last, we make some conclusions in Section 5.

2 Gabor Time-Frequency analysis

Transient interferences are non-stationary signals and Time-Frequency methods are often used to describe non-stationary signals. Several possible linear time-frequency transforms are available, but we have selected the Gabor transform representation because it uses complex exponential basis functions that appear also in the transient signals of linear systems. For completeness, we recall the definition of the Gabor expansion. For a discrete time sequence y(t) of length L, the finite approximation of the Gabor expansion is defined as[8][10]

$$y(k) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} C_{m,n} g_{m,n}(k) \tag{1}$$

for k=0,…,L-1. $C_{m,n}$ are the Gabor coefficients and N and M are the maximum allowable time and frequency shifts respectively. The synthesis function $g_{m,n}(k)$ is given by

$$g_{m,n}(k) = \tilde{g}(k - ma)\exp(j2\pi nb / L) \tag{2}$$

where the $\tilde{g}(k)$ is the periodic extension of the window function g(k). Some constraints need to be imposed on the parameters of the synthesis function for the transform in (1) to be stable. Details can be found in various treatments of the Gabor transform, e.g. [10].

The window function is defined as the Gaussian

$$g(t) = 2^{1/4}\exp(-\pi t^2)$$

the corresponding bi-orthogonal function is given in [5].

3 Spectrum sensing in Gabor domain

A simplified sensor network model is shown in Fig. 1. In the application scenarios involving geographically distributed radios, distributed spectrum sensing and transient interference detection is determined by the severity of the noise, and the amount of available knowledge about the signal. Suppose that a total of B Hz in the frequency range [f_0, f_N] is available for a wideband wireless sensor network. Currently, most RF-chips support multiple channels for sensor node design. Being cognitive, the network supports heterogeneous node devices that may adopt different wireless protocols for transmission over different bands in the frequency range. A CR at a particular place and time needs to sense the wireless environment in order to identify spectrum holes for opportunistic use. Suppose that the radio signal received by the CR occupies N spectrum bands, whose frequency locations are to be detected and identified. These spectrum bands lie within $[f_0, f_N]$ consecutively, with their frequency boundaries located at $f_0 < f_1 \ldots f_N$. The n-th band is thus defined by B_n:

$$\{f \in B_n : f_{n-1} \le f < f_N\}, N = 1, 2, ..., N$$

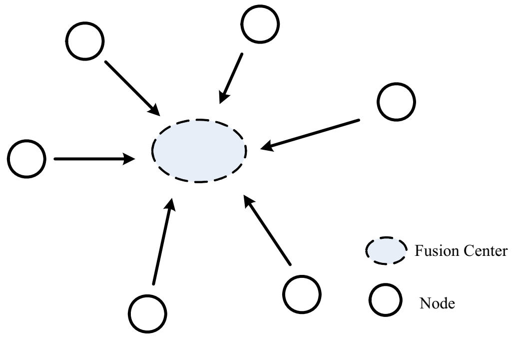

Fig. 1 The simplified sensor network model

Another application, interference signal detection in time series data is governed by the theory of statistical hypothesis testing. However, when the prior signal amplitude parameters are unknown, energy radiometric is not an optimal detector. In essence, we wish to make cognitive radio's spectrum sensing more robust to unknown transient interference in severe fading environments and doesn't require any prior information for signal.

In this section, we propose a detector based on the Gabor coefficients, and analyze its distributions under the hypotheses of noise only (H_0) and signal plus noise (H_1). The detector is based on a generalized likelihood ratio test and is localized, i.e., it examines sets of coefficients $\{C_{m,n}\}$ spanning relatively short time intervals. While not strictly necessary, localized detection is better suited to the nature of signals that are assumed to be present than a global detection.

Let us thus assume that

1) Under H_0, no signal is present, i.e., y(t) is a white Gaussian noise;
2) Under H_1, y(t) consists of a transient plus white Gaussian noise; furthermore, the transient is such that only the coefficients $\{C_{m,n}; 0 \le m \le M-1,$ $n \in \Im\}$ are nonzero, where $\Im$ is a subset of K integers in the range [0, N-1].

Assumption ii) allows for a variety of situations. The simplest case is when K=1, i.e., when we want to test for a single, relatively short transient. Another possibility is when the K indexes are consecutive, i.e., $N_0 \le n \le N_0 + K - 1$ for some N_0.

