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A Cluster Based Selective Cooperative Spectrum Sensing Technique for Cognitive Radio Network

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ABSTRACT

Cognitive radio (CR) has been recently proposed as a promising technology to improve spectrum utilization by enabling secondary access to unused licensed bands. A prerequisite to this secondary access is having no interference to the primary system. This requirement makes spectrum sensing a key function in cognitive radio systems. Among common spectrum sensing techniques, energy detection is an engaging method due to its simplicity and efficiency.

The growing demand of wireless applications has put a lot of constraints on the usage of available radio spectrum which is limited and precious resource. Cognitive radio is a promising technology which provides a novel way to improve utilization efficiency of available electromagnetic spectrum. In this paper, a cluster-based optimal selective CSS scheme is proposed for reducing reporting time and bandwidth while maintaining a certain level of sensing performance. Clusters are organized based on the identification of primary signal to-noise ratio value, and the cluster head in each cluster is dynamically chosen according to the sensing data qualities of CR users.

The cluster sensing decision is made based on an optimal threshold for selective CSS which minimizes the probability of sensing error. A parallel reporting mechanism based on frequency division is proposed to considerably reduce the time for reporting decision to fusion center of clusters. In the fusion center, the optimal Chair-Vashney rule is utilized to obtain a high sensing performance based on the available cluster's information.

Keyword-- Cooperative spectrum sensing, Cluster, Selective combination, Parallel reporting mechanism

I. INTRODUCTION

The idea of cognitive radio is first presented officially in an article by Joseph Mitola and Gerald Q. Maguire, Jr. [1]. It is a novel approach in wireless communications that Mitola later describe in his PhD dissertation as: "The point in which wireless Personal Digital Assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs."

It is thought of as an ideal goal towards which a software-defined radio platform should evolve: a fully reconfigurable wireless black-box that automatically changes its communication variables in response to network and user demands.

The above citation originates from the following fact. On one hand, the growing number of wireless standards is occupying more and more naturally limited frequency bandwidth for exclusive use as licensed bands. However, large part of licensed bands is unused for what concerns a large amount of both time and space: even if a particular range of frequencies is reserved for a standard, at a particular time and at a particular location it could be found free. The Federal Communication Commission (FCC) estimates that the variation of use of licensed spectrum ranges from 15% to 85%, whereas according to Defense Advanced Research Projects Agency (DARPA) only the 2% of the spectrum is in use in US at any given moment. It is then clear that the solution to these problems can be found dynamically looking at spectrum as a function of time and space.

With the high demand of bit transmission rate for 4G or IMT-advanced high-speed wireless applications, there are several approaches to increase the system capacity as stated in the following equation:

$$C = n\,B\log_2(1+SNR) \quad (1)$$

The first approach is using MIMO to increase *n*, so that capacity may have a gain proportionally. The second approach is trying to increase *SNR*. The third one is focusing on the bandwidth. Cognitive radio is among the third category, and thrives to fully utilize the frequency.

1.2 Functionalities of Cognitive Radios

The main functionalities of cognitive radios are [2]:

Spectrum Sensing (SS): detecting the unused spectrum and sharing it without harmful interference with other users, it is an important requirement of the cognitive Radio network to sense spectrum holes, detecting primary users is the most efficient way to detect spectrum holes. Spectrum sensing techniques can be classified into three categories:

Transmitter detection: cognitive radios must have the capability to determine if a signal from a primary transmitter is locally present in a certain spectrum, there are several approaches proposed:

- Matched filter detection
- Energy detection
- Cyclostationary feature detection

Cooperative detection: refers to spectrum sensing methods where information from multiple cognitive radio users is incorporated for primary user detection.

- Interference based detection.

Spectrum Management (SMa): Capturing the best available spectrum to meet user communication requirements. Cognitive radios should decide on the best spectrum band to meet the quality of service requirements over all available spectrum bands, therefore spectrum management functions are required for cognitive radios, these management functions can be classified as: spectrum analysis and spectrum decision.

Spectrum Mobility (SMo): is defined as the process when a cognitive radio user exchanges its frequency of operation. Cognitive radio networks target to use the spectrum in a dynamic manner by allowing the radio terminals to operate in the best available frequency band, maintaining seamless communication requirements during the transition to better spectrum.

Spectrum Sharing (SSh): providing the fair spectrum scheduling method, which is one of the major challenges in open spectrum usage is the spectrum sharing. It can be regarded to be similar to generic media access control MAC problems in existing systems.