This corresponds to a test for a single, relatively long transient (i.e., longer than one time-bin). Yet another possibility is when $\Im$ consists of two sets of consecutive indices, in which case we want to test for two transients, etc. We can include, under H_1, up to 2^N different tests (this doesn't necessarily imply that one would want so many tests in a specific application).

The development of a transient detection scheme based on a transform domain representation of the signal begins with the observation that we can construct a statistical test in the transform domain. If the transform is constructed using orthogonal basis functions, the probability density function of the transform coefficients for zero mean Gaussian noise will also have a zero-mean Gaussian distribution. If the transform is not orthogonal, an additional orthogonalization step must be performed on the transform coefficients. Under these conditions, a likelihood ratio based hypothesis test for signal detection can be designed based on the transform coefficients.

For the null hypothesis, H_0, the Gabor coefficients have a zero-mean distribution, and under the alternative hypothesis, H_1, the coefficients where signal energy is located will have a non-zero mean Gaussian distribution. The transient signal can contain multiple components, at different arrival times and frequencies, resulting in multiple non-zero components. The detector is realized as a test on specific coefficients or a group of coefficients in the grid, and the alternative hypothesis, H_1 is designed accordingly. Unfortunately, this implies that the locations of these components must be known. If no location information is available, the H_1 hypothesis must test all coefficients, and this corresponds to creating an energy based detector in the transform domain. Ideally, each damped complex exponential component in the signal corresponds to a coefficient that is included in the test. However, computation of the Gabor transform is sensitive to the alignment of the transient signal components with the time-frequency grid. Unless a component of the signal can be described exactly by one basis function, the coefficient energy spreads out over a set of neighboring coefficients, corresponding to a representation that utilizes multiple basis functions. Grouping neighboring elements in the H_1 hypothesis improves the robustness of the detector against mismatch, but at the cost of reduced sensitivity.

4 Simulations

The performance of the GLRT based detector in Gabor domain is evaluated based on the statistical properties of the Gabor transform coefficients. The transform coefficients of white noise are jointly Gaussian. The transform coefficients of a transient signal will have non-zero mean value in the subset of the time-frequency plane where the signal is located. This becomes the hypothesis H_1. The test is constructed on the probability ratio of non-zero mean value in the subset of the time-frequency plane. If multiple regions are to be evaluated, multiple tests are required. Each region then corresponds to a different component of the transient signal. Fig.1 illustrated the use of regions in the TF grid.

The first example, two signal source with FM signal modulation will transmit 1s duration data in every 5s period. Through the addition of the two signals, we treat this combination as the wideband interferences should be detected by Gabor detector. Through Gabor transform, we can see the distribution of Gabor coefficients in Time-Frequency platform under the environment of C/N is 10dB in Fig. 2. Then the GLRT algorithm is employed to sense the spectrum and interferences. The results is shown in Fig.3 and compared with the Time domain GRLT. The choice of parameters depends on the characteristics of the transient signals of interest. Here, L=4.8e6, M=100, N=24.

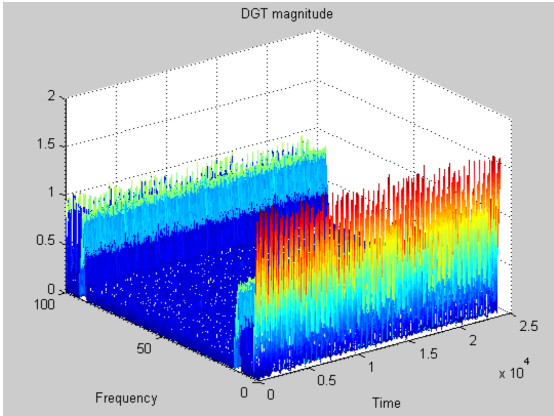

Fig. 2 Gabor transform of Two FM signal combination, C/N=10dB

The second example, a Blue-tooth FHSS signal source with 1600 hops every second is used to generate transient interferences and the distribution of Gabor coefficients in Time-Frequency platform under the environment of C/N is 10dB in Fig. 3. This result could show the transient signal detection capability and wide spectrum sensing capability of Gabor detector.