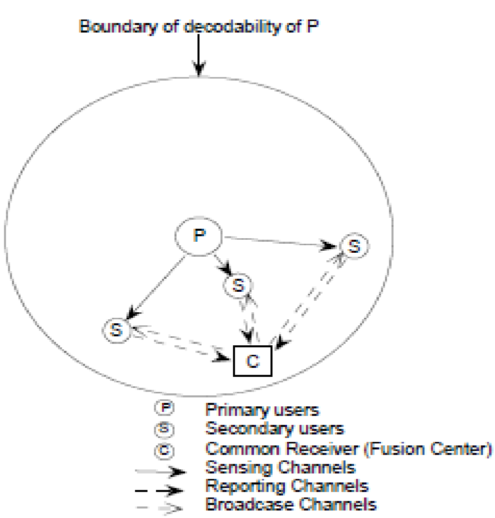

Figure 1 A typical cognitive radio network

1.3 Individual and Cooperative Spectrum Sensing

Spectrum sensing can be conducted either non-cooperatively (individually), in which each secondary user conducts radio detection and makes decision by itself, or cooperatively, in which a group of secondary users perform spectrum sensing by collaboration. No matter in which way, the common topology of such a cognitive radio network can be depicted as in Figure 1. Individual spectrum sensing is conducted by secondary users on its own, and each user has a local observation and a local decision accordingly. Thus, in Figure 1, each secondary user performs the spectrum sensing locally and no communication is between one another, nor is the common receiver (fusion center). In such a condition, cognitive radio sensitivity can only be improved [3] by enhancing radio RF front-end sensitivity, exploiting digital signal processing gain for specific primary user signal, and network cooperation where users share their spectrum sensing measurements. However, if the sensing channels are facing deep fading or shadowing, then affected individuals will not be able to detect the presence of the primary user, which leads to missing detection failure.

In order to improve the performance of spectrum sensing, several authors have recently proposed cooperation among secondary users [4, 5, 6, and 7]. Cooperative spectrum sensing has been proposed to exploit multi-user diversity in sensing process. It is usually performed in three successive stages: sensing, reporting and broadcasting. In the sensing stage, every cognitive user performs spectrum sensing individually. This can be shown as in Figure 1, where secondary users try to collect the signal of interest through sensing channels. In the reporting stage, all the local sensing observations are reported to a common receiver via reporting channels and the latter will make a final decision on the absence or the presence of the primary user.

Finally, the final decision is broadcasted via broadcast channels to all the secondary users concerned, which include not only the ones involved into the sensing stage, but also those that do not have sensing capabilities but want to participate into the spectrum sharing stage. There are several advantages offered by cooperative spectrum sensing over the non-cooperative ones [6, 8, 9]. If a secondary user is in the condition of deep shadowing and fading, it is very difficult for a secondary user to distinguish a white space from a deep shadowing effect. Therefore, a non-cooperative spectrum sensing algorithm may not work well in this case, and a cooperative scheme can solve the problem by sharing the spectrum sensing information among secondary users. Moreover, because of the hidden terminal problem, it is very challenging for single cognitive radio sensitivity to outperform the primary user receiver by a large margin in order to detect the presence of primary users. For this reason, if secondary users spread out in the spatial distance, and any one of them detects the presence of primary users, then the whole group can gain benefit by collaboration.

Authors of [10] quantify the performance of spectrum sensing in fading environments and study the effect of cooperation. The simulation results in [10] indicate that significant performance enhancements can be achieved through cooperation. Authors of [9] study the possibility to forward the signal with higher SNR to the one on the boundary of decidability region of the primary user. The performance is evaluated under correlated shadowing and user compromise in [8]. When the exchange of observations from all secondary users to the common receiver is not applicable, authors of [11] show that it is still worth doing by cooperating a certain number of users with relatively higher SNR. Moreover, in [12], a linear-quadratic (LQ) fusion strategy is designed with the consideration of the correlation between the nodes. In order to further reduce the computational complexity, authors of [13] propose a heuristic approach so as to develop an optimal linear framework during cooperation. Sensing-throughput tradeoff is analyzed in [14] for both multiple mini-slots and multiple secondary users cooperative sensing.

II. SIGNAL PROCESSING TECHNIQUES FOR SPECTRUM SENSING

Spectrum sensing (SS) is the procedure that a cognitive radio user monitors the available spectrum bands, captures their information, reliably detects the spectrum holes and then shares the spectrum without harmful interference with other users. It still can be seen as a kind of receiving signal process, because spectrum sensing detects spectrum holes actually by local measurement of input signal spectrum which is referred to as *local spectrum sensing*. The cognitive users in the network don't have any kind of cooperation. Each CR user will independently detect the channel through continues *spectrum sensing*, and if a CR user detects the primary user it would vacate the channel without informing the other CR users.

The goal of *spectrum sensing* is to decide between the following two hypotheses:

H_0: Primary user is absent

H_1: Primary user is present in order to avoid the harmful interference to the primary system.

A typical way to detect the primary user is to look for primary transmissions by using a signal detector. Three different signal processing techniques that are used in the systems are *matched filter*, *energy detector* and *feature detection*. In the next subsections we discuss advantages and disadvantages about them.

2.1 Matched Filter

The optimal way for any signal detection is a *matched filter* [15]. It is a linear filter which maximizes the received signal-to-noise ratio in the presence of additive stochastic noise. However, a matched filter effectively requires demodulation of a primary user signal. This means that cognitive radio has *a priori* knowledge of primary user signal X[n], such as modulation scheme, pulse shaping, and packet format. Such information must be pre-stored in CR memory, but the inconvenience part is that for demodulation it has to achieve coherency with primary user signal by performing timing and carrier synchronization, even channel equalization. This is still possible since most primary users have pilots, preambles, synchronization words or spreading codes that can be used for coherent detection, for examples: TV signals has narrowband pilot for audio and video carriers; CDMA systems have dedicated spreading codes for pilot and synchronization channels; OFDM packets have preambles for packet acquisition. If X[n] is completely known to the receiver then the optimal detector is:

$$T(Y) = \sum_{n=0}^{N-1} Y[n]X[n] \mathop{\gtrless}_{H_0}^{H_1} \gamma \qquad (2)$$

Here γ is the detection threshold.

Then the number of samples required for optimal detection is:

$$N = [Q^{-1}(P_D) - Q^{-1}(P_{FD})]^2 (SNR)^{-1} = O(SNR^{-1}) \qquad (3)$$

Where P_D and P_{FA} are show as the probabilities of detection and false detection. The main advantage of *matched filter* is that due to coherency it requires less time to achieve high processing gain since only $O(SNR^{-1})$ samples are needed to meet a given probability of detection. However, a significant drawback of a matched filter is that a cognitive radio would need a dedicated receiver for every primary user class.

2.2 Energy Detector

One approach to simplify matched filter approach is to perform non-coherent detection through *energy detection* [15]. The structure of an energy detector is shown in Figure 2.

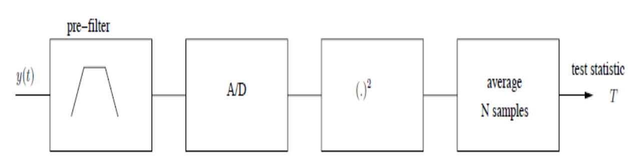

Figure 2.Block diagram of an Energy Detector.

It is a sub-optimal detection technique and it has been proved to be appropriate to use it to determine the presence of a signal in the absence of much knowledge concerning the signal. In order to measure the energy of the received signal the output signal of band pass filter with bandwidth W is squared and integrated over the observation interval T. Finally the output of the integrator is compared with a threshold to detect if the primary or licensed user is present or not. However, due to non-

coherent processing $O(SNR^{-2})$ samples are required to meet a probability of detection constraint.
In this case we have:

$$T(Y) = \sum_{n=0}^{N-1} Y^2[n] \gtrless_{H_0}^{H_1} \gamma \qquad (4)$$

$$N = 2[Q^{-1}(P_{FA}) - Q^{-1}(P_D)]^2 = O(SNR^{-2}) \qquad (5)$$

There are several drawbacks in using *energy detection*. First, a threshold used for primary user detection is highly susceptible to unknown or changing noise levels. Even if the threshold would be set adaptively, presence of any in-band interference would confuse the energy detector. Furthermore, in frequency selective fading it is not clear how to set the secondary the threshold with respect to channel notches. Second, since the *energy detection* is only concerned with the energy of the incoming signal, it does not differentiate between modulated signals, noise and interference. Since, it cannot recognize the interference, it cannot benefit from adaptive signal processing for cancelling the interferer. Furthermore, spectrum policy for using the band is constrained only to primary users, so a cognitive user should treat noise and other secondary users differently. Lastly, energy *detection* does not work for spread spectrum signals: direct sequence and frequency hopping signals, for which more sophisticated signal processing algorithms, need to be devised.