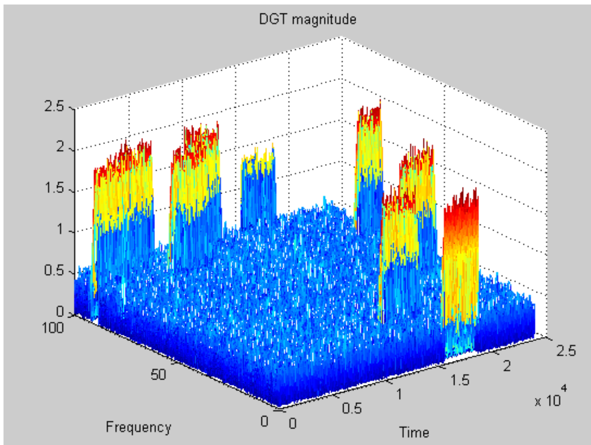

Fig. 3 Gabor Transform of FHSS, C/N=10dB

The third example, we study the weak signal detection in Gabor domain in low SNR environments. The signal source is also two FM signal combination, but with the different signal periods. We can see it is difficult to sense the spectrum and detect interference in the CNR below 10dB in Fig. 4. Here L=4800, M=100, N=24.

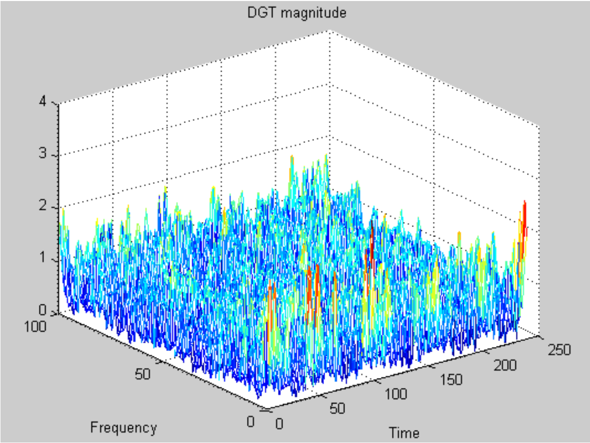

Fig. 4 Gabor transform of Two FM signal combination, C/N= -10dB

5 Conclusion

In this paper, we present detection schemes based on a time-frequency representation of the signal and likelihood ratio detectors based on GLRT approaches, where the decision function is constructed as a GLRT on the transform domain coefficients. A framework for non-parametric transient detection in the TF frequency domain is based on a Gabor domain representation of the transient signals. The Gabor transform is a linear transform using windowed complex exponentials as the basis functions. The familiar Gaussian function is used as the window function in the Gabor transform.

References

[1] G. Ganesan and Y. G. Li, "Cooperative spectrum sensing in cognitive radio networks", *in Proc. IEEE Symp, New Frontiers in Dynamic Spectrum Access Networks (DySPAN'05)*, Baltimore, USA, Nov. 8-11, 2005, pp. 137-143.

[2] Gang Zhou, John A. Stankovic and Sang F. Son, "Crowded Spectrum in Wireless Sensor Networks", *IEEE EmNets 2006*, Cambridge, MA, May 2006.

[3] S.M. Mishra, A. Sahai, R. W. Brodersen, "Cooperative Sensing among Cognitive Radios", *ICC 2006*, Istanbul, June 11-14, 2006

[4] A. Sahai, R. Tandra, N. Hoven, S. M. Mishra, "Sensing for Communication: A case for Cognitive Radios", *44th Annual Allerton Conference on Communication, Control, and Computing,* Sept 27-29, 2006

[5] A. Sahai, R. Tandra, and N. Hoven, "Opportunistic spectrum use for sensor networks: the need for local cooperation", *In Proceedings of Information Processing in Sensor Networks (IPSN 2006)*.

[6] D. Čabrić, A. Tkachenko, R. W. Brodersen, "Spectrum Sensing Measurements of Pilot", Energy and Collaborative Detection, *IEEE Milcom 2006*, Oct 23-25, 2006

[7] D. Cabric, A. Tkachenko and R. W. Brodersen, "Experimental study of. spectrum sensing based on energy detection and network cooperation", *IEEE MILCOM 2006*.

[8] S. Kadambe, R. Orr, "Application of Gabor analysis for detection, estimation and classification of underwater acoustic data", *29th Asilomar Conference on Signals, Systems and Computers (2-Volume Set)*, Asilomar, pp.569, 1995

[9] Z. Tian and G. B. Giannakis, "A wavelet approach to wideband spectrum sensing for cognitive radio", *in International Conf on CROWNCOM,* Greece, June 2006

[10] B.Friendlander and B.Porat, "Detection of transient signals by the Gabor representation",*IEEE Trans. on Acoust., Speech, Signal Processing*, vol. 37, no.2, pp. 169-179, Feb.1989.