2.3 Feature Detection

An alternative method for the detection of primary signals is *Cyclo-stationary Feature Detection* [6] in which modulated signals are coupled with sine wave carriers, pulse trains, repeated spreading, hopping sequences, or cyclic prefixes. This results in built-in periodicity. These modulated signals are characterized as cyclo-stationary because their mean and autocorrelation exhibit periodicity. This periodicity is introduced in the signal format at the receiver so as to exploit it for parameter estimation such as carrier phase, timing or direction of arrival.

These features are detected by analyzing a *spectral correlation function SCF*. The main advantage of this function is that it differentiates the noise from the modulated signal energy. This is due to the fact that noise is a wide-sense stationary signal with no correlation however modulated signals are cyclo-stationary due to embedded redundancy of signal periodicity.

Analogous to autocorrelation function spectral correlation function (SCF) can be defined as:

$$S_x^{\alpha}(f) = \lim_{T\to\infty} \lim_{\Delta t\to\infty} \int_{-\Delta t/2}^{+\Delta t/2} \frac{1}{T} X_T(t, f + \tfrac{\alpha}{2})\, X_T^*\Big(t, f - \alpha 2dt, \qquad (6)$$

Where the finite time Fourier transforms is given by:

$$X_T(t, v) = \int_{t-T/2}^{t+T/2} x(u) e^{-j2\pi v u}\, du \qquad (7)$$

Spectral correlation function (SCF) is also known as cyclic spectrum. While power spectral density (PSD) is a real valued one dimensional transform, SCF is a complex valued two dimensional transform. The parameter α is called the cycle frequency. If $\alpha = 0$ then SCF gives the PSD of the signal. Because of the inherent spectral redundancy signal selectivity becomes possible. Analysis of signal in this domain retains its phase and frequency information related to timing parameters of modulated signals. Due to this, overlapping feature in power spectral density are non-overlapping feature in cyclic spectrum. Hence different types of modulated signals that have identical power spectral density can have different cyclic spectrum. Because of these entire properties cyclo-stationary feature detector can perform better than energy detector in discriminating against noise. However it is computationally complex and requires significantly large observation time.

III. LOCAL SPECTRUM SENSING LIMITATIONS

Since cognitive radios are considered lower priority or secondary users of spectrum allocated to a primary user, a fundamental requirement is to avoid interference to potential primary users in their vicinity. On the other hand, primary user networks have no requirement to change their infrastructure for spectrum sharing with cognitive networks. Therefore, cognitive radios should be able to independently detect primary user presence through continuous *spectrum sensing*.

Although interference theoretically only happens at receivers, it is difficult for CR to have direct measurement of the communication link between primary trasmitter and receivers. Consequently because of the complex wireless environment and uncertainness of the locations of primary receivers, the CR must have high sensitivity that outperforms primary user (PU) receivers by a large margin in order to prevent *hidden terminal problem*.

Hidden terminal problem occurs when the cognitive radio is shadowed, in severe multipath fading, or inside buildings with high penetration loss while in a close neighborhood there is a primary user whose is at the marginal reception, due to its more favorable channel conditions. Consequently, the cognitive radio would cause interference to such primary user. Therefore the spectrum sensing performance under low signal-to-noise (SNR) is crucial for above reason.

These results in a complexity detection of primary activity that can be related by the tradeoff between false alarm probability and missing detection probability: high false alarm probability produces low spectrum utilization; high missing detection probability increases interference to primary user.

From above discussion we can see that *local spectrum sensing* can never surpass its limitation on detecting weak signal. Hence *Cooperative Spectrum Sensing* (CSS) is needed for improving spectrum utilization and the detection ability of CR nodes especially under low SNR situations.

IV. CONCLUSION

We have proposed a cluster-based CSS scheme which includes the selective method in the cluster and the optimal fusion rule in the FC. The proposed selective combination method can dramatically reduce the reporting time and energy consumption while achieving a certain high level of sensing performance especially when it is combined with the proposed frequency division-based parallel reporting mechanism.

